Proposal in Response to PWGSC Solicitation No. 9F007-09-0217/A, RFP File No. MTB-9-30283 (575)

PHEMOS Category B - GeoSpace Imaging

Global Auroral Imaging on PCW

Section I : Technical and Managerial Bid
Phase 0/A

The Ultra Violet Imagers (PCW-UVI) are a proposed secondary science payload for the Polar Communications and Weather (PCW) mission. PCW-UVI would build on Canada's successful auroral imaging heritage, take optimum advantage of the PCW mission, and provide the best global auroral imaging ever achieved. Specifically, PCW-UVI would provide the first ever 24/7 view of the entire auroral oval and polar cap, the first ever real-time global auroral images, and the best ever temporal and spatial resolution images of the aurora from space. These images would enable world-class science both stand-alone and in coordination with data from other programs, and PCW-UVI would complement virtually all other major Geospace initiatives worldwide.

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PCW-UVI

Canada's Eye on the Northern Sky

University of Calgary • Routes AstroEngineering Ltd.

2 Executive Summary

The (planned) Canadian Polar Communications and Weather (PCW) satellite program will carry out imaging of polar tropospheric weather. PCW will fill an important gap in the international tropospheric imaging capability, and in addition will provide high bandwidth communications to the North. Through PCW, Canada will be asserting Arctic sovereignty, supporting operations in the Canadian Arctic, supporting ongoing climate change research, and through additional instruments enhancing Canadian space weather capabilities.

The objectives of the primary PCW mission include long-term "24/7" imaging and communications with everywhere above 45º geographic latitude [*Garand et al., PCW User Requirements Document, 2008*]. This will be achieved by two three-axis stabilized satellites on Molniya (northern apogee) orbits, with the satellites relatively phased so that when one is at apogee, the other is at perigee. The satellites will carry a primary payload consisting of communications, meteorological, and space weather instruments. An AO has been released inviting proposals for Phase 0/A studies for contributions to a secondary payload under three categories, including Category B for "Geospace Imaging".

The solar wind interacts with Earth's magnetic field, creating a region of space around our planet called the magnetosphere. Processes within the magnetosphere are interesting because they affect our environment, and as exemplars of fundamental phenomena that happen in plasmas in more distant cosmic systems. One consequence of these "Geospace" processes is the aurora, which is a projection, along magnetic field lines, of the dynamics and structure of the magnetosphere. Auroral imaging is our most effective way of remote sensing magnetospheric dynamics and structure, and provides information essential for studies of auroral electrodynamics and magnetosphere-ionosphere coupling, for specification of space weather, and for understanding how space weather affects Earth's upper atmosphere and technological systems.



Figure 1 (from left): the solar wind is constantly expanding outwards through space (SOHO solar wind image); interactions between the solar wind and Earth's magnetic field form the magnetosphere (schematic in middle panel); magnetospheric dynamics create and impress the aurora on the Earth's atmosphere (northern hemisphere image of the aurora from IMAGE FUV).

This **Category B (Geospace Imaging) proposal** is for a Phase 0/A study to develop a technology roadmap and initial design for UltraViolet Imagers (UVIs) to be flown on both PCW satellites. The **overall "PCW-UVI" objectives** are to image the global northern hemisphere aurora and to use those data, both stand-alone and with data from other projects, to answer questions at the forefront of space physics. PCW-UVI would also contribute to understanding how space weather impacts the atmosphere and technological systems.

PCW would enable better space-based global auroral imaging than has ever been achieved. The satellites will not be spinning, so platform-related problems that have plagued all global auroral imaging programs will not apply. Nadir pointing imagers on PCW would provide the highest spatial and temporal resolution global auroral image sequences ever obtained, with excellent pointing, and out-of-band rejection enabling the best daylight suppression and LBHL and LBHS isolation ever achieved. Imagers on both PCW satellites would provide the first ever 24/7 view of the entire auroral oval and polar cap, as well as the first ever real time global auroral images. The target spatial and temporal resolutions are 40 km and 20 s, respectively, and the 24/7 observing would be sustained for the anticipated six year duration of PCW, starting from the planned launch in 2016.

The **science innovations** that would be enabled by PCW-UVI are significant and numerous, including the following. Stand-alone PCW-UVI data would be transformational for our understanding of the aurora as a multi-scale phenomenon. The high time and space resolution image sequences would allow significantly better specification of the distribution of auroral scale sizes than ever before, and for studies of how "scaling parameters" vary in time. Relative LBHL and LBHS intensities would identify the spatial distribution of different auroral acceleration mechanisms, and how that distribution evolves in time. PCW-UVI would provide the first sequences of global auroral images spanning long duration geomagnetic disturbances such as magnetic storms, providing the most comprehensive physical picture of those disturbances ever obtained. Spatial and temporal variations in the global auroral distribution would be used to investigate magnetotail instabilities, and to test the validity of simulations of magnetotail dynamics.

PCW-UVI data, used with observations from other initiatives, would impact virtually every aspect of Geospace science. It is literally not possible to list all the examples of world-class coordinated studies that would utilize PCW-UVI data. The timeframe 2016-2022 will be an exciting one in terms of major Geospace initiatives. New missions that will certainly or very likely be flying at the time include Swarm, MMS, Scope, and KuaFu. Ongoing and likely enhanced ground-based initiatives during that period will include CGSM, AMISR, and international SuperDARN. The combination of PCW-UVI and these programs will place the space physics community in an unprecedented position from which to simultaneously observe the geospace at the system-level and the details of smaller-scale physical processes through which coupling and mass and energy transport within geospace are achieved. From this perspective, PCW-UVI would play a critical role in determining the roles of processes like magnetic reconnection in the large-scale geospace dynamics, in investigations of interactions between large Geospace sub-systems such as the central plasma sheet and ring current, and how auroral precipitation affects the upper atmosphere.

The high time and space resolution, out of band rejection, and wavelength isolation that are being proposed for PCW-UVI would give rise to challenges that will require **technical innovations**. These innovations would include accomplishing far-ultraviolet filtering via thin films on optical surfaces, achieving focus and alignment utilizing a three-mirror system, and the selection of an appropriate window and photocathode. The most challenging **technical objectives of the** Phase 0/A studies are as follows:

1. Use PCW-UVI science goals to establish measurement objectives and requirements;
2. Develop a PCW-UVI technical roadmap and preliminary instrument design;
3. Establish the PCW-UVI data needs and preliminary interface requirements for PCW;
4. Identify potential suppliers of all PCW-UVI components;
5. Identify and plan for mitigation of risks;
6. Plan for PCW-UVI for Phases B-D, including budget estimates, and milestone identification;
7. Establish the roles of all partners in the PCW-UVI project for Phases B-D.

Specific **technical risks** for PCW-UVI that would be addressed during the proposed PCW-UVI Phase 0/A study include potential difficulties in acquiring key components, potentially significant radiation exposure on the Molniya orbit, implications of wide field of view on optical design, and challenges related to optical focus. These are in addition to standard risks like observing requirements that might lead to unreasonable mass/power/telemetry needs (although that would be dealt with by reassessing science requirements).

Major **milestones and deliverables** of the proposed PCW-UVI study would include specification of PCW-UVI science objectives and user needs, preliminary PCW-UVI interface requirements, PCW-UVI conceptual design, and PCW-UVI preliminary cost and schedule estimates (Phase 0), and PCW-UVI mission and science payload/systems requirements, and the mission development plan (Phase A).

In summary, the two three-axis stabilized PCW satellites in Molniya orbits are an ideal platform for such an auroral imaging mission, and so PCW-UVI would be taking the absolute optimum advantage of PCW. PCW-UVI would build on Canada's heritage of auroral imaging, and provide the best global auroral imaging ever achieved, 24/7, and in real time. These data would produce world-class science both stand-alone and in coordination with data from other contemporaneous programs, and PCW-UVI would compliment all other major Geospace initiatives worldwide. PCW-UVI would have the impact of a stand-alone major geospace mission, for the incremental cost of just the instruments.

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4 Scientific Objectives and Impact

4.1 Scientific Objectives, Originality and Impact

The Polar Communications and Weather (PCW) Satellites will be a two satellite mission designed to provide continuous polar weather imaging and communications. The PCW satellites will be on Molniya orbits, phased so that when one is at apogee the other is at perigee. The highly elliptical Molniya orbits guarantee continuous viewing of everywhere above 50º geographic. Apogee is maintained at the highest latitude, guaranteeing the duration of excellent imaging and communications will not be limited by precession of the line of apsides. The weather imaging and polar communications require three-axis stabilization and excellent pointing accuracy.

We are proposing an Ultraviolet auroral Imaging (UVI) secondary science payload for PCW that will take maximum advantage of the orbital configuration, three-axis stabilization, and pointing accuracy to provide the first-ever continuous stream ("24/7") of global[1] auroral images with the best spatial resolution, cadence, isolation of two FUV bands, and daylight suppression ever obtained.

PCW is a dream platform for global auroral imaging from space. The quality of PCW-UVI data will be unique in the history of space physics and relevant to essentially all geospace research. PCW-UVI comes at the ideal time given the planned international mission lineup, and the fact that there are no plans for global auroral imaging, except by KuaFu[2], during that time. PCW-UVI complements Canadian initiatives including CGSM, FDAM, and RISR-C, and is relevant to all geospace themes in planning documents such as 2009 Space Environment Workshop Report (SEW2009). Internationally, PCW-UVI will overlap with missions including Swarm, THEMIS, MMS, RBSP, Swarm, and potentially ADEx, Scope, CrossScale, Kuafu, and EAGLES. The PCW-UVI imager data will be used, for example,

- with *in situ* observations (e.g., THEMIS, RBSP, ADEx, MMS, etc.) in studies of how aurora relates to magnetospheric dynamics, and of the role of smaller-scale processes in larger-scale geospace dynamics;
- with observations from RISR and EISCAT to investigate how dayside processes couple to convection and other dynamics in the cusp/cleft and polar cap regions;
- with synoptic ground-based observations to provide a global picture of ionospheric convection, currents, and aurora, and how they change in response to solar wind and magnetospheric variations.
- with Swarm data to explore the relationship between currents, Poynting flux, and aurora;
- by modelers to constrain and/or test global simulations;
- to track the spatio-temporal evolution of the magnetospheric system, as projected along magnetic field lines, during long-duration processes such as storms, SMCs, and "sawtooth" events.
- to quantify the auroral energy input into the upper atmosphere;
- with observations from *in situ* low-energy ion detectors and/or ENA images from high-altitude satellites to explore the relationship between aurora and ion outflow;
- to provide important information about the state of the geospace for virtually all "event"-type studies during PCW.

In the remainder of this section we briefly discuss *system-level* geospace investigations, and the lineup of relevant geospace missions during the PCW era. We then present our science objectives which fall under the overarching theme of **making global connections in geospace,** describe the data needed to deliver our science, and provide a preliminary list of data products. We discuss the prospects for remarkably extensive use of our auroral image data, supported by letters from prominent independent researchers including the PIs of MMS, THEMIS, ADEx, Scope, as well as the RBSP program scientist. Most of our science will be derived by using the auroral data together with observations from other projects. From our view, this is indicative of PCW-UVI being a *facility class* project at the heart of a rich international effort to address long standing issues in geospace science.

Early on, it was discovered that geospace sub-systems interact with each other, and that larger-scale processes are powered by radiation and the solar wind. *Dungey* [1961] and *Axford and Hines* [1961] led the way, proposing theories of global convection powered by magnetic reconnection and viscous interactions. The objectives of the

[1] Note that we use the term "global" to refer to everywhere above a specified latitude.
[2] We are proposing a much better auroral imaging program than KuaFu, If our proposed PCW payload goes forward, then KuaFu would be re-profiled to focus on southern hemisphere imaging or by dropping the auroral imaging altogether.

International Solar Terrestrial Physics[3] (ISTP) program were to identify energy and mass pathways through geospace, quantify their effects, and to understand the underlying physics (*Acuña et al.*, [1995]). Figure 4.1 represents this overarching concept of smaller-scale plasma processes mediating energy and mass transport from the solar wind and through geospace.

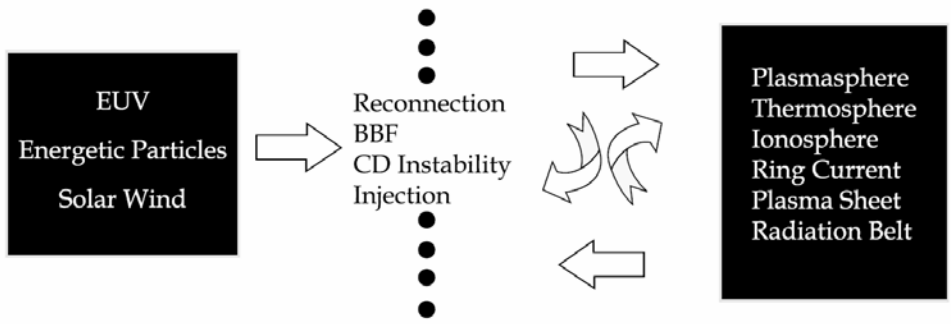


Figure 4.1: Energy and mass enters geospace from the Sun and solar wind. Physical processes affect mass and energy transport through geospace, and how it is divided and deposited in sinks (right box). These sinks interact with each other through physical processes. In this way, geospace is active, and much of the observed dynamics are intrinsic to the system rather than impressed upon it. Figure from *Donovan et al.* [2007].

Geospace energy and mass transport requires simultaneous solar input, geospace system-level[4] information, as well as *in situ* observations. *In situ* contributions in the equatorialplane target the processes and gradients such as reconnection or boundaries, while system-level measurements are used to quantify effects on elements like the ionosphere and the Central Plasma Sheet (CPS). This "telescope-microscope" approach [*Baker et al.* 2002] motivated the choice of instruments and orbits in the ISTP constellation. Cluster, Geotail, and Polar provided direct observations of small-scale processes, and the system-level view came from imagers on Polar and extensive networks of ground-based instruments (see e.g., the ISTP special issue, *Space Science Reviews,* 71:1-877). Presently increasing focus is being paid to the system-level geospace approach, where different tools simultaneously probe processes on different scales. This figures highly, for example, in the Executive Summary (page v) of the NASA 2009 Heliophysics Roadmap[5] (herein NASA2009). It is interesting to contemplate the geospace missions planned for the 2012-2016 Canadian Polar Communications and Weather (PCW) satellites era. Figure 4.2 shows the geospace mission lineup based on information from various sources including NASA2009.

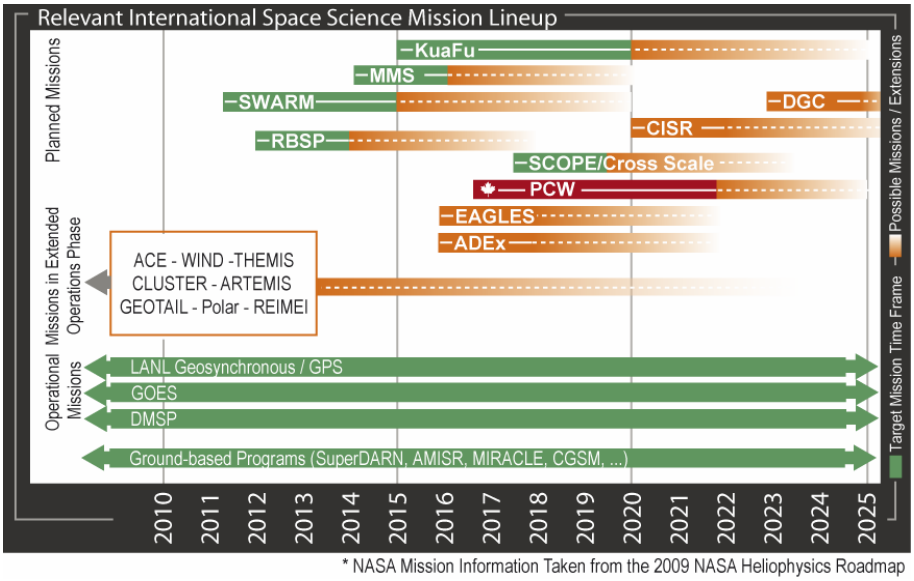


Figure 4.2: Geospace mission lineup. Green and orange indicate approved and proposed (or extended) missions.

[3] This applies also to the subsequent International Living With a Star (ILWS) program.
[4] This can be thought of as synoptic and/or large (even global) scale.
[5] See http://sec.gsfc.nasa.gov/sec_roadmap.htm

We point out four missions specifically, as acronyms/scenarios of the others are part of the lexicon of our field. ADEx (Auroral Dynamo Explorer) is a proposed NASA mission of 9 near-equatorial satellites with the objective of identifying the magnetospheric driver of auroral arcs (see Kepko letter). CISR (Climate Impacts of Space Radiation) is LWS science target #7 in the NASA Roadmap with a yet to be identified mission. DGC (Dynamic Geospace Coupling) is another Roadmap science target (LWS #8), aimed at imaging multiple geospace systems (e.g., the inner CPS and the aurora) simultaneously. EAGLES is a proposed Mission of Opportunity that would carry out Energetic Neutral Atom (ENA) imaging from two geosynchronous satellites (see Brandt letter).

Between GOES, LANL, MMS, THEMIS, RBSP, and possibly Scope/CrossScale and ADEx, the PCW era promises the most comprehensive probing of the near-equatorial magnetosphere in history. There will be at least 15 and as many as 30 satellites giving us an unprecedented opportunity to investigate the smaller scale processes important in geospace. Surprisingly, no system-level observations (except the EAGLES ENA imaging) are planned for this timeframe. There is a risk that in spite of this remarkable armada, we will not know how these processes act across scales, how they fit into the larger dynamics, nor will we be able to address fundamental long-standing questions related to magnetosphere-ionosphere coupling and the aurora. **PCW-UVI will address this.**

Cross-scale coupling is critical to Geospace dynamics. Mid-tail magnetic reconnection involves spatial scales ranging from kinetic (diffusion region), to large-scale plasma transport and redistribution, such as during the substorm expansion phase. Bursty plasma jets and new plasma intrusions in the magnetotail provide another example of an intense cross-scale coupling associated with interplay between the size of the plasma bubble (typically 1-2 Re), the traveled distance (many Re), and the small-scale eddy turbulence at the boundaries of the plasma channel (fractions of Re). Near-Earth plasma sheet instabilities associated with current disruption are thought to begin at kinetic scales and propagate up to the global MHD scales in an inverse-cascade.

The future of geospace science will be defined by how well we understand primary mechanisms and basic phenomenology of cross-scale plasma coupling. Auroral observations will be crucial as they remain the only consistent source of instantaneous information on spatially separated but physically connected parts of the magnetosphere-ionosphere system. Most of the scientific results from THEMIS would not be possible without the spatiotemporal picture of moving, evolving, and interacting auroral forms provided by the All-Sky Imagers (ASIs) [see e.g., *Angelopoulos et al.,* 2008; *Kepko te al.,* 2009]. An innovative global auroral imaging mission, taking maximum advantage of the PCW mission design would be able to do this job even better.

Science Objective 1: Magnetospheric Drivers of Auroral Type, Structure, and Dynamics [**Obj.S1**]

In spite of the successes of the coordinated THEMIS *in situ* and auroral observations, there are significant limitations in our knowledge of connections between aurora and their magnetospheric drivers. Addressing this topic motivates our first science objective, work on which will enable more effective use of auroral observations to remote sense the magnetosphere, and answer fundamental questions about the physics of the aurora. There are two subthemes, the first of which is the establishment of one-one connections between specific aurora and magnetospheric counterparts, and involves questions exemplified by "**what is the magnetospheric counterpart of an auroral arc**?", "**is there an ionospheric signature of mid-tail reconnection?**", and "**what physical processes give rise to diffuse aurora?**"

These long-standing questions need to be resolved in order to establish a complete picture of auroral physics. There has been some headway on each. Comparisons of *in situ* plasma and magnetically conjugate ASI observations have hinted at a connection between sharp steps in CPS electron temperature and auroral arcs [*Borovsky, Cully, separate private communications*], and Field Line Resonance fields (thought to be associated with arcs) that have been observed *in situ* [*Sarris, et al.,* 2009]. Previous studies have ascribed the formation of arcs, auroral brightenings, and X-ray enhancements to mid-tail reconnection [e.g., *Ieda et al.*, 2001; *Sergeev et al.*, 2005; *Borg et al.*, 2007]. Recent theoretical work and *in situ* observations are making connections between plasma wave modes and pitch angle scattering that is ostensibly the cause of diffuse auroral precipitation [e.g., *Ni et al.,* 2008; *Liang et al.,* 2010]. The reality is, however, the connections that have been made between these aurora and their magnetospheric counterparts are tenuous. Difficulties include the subtlety of the magnetospheric effects and lack of simultaneous auroral arc observations, inadequate global scale observations and *in situ* measurements from single satellites that cannot adequately isolate magnetospheric effects like reconnection, and lack of simultaneous auroral and *in situ* measurements and the fact that there are a number of different types of diffuse aurora.

During the PCW timeframe, the Cluster-type geospace missions (e.g., MMS and Scope) will directly observe the gradients and reconnection. All geospace satellites will obtain point measurements of wave modes and reconnection effects, and the plasma conditions around sharp boundaries. The overall effect could approach that envisaged for Magnetospheric Constellation[6], with a fleet of satellites providing *in situ* observations of the plasma properties and dynamics related to aurora, with the required density (from the clusters) and extended coverage and quality of measurement (from all) to separate space and time effects and appropriately sample the magnetospheric counterparts to the sub-auroral, and auroral regions. One significant opportunity, for example, will be the first extensive probing of the transition region between stretched and dipolar field lines, a region which has been the focus of Canadian efforts to understand auroral physics [e.g., *Samson et al.,* 1992; *Knudsen,* 1996; *Rankin et al.*,2005]. PCW-UVI will make appropriate images of aurora magnetically conjugate to the *in situ* observations *always available*. We expect, with PCW-UVI in conjunction with contemporaneous *in situ* geospace observations, to bring closure to the three questions listed above, and usher in a new era of understanding **the relationship between auroras and their magnetospheric drivers.**

The connection between aurora and the magnetosphere complements our second subtheme**,** multi-scale processes in the magnetosphere-ionosphere system. There is growing interest in multi-scale analysis of auroral and other geospace data from which various scaling laws and inferences about the physics that underlies geospace dynamics have been made. One example is recent work showing the power law for the auroral spatial distribution depends on latitudinal position with the auroral oval, ostensibly pointing to different dynamical drivers in the inner and outer CPS [*Uritsky et al.,* 2009]. This type of "Natural Complexity" work is founded on the principles of statistical physics, and brings the concepts like Self Organized Criticality (SOC) to geospace science [e.g., *Watkins et al.,* 2001]. The auroral distribution offers us our best view across all relevant scales, but there are difficulties. There is a lack of simultaneous observations across all relevant scales, a lack of time series of such observations, limited understanding of the connections between aurora and their magnetospheric drivers (e.g., how much of the auroral structure is reflective of structure in the CPS?), and difficulties with bridging the gulf between complexity research and the more traditional "reductionist" geospace style.

Research under the first subtheme will better enable us to assess how well auroral structure reflects structure in the CPS. High quality auroral imaging during the PCW timeframe when the magnetospheric fleet discussed above is operating, will provide our community with an unprecedented opportunity to foster stronger ties between the traditional geospace community and the natural complexity community. We will take advantage of the PCW mission characteristics and design PCW-UVI to specifically address the lack of simultaneous auroral observations across all scales, and the lack of time series of those observations (see data subsection). These new auroral observations will allow us to use PCW-UVI to address and close exciting new questions related to multi-scale dynamics. Two examples of such questions are "**what are the dominating particle acceleration mechanisms operating at different spatial auroral scales?"** and "**how do the scaling parameters of the auroral oval (probabilistic scaling laws, structure function exponents, spatial power spectra) change with large-scale reconfigurations in the magnetosphere-ionosphere system as reflected by global geomagnetic indices (AU/AL/AE, Pc, Kp, Dst, etc.)?**"

Science Objective 2: Geospace Dynamic Coupling [Obj.S2]

We borrowed the name of this objective from the NASA2009. This objective will be realized with an innovative imaging strategy on PCW, carried out at the same time as *in situ* observations. We will address questions in three subthemes, the first being "solar wind driving of geospace dynamics". Dayside physical processes have a direct impact on magnetospheric and ionospheric dynamics through reconnection, surface waves, and other processes. Some of our best insights into these processes and their geospace effects have come from *in situ* observations near the magnetopause combined with radar and optical observations in the vicinity of the cusp [see e.g., *Amm et al.,* 2005, and references therein].

During PCW, the THEMIS, MMS, and possibly Scope/CrossScale missions will provide unprecedented multi-scale dayside magnetopause observations. The new PolarDARN and RISR radars will provide unprecedented, multi-scale observations of the convection response to the dayside processes. Finally, PCW-UVI will provide

[6] See http://stp.gsfc.nasa.gov/missions/mc/mc.htm

unprecedented multi-scale dayside auroral observations. The combined radar and optical observations would always be available complementary to *in situ* dayside observations, and would provide quantitative evidence of electric currents, dayside reconnection, and convection changes in response to dayside phenomena [see eg. *McWilliams et al.,* 2001; *Mozer et. Al.,* 2003; *Moen et al.,* 2008; *Hosakawa et al.,* 2010] Using this combination of observations, we will address specific questions including "**how do dayside conditions determine if magnetic reconnection is steady or bursty?**", "**how do dayside processes affect the formation of polar cap patches?**", "**how are poleward moving auroral forms produced?**" and "**what is the impact of solar wind turbulence on the polar cap plasma?**". Answers to these and related questions will provide insights into how dayside processes form structure in geospace plasmas, and drive magnetospheric dynamics.

The second subtheme is long-duration geomagnetic events. This subtheme was the original motivation for the Ravens mission as outlined in the Ravens Mission Concept and *Donovan et al.* [2007]. Every global imaging mission flown to date has utilized only a single satellite platform, which means that the longest duration global imaging achieved to date is around ten hours. However, many geospace events such as steady magnetospheric convection (SMS) events, sawtooth events, and geomagnetic storms last for many hours or even days (see e.g., *Yahnin et al.,* [1994], *Belian et al.,* [1995], and *Chapman and Bartels*, [1967], respectively). Consequently the system-level view that would be provided by PCW-UVI was not available for the durations of these events, limiting our ability to quantify, for example, energy deposition and magnetospheric state during those events.

PCW-UVI images will be continuously available for the duration of the mission. The auroral observations, in combination with radial cuts of the CPS/ring current (see e.g., Figures 2 and 3 of *Runov et al,* [2008]) by magnetospheric satellites including THEMIS, RBSP, and possibly ADEx, will allow us to determine the ionospheric projection of the earthward edge of the electron plasma sheet. Particularly at the inner edge of the plasma sheet, there is an interesting and not fully understood relationship between convection, flux tube energy content, precipitation, and the cross-tail, ring and Region II field-aligned currents. This is particularly interesting during extreme long-duration events such as storms, which have durations of several days or more. During these events, auroral activity moves equatorward to even mid-latitudes, and the CPS moves inward across the outer radiation belts, providing a seed population for the ring current, while at the same time plasmaspheric material is drawn outwards into the trough and inner CPS [see e.g., *Goldstein et al*., 2005; *Henderson et al*., 2010]. With continuous global auroral imaging we will be able to image such long-duration geomagnetic events end-end for the first time. We will be able to address questions including "**how does the CPS act as a seed population for the inner magnetosphere?**"

The possibilities for exploring the inner magnetospheric dynamics using PCW-UVI are dramatic, especially when one considers the possibility of simultaneous multi-point ENA observations from EAGLES, should that Mission of Opportunity be selected. ENA imaging is the only method we have at our disposal for imaging the 3D magnetospheric plasma pressure [see e.g., *Roelof et al.,* 1985; *Burch,* 2005]. The particle pressure distorts the geomagnetic field magnetic field and drives a 3D electrical current system that connects the magnetosphere with the ionosphere which can be inferred from the ENA images [see e.g., *Brandt, et al.*, 2008]. Note that while such combined imaging has been available before, the combination of PCW-UVI and EAGLES ENA would be the first time that such geospace imaging was available 24/7 and in 3D (for the ENA images from two geosynchronous satellites).

PCW UVI, together with EAGLES ENA imaging, will allow us to simultaneously image the auroral distribution and 3D magnetosphere. This capability, illustrated by ENA and UV images from IMAGE, is illustrated in Figure 4.3. If EAGLES and PCW-UVI are funded, we will be able to track the time-evolving auroral distribution and 3D inner magnetospheric plasma distribution through long-duration geomagnetic events. With this capability, we could address questions such as "**what is the role of the substorm in the storm?"** and "**how does O^+ of ionospheric origin affect geospace dynamics during long-duration geomagnteic events?"**

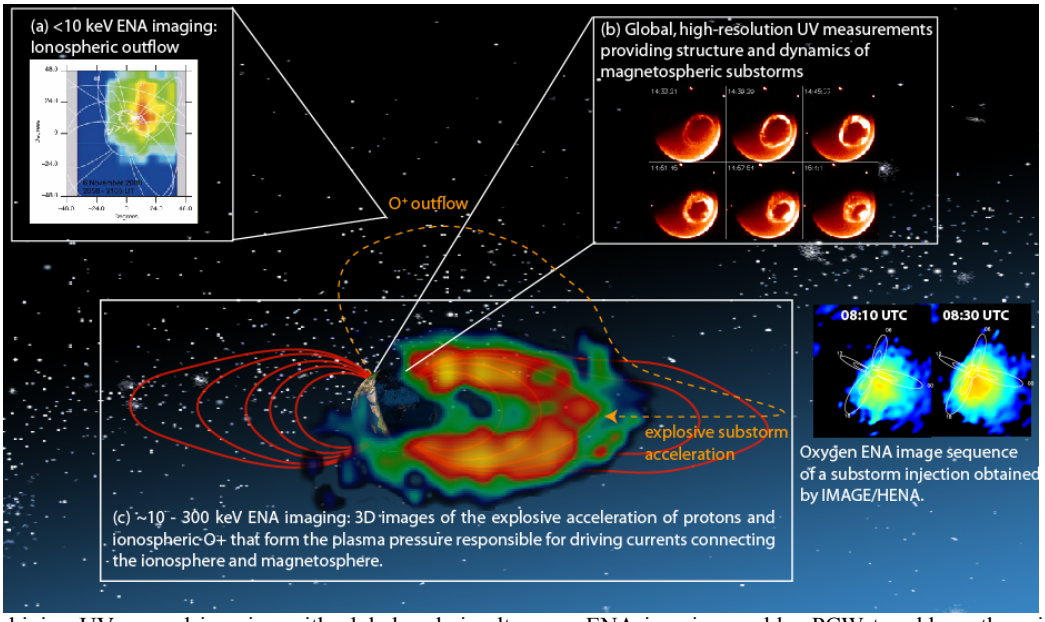


Figure 4.3: Combining UV auroral imaging with global and simultaneous ENA imaging enables PCW to address the critical question in space weather at the system-level for the first time.

Science Objective 3: Space Weather Effects on Climate [Obj.S3]

Our third science objective, which relates to the important environmental issue of ozone depletion in Earth's stratosphere, is our riskiest but potentially has the most societal impact. Nitrogen oxides (odd nitrogen) NO_x = NO + NO_2 are the dominant ozone-depleting substance [*Ravishankara et al.*, 2009]. A significant source of NO_x comes from energetic (including auroral) particle precipitation [*Funke et al.*, 2005; *Randall et al.*, 2007], which causes excitation, dissociation, and ionization of neutrals, generating odd nitrogen at high altitudes which is transported downward during the polar winter to the stratospheric ozone layer initiating its catalytic destruction. There have been no continuous global optical observations for tracing auroral zone NO_x generation over the extended periods relevant to the atmospheric response [*Lopez-Puertas et al.*, 2005]. NOAA POES is used for this, but infers the auroral power based on *in situ* measurements from polar passes separated by 100-minute time gaps. Without consistent quantitative global auroral data, evaluation of middle atmosphere chemistry climate models and isolating environmental NO_x effects is difficult.

We propose to use PCW-UVI for exploring linkage of solar variability, magnetospheric dynamics, and the chemical and climatological state of the middle atmosphere. PCW-UVI would give a total auroral power time series as well as the spatial distribution of precipitating auroral particles. Using estimates of mean energy and energy flux precipitation models would be used to generate NOx profiles in the MLT which would be used in CMAM to estimate impacts in the middle atmosphere [*Semeniuk et al.*, 2008]. Enhancement of NOx in the middle atmosphere may be apparent in enhanced HNO3 measured by PHEMOS-FTS in nadir viewing. There may be other limb viewing satellites such as PREMIER for vertical profiles. We will utilize data from PCW spectroradiometer LWIR channel (total ozone), national ozone monitoring programs around the world[7] and instruments on potential NASA[8], ESA[9], or CSA missions, and/or the potential PCW/PHEMOS FTS/UV-vis-NIR instrument to track the ozone response.

We will have time series of auroral input and ozone. We will use these measurements to study direct and indirect (delayed) response of odd nitrogen species in lower thermosphere and upper mesosphere to auroral precipitation events. Our objective will be to answer questions such as "**What is the typical time sequence, and what are the characteristic time scales, of the ozone depletion initiated by auroral precipitation events**?" and "**How does the position of a precipitation event affect the production of NO_x in a local and global sense, and which auroral regions provide the largest concentration of NO_x?"** Finally, using the data from solar wind and

[7] This includes Canada's Ozone and Ultraviolet Research and Monitoring (http://woudc.ec.gc.ca/e/ozone/ozone.htm)
[8] E.g., NASA's Earth Science Mission Profile plans for two Ozone Mapping and Profiler Suites during the next decade.
[9] E.g., ESA EOP MetOp series.

geosynchronous satellites, we will study the role of the solar wind driver, as well as relative contribution of ionization due to solar proton events, energetic electron precipitation, and low-energy electron precipitation to this process, to address the question **"Under what physical conditions does the auroral precipitation become the dominant factor for NO_x production?"**

This research would be a partnership between auroral researchers and atmospheric scientists, and could form the basis for a PHEMOS Science Payload incorporating elements from Category A and Category B. The results of proposed studies will be useful for evaluating and constraining global ozone depletion models including the odd nitrogen contribution, for exploring any influence it might have on climate and environment. They will also provide a better understanding of the relative importance of space weather factors and human activities in NO_x emissions, which could impact future political decisions involving protection of our planet`s ozone shield.

Science Objective 4: Space Weather Effects on Global Navigation Satellite Systems (GNSS) [Obj.S4]

Our fourth science objective is our most applied. Ionospheric range delays are the largest GNSS error source[10] [*Klobuchar,* 1996]. They are proportional to the free electron density along the signal path. These effects are reduced by applying an external model or differential processing. Such methods are not generally effective, however, during enhanced ionospheric activity [*Skone and Yousuf,* 2007].

Canadian efforts have focused on reducing the impact of auroral phenomena on GNSS. Auroral zone meters- to kilometers-scale irregularities cause rapid GNSSS signal phase and amplitude variations which can cause the loss of GNSS capabilities [*Smith et al.*, 2008]. During the past solar maximum such scintillation effects correlated with auroral events [*Skone,* 2001]. Lacking any real-time space weather warning service, surveyors in northern Canada used their own magnetometers in the field to measure auroral activity. Decisions regarding probability of a successful survey and whether to commit cost-intensive resources (e.g. helicopters and manpower) were based on the magnetic fluctuations observed. Other northern GNSS applications adversely affected by enhanced auroral activity include marine navigation – in support of Arctic mapping and hydrographic surveying initiatives – and wide area GNSS augmentation systems for commercial aviation.

The U. Calgary CANGIM[11] tracks GNSS effects of ionospheric auroral scintillations, but only at CANGIM stations [*Skone and Hoyle,* 2005]. We will compare PCW-UVI images and CANGIM assessment of ionospheric effects on GNSS to answer "**how does auroral type relate to the effect of auroral precipitation on GNSS accuracy?"** Our objective is to establish a basis for using auroral characteristics[12] as a proxy for GNSS risk due to ionospheric scintillations. This will form a basis for using PCW-UVI images to create a real-time space weather product. By entering their approximate location a GNSS user would be provided with a map of their GNSS satellite links (PRNs) affected and statistics for expected loss of signal lock, positioning error, etc., based on level of local ionospheric activity as inferred from the PCW-UVI images in real-time. Ultimately, our intention is to work with a Canadian GNSS manufacturer such as NovAtel Inc. to incorporate such a warning into a GNSS augmentation system capability.

The four science objectives and corresponding subthemes listed here represent investigations at the forefront of geospace science and are well aligned with national and international research community interests as espoused in various planning documents. The first science objective encompasses the primary ADEx science objective of establishing the magnetospheric driver of auroral arcs. The auroral and geospace dynamics themes that comprise objectives 1 and 2 are relevant to essentially every geospace theme in SEW2009. The theme of Dynamic Geospace Coupling is NASA2009 science target LWS #8, which specifically identifies global auroral and ENA imaging as enabling observations. In the NASA 2010 Heliophysics Roadmap, "Climate Impacts of Space Radiation" is a priority science target (LWS #7). The NASA roadmap committee has "penciled in" a mission under this theme for 2018 (Figure 2). They identify NO production by aurora, vertical transport, and ozone depletion as a critically important problem under this theme, and auroral inputs to the upper atmosphere as one of the measurements necessary for attacking this theme.

[10] This includes the best known GNSS, the Global Positioning System (GPS).
[11] CAnadian GPS Network for Ionospheric Monitoring
[12] Here, we mean spatio-temporal characteristics including intensity, temporal variation, spatial scale, etc.

Measurements, Data Products, and Data Use

We must establish our global auroral imaging measurement needs[13], which are spatial/temporal resolution, and the desired spectral bands. Naively, one wants arbitrarily good spatial resolution, however, given a finite height of the emission region, there is a fundamental limit on spatial resolution averaged over the entire auroral region. In the Ravens Concept Study Report, we showed that this limit is most likely around 30 km, and so there is no need to aim for better (see pg 108 of that report). We have settled on 40 km as our target nadir resolution from apogee[14]. From the Ravens Concept Study Report, and *Uritsky et al.* [2010], we know that larger-sized features tend to change more slowly than smaller features, so that for a given spatial resolution, there is actually an optimum cadence[15]. Based on the *Uritsky et al.* [2010] study, we have selected 20 seconds as our target cadence.

This combination 40 km/20 seconds is significantly better than the real resolutions of any previous global auroral imager to date (see *Donovan et al.* [2007]). Furthermore, this spatial resolution should allow us to identify auroral features for Science Objective 1 Theme 1 (magnetospheric drivers of aurora), as well as for Science objective 4 (GNSS). This will not allow us to simultaneously capture the full spectrum of auroral spatial scales (Science Objective 1, Theme 2), however PCW-UVI, together with contemporaneous ground-based ASI imagers, will be able to. Science Objectives 2 and 3 have lower requirements for spatio-temporal resolution.

Science Objectives 1, 2, and 3 require precipitating electron characteristic energies. We want to (1) investigate the relationship between structure and both energy deposition and acceleration mechanism, to (2) quantify energy input into the ionosphere, and to (3) model NOx production due to auroral preciiptation. We can exploit LBH and OI emissions to obtain such information [e.g., *Strickland et al*., 1983; *Germany et al*., 1990]. Specifically, the intensity of LBH "long" emissions is proportional to the energy flux of precipitating electrons. The intensity of the LBH in the "short" part of the band, which is partially absorbed by atmospheric O2, can be compared to the LBH-long emissions to estimate the characteristic electron energy [Germany et al., 1997;1998]. Alternately, one can exploit other FUV ratios, such as LBH to OI 1356, to get characteristic energy. There are advantages and disadvantages to each scheme that we will investigate during the Phase 0/A, but for now we state that we will be needing intensities in two FUV bands to get electron energy.

Finally, daylight suppression, needed for Science Objective 2, will be accomplished as an ancillary benefit of adequately isolating the FUV spectral bands, and "long-duration events" requires continuous viewing, enabled by the PCW satellite pair. Table 1 is a tentative list of PCW-UVI data products.

Data Product [Format]	Description
Level 0 [PGM]	**Single Imager Product.** Reconstructed, unprocessed imager data at full resolution, with any and all communication artifacts (e.g. CCSDS packet headers, synchronization frames, etc.) removed.
Level 1-B [PGM, CDF]	**Single Imager Product.** Radiometrically corrected brightness, time referenced and annotated with ancillary information (e.g. spacecraft location, calibration version, etc.).
Level 3-1 [CDF, JPG*]	**Combined Imager Product.** Radiometrically corrected brightness mapped onto a geographic grid using pixels with the highest spatial resolution at each location, time referenced (at full temporal resolution) and annotated (in the case of CDF) with ancillary satellite information.
Level3-2 [CDF,JPG*]	**Combined Imager Product.** Same as Level3-1 but in geomagnetic coordinates.
Level3-3 [CDF, JPG*]	**Combined Imager Product.** Derived auroral energy flux and average energy mapped onto a geographic grid using pixels with the highest spatial resolution at each location, time referenced (at full temporal resolution) and annotated (in the case of CDF) with ancillary satellite information.
Level3-EPO [JPG*]	**Combined Imager Product.** Radiometrically corrected brightness (at full temporal resolution) mapped onto geographic grids using pixels from the satellite with the highest spatial resolution at each location. EPO data products will be made available in a variety of map projections (highlighting different locations on the Earth) and in a variety of image sizes (to allow for web-streaming content). The EPO set of data products will likely evolve as the EPO needs become more clearly defined.

Table 1: Anticipated PCW-UVI standard data products (SDPs). Processing level designations are based on the Earth Observing Science Data Information System (EOSDIS) data definitions (see NASA's Earth Observing Science Data Resource document). [*or equivalent raster image format (e.g. PNG)].

[13] We assume measurements from other programs will be available, but will revisit that issue in Phase 0/A.
[14] Meaning significantly better resolution near nadir when the satellite is at lower altitude.
[15] This means that for a given spatial resolution, there is a time resolution that there is little or on reason to do better than.

To support our assertion that PCW-UVI data will be extensively used, we include letters from leaders of most major programs approved or planned for the PCW-UVI timeframe. The authors of the letters are

Angelopoulos	THEMIS PI	Lynch	Sounding Rocket PI
Burch	MMS & IMAGE PI	Raeder	Representative Modeler
Friis-Christensen	Swarm Scientific Leader	Ridley	Representative Modeler
Fujimoto	Scope Mission Scientist	Ruohoniemi	SuperDARN PI
Kepko	ADEx PI	Sibeck	THEMIS & RBSPProject Scientist
Lessard	Sounding Rocket PI	Thayer	CEDAR SteeringCommittee Chair
Liemohn	GEM Steering Committee Chair		

Thayer and Liemohn describe synergies between PCW-UVI and essentially all aspects of CEDAR and GEM, representing >500 researchers. Sibeck communicates the relevance of PCW-UVI to the NASA mission lineup, while Angelopoulos, Burch, Fujimoto, Kepko, and Brandt[16] (EAGLES) write as mission PIs. For each mission complementary to PCW-UVI, the synergies would enable new science and lead to use of the PCW-UVI data by their respective teams representing again a large number of researchers worldwide. Ridley and Raeder are modelers who communicate the value of global imaging for geospace studies. More than 100 researchers worldwide are carrying out global simulation work that would directly benefit from PCW-UVI. Ruohoniemi writes as PI of several SuperDARN radars, also anticipating extensive use of the PCW-UVI data. It is easy to imagine that the international communities who utilize magnetometers, GPS networks, riometer networks, and incoherent scatter radars would find similar value in PCW-UVI. Lessard[17] and Lynch are PIs of sounding rockets who describe benefits PCW-UVI would provide by decreasing their reliance on ground-based imagers for calling launches, and for the contextual information PCW-UVI would make available in real time. They both state PCW-UVI data would decrease the number of days spent waiting for ideal launch conditions.

PCW-UVI would be the only global auroral imaging mission at a time when the international fleet of *in situ* satellites would be comprised of an unprecedented constellation. For the uniqueness of the data, and the list of technical firsts that would be achieved, we assert that PCW-UVI would produce one of the most highly visible, highly relevant, and most widely utilized geospace data sets. **Overall, we assert that PCW-UVI, as a secondary science payload on PCW, would have the science impact of a NASA Explorer class mission.**

4.2 Socio-Economic Impact

In asserting the socio-economic benefits of PCW-UVI, we make reference to the 2007 *Mobilizing S&T to Canada's Advantage* and the 2009 *Progress Report*, as well as the *2008 Throne Speech* (herein ST7, ST9, and TS8). We include quotes[18] from ST7 and ST9, followed by statements of how PCW-UVI will address those points. We assert PCW-UVI aligns broadly with issues identified in ST7 and ST9[19]. These include strategic research priorities, excellence on the world stage, international collaborations and partnerships, skilled personnel, and science outreach. We use TS8 to point to Canada's significant strategic interest in the Arctic, and we argue the obvious importance of PCW-UVI to Canada's Arctic interests.

Through ST7, the Government of Canada (GC) seeks to "create a Knowledge Advantage: GC[20] will focus strategically on research in areas that are in the national interest from a social and economic perspective…" three of four being "environmental science", "natural resources and energy", and "information and communications". Prioritized research is a prominent theme throughout ST7 and ST9. There has been a significant increase in awareness of climate change (environment). Space weather affects the upper atmosphere and possibly climate (see Obj.S3). PCW-UVI data and other atmospheric observations[21] will identify how aurora affects upper atmospheric minority constituents such as NOx, which in turn affect stratospheric ozone and other species. Knowledge of space

[16] Brandt is a collaborator on this proposal.
[17] Lessard is a science collaborator on this project, so his letter is not *independent* in that sense.
[18] For ST7 quotes, we indicate only the page number (e.g., "p23"), while we use "ST9pN" to refer to ST9 page N.
[19] Our ST references are mostly to ST7, as our read of ST9 is that it mostly relates to implementing ST7 priorities.
[20] To save space, we have abbreviated some quoted expressions (e.g., "GC" for "Canada's Federal Government").
[21] Some from PCW – see the letter from J. McConnell.

weather effects on the atmosphere and climate is critical to inform policy[22]. Ill-understood space weather effects often complicate environmental decision-making. Developing a much clearer understanding of how space weather couples to our atmosphere and climate, even (or especially) by placing reliable upper-limits on those effects, would be a significant step forward[23].

ST7 asserts "S&T enables Canada to address public safety, [and] security" [p22]. Space weather (aurora) affects technologies that depend on ionospheric RF propagation. In Canada, one reason this is important is the indirect effect of aurora on reliability of GNSS, and on RF communications with aircraft. There is international interest in knowing the auroral distribution in Real-Time (RT), which PCW-UVI would be the first to deliver. We would develop RT products allowing those depending on ionospheric RF propagation to determine susceptibility to space weather effects based on location (see Obj.S4). We have included a letter of from US Space Weather Prediction Center[24] Director T. Bogdan describing the likely impact of PCW-UVI on space weather operations. He states PCW-UVI would significantly improve RT knowledge of the auroral distribution, and supports our asserted value of the PCW-UVI RT products. Ultimately, we would be enhancing the safety and security of GPS[25] users at high latitudes, and work with Canadian industry to enhance competitiveness by with products that automatically utilized this RT information.

GC argues the importance of world-class S&T and "is committed to maintaining Canada's current G-7 leadership in public research" [p29], stating that international S&T leadership gives Canada a "stronger, more respected voice on the world stage" [p23], and that S&T excellence fosters international opportunities for entrepreneurs and is a "magnet for talent". In ST7, there is a significant focus on "benchmarking … against international standards" [p15], and a recognition that an important measure of Canadian S&T is the fact that "Canadian researchers are at the forefront … as measured by publications and citations" [p28].

PCW-UVI would be an example of true international S&T leadership by Canada on the world stage. These would be the best space-based auroral imagers ever produced. The project would take advantage of the PCW mission characteristics (e.g., non-spinning satellites, best-ever pointing information for space-based auroral imagers, and the 24/7 vantage), as well as innovative instrumentation (enabling daylight suppression and passband isolation), to provide the world with the best global auroral images ever produced by any program in the world. This is a Canadian project that would be the best of its type in the world. This data would be widely used by the international science community (see section 4.1), and highly visible in the international media (see below), meaning that it would highlight world-class Canadian S&T activity in the science community and to the world in general. This project would therefore contribute to Canada's voice on the world-stage, be an innovative high-tech project through which Canadian entrepreneurs and academics would demonstrate excellence before potential partners and clients of Canadian industry, and be a natural "magnet for talent" (see below). Finally, given the past successes of auroral imaging projects, and the other geospace missions that will be operating during PCW, we assert that PCW-UVI will generate hundreds (if not more) of refereed publications (see section on data use, above), enhancing Canada's position at the forefront of science.

The S&T strategy supports international **"**collaborations and partnerships" [p34], and argues that "the selection of world-class research initiatives [must be] informed by international developments" [p67]. The basis for this is that countries are "putting more emphasis on international collaborations … sharing major research infrastructure and research projects to address global challenges" [p34], and that these partnerships strengthen "Canada's ties to the global supply of ideas, talent, and technology [p99]. On multiple levels, PCW-UVI will be an exemplar of utilizing significant international partnerships to address truly global science challenges. Within PCW-UVI, science collaborators in the UK, Norway, Finland, and the US will explore possibilities for small hardware contributions to

[22] In ST7 the GC states that policy "decisions must be based on the highest-quality science available. In turn, this requires cutting-edge technology in the hands of top-notch researchers, long-term monitoring, data management, and the ability to interpret and transform new knowledge into sound science advice." [p69]

[23] Note that "Climate Impacts of Space Radiation" has been identified as one of the major US space science themes in the NASA 2009 Heliophysics Roadmap. The example they chose to focus on was the relationship between aurora, NOx, and stratospheric ozone.

[24] SWPC is arguably the world's leading space weather service, playing an international leadership role in the provision of information to those affected by space weather.

[25] We foresee other uses, e.g. for assisting air traffic controllers in predicting RF problems "over the pole".

PCW-UVI (e.g., there is the possibility of high-voltage power supplies from the UK[26], and calibration at U. New Hampshire). As well, PCW-UVI would fit into an international space physics mission line-up as the only global auroral imaging program, providing a highly important multi-faceted role for Canada in the international geospace program (see the letters of support from mission PIs and other scientists).

The S&T strategy references as fundamental the training of Highly Qualified Personnel (HQP) for the high-tech sector, that "skilled, creative people are the most critical element of a successful national economy" [p10]. This is predicated on the need for a talented workforce to enable innovations and economic success [p28; p89], and acknowledges as essential a strategy that begins with "getting Canadians excited about S&T" [p77], "fostering a strong S&T culture through innovative science outreach" [ST9p39], and "investment in education" [p77]. Specific mention is made of increasing "the number of graduates with both research and business skills" [p98]. PCW-UVI would be an outstanding vehicle in terms of HQP. Graduate students and scientists from other countries would be attracted to Canadian institutions to join this high profile international project. PCW-UVI would evolve as an unusually close partnership between industry and academia, giving industry personnel a better understanding of the science culture that incubates the ideas that drive innovation and university personnel an excellent opportunity to gain critically important business and industry skills.

The aurora is arguably the most visible and beautiful of geospace processes. It captivates in ways that give us a straightforward path to a high impact Education and Public Outreach (EPO) program that will make the public aware of the benefits of the mission, excite Canadians about S&T, and enhance Canada's international reputation as an S&T leader. We will present PCW-UVI image data in the way weather images from PCW (and GOES) will be prepared for TV weather reports, and will work with broadcasters to incorporate these images in nightly and/or special broadcasts. We have included letters from CBC expressing interest in this, and pointing to the fact we are already discussing the hopefully frequent (possibly daily) use of PCW-UVI images on TV broadcasts. In addition, we will develop EPO programs that will build on current projects based on ground-based auroral images. An example is the joint CSA, Astronomy North, and U. Calgary *AuroraMax* project, wherein an EPO web site presents RT images and supporting information from an ASI in Yellowknife. We have included a letter of support from J. Pugsley, *AuroraMax* partner and Astronomy North CEO, describing how PCW-UVI will impact space EPO. National and international media frequently show auroral images. We expect that the PCW-UVI images will be high profile in media releases related to geospace during the PCW era.

Although most Canadians do not live in the arctic we see ourselves as an arctic nation. We chose the Inukshuk as our symbol for the 2010 winter games, and images of the North and the aurora appear frequently in advertisements and other media focusing on Canada. In TS8, outlined the need to research arctic climate change and assert arctic sovereignty for reasons of national security, transportation and access to resources. We discussed climate change and (arctic) safety and security. In addition, Canada has by far the largest land mass under the auroral zone, and as stated above, Canadians identify strongly with the North. Through PCW-UVI, Canada would be positioning itself as *the* international leader of global auroral observations, contributing strongly to the sense that the GC is committed to issues related to arctic Canada, and thereby contributing to efforts to assert Canadian Arctic sovereignty.

We are asserting that PCW-UVI would contribute to sustainable development and prosperity as envisaged in ST7 and ST9. This is an area of true Canadian leadership, coupled with excellent opportunities for training the HQP and contributing to an interwoven industrial and academic environment conducive to turning "knowledge into new and important innovations" [p20]. We finish this section with a statement of past success and its relevance here: over the last 25 years U. Calgary auroral imaging activities have spawned two successful high-tech spinoff companies[27] which now employ more than 20 people. PCW-UVI offers hope for an even greater socio-economic impact. We anticipate developing new technologies, enhancing the capacity for innovation at U. Calgary and within smaller companies such as Routes Astroengineering. An effective partnership between Routes (for example) and U. Calgary would create opportunities for greater innovation than typically possible in small companies addressing on a small scale a problem identified in ST7[28]. PCW-UVI would strengthen "private-sector commitment to S&T" [p9]

[26] The UK provided this for the Canadian contribution to UVIT (Ultra-Violet Imaging Telescope).
[27] These are ITRES and Keo Scientific.
[28] "Smaller firms often have more difficulty financing and managing R&D and adopting new technology" [p27]

and be an ideal example of a program "at the forefront of scientific development and technological achievement" [p9].

5 Scientific / Technical Concept and Feasibility

5.1 Scientific / Technical Concept

PCW-UVI is about world class global auroral imaging. Previous development of this concept has been carried out by the Bidder in Canadian Space Agency contracts 9F007-033080 (Ravens Concept Study) and 9F007-080324 (UVAMC Pre-PhaseA Study). The Ravens concept study was completed in December 2006 and the UVAMC Pre-PhaseA study is scheduled for completion in October 2010. Expanding on results from these contracts, we present an innovative global auroral imaging payload specifically targeted for the PCW mission. The PCW-UVI mission concept involves placing auroral imaging payloads on each PCW satellite to obtain the world's first continuous, real time, global auroral imaging facility. Recent improvements in Far Ultra-Violet (FUV) optics combined with the PCW three-axis stabilized platform dramatically improve detection capabilities in this spectral emission region. As a result, the science objectives described in Section 4.1 are, for the first time ever, achievable via satellite based auroral imaging.

A similar auroral imaging mission concept was proposed for, and subsequently developed with the Ravens Concept Study[29]. Ravens was envisaged as a two-satellite imaging mission providing 24/7 multi-channel FUV observations. The orbits were to be 90^{o} inclination, with geocentric apogee and perigee at 8 and 1.8 Re, respectively. The satellites were to be spinning. This mission concept was exactly that of KuaFu-B, which was based on Ravens. PCW provides a *slightly lower* quality of view averaged over the auroral and polar cap regions than Ravens[30] but is arguably the best imaging platform to date for the purpose of imaging the North. The Molniya orbits maintain apogee at the highest latitude part of the orbit for the mission duration, so precession of the line of apsides does not limit the duration of effective high-latitude imaging. The satellites are not spinning so that PCW payloads can image at a higher cadence with longer integration times, meaning higher frame rate and better SNR. The pointing requirements for the primary meteorological payload are significantly better than would have been possible on the spinning satellites, so as a matter of course, knowledge of position of auroral features will be optimized and negative effects of wobble will be minimized. The longer integation time and stable pointing of the nadir pointing imagers will also allow for better spatial resolution than would otherwise be possible. PCW-UVI will produce the most spectacular and scientifically useful global auroral imagery to date. In this section we describe: 1) the flowdown from PCW-UVI science objectives to a preliminary payload concept, 2) the instrument heritage and Technology Readiness Level (TRL), 3) failure modes and mitigation strategies, and 4) the expected results of the mission/science objectives.

PCW-UVI Payload Concept Flowdown

The preliminary payload concept design is driven by both the measurement criteria required to achieve all of the science objectives (as outlined in Section 4.1), and the observing characteristics imposed by the PCW mission. The pointing stability and accuracy provided by the PCW platforms facilitate an imager design concept that will provide higher spatial and temporal resolution than would be feasible for a spin-stabilized platform within the same volume/mass constraints. For this reason, some of the PCW-UVI measurement targets are attainable as a direct consequence of the PCW mission parameters[31]. The left panel of Table 5.1 contains a preliminary set of PCW-UVI system measurement requirements that adequately capture the measurement needs associated with the overarching science objectives. Each objective and requirement presented here has been assigned a label (e.g., Obj. S1 or Req. S1-M1) that is used for reference throughout the remainder of this section. *The instrument-specific design requirements*[32] needed to meet the scientific measurement criteria are listed in the right panel of Table 5.1 (together with the measurement requirement that it addresses). An initial draft of the PCW-UVI flowdown from science objectives to science payload measurement requirements is contained in CDRL SC1 of Appendix IX.

[29] and the ongoing UVAMC study
[30] when Ravens has apogee at 90 degrees latitude
[31] Science payload requirements which are directly enabled by the PCW platform have been explicitly identified in table 5.1.
[32] The measurement requirements presented here are preliminary and would be refined and finalized in PhaseA (WP3.2-A)

Preliminary Mission/Science Definition (Summary of CDRL SC1 – Appendix IX)		**Preliminary Measurement Requirements**	**Science Driven Instrument Requirements**
Science Objectives	**Measurement Needs**		**Imaging System**
Obj. S1 :The Magnetospheric Drivers of Auroral Type, Structure, and Dynamics *Image global auroral dynamics with sufficient temporal and spatial resolution to identify auroral type and structures at apogee. . Imaging during timeframes of appropriate magnetospheric measurements (for example, plasma sheet dynamics, LEO boundary measurements, etc.)*	Global images of auroral luminosity	**Req. S1-M1** Instantaneous coverage of entire northern auroral oval (>55° geomagnetic latitude)	Image spatial and spectral FUV aurora 115-180 nm. **Addresses Req#** **S1-M1, S1-M4, S2-M5**
	Observe full range of aurora luminosity	**Req. S1-M2** Sufficient intrascene and interscene dynamic range to record full range of expected auroral luminosity	20 deg FoV **S1-M1, S1-M3,S2-M6**
	Average image resolution of 40km or better across the FoV	**Req. S1-M3** Apogee ground mapped pixel to pixel distance of 40km **Associated Interface Requirement, Req. I1** Knowledge of S/C pointing to within one pixel (0.06°) ***Enabled by PCW Mission*** **Req. I2** S/C pointing stability less than half a pixel (0.03°) over a 20 sec period ***Enabled by PCW Mission***	Image Sensor with sufficient pixel count and area to yield required sensitivity and resolution **S1-M1,S1-M2,S1-M4**
	Image Cadence 20 seconds	**Req. S1-M4** Sufficient imager sensitivity at apogee to achieve acceptable SNR in 20 sec exposure	High rejection of VIS-IR albedo for high FUV sensitivity **S2-M5, S2-M6** High dynamic range sensor and ADC **S1-M2**
Obj. S2 : Geospace Dynamic Coupling *Specify the energy input in the auroral region under different geospace coupling conditions. For long duration events (such as geomagnetic storms) provide continuous measurements of precipitating electron flux and energy.*	Dual band auroral images (sufficient to derive e⁻ energy flux and energy) Auroral N2 (LBH long and LBH short) bands *-Or-* Images of the auroral LBH and OI bands	**Req. S2-M5** To sufficiently (so as to enable meaningful quantitative work) separate LBH-l and LBH-s while rejecting the strong adjacent OI lines and maintaining adequate signal *- Or -* To sufficiently (so as to enable meaningful quantitative work) separate the LBH band from the intense OI line.	Adequate stray light rejection by proper optical design and baffling **S2-M5, S2-M6** Adequate S/C orbit (and/or number of satellites) to maintain 24/7 view of northern auroral oval **S2-M7** ***Enabled by PCW Mission***
	Image entire auroral oval (including dayside)	**Req. S2-M6** Sufficient rejection of VIS-IR Earth albedo.	**Data System**
	24/7 viewing of northern auroral oval	**Req. S2-M7** Continuous imaging operations	Download binned sensor, houskeeping and pointing data **S1-M1, S2-M5, S2-M7** Handle data from 2 imagers (LBH-l and LBH-s) **S2-M5, S2-M7**
Obj. S3 :Effects of Space Weather on Climate	Enabled by measurement needs above	No additional Measurement Requirements	Sufficient available telemetry bandwidth **S1-M1, S1-M2, S1-M3, S2-M5, S2-M7** ***Enabled by PCW Mission***
Obj. S4 : Space Weather Effects on GNSS	Enabled by measurement needs above	No additional Measurement Requirements	

Table 5.1 Flowdown from Science Objectives to Measurement Needs to Instrument Requirements

The PCW-UVI payload will be comprised of two co-aligned FUV imagers with one common electronics unit. Figure 5.1 shows the preliminary design concept for an individual imager. FUV measurements offer two distinct advantages for auroral imagery: 1) the absence of contamination from the Earth's surface albedo allowing auroral displays to be detected in the sunlit polar region (S2-M6), and 2) that atmospheric particle excitation that results in radiated FUV emissions cannot result primarily from complex molecular processes such as chemical reactions or molecular energy transfer (these processes involve energies that are lower than the FUV range of energies [Monchick et al., 1985]). For these reasons, radiation detected by PCW-UVI in the FUV auroral emission bands can be assumed to be exclusively the result of electron impact processes, providing a direct measure of auroral emissions. Each imager will deliver quantitative intensities from a single unique auroral emission band within the FUV spectrum. The two imager targeted emission bands must be well-separated spectrally to enable estimates of

precipitating electron energy flux and characteristic energy (contributing to the fulfillment of preliminary measurement requirements S1-M1, S1-M4 and S2-M5). We are proposing to use two halves of the LBH band (we refer to them as LBH-long and LBH-short) but are also investigating using the entire LBH band and OI lines for signal intensity reasons (work to done in Phase 0). A more complete description of the auroral emission band options is provided in the CDRL SC1 (Appendix IX). The final decision will be made in the Phase0 contract. Note that, at this point, the impact on the preliminary design of each option is considered negligible.

Both payload imagers will nominally have a field of view of 20 degrees, such that the effective imaging area encompasses the entire northern auroral oval for ±3 hours around apogee in the PCW orbit (addressing preliminary measurement requirement S1-M1). This field of view, in combination with the PCW mission characteristics (twin satellites in 12-hour Molniya orbits, with long loitering times near apogee), will provide the first-ever 24/7 viewing of this region, addressing preliminary measurement requirement S2-M7.

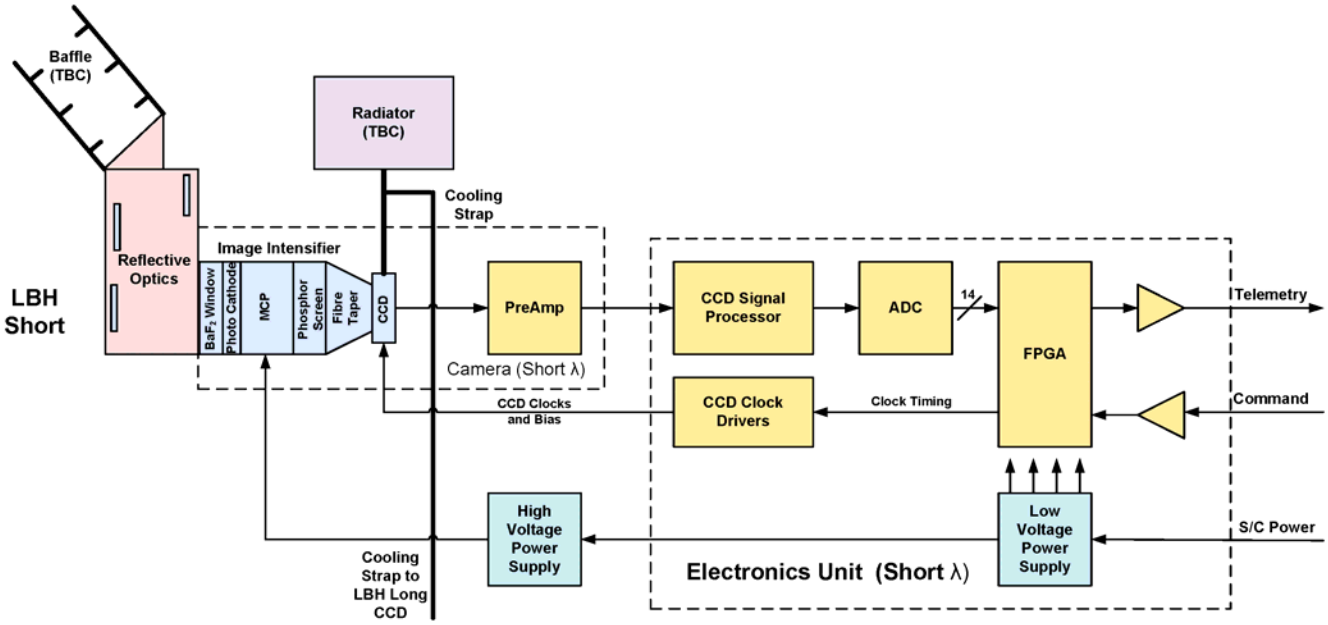


Figure 5.1. Functional Block Diagram of one imaging channel. Different colour schemes are used for Optics, Detector, Electronics, Power, and Thermal subsystems; see text for details. Two co-aligned such channels are proposed.

The image-forming section of the PCW-UVI imagers will be comprised of fast, all-reflecting telescopes. The imagers will be operating in the "self filtering" mode [Zukic, 1990, 1995], in which the imaging mirrors themselves are coated with all-dielectric multilayer filters, which only reflect the desired wavelength. As such, the filtering and imaging properties are combined, reducing instrument size and mass while at the same time improving instrument performance (addressing preliminary measurement requirements S1-M1, S1-M4, S2-M5, and S2-M6). Adequate baffling will be provided in front of the aperture in order to reduce stray light (addressing measurement requirements S1-M2, S2-M5 and S2-M6). The baselined image sensor is a passively cooled image-intensified CCD (or CMOS). The pixel count and area of the sensor are to be determined in Phase 0, but they will be required to have sufficient pixel count and area to yield the required sensitivity and resolution at apogee (addressing preliminary measurement requirements S1-M3 and S1-M4). The image intensifier consists of an entrance window, solar-bind photocathode, microchannel plate (MCP), phosphor screen and fiber-optic taper to provide demagnification and proximity focusing of the image onto the CCD. The detector will operate in the analogue (as opposed to photon-counting) mode, with MCP gain set to generate a known number of CCD electrons per rayleigh of incoming light. A high voltage (HV) power supply will provide the required voltages to the intensifier, while the MCP voltage will be adjustable to provide intensifier gain variability (contributing to the fulfillment of preliminary measurement requirements S1-M2 and S1-M4). A low-noise pre-amp will reside in the optical housing to provide amplification of CCD output signals, and an A/D converter will present the digitized image data from the CCD signal chain to the FPGA, which will then store and format data for transmission to the spacecraft science data

handling subsystem. The spacecraft provides commands to the instrument, and the instrument provides engineering telemetry data to the spacecraft.

Critical Technology Items (CTI)						Concept Design Application of CTI	
Ref.	**CTI Description**	**Technology**	**Key Parameter**	**Mfg.**	**TRL (flight history)**	**Required Modifications**	**Mod. TRL**
CTI-1	UV aspheric mirrors	Diamond turning and polishing	Low surface roughness for UV, high curvature	B-Con Engineering Inc. (Cdn.)	**TRL9** *(Polar UVI)*	Modify radii of curvature	**TRL3**
CTI-2	Baffles and internal surfaces	Grit blast and Black Anodize	Low UV and visible reflectivity, repeatable processes	Routes and CP Tech (Cdn.)	**TRL9** *(OSIRIS)*	Modify surface treatments for required blackening requirements	**TRL4**
CTI-3	UV Mirror Coating	Multilayer Coatings (thin films)	UV reflectivity, visible rejection, angle of incidence dependence	Cascade Optical Corp (U.S.), INO (Cdn.)	**TRL9** *(Polar UVI / IMAGE WIC)*	Modify for required passbands and relevant thermal / radiation environment	**TRL3**
CTI-4	UV Transmission Filters (TBC)	Multilayer coatings (thin films)	UV passbands/ transmission for auroral imaging (in addition to mirror coatings)	Acton Res. Corp (U.S.)	**TRL9** *(DE-1 SAI)*	Design for modified passband requirements	**TRL3**
CTI-5	HV Power Supply	Electronics, insulation	Breakdown voltage	MSSL (U.K.)	**TRL9** *(UVIT,XMM)*	Replace any rad soft parts with rad-hard versions	**TRL4**
CTI-6	Image Intensifier	Microchannel plate	Solar-blind Photocathode, UV Quantum Efficiency	Photek (U.K.)	**TRL8** *(UVIT)*	Higher level of CsI purity, higher QE	**TRL4**
CTI-7	Image Sensor, plus bond	CCD/CMOS	Interface to fibre optic taper	e2v (U.K.)	**TRL8** *(UVIT)*	Bond fiber optic taper to new CCD (e2v CCD47-20)	**TRL7**
CTI-8	Electronics (rad hard, 7yr mission lifetime)	Microelectronics	Rad-hard (30 - 100 krad), quality ststus, cost, availability, ITARS status	Various (U.S. qualified)	**TRL8** *(SAPPHIRE/Orbitals)*	Replace any rad soft parts with rad-hard versions	**TRL4**
CTI-9	Fiber Taper	Glass, fiber optics, cladding	Rad-hard glass, quality, availability of required ratio, interface to sensor	Schott, Incom, Various (U.S.)	**TRL9** *(Viking/Freja, UVIT)*	See CTI-7	**TRL9**

Table 5.2: Critical technologies associated with the PCW-UVI payload.

Instrument Heritage and Technology Readiness Level

The overall instrument architecture presented here is similar to previously flown Canadian UV imagers (Viking, Freja, Interball, IMAGE WIC) and builds on what we have learned from decades of global auroral imaging. The proposed reflective optics will have 3 mirrors in an off-axis system, as compared to the 2-mirror on-axis systems previously flown Canadian instruments. A three-mirror system yields quantifiably superior performance such as lower aberration and scattering, and better out of band rejection. A similar mirror configuration has been flown successfully on Polar-UVI [Torr et al., 1995], the best FUV auroral imager to date, but the PCW-UVI design is expected to have distinct improvements that enhance imager performance and detection capabilities. State-of-the-art mirror coatings combined with a purer CsI photocathode and a suitable intensifier window material are expected to provide superior out-of-band rejection and higher in-band sensitivity. As well, the twin imager solution provides truly simultaneous measurements of the FUV auroral emission bands while Polar-UVI employed a filter wheel, resulting in non-simultaneous measurements. Much of the PCW-UVI electronics will be derived from UVIT (FPGA, HV supply, intensifier) and Sapphire (CCD readout, FPGA). Concerns about high voltage power supplies (which were the ultimate failure modes for previous Canadian FUV imagers) have been addressed. The high voltage power supplies used on previous Canadian UV imagers were derived from a design used for sub-orbital rocket flights (U.S.) and found to be unreliable for long duration space platforms. The HV supply for the UV imagers proposed here is derived from a design used for XMM-Newton Optical Monitor (ESA) and UVIT on

Astrosat (Canada/India). On the XMM platform this HV power supply has operated for 10 years under similar conditions to PCW.

Table 5.2 identifies individual critical technology items (CTIs) for the proposed payload and includes information on manufacturers (Mfg.) as well as the Technology Readiness Levels (TRL) of the technology from a heritage perspective (previous flight history). The TRLs presented here are preliminary (to be reassessed in Phase 0/A) and evaluated according to the criteria described in CSA-ST-GDL-001 (Technology Readiness Levels and Assessment Guidelines, January 2009) and the present conceptual design. All of the critical technologies used by the PCW-UVI payload have either been flight proven or are flight qualified and included in instruments scheduled for launch. However, in most cases the application and/or configuration of the technology proposed in the PCW-UVI concept design have been modified relative to the flight proven designs. For this reason we include a second TRL (last column) which identifies the current TRL of the critical technology as applied in the PCW-UVI concept design, together with a short description of the required modifications needed to adapt the critical technology to the PCW-UVI design. In accordance with the description of the "reuse of mature technologies in new applications" in the CSA's TRL assessment guidelines, we have designated TRL4 for the electronics, image intensifier, power supply and baffles. We expect the TRL of these components to rise relatively quickly since the modifications required by the PCW-UVI design are straightforward and minor (to be investigated in Phase 0/A). For UV optical components, the proposed utilization of the technology is somewhat further from the heritage configuration of the CTI, and thus these components are placed at a TRL3. For example in the proposed application of CTI-1, PCW-UVI imagers have a different f-number and a wider field of view than imagers previously flown, requiring the manufacturing of new aspheric mirrors of smaller radii of curvature, and different surface roughness requirements.

Failure Modes and Mitigation Strategies

We have identified the performance of the UV optics (the most innovative portion of the design) as our primary risk to the science/mission objectives at this point (see discussion of risks in Section 5.2.3). Operational mitigation strategies for inadequate UV optical performance are critically tied to the PCW mission flight characteristics (and ultimately are the reason why we can use the proposed UV technology with confidence). For example, the 3-axis platform stabilization allows for long duration exposure with high pointing stability. In the event of lower than expected signal at the sensor (one possible failure mode of the optical chain), we will be able to increase the exposure time without impacting the spatial resolution or quality of the resulting images. A complete description of this risk, and our mitigation and contingency plans is detailed in Section 5.2.3.

Other non-optical failure modes for PCW-UVI payload include the standard failures associated with flight electronics, and are expected to have a lower occurrence probability. Mitigation strategies are still been considered for these cases to eliminate risk. One example of a potential PCW-UVI internal failure would be a high-voltage arcing scenario which would result in an elevated current draw from the main satellite power bus. Standard design practices will be used to circumvent this type of propagating electrical failure. For instance, an internal payload current limiter minimizes the effect on the satellite bus until a command could be sent to switch the instrument off. This strategy would eliminate the fault, but would result in a failed camera. We note that at this point however, a failure of a single imager does not affect the primary science objective. We are capable of fulfilling the primary PCW-UVI science objective even if three of the four proposed imagers were to fail at any point after launch.

The most critical payload failures that pose problems for satellite operation would be *electrical* failures in the interface circuitry, and they would be most likely to occur at the component level. It is expected that the satellite bus will be designed such that a failure in a payload interface does not affect any other interfaces or functions of the satellite bus to other payloads or satellite subsystems. It is also anticipated that interfaces (at both ends) be fault tolerant, and that the satellite bus provider will dictate to the payloads the method of power interface and architecture, all of which is to be confirmed during Phase A (WP 3.1.1-A, WP3.3.1-A, WP4.1.1-A, WP4.3.1-A). *Mechanical* failures are also possible, including failures due to vibration during launch. Structural analysis will be performed to ensure that this probability is very low. A complete analysis and documentation of all known failure modes will be conducted in Phase A WP4.3.1-A (to be included in CDRL EN5).

The PCW-UVI imagers will be aligned, characterized and calibrated prior to launch. Our goal is for each instrument to operate for the entire duration of the PCW mission, i.e., 5 years [*PCW Mission User Requirements Document V4.0, October 2008*]. Instrument sensitivity however is expected to degrade slowly over the course of

the mission due to the finite lifetime of the MCP intensifier tubes. Since the PCW mission lifetime is significantly longer than that of previous Canadian FUV imagers flown (each targeted 2 years), the effect of aging of photocathodes and other significant optical components and electronic subsystems (such as, low-noise preamps) will be carefully assessed during Phase A. PCW-UVI sensitivity specifications will be targeted at End-of-Life (EOL) performance. Possible means of characterizing and mitigating instrumental sensitivity drift will also be identified in WP2.2-0 and WP3.2-A, WP4.1-A. At least three techniques exist for quantifying, on an ongoing basis, the effects of degradation of instrument components (e.g. the detector, intensifier, etc.) during the mission. One technique, for example, is to utilize top-side ionospheric particle measurements together with transport code [Frey et al. 2001, 2003 and Carbary et al., 2004] to infer FUV brightness and compare these with measured intensities.

Expected Results and Benefits

Under successful operation aboard PCW, the proposed instrument payload described above will fulfill all preliminary measurement requirements. Based on the conceptual design presented here and some assumed materials that might be used to fabricate the design, we can estimate the performance of the proposed design concept aboard the PCW platform and determine some preliminary interface requirements for the PCW satellite. The numbers and materials presented here are not intended as final design specifications, but rather a plausible demonstration that a final design can be successfully achieved from our starting point. The final conceptual design will be addressed in Phase A including potential material usage and trade-offs.

Leveraging a 1024 x 1024 pixel CCD, with 3x3 pixel on-chip binning, the targeted 40 km apogee spatial resolution can readily be achieved from the PCW orbit. Furthermore, initial modeling (see spreadsheet in Appendix XII) suggests that by employing a 25 mm diameter solar-blind CsI photocathode, combined with SiO2, BaF2 and CaF2 intensifier window materials, for LBH-short, –long, and OI respectively, better than 50 R sensitivity (at SNR = 2.5) can be achieved in a 20 second exposure with the proposed f/5 optical system (3 mirrors, 20 degrees FoV). The resulting imaging payload will occupy a total mass of 30 kg per satellite (including two imagers, all associated electronics and power supplies, and including 30% contingency). Preliminary estimated physical envelope is 32 x 20 x 12 cm^3 for each of the two 3-mirror optical units, and 46 x 33 x 8 cm^3 for the common electronics unit. The two HV power supplies will each occupy 15 x 14 x 12 cm^3. The power requirements of the PCW-UVI payload are expected to be rather modest. No heavy-duty, fast-framerate imaging is planned and the CCD readout/processing is expected to consume less than 8W per camera. The image intensifier and HV PSU is expected to require 2.5W each. Efficiency of the DC/DC converters is assumed to be 75%. The total (average) instrument power for two imagers (including 30% contingencies) using these numbers is expected to be less than 34W. These figures will be reassessed during Phase A, WP4.2.1-A.

Figure 5.2 is the expected imager spatial resolution (combined from both satellites) as a function of geographic location, as calculated for the PCW orbital characteristics and the initial imager specification described above. This model is calculated using the ground-tracks and orbits identified in the MDA Preliminary Concept of Operations Document[33] (MDA-PCO) and imager operational timeframe of ±3.5 hours from apogee, the same as the MET payload [*PCW Mission User Requirements Document V4.0, October 2008*]. Panels are separated by one hour of sidereal time and the entire range encompasses one orbital period for PCW. Ground tracks of the PCW spacecraft are indicated with red and purple lines, satellites individual positions are indicated with dots, and the typical location of the auroral oval lies between the grey contours. The design concept presented in this proposal, aboard the two PCW spacecraft, would provide at worst 100km resolution in a small fraction of the auroral oval with the vast majority of the oval covered at (or above) 60 km resolution.

With the proposed operational mode we can reasonably expect the entire payload to produce less than 40 kB/sec of uncompressed data (combined twin imagers, 14 bit A/D) per spacecraft. Figure 5.3 details how the uncompressed bandwidth of the PCW-UVI payload will vary as a function of the image cadence and the final image size. Signal strength will physically limit our image cadence, and we anticipate that all advisable operating modes that are available to the proposed payload will not exceed 1Mbps bandwidth. Furthermore, the imaging period of PCW-UVI is nominally the same as the PCW primary meteorological and telemetry requirements would be less than a tenth of a percent of the MET payload [PCW Meteorological Payloads Concept, Summary of Phase0, Second Workshop on Satellite Imaging in the Arctic, CSA, 14-15 Sept. 2009].

[33] MDA-PCO - document contained on the CSA ftp site, Contract No. 9F028-070394/001MTB, CDRL No. PCW0-TN-02-MDA

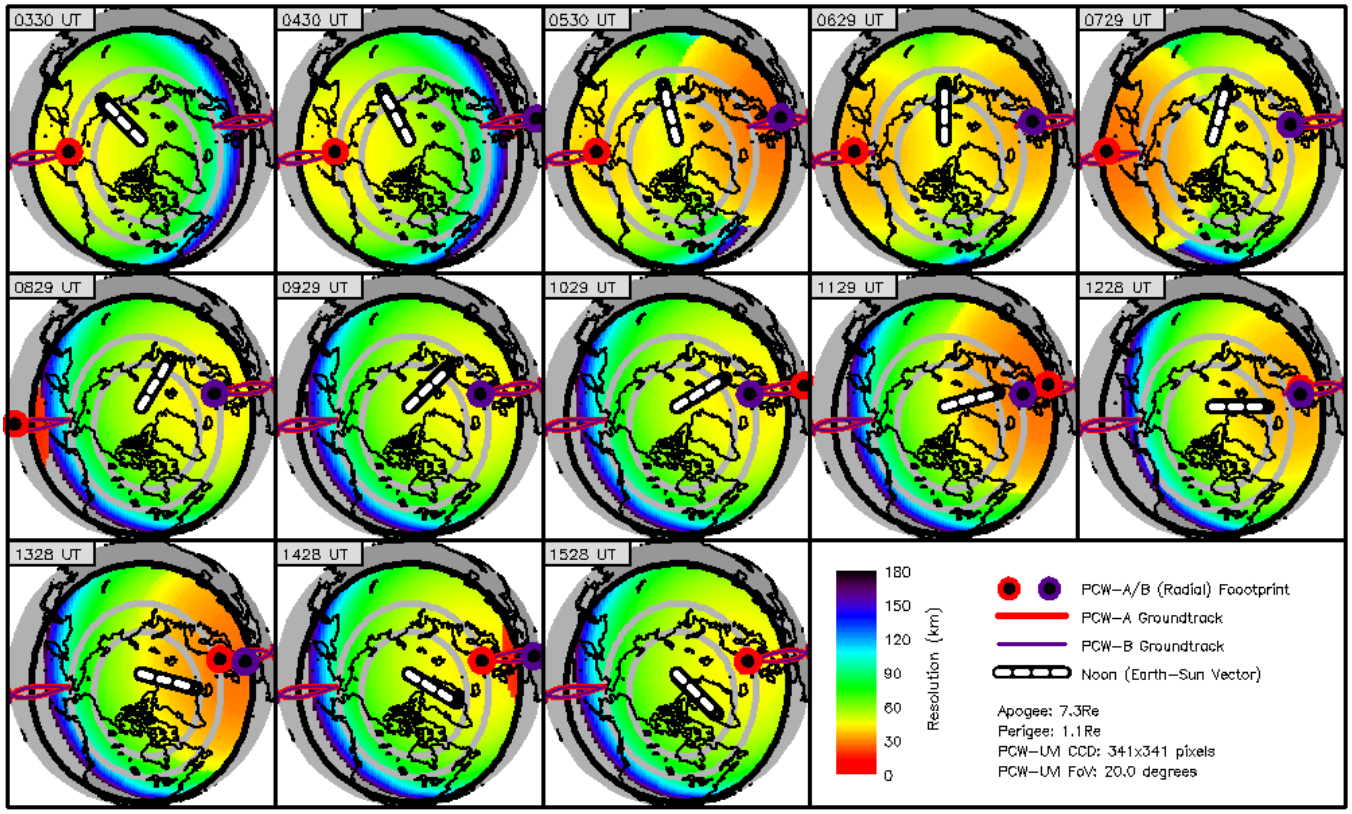


Figure 5.2: Quality of viewing analysis for an orbital period of the proposed PCW-UVI imagers. Resolution calculations are based on a 342x342 image size and a 20 degree imager field of view from the PCW orbit. Imager operational time is assumed to be ±3.5 hours from apogee. The combined spatial resolution of both imagers is colour coded as a function of geographic location, the resolution at a given point is defined as the best resolution between the two imagers. We have used the (rough) apogee longitudes as indicated in MDA-PCO. Any other choice of apogee longitudes (e.g., alignment with the Churchill meridian) would improve auroral viewing over central Canada, but not change the average time integrated quality of view.

The end data products provided by PCW-UVI will be a significant improvement on previously flown global auroral imagers. The systematic and constant viewing of the northern auroral oval by PCW-UVI will, in itself, transform the data landscape of the space science community. The PCW-UVI twin imagers will provide the first simultaneous, wavelength-separated LBH electron auroral observations over the global auroral distribution, which is true snapshot ability in calculating intensity ratios and derived physical quantities. PCW-UVI also boasts the highest spatial and temporal resolution of any global auroral imager flown to date. While our spatial and temporal resolution targets may appear to only be an incremental step forward, the optical technology and capability of PCW-UVI far exceed any other global imaging system. Our

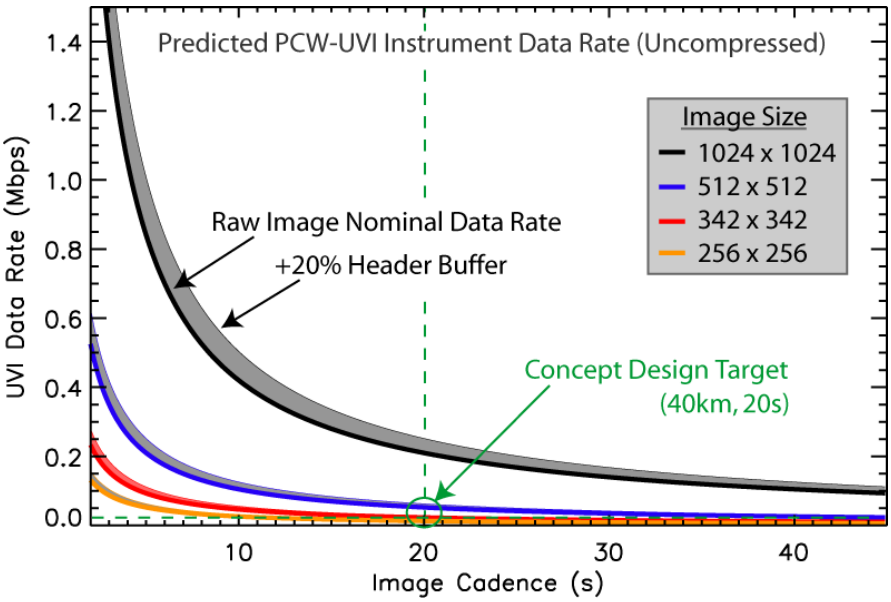


Figure 5.3: Expected data rate per payload (2 imagers uncompressed) for the PCW-UVI imagers. Calculations are based on a 14bit sensor. The data rate associated with the mission targets is identified with a green arrow.

spatial resolution target is intended to be a "typical" or "average" imaging scenario (see Figure 5.2) and as such we expect the data to far exceed the requirements for significant portions of the PCW orbit. This is in contrast to figures quoted by previous missions where the quality of viewing changes dramatically over the mission lifetime and often resolution numbers represent the best case scenario. In this sense, it is unclear how the actual resolution of previous imagers will compare to PCW-UVI. Instead we highlight the significantly improved imager design presented here and the enabling factors of the PCW platform and hope that the reader identifies the unique capabilities and potential of this imaging system.

5.2 Scientific and Technical Feasibility

5.2.1 Science / Technical Compatibility with PCW

The PCW URD[34] spells out the mission objectives. The meteorological objectives are to be met by the primary meteorological instrument, the spectroradiometer [URD section 3.5]. PCW-UVI will carry out continuous imaging of an important *upper* atmospheric phenomenon, the aurora. One of the PCW-UVI science objectives [Obj.S3] targets space weather effects on climate, and will utilize data from at least one channel of the spectroradiometer. PCW-UVI space weather work, will be aimed at developing space weather data products, based on PCW-UVI real-time auroral images, that will provide geographic maps of risk to RF communications at high latitudes, beginning with the GNSS application outlined in [Obj.S4]. This complements the PCW communications objectives outlined in URD section 4, will serve the needs of PCW communications users as outlined in URD section 4, and augments space weather operations (described in URD section 6) aimed at providing warnings to users of RF communications in the North of space weather effects (URD section 6.3 and 6.4). Overall, PCW-UVI has significant science compatibility with PCW, complementing and utilizing PCW imaging, providing valuable space weather information to PCW communications clients, and augmenting PCW space weather operations.

PCW will provide continuous, near-real time, high spatial resolution Earth observations of the high arctic for the purposes of weather prediction and monitoring climate change. It will also facilitate two-way, high bandwidth communications with the Canadian north. Together, these two objectives have driven the design of the PCW platform and orbital configuration, meaning two three-axis stabilized satellites (with excellent pointing accuracy) in elliptical Molniya orbits, phased so when one is at apogee the other is at perigee, affording 24/7 viewing above 50º geographic latitude, and continuous communications with the North. As stated in section 4, taken as a whole this makes PCW a dream platform for global auroral imaging. As a consequence of almost identical *technical* objectives, the technical compatibility of PCW-UVI and PCW is excellent.

The PCW-UVI preliminary Concept of Operations is in many ways similar to that of the PCW primary meteorological (MET) payload. PCW-UVI will collect images continuously while northern auroral oval is within its field of view which is nominally ±3.5 hours around apogee. This viewing interval coincides with the imaging interval used for the MET payload (see URD). The PCW-UVI imagers will power down during non-imaging intervals to preserve power, as well as to avoid potential hardware failures associated with passage through the radiation belts and other high risk geo-space environments (again, similar to the PCW primary meteorological payload). Due to the relatively low bandwidth requirements of PCW-UVI (see Figure 5.3) and the large communications capability afforded by the PCW platform, we expect to recover the entire data stream in real-time with little to no impact on PCW operations (uncompressed bandwidth requirements are less than 0.1% of those needed for the MET payload). The data recovery plan presented here will be sufficient to produce the Level0 data products described in Section 4.1 PCW-UVI imager command and control requirements are expected to be fairly modest. Most of these commands are anticipated to be programmatic in nature and should occur infrequently. Motivations for issuing commands would include optimizing imager response for payload operations or invoking failure mode mitigation strategies (see section 5.2.3). As the instrument design evolves (Phase A WBS4-A), the requirements for accommodating the payloads mass, thermal, volume, etc. will become increasingly apparent, and by the end of Phase

[34] *PCW Mission User Requirements Document, V4.0 October 2008*

5.2.2 Science / Technical Methodology

Science Methodology

The science goals of the PCW-UVI mission (see sections 4.1 and 5.1) drive instrument requirements for science payload concept designs. Increasingly demanding science requirements result in increased design complexity which in turn leads to higher overall mission risk. The science methodologies presented here are employed to produce a benchmark system to map individual technical design concepts back to the science requirements that drive their inclusion in instrument design. As a result science and technical team members can easily evaluate the scientific impact that results from specific design modifications. This tool will ultimately provide a basis for determining impacts on the mission's scientific objectives from proposed performance/risk/cost tradeoffs.

The first step in defining a successful science payload design is to prioritize the mission science objectives. As a result, if unacceptable risks (or costs) are found in the later phases of the contract, it is clear which mission objectives should be modified and/or removed to rectify the mission design logistics. Next, the system-level requirements needed to physically resolve observable signatures are identified (see column labeled "measurement needs" in table 5.1). Identifying which observable signatures should be targeted, and assessing the constraints on the reliable detection of those phenomena requires a comprehensive knowledge of the physical system being studied. Our science team has (and in WBS2-0) performed numerous literature searches to collate theoretical and empirical information about targeted signatures and their relationships to the science objectives (section 4.1). For example, *Uritsky* [2010] showed that there is a coupling between spatial scale sizes and lifetimes of auroral forms. There is a characteristic lifetime for auroral features that are near the minimal detectable size limit of the satellite imager, this puts an upper bound on the cadence needed to characterize the auroral forms temporally. Our team understands that the required spatial and temporal sensitivity are tied to the auroral forms of interest and once those requirements have been met there are no advantages to aiming for better imager resolution that could introduce additional cost and mission risk.

The resulting measurement criteria needed to observationally capture the physical signatures (that are linked to the science objectives) from onboard the PCW satellite platform are the "preliminary measurement requirements" for PCW-UVI (see table 5.1). These measurement requirements form the evaluation criteria that all candidate science payload concept designs will be graded against. Quantitative values have been extracted from this scale size analysis mentioned above and have been used to form an initial set of preliminary measurement requirements. Each identified preliminary measurement requirement has been labeled with the initial science objective that it resulted from. This provides measurement requirement traceability and a way to gauge scientific impact should a requirement not be met (see section 5.2.3 for risk mitigation strategies). The initial assessment of the preliminary measurement requirements presented in this proposal will be revisited and refined (if necessary) in Phase 0.

The second step in defining a successful science payload design is to derive a set of minimum instrument design requirements (see column labeled "Science Driven Instrument Requirements" in table 5.1) that completely characterize the systems preliminary measurement requirements derived above. These form the basis for all instrument technology selections and component integration strategies to be used candidate imager designs (further discussion of instrument component design is included in the technical methodologies section below). To address this, both science and technical team members have reviewed previously flown missions to create a baseline for this conversion, and then have put in considerable effort to make sure all PCW-UVI specific requirements have been accounted for. Back of the envelope calculations are made at every opportunity in the concept design to ensure consistency with the initial science requirements. For example, a "quality of viewing" tool (developed by Eric Donovan) models the resultant imager spatial resolution given a set of instrument design requirements, and PCW orbital characteristics. We use this tool as a crosscheck to ensure the expected imagery results will meet the spatial resolution preliminary measurement requirement.

Technical Methodology - Phase 0

The Science Payload Concept, will be approached using the methodology defined below. Note that the activities denoted are performed in WP 4.1-0/A, unless otherwise identified.

Performance Model: The derivation of the instrument measurement requirements from the Science Objectives (see science methodology section above) will form the starting point for the technical activities in Phase 0. A system

performance model will be developed that will assess the throughput of each element in the optical, detection, and front end electronics in order to determine the overall instrument throughput from "input photons" to "A/D range output". Initially, the performance of each of the system elements will be estimated based on experience gained from our knowledge of previous auroral instruments having established TRL9 heritage plus a review of technical literature. The reference documents from the PCW mission will be evaluated to determine what, if any, additional constraints are presented by the PCW mission (e.g. platform stability), and these constraints will be factored into the performance model.

Optical Design Analysis: It is our intent to leverage previous work done in the Ravens and UVAMC studies, where a number of candidate optical designs were researched for different mission scenarios. The orbit characteristics (Molinya orbit), coupled with the PCW pointing limitations will be used to understand the operational context, and to select which type of optical design is a good fit with the PCW orbit and mission constraints. ZEMAX raytracing software will be used to define optical elements in candidate optical designs and to assess the performance of the optics chain in terms of focused spot size, distortions, uniformity across the field of view, and rejection of unwanted wavelengths. The characteristics of the throughput of the optics is then fed into the Performance Model to determine if the candidate optics, when integrated with the detection system and front-end electronics, will result in a design that meets the preliminary instrument measurement requirements. Based on our initial evaluations of the Science Requirements, we believe that an optical chain consisting of three optical elements will be sufficient to meet the requirements, and will verify this initial evaluation during Phase 0.

A preliminary assessment of the baffle design will be made by evaluating the PCW orbit using STK software to identify the relative positions of light sources (sun, earth, planets) and reflections sources (PCW satellite) relative to the instrument desired FOV and pointing direction. In Phase 0 this activity will be restricted to defining a ROM size of the baffle for instrument sizing purposes.

Mechanical/Thermal Design: The mechanical & thermal concept design will be developed after the layout and size of the optical elements and the baffle requirements are known. Solidworks CAD software will be used to define the relative position of the optical elements, detector system and electronics. SPENVIS software will be used to characterize the radiation dose in the PCW orbit over the instrument required lifetime. Together with an evaluation of the PCW vibration environment, the packaging requirements will be defined and physical resources such as mass, volume, and interface requirements will also be defined (WP 4.2, 4.3). COSMOSWORKS thermal analysis software will be used to determine the rough order instrument temperatures, and given expected PCW deck temperatures, to determine if it will be necessary to add radiators and/or thermally isolate the instrument from the PCW deck (WP3.2,4.3).

Electronics Design: A high level system block diagram will be developed to identify the functional blocks in the instrument and define their inter-relationships. The requirements for image readout size, readout speed, and supported PCW data rates will define the instrument onboard data storage and processing requirements. External interfaces will be defined, and resource requirements (power, size, physical interfaces) will be estimated based on performance of similar systems (e.g. UVIT, SAPPHIRE, ePOP). Computing requirements will also be calculated.

Concept of Operations: A concept of operations will be developed to provide the measurement regimes required by the Science Objectives and User Needs. Instrument operational modes will be defined, and compatibility with the PCW mission will be assessed (outputs to WP 3.2, 4.3).

Concept Design Compliance Assessment: The design methodology described above will be used to establish a concept design that will define the performance, functional decomposition, external & internal interfaces, and an assessment of the required resources (mass, power, volume), and compatibility with PCW mission/satellite. The concept design will be captured in CDRL EN2/5, and its compliance with the Science Objectives & User/Data Needs will be evaluated.

Development Plan: Based on the concept design developed above, a preliminary cost and schedule assessment will be performed in WP 5.1 for phases BCD, based on a proposed model philosophy to address & retire technical risk that may include some or all of the following: Breadboard, Prototypes, Engineering Models, Qualification Models, Protoflight Models, and Flight Models. The model philosophy will respect schedule and cost constraints. Critical

Technologies will be listed (WP 5.2), their initial TRL levels will be assessed, and activities in the cost/schedule will be identified in an effort to reduce/eliminate the technology risk.

Technical Methodology - Phase A

Concept Design Tradeoffs: The purpose of the concept tradeoffs activity (WP 4.1-A) is to perform a more detailed assessment of the range of performance of the instrument given a variety of inputs, including a more detailed review of the current and expected future performance of the critical technologies as well as establishing the capabilities and limitations of potential suppliers. Concept tradeoffs are an iterative process, whereby the instrument performance analysis & optical/mechanical/thermal/electronic designs are modified in a top level way in rapid form and the resultant impact of the change is identified. In general, improvements in one aspect of the design (e.g. larger aperture) will lead to consequences in other parts of the design (e.g. increase in mass & volume). The goal of the concept tradeoffs is to establish an optimum point between minimum/enhanced instrument performance vs. technology risk (including ITARs impacts) vs. resource requirements vs. complexity to manufacture/align/test, and recommend one (or more) concept designs that best satisfies the envelope of requirements (performance, risk, resources, cost, schedule).

Manufacturability, Alignment, Test: The complexity of the optics design from a manufacture/alignment/test perspective can be a significant driver in terms of technical risk, and cost/schedule. We will solicit support form one or more optical manufacturing houses to both ensure that the optics design is actually able to be manufactured and aligned/tested, but also to determine changes in the design that would simplify these processes. This "design for manufacture/test" approach will be factored into the concept tradeoffs and assessed using the Performance Model. HIA will be engaged to support iterations and optimizations of the optical and baffle design concepts.

Critical Technologies Assessment & Roadmapping: In WP 5.2, experts will be consulted/retained as required to: 1) substantiate the present & future performance of the critical technology elements, 2) identify the challenges/risks, and 3) collect their rough order assessments of downstream cost/schedule. This information will be used to refine the performance analysis in WP 4.1, to feed the Critical Technologies assessment and roadmapping activity (WP 5.2), and to enhance the Development Plan and associated Phase BCD cost & schedule estimates (WP 5.2). For all Critical Technologies, we will attempt to identify a minimum of two sources (with a goal of identifying at least one supplier from within Canada) and will identify development roadmaps for each technology to bring it to an appropriate TRL maturity level for the mission. An example of a technology roadmap in graphical format is shown in Figure 5.4 below. Boxes labeled STDP imply that the corresponding technology may be a candidate for breadboarding under an STDP program.

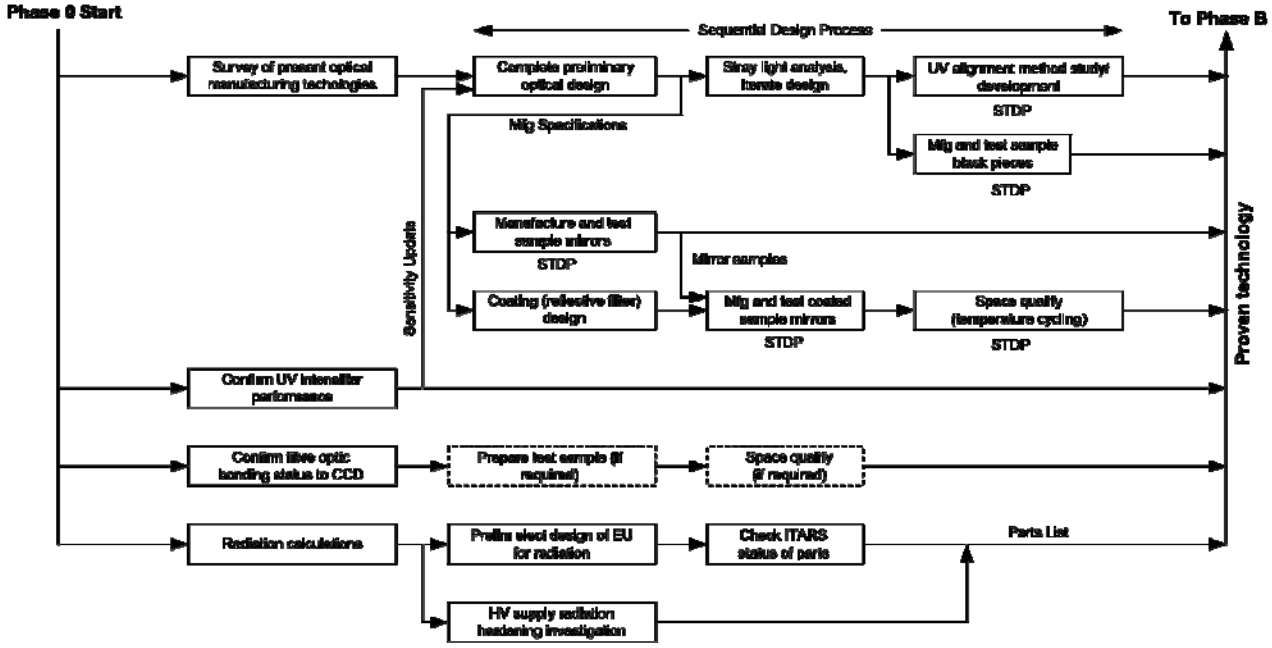


Figure 5.4: Critical Technology Assessment/Development Roadmap

Design Review, Verification of Compliance to Requirements, Concept Design Freeze: Once the concept tradeoffs have progressed to the point that further changes do not yield significant improvements to instrument performance, or reductions in technology risk, cost or schedule, the concept design will be frozen and an internal review will be held consisting of UofC, Routes, and HIA in order to assess/confirm that the proposed optimized concept design(s) are compliant with the Science Objectives and User Needs, and to amend the draft instrument requirements if required. At this point, the proposed design concept(s) will be frozen, the remaining details of the design will be updated, and the relevant inputs to the PCW interfaces, compatibility, and resource requirements will be updated.

Phase BCD Development Plan Update: The model philosophy and cost and schedule estimates for Phases BCD will be updated (WP 5.1) in line with the optimized concept design, the Critical Technologies roadmap activities, and a review/assessment of the PCW Product Assurance Requirements (WP 5.3). Technical and programmatic risks will be identified, ranked and mitigation strategies will be summarized.

5.2.3 Science / Technical Risks Assessment

This risk assessment addresses the large scale challenges identified in the preliminary concept design. Detailed work will be performed in Phase A to identify each individual risk component that contributes to the overarching project risks presented here. Table 5.2 (in Section 5.1) identifies the critical technologies for the proposed payload together with their associated current Technology Readiness Level (TRL). All of the TRLs identified here will be reassessed and/or refined during Phase 0. These are initial estimates based on the current conceptual design. As stated in section 5.1, the overall imaging system concept is derived from components with successful flight history, being used in a new configuration. What follows is a systematic look at the preliminary TRL for each identified component, logically divided into three groupings:

OPTICS. UV aspheric mirrors are assessed at TRL3 since the technology concept and application is well-known, but their manufacturability is not. The key concern regarding fabrication is whether a suitable surface roughness is achievable at the required mirror curvature (roughness impacts both thin film adhesion and optical aberration). Baffles and internal surfaces are rated at TRL4 as they have been flight proven on OSIRIS, but potentially will need modifications for the proposed optical design and wavelengths of interest. FUV thin film mirror coatings were successfully used on POLAR UVI and IMAGE WIC, but are considered TRL3 for this mission due to the likely use of mirrors with different curvatures than those of previous missions. FUV transmission filters, which might be employed if the OI auroral emission band is selected for measurement, were used on Dynamics Explorer 1 (SAI) and Polar VIS (FUV Earth Camera). However, these missions did not employ identical bandpass requirements to those needed for PCW-UVI, so the filters are assessed at TRL3.

DETECTOR. MCP Image Intensifier with solar-blind photocathode is at a TRL4. They have been flight qualified through testing and are awaiting launch on UVIT, but will likely require a different photocathode to be used in the PCW configuration (at a minimum). The CCD/CMOS image sensor technology has been demonstrated (UVIT), minor modifications to the interface are required, all of which have been tested at TRL7. Fiber taper coupling intensifier phosphor to CCD/CMOS sensor is at TRL9, with Viking, Freja flight heritage, and ePOP FAI flight qualification. A vastly improved intensifier photocathode technology (yielding very high quantum efficiencies) using Gallium Nitride (GaN) is still at an early TRL and will be assessed during Phase 0.

ELECTRONICS. Radiation-hard sensor readout and processing electronics sits at TRL4. Electronics designed with parts of known radiation tolerance have been prototyped (to be launched on Sapphire). Tolerance to operation in higher radiation environments would be achieved by additional shielding to reduce the radiation levels 'seen' by the electronics to the same as the equipment currently designed. The HV power supply is at TRL4, as the HV supply for the UV imagers proposed here is derived from a design used for XMM-OM and UVIT. It will modified for the specific PCW-UVI demands, which we initially expect to be lower than UVIT.

The presently identified technical risks which form the basis of the above listed TRL assessments are included in Table 5.2. They are relatively few in number, and are easily quantified at this stage. The left column of each risk table is color coded according to risk assessment (red=high, orange=medium and green=low). A detailed discussion on mitigating the higher technical risk areas of this concept design follows after Table 5.3

T1	**Inadequate performance of UV optics**
Definition	**Condition:** A total of 1E+4 visible (solar wavelengths) light rejection in front of the image intensifier is required in order to realize the science goals of dayside auroral imaging. The optical design required to achieve this uses configurations and/or applications of materials that have no flight history. **Consequence:** HIGH. (a) If performance is inadequate and attenuates the in-band signal there will be a reduction in the signal intensity at detection and possibly a complete signal loss. (b) If performance is inadequate and does not provide enough filtering, wavelength separation (and science objective 2) will not be achieved. Science objective 1 is independent of (b)
Impact	**Probability:** MEDIUM. **Assessment:** HIGH
Strategy	**Mitigation:** Invest significant resources in the phase0/A optical design, targeted towards the UV reflective optics. Raise the TRL of the reflective optics as much as possible prior to the final design. Have two or more suppliers design and manufacture prototypes; e.g., INO (Canadian) and Acton (U.S.), use STDP process to develop before Phase B/C/D, identify potential suppliers in Phase 0. Investigate possible in flight mechanisms to allow for compensation of varying signal strengths at the image sensor. **Contingency:** Scale back on targeted out-of-band rejection, move to an optical design with a higher initial TRL
T2	**Large envelope size of optics**
Definition	**Condition:** Size of optics (2 channels) may be considered or viewed as too large for a PCW secondary science payload; resolution and sensitivity are main drivers **Consequence:** HIGH. UV imager payload not selected
Impact	**Probability:** LOW. **Assessment:** MEDIUM.
Strategy	**Mitigation:** Examine several optics designs from several different optical designers during Phase 0/A. Smaller envelope will cause a reduction in sensitivity, which can be mitigated by decreased temporal and spatial resolution. **Contingency:** If envelope size is deemed too large, consult PI on requirements targets.
T3	**Design requires very specialized parts, materials, and processes with low yield**
Definition	**Condition:** Optical design (reasonable size) may be difficult to manufacture; e.g., tight tolerances, mirrors hard to mount, low roughness (for UV) aspheric surfaces required. Past experience demonstrates difficulties in manufacturing optical components, failures in space qualification, and the possible need for multiple manufacturing attempts. **Consequence:** MEDIUM. Increased schedule and cost with additional re-design and mfg attempts, science goals not achieved (e.g., visible light rejection). Spatial resolution and visible light rejection less than science requirement (goals may not be achieved)
Impact	**Probability:** MEDIUM. Science requirements are strict and the proposed optics relies on advanced technologies. Proposed FUV optics is innovative and requires strict manufacturing tolerances. **Assessment:** MEDIUM.
Strategy	**Mitigation:** Early design and breadboard items that are viewed as high risk or difficult; eg. high-curvature UV mirrors . Have two or more suppliers (preferable Canadian) manufacture prototype pieces using STDP process to develop before Phase B/C/D, identify potential suppliers in Phase 0, also address mounting issues **Contingency:** Use STDP to address potential design and manufacturing issues, e.g., high-curvature UV mirrors. Use technically best supplier, Canadian if possible.
T4	**Optics design complexity higher than expected in order to meet the minimal science requirements**
Definition	**Condition:** Optical design (reasonable size) may be difficult to manufacture; e.g., tight tolerances, mirrors hard to mount, low roughness (for UV) aspheric surfaces required. Past experience demonstrates difficulties in manufacturing optical components, failures in space qualification, and the possible need for multiple manufacturing attempts. **Consequence:** MEDIUM. Increased schedule and cost with additional re-design and mfg attempts, science goals not achieved (e.g., visible light rejection). Spatial resolution and visible light rejection less than science requirement (goals may not be achieved)

Impact	**Probability:** MEDIUM. Science requirements are strict and the proposed optics relies on advanced technologies. Proposed FUV optics is innovative and requires strict manufacturing tolerances. **Assessment:** MEDIUM.
Strategy	**Mitigation:** Early design and breadboard items that are viewed as high risk or difficult; eg. UV coatings . Have two or more suppliers (preferable Canadian) manufacture prototype pieces using STDP process to develop before Phase B/C/D, identify potential suppliers in Phase 0, also address mounting issues **Contingency:** Use STDP to address potential design and manufacturing issues, e.g., UV coatings. Use technically best supplier, Canadian if possible.
T5	**PCW mission/orbit/platform compatibility and resource constraints on instrument**
Definition	**Condition:** Based on past experience there can be accommodation difficulties of instrument on spacecraft with respect to optics and electronics mounting. **Consequence:** MEDIUM. Spacecraft constraints will increase instrument design complexity, and possibly require use of advanced, unproven technology.
Impact	**Probability:** LOW. PCW S/C is expected to provide ample resources as to mass/volume/power/telemetry. **Assessment:** LOW.
Strategy	**Mitigation:** Work with spacecraft mission designers to made needs known early, negotiate resources, and ensure that there is a mutual and full understanding of issues. **Contingency:** Iterate instrument design with negotiated resources.
T6	**Restrictions in design implementation due to ITARS export permits**
Definition	**Condition:** Past experience demonstrates cost-overruns and schedule-slips caused by having to obtain export licenses. **Consequence:** MEDIUM. Schedule delay in obtaining ITAR parts and materials, or budget for additional mass and power if non-ITAR versions need to be used.
Impact	**Probability:** MEDIUM. **Assessment:** MEDIUM.
Strategy	**Mitigation:** If part or material cannot be substituted for non-ITAR version, then work closely with supplier to anticipate and minimize delays. **Contingency:** Identify potential ITAR parts early on in the project.
T7	**High Voltage power supply reliability**
Definition	**Condition:** Past experience with previous UV imagers have shown HV failures caused by arcing through small potted enclosures **Consequence:** MEDIUM. High reliability unit requires greater mass, volume, and power
Impact	**Probability:** LOW. **Assessment:** LOW.
Strategy	**Mitigation:** Use same design as UVIT and XMM-OM (made by MSSL) which do not use potting **Contingency:** Discuss any new requirements with MSSL such as increased radiation, also any lessons learned from UVIT and XMM-OM, ensure mass, volume, and power are not issues

Table 5.3 Technical Risk Assessment.

Mitigation Strategies

At this stage the highest risk components are associated with the UV reflective. They are also a significant science enabler within the design concept. The UV optics will facilitate high sensitivity measurements of the FUV aurora and control the signal throughput of the system, and ultimately the scientific usefulness of the data. There are two possible performance failure modes for the UV optics: 1) the UV optics attenuate the in-band signal, reducing the overall throughput to the detector, and 2) too much signal is transmitted and the active filtering of the mirror

system is insufficient for the targeted visible/IR rejection. Mitigation measures for both failure modes have been identified at two stages within the concept design (optical design development and imager operations).

From a development standpoint, both identified UV optics failure modes result from the same risk: insufficient fabrication of, or thin film deposition on, the aspheric mirrors. We have devoted significant resources in the proposed Phase0 (and PhaseA) budget and timeline for the development of the UV optics. Optical experts from multiple institutions are members of the PCW-UVI key personnel (see section 6.1.1 and resumes of Donna-Lee Desaulniers, Trond Trondsen, and John Pazder). Our team will interface with industry leaders in optical coatings application and component manufacturing and evaluate performance, acceptable fabrication tolerances, and potential mitigation strategies for each candidate design (see letters of support from INO, MSSL and Photek). Based on the critical nature of the UV optics to the ultimate success of the PCW-UVI mission, it is our largest design priority to increase the TRL of this component prior to finalizing the payload design.

From an operational standpoint, both failure modes of the UV optics would be mitigated at the detector level. If incident radiation levels at the detector are not within the predicted range for the instrument design then adjustments need to be made in the detector exposure time, hardware binning configuration, and/or gain settings (all of which will be made remotely configurable). This type of adjustment will compensate for light detection characteristics at the sensor, but cannot mitigate the spectral bandpass characteristics of the UV optics. That being said the selection of well-separated/isolated auroral emission bands should prevent excessive contamination from all but the worst bandpass misalignment scenarios. In this sense, if the failure does not result in a complete loss of signal, or excessive saturation, we are confident that the instrument will still function and would likely meet our science objectives.

6 Managerial Section

6.1. Team Expertise and Organization

6.1.1 Key Personnel Qualifications

Science Team	
Personnel {Backup}	[Specific Role] Relevant Experience and Expertise
Dr. Eric Donovan *UCalgary*	[Principle Investigator (PI)] Dr. Donovan's research is on energy and mass transport in the magnetosphere, and using optical data to remote sense magnetospheric dynamics. He has been the author or co-author of over 125 publications, and has given over 40 invited talks including GEM tutorials in 2007 and 2008, and a COSPAR plenary talk on global auroral imaging in 2008. He is on ESA's SWARM Mission Advisory Group, and the GEM Steering Committee, and has served on the CEDAR Steering Committee. He co-wrote the science plan for the second phase of CANOPUS, which led directly to the establishment of the CSA funded CGSM Program. He is the PI of the CGSM ASI and Riometer arrays. His group deployed, operates, and recovers the data from the 16 white light ASIs located in Canada as part of NASA's THEMIS mission, and founded the international GAIA Virtual Observatory program. Most recently, he was awarded a CFI grant for the second face of the Resolute Bay ISR. With CSA support, he developed the concept of Ravens, a two-satellite auroral imaging mission which was the inspiration for the Chinese KuaFu-B satellite pair. He is on the KuaFu Mission Executive, and will play a critical role in establishing a new vision for KuaFu should PCW-UVI move forward (auroral imaging on PCW would be far superior to that planned for KuaFu). He plays a leadership role in developing an international vision for global auroral imaging, as evidenced by the COSPAR lecture, other significant invited talks on global imaging, and invitations for review papers on global auroral imaging within the context of ILWS.
Dr. Emma Spanswick *UCalgary*	[Deputy PI, Science and Data Requirements, Data Product Generation] Developed novel techniques for using imager and riometer data to remote sense the conjugate magnetosphere. She plays an instrumental role in managing data recovery/distribution for the THEMIS ASIs and CGSM riometers, ASIs, and MSPs. She has developed novel techniques for merging images from multiple imagers, and for web-based browsing of large auroral data sets, the latter forming the basis for GAIA and other auroral data browsers. She has expert-level knowledge of most issues

	related to data access, files, and integrity.
Dr. Vadim Uritsky *UCalgary*	[Science Requirements] Expert in quantitative analysis of auroral data, and develops tools for auroral image analysis, including identification of spatial and temporal scales of auroral phenomena. At present, he is working to establish quantitative methods for matching spatial resolution to cadence/integration time for auroral imaging, including for PCW-UVI.
Dr. Leroy Cogger *UCalgary*	[Risk Identification and Mitigation] His career theme has been the investigation of the upper atmosphere utilizing optical observations. He was deeply involved in Viking, Freja, and Interball UV imagers, and developed the CANOPUS ASI. Dr. Cogger's research and technical contributions were the heritage for the CGSM ASIs, and he continues as a mentor for the growing U. Calgary auroral imaging group. He is also a PI of the ePoP Fast Auroral Imager.
Dr. Trond Trondsen *UCalgary*	[System and Mission Requirements] 23 years of expertise in auroral imaging from ground and space. Directly involved in the design of Visible and FUV auroral imagers on the AURIO (Phase A), Freja, IMAGE, and e-POP missions. Actively participated in Freja Design Reviews. U. Calgary technical liaison between CSA and NASA on the IMAGE project. PI of e-POP Fast Auroral Imager through to successful completion of PDR (and coI since), spearheading the optical design, sensor and filter selection, design of low-noise readout and processing electronics.
Technical Team	
Don Asquin *Routes* {Simon Bazley}	[Technical Lead and System Requirements & Electrical Engineering Support] Broad experience with involvement in electronics design, spacecraft instrumentation and astronomy for over 20 years. Mr. Asquin has been involved in the definition, design, implementation and test of space based UV, Visible and IR imagers for Routes. His ability to merge scientific requirements and system design capabilities has made for extremely successful instruments.
Greg Enno *UCalgary* {Mike Greffen, Trond Trondsen}	[Systems Engineering Support and Integration] Experience in the development, test and operation of 4 satellite auroral imagers (ISIS-II,Viking, Freja, InterBall) and 5 sounding rocket CCD electron/ion imagers. Project and systems engineering for the 8 instruments of the e-POP Payload, including, liaison with CSA, the mission integrator, international partners and subcontractors. Design of MGSE/EGSE and instrument test and operations configurations. Design and development of the e-POP Science Operations Center (eSOC). Design and implementation of the e-POP payload integration and test plan for S/C AI&T. Production of scientific satellite operation scenarios and on-orbit video simulations.
Ken Smith *Routes* {Don Asquin}	[System & Instrument Requirements] Has spacecraft instrumentation experience spans over 30 years, giving him great insight into the trade-offs between technologies and science goals. Main expertise is in specifying and developing Ultraviolet imagers with complex scientific requirements. He is extremely well versed with both existing and emerging technologies and will be a key player in determining the design of the instrument
Donna-Lee Desaulniers *Routes* {John Pazder}	[Optical Systems Engineering Support] Wide ranging optical experience, both within Routes and other Canadian Aerospace companies have given her the ability to envision a solution and work within scientific and physical constraints to develop a workable design.
Paul Marchand *Routes*	[Mechanical Engineering Support] A strong background in mechanical design to the team. He has been a key mechanical designer in several of Routes projects and has exceptional skills and creating simple of effective designs that meet requirements. Mr. Marchand has exceptional skills in developing structural and thermal models of mechanical systems and has been instrumental ensuring that Routes designs can achieve rigorous specifications.
John Pazder *HIA*	[Optical Systems Engineering Support] 15 years experience in optics and optical design, with expertise in astronomical optics, space optics and stray light analysis. Team leader of the optics group at the Herzberg Institute of Astrophysics and the optical systems engineer for the Thirty Meter Telescope. Experience includes: Lead optical designer on MOST space telescope, ASTRA spectrograph, WFOS spectrograph feasibility study. Contributor to: Gemini GLAO feasibility study, VLOT 20m study, CFHT PUEO, CFHT Mega Prime GFSU unit, CFHT IMAKA GLAO study, and JWST fine guidance sensor.
Project Management	
Mike Greffen *UCalgary* {Greg Enno}	[Project Manager] Currently the project manager on 6 CSA contracts held by Eric Donovan including a Pre-phase 0 study of an Ultraviolet imager, as well as a $25M CFI project to build an ISR at Resolute Bay, NU. Ultimately responsible for the operations of over 40 ground based instruments located across Canada. Manages a team of 10-15 people ranging from engineers to research scientists.

Blair Gordon *Routes* {Dave Friberg}	[Project Manager, Routes] Strong background in project management of multiple programs within Routes and other Canadian Aerospace Companies. Mr. Gordon's style of inclusion allows technical designs to flourish while still maintaining strong schedule and financial controls. Held Technical Lead and/or Project Management roles on many previous auroral imaging instrument projects including ePOP-FAI, IMAGE-WIC, FREJA-FAI, and UVAI. Will use this experience to guide the technical team. Mr. Dave Friberg held similar roles on the VIKING F5 ultraviolet imager, WINDII, and a number of Space Station projects.

Major Subcontractors

Routes AstroEngineering located in Ottawa, ON will perform the majority of the technical work required in Phase 0 and A. The company has 20 years of experience developing space science instrumentation.

Herzberg Institute of Astrophysics (HIA) located in Victoria, B.C. will serve as an expert co-reviewer to the Routes Optical Design. John Pazder will be serving as a cross check for the Routes optical design.

Secondary Subcontractors (Phase A)

During the Phase A cycle, several key organizations and companies will be engaged to help develop a technology roadmap to create solutions necessary for the development of the imager (see letters from Photek, INO, and MSSL in Appendix VI). The emphasis will be on Canadian participants who either already have the available expertise and technical solutions or can create a plan that would enable them to be able to develop the solutions. If a Canadian solution is not available, organizations worldwide will be contacted to assist in developing the instrument.

6.1.2 Team Organization and Arrangements

The UofC PCW-UVI team (UofC) will be the Prime Contractor and will be led by Eric Donovan (PI) and comprised of members of the Institute for Space Imaging Science. The major subcontractor during Phase 0 and A will be Routes AstroEngineering (Routes). The UofC and members of the Routes team have a working relationship that spans several decades over many projects, including development of the auroral imagers for VIKING, UVAI, FREJA-FAI, IMAGE-WIC, and ePOP-FAI. Members of UofC have also worked with Routes on the Ravens project which evolved into a conceptual imager design for KuaFu.

UofC, led by the PI and in consultation with the Science Team members and collaborators, will develop, and revise if required, the Science Objectives and Measurement Needs of the mission. Communications between the Science Team and UofC Project Manager (Greffen) will be facilitated by the Deputy PI (DPI, Spanswick) who will also represent the interests of the Science Team in many of the Work Packages. The DPI may represent the PI (Donovan) at meetings if required. The DPI will also act as the CADM officer and as such will integrate the output from the Work Packages into DID compliant deliverables.

The PPM (Greffen) will be responsible for coordinating the efforts of, and facilitating communications between, all of the project stakeholders (including the CSA and PWGSC). The PPM will be accountable to the PI (Donovan) for all non-science aspects of the project, including the budget, scope, schedule and quality of output. All project communications, including progress reports, requests for change and action items, will flow through the PPM.

The Technical Lead at UofC will be Trond Trondsen who will carefully monitor, and where required, contribute to the technical work performed. Trondsen will work as part of the optical design team (with Desaulniers and Pazder). Trondsen, Greg Enno (Systems Engineering Support), Leroy Cogger (Risk Identification and Mitigation) and Spanswick (DPI) will play key roles in checking the various stages of the design for compliance with the Science Requirements and will also work closely with Routes on monitoring other key quality metrics (such as risk, compatibility with PCW, associated technology readiness level etc).

Routes will be responsible for the instrument concept design in Phase 0, as well as assessment of the physical and interface requirements of the instrument package. Routes will also be responsible for developing the cost and schedule estimates for Phases BCD and for assessing the status of the critical technologies. In Phase A, Routes will perform the instrument concept tradeoffs, and update the physical and interface requirements, assess a concept of operations and failure modes / mitigation strategies. Routes will be responsible for the Development Plan, including developing updated cost & schedule estimates, the critical technology roadmap, and factoring in the PA Requirements.

The Routes team will be led by Blair Gordon (Routes PM). Gordon will oversee all aspects of the work preformed by Routes and act as the primary communications conduit between UofC and Routes. The Technical Lead at Routes will be Don Asquin who will report to Gordon, and take the lead role in the majority of the technical Work Packages. Asquin will be responsible for identifying the physical and interface requirements for the instrument, and to be sure that all aspects of the design (optical, electrical, mechanical, thermal, manufacturing, test, operations) are considered. Don will also coordinate the Technology assessment activities. Ken Smith will provide combined Systems Engineering and Electrical Engineering support and will be responsible in Phase 0 for confirming that the performance of the concept design will meet the measurement needs derived from the science requirements. Ken will also assess the performance impact of changes in the design as the tradeoff space is evaluated during Phase A. Donna-Lee Desaulier will lead the optical design effort and will assess the optical performance of the optics, coatings and baffles. Paul Marchand will provide Mechanical/Thermal Engineering design support and will assess the packaging in the context of the PCW mission environmental requirements.

During both Phase 0 and Phase A, John Pazder from the Hertzberg Institute of Astrophysics (HIA) will act as an optical design consultant under sub-contract to UofC. Pazder will work with Desaulniers and Trondsen to refine and develop the conceptual optical design of the instrument.

In addition to the key personnel identified above, we have formed a PCW-UVI team of Science Collaborators for this proposal (herein referred to as the Science Team). Science Team members are not listed directly as resources in any work packages associated with this proposal and as such are not identified as key personnel. Our rationale for inviting each member was as follows:

- Connors, Jayachandran, Kabin, Knudsen, McWiliams, McConnell, Rankin: Representatives of other Canadian space physics institutions, guaranteeing integration with major Candaian initiatives (e.g., FDAM, SuperDARN, CHAIN, AUGO, etc.)
- Skone: UofC Engineering faculty member studying auroral effects on GPS accuracy
- Pulkkinen, Ostgaard, Lester, Lessard, Spann: International team members who have a significant science interest in the project and who will investigate possible small hardware contributions to PCW-UVI.
- Brandt: PI of proposed EAGLES (ENA imaging) NASA Mission of Opportunity
- Chi, Fu: Chinese members of KuaFu who will help integrate PCW-UVI and KuaFu

Letters from the team members express their specific basis of involvement, and are included in Appendix VII. We make two specific comments here. First, Brandt is the only team member specifically identified because of a complementary project (EAGLES). This is for several reasons. The combination of PCW-UVI and EAGLES, effectively two Missions of Opportunity, would provide a remarkable opportunity for simultaneous imaging of the inner CPS/ring current and global auroral distribution, essentially fully satisfying the observational needs for NASA LWS Science Target #8 Dynamic Geospace Coupling (see NASA Heliophysics 2010 Road Map pages 74-75). We expect PCW-UVI would greatly enhance the likelihood of EAGLES being funded, and if both are approved we expect close connections between the two projects as they evolve. Second, the three team members from China would work with us to develop a revised plan for KuaFu-B should PCW-UVI be approved. One excellent prospect for that would be to change KuaFu-B to a single satellite with apogee over the southern hemisphere. Although KuaFu auroral imaging would be significantly inferior to that possible with PCW-UVI, there would be obvious science benefits to having even inferior auroral images conjugate to the northern hemisphere images provided by PCW-UVI.

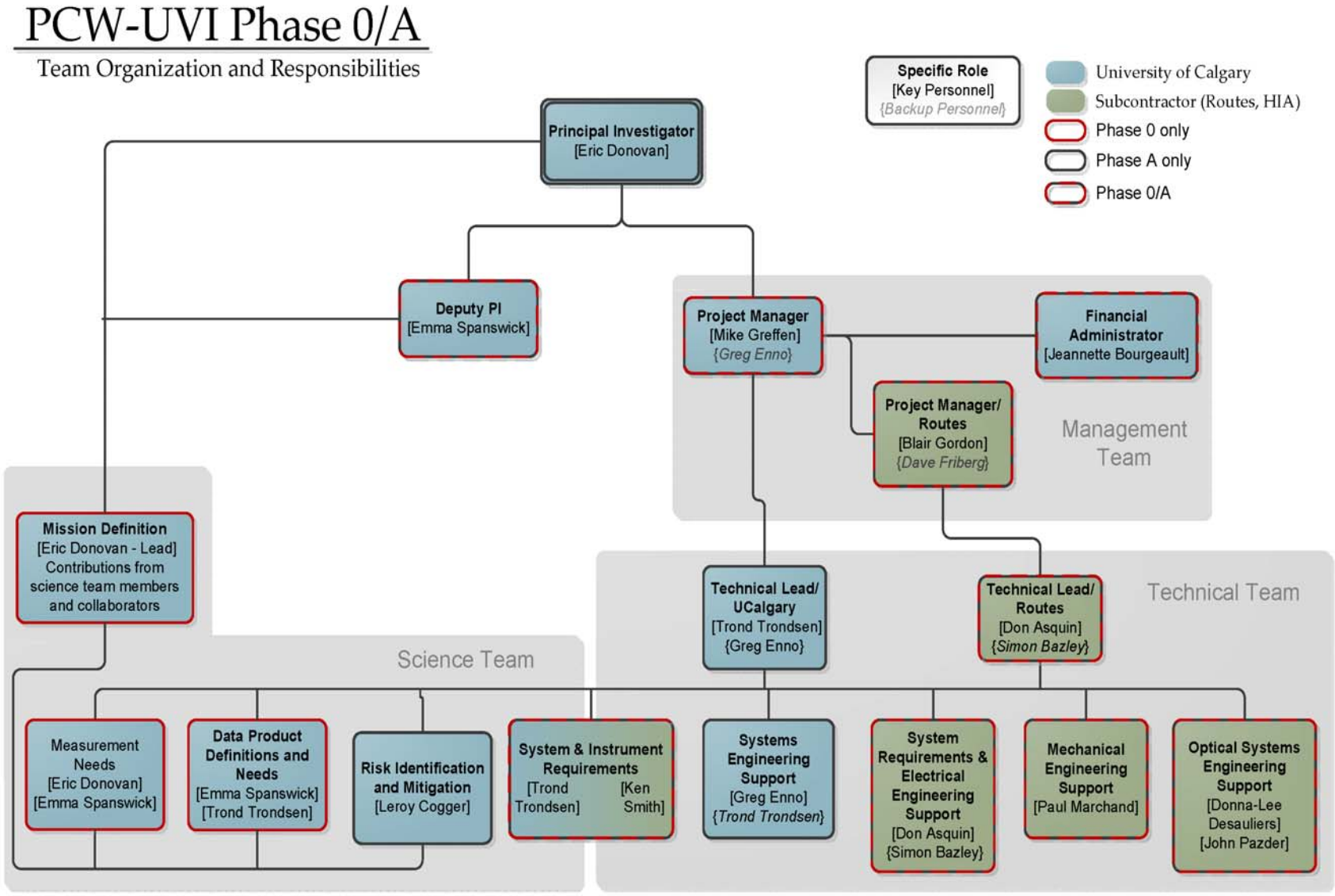


Figure 6.1: Organization Chart showing the structure of the proposed team for both Phase 0 and A.

6.1.3 Bidder's Background and Related Experience

The Bidder is the University of Calgary, a comprehensive research university ranked one of Canada's top seven research universities. The University of Calgary has 17 faculties with more than 60 departments and more than 30 research Institutes and Centres. The proposed work would be spearheaded by Dr. Eric Donovan's research group, which is part of the University of Calgary's Institute for Space Imaging Science (ISIS). Space Imaging within ISIS encompasses fundamental and applied research in planetary science, astrophysics, and geomatics and includes research and development of enabling technologies in imaging required to advance research goals. Over the past four decades, Space Imaging groups (namely, the former Institute for Space Research) at the University of Calgary and industrial partners have made major contributions to both the technology of auroral imaging and to the advancement of knowledge of the Solar-Terrestrial environment through the acquisition and analysis of auroral images obtained from both satellite-based and ground-based instruments. The University of Calgary, along with industrial partners, has designed and built satellite borne imagers for successful auroral imaging missions such as ISIS-2, Viking, Freja, Interball and Image WIC. The University of Calgary has also successfully designed, built, and operated ground-based auroral imagers since the 1980's.

Dr. Donovan's research group is located on the main University of Calgary campus, and occupies roughly 4,000 square feet in the Science B building. This includes two labs for electronic work, two dark-rooms used for instrument calibration purposes. This research group has full access to the ISIS vacuum calibration chamber, capable of calibration across wavelengths from vacuum FUV (120 nm) through to the Near Infrared. The University of Calgary provides secretarial as well as access to computing infrastructure. Dr. Donovan, Canada Research Chair in Auroral Physics, currently has a staff of 10 (two research associates, one post doc, one program manager, and technicians), plus several Co-Op students. Dr. Donovan has received prior funding for the development of global auroral imaging concept through the Canadian Space Agency [9F007-033080 (Ravens Concept Study), and 9F007-080324 (UVAMC Pre-PhaseA Study)].

6.2 Methodology and Risks

6.2.1 Management Plan

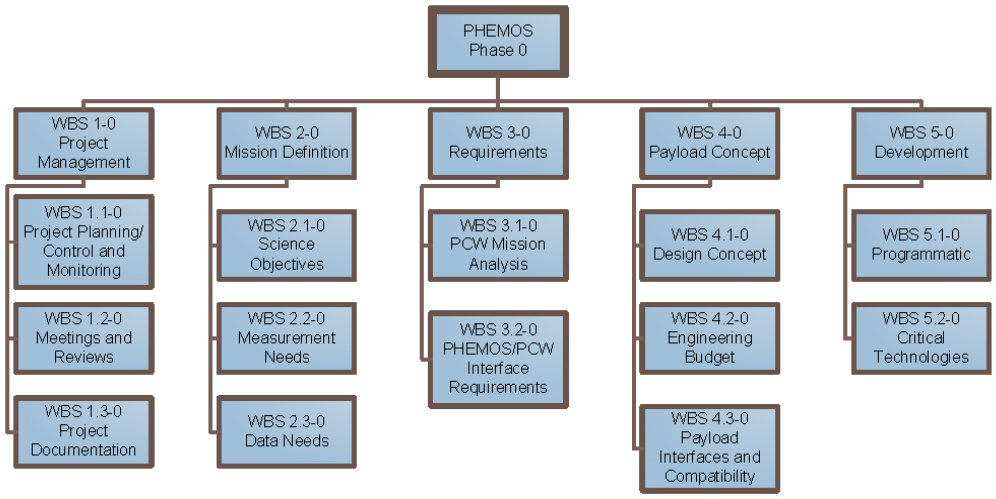


Figure 6.2: Phase 0 Work Breakdown Structure (WBS)

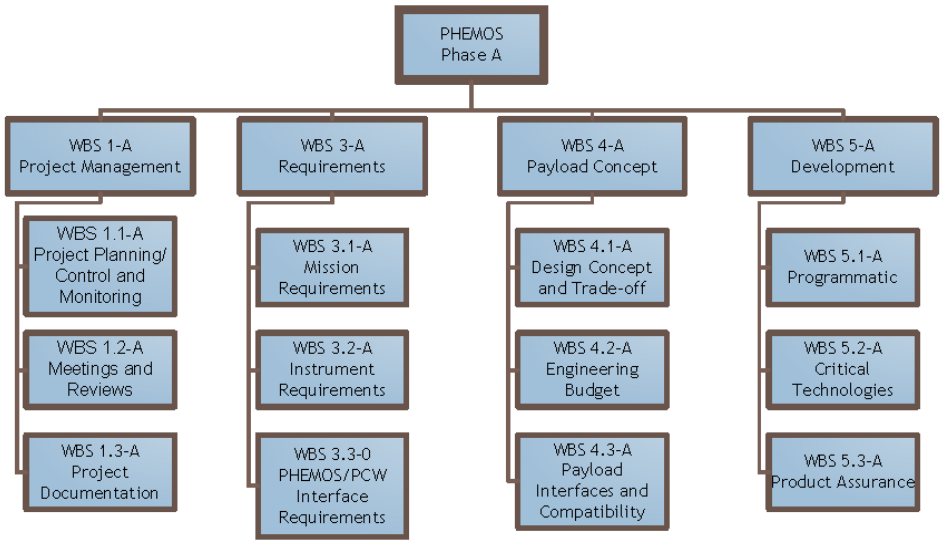


Figure 6.3: Phase A Work Breakdown Structure (WBS)

Work Package Descriptions

WBS1 Phase0/A Work Package Descriptions

Scheduled Start and End times are shown in working days calculated taking Statutory Holidays and 2 weeks of vacation/summer closure into account. Estimate Effort is shown in hours billed to the project followed by italicized contributed hours in brackets. Contributed hours will be provided by Prime and Routes at no cost to the contract. Some of the contributed level of effort will be completed by UofC personnel, in scope and on budget, under the current UVAMC Pre-phase A contract (9F007-080324) held by Eric Donovan at UofC.

The work encompassed in WBS 1 is the same for both Phase 0 and Phase A except for Scheduled Start and End dates and the appropriate CDRL numbers. For the sake of brevity, we have combined the two descriptions in the following tables and separated Phase 0 and Phase A information with a "/" where appropriate (ie. Phase 0/Phase A). In all instances, Phase 0 details are reported first.

PROJECT: PCW-UVI [PHASE 0/PHASE A]	**WBS Ref: WP 1.1-0/A**
Work Package Title: Project Planning/Control and Monitoring	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:** T0 /T1+8/10 mths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Mike Greffen
Estimated Effort:0/26 *(81/74c)*hrs	**Resources:** Mike Greffen, Blair Gordon
OBJECTIVES: ▪ Finalize Project Management Plan ▪ Maintain CWBS and Schedule ▪ Complete Phase 0/A on time and on budget with a high quality product	
INPUTS: ▪ CDRL PM1 Initial Release	
TASKS: ▪ Update and finalize the proposed Project Management Plan (CDRL PM1) with emphasis on changes in resource availability, the Responsibility Allocation Matrix, the Project Risk Assessment Matrix and the budget and timeline. ▪ Review and update the CWBS and the Work Package Descriptions at the start of the phase and prior to each Monthly Progress Meeting. (scope verification)	

- Define all stakeholders' roles and responsibilities. Manage the stakeholder's expectations to keep the project on scope. Facilitate stakeholder communication via regular meetings and an effective Configuration and Document Management office (communications management).
- Continually track project progress using Earned Value Management or equivalent. Monitor and control the timeline, budget and scope and quality of all Phase 0 work (schedule, cost, scope and quality control). Maintain schedule, update in Monthly Progress Reports (CDRL-PM8/PM18).
- Monitor and control project management risks. Track risks identified in the preliminary management risk analysis and identify new risks as appropriate. Update or develop mitigation strategies for identified risks. Monitor the contingency reserves in the project (risk management)
- Facilitate all communication with CSA.

OUTPUTS AND DELIVERABLES:

- CDRL-PM1/PM11 (Project Management Plan) delivered Final at Kick Off Meeting
- CDRL-PM8/PM18 (Monthly Progress Reports)
- CDRL-PM2/PM12 (CWBS and Work Package Descriptions)

PROJECT: PCW-UVI [PHASE 0/PHASEA]	**WBS Ref: WP 1.2-0/A**
Work Package Title: Meeting and Reviews	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:** T0/T1+8/10mnths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Mike Greffen
Estimated Effort: 0/106 *(220/157c)* hours	**Resources:** Mike Greffen, Eric Donovan, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers

OBJECTIVES:

- Stay connected with the progress of the PCW work currently underway
- Communicate project progress to the CSA and other stakeholders

INPUTS:

- PHEMOS RFP (Solicitation 9F007-090217/A)

TASKS:

- Arrange and attend project meetings listed in the PHEMOS RFP, either in person or by teleconference or videoconference.
- Attend PCW mission meetings listed in the PHEMOS RFP. Communicate latest mission level information to the project team.
- Conduct PHEMOS reviews listed in the PHEMOS RFP.

OUTPUTS AND DELIVERABLES:

- None (see WP 1.3-0/A)

PROJECT: PCW-UVI [PHASE 0/PHASEA]	**WBS Ref: WP 1.3-0/A**
Work Package Title: Project Documentation	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:**T0 /T1+8/10mnths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 44/306 *(230/231c)* hours	**Resources:** Emma Spanswick, Mike Greffen, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers, Eric Donovan

OBJECTIVES:

- Provide configuration controlled versions of all CDRL documents listed in the PHEMOS RFP (solicitation 9F007-090217/A).
- Foster clear communication of project progress to all stakeholders.

INPUTS:

- PHEMOS RFP (solicitation 9F007-090217/A)

TASKS:

- Receive inputs to CDRL documents from appropriate Work Packages.
- Integrate inputs into Data Item Description compliant documents and place under Configuration Control.
- Distribute CDRL documents to stakeholders.

OUTPUTS AND DELIVERABLES:
▪ Preliminary, Initial Release and Final (as required) versions of all project CDRL documents.

Phase0 Work Package Descriptions

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 2.1-0**
Work Package Title: Science Objectives	**Sheet:** 1 of 1
Scheduled Start: T0 **Scheduled End:** T0+75.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Eric Donovan
Estimated Effort: 15 *(26c)* hours	**Resources:** Eric Donovan, Emma Spanswick
OBJECTIVES: ▪ To detail the science concept and objectives of the mission in sufficient depth to allow for the specification of measurement and data needs.	
INPUTS: ▪ Preliminary CDRL SC1 submitted with PCW-UVI Phase 0/A proposal	
TASKS: ▪ Review (and if necessary revise) the preliminary science concept and objectives description contained in the preliminary CDRL SC1 submitted with the PCW-UVI Phase0/A proposal. This includes a review (and complete documentation) of the science concept, objectives and prioritization. ▪ If necessary, review and revise the science objectives and prioritization (initiated by MTR or WP4.1-0) and iterate towards a finalized science concept and objectives document.	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0, WP2.2-0, WP2.3-0]. ▪ Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]	

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 2.2-0**
Work Package Title: Measurement Needs	**Sheet:** 1 of 1
Scheduled Start: T0+20 days **Scheduled End:** T0 + 71 days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 32 *(33c)* hours	**Resources:** Emma Spanswick, Eric Donovan, Blair Gordon, Ken Smith, Don Asquin, Donna-Lee Desaulniers
OBJECTIVES: ▪ To detail and prioritize the mission measurement needs in sufficient depth to enable instrument conceptual design (WP4.1-0)	
INPUTS: ▪ Preliminary science objectives contained in CDRL SC1 from WP2.1-0	
TASKS: ▪ Based on the science objectives section contained in the preliminary version controlled CDRL SC1 (initial output from WP2.1-0), identify and name the key measurement needs. These will include (but are not limited to): observational area of interest, measurement quantities, energy resolution and daytime viewing needs. ▪ Determine values/ranges for measurement needs based on the science objectives output from WP2.1-0. ▪ Prioritize measurement needs based on the prioritization of science objectives output from WP2.1-0. ▪ If necessary, review and revise the measurement needs and/or prioritization (initiated by MTR and/or WP4.1-0) to iterate towards a final release of CDRL SC1. ▪ Provide a preliminary set of instrument requirements (ie. FUV spectral range, resolution, etc.) to enable conceptual design (WP4.1-0)	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0, WP4.1-0] ▪ Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]	

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 2.3-0**
Work Package Title: Data Needs	**Sheet:** 1 of 1
Scheduled Start: T0+20 days **Scheduled End:** T0 + 73 days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 60 *(20c)* hours	**Resources:** Emma Spanswick

OBJECTIVES:
- To detail and prioritize the data needs of PCW-UVI

INPUTS:
- Preliminary science objectives and measurement needs contained in CDRL SC1 (initial output from WP2.1-0 and WP2.2-0).

TASKS:
- Based on the output of WP2.1-0 and WP2.2-0 review (and if necessary revise) the list of potential PCW-UVI data products.
- For each data product, identify the needs of potential end users. These will include (but are not limited to): data availability, turn-around-time, and image mapping requirements.
- For each data product, identify its relationship to the PCW-UVI science objectives and prioritize data needs based on the prioritization of science objectives output from WP2.1-0.

OUTPUTS AND DELIVERABLES:
- Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0]
- Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 3.1-0**
Work Package Title: PCW Mission Analysis	**Sheet:** 1 of 1
Scheduled Start: T0 **Scheduled End:** T0+164days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 24 *(68c)* hours	**Resources:** Emma Spanswick, Ken Smith, Don Asquin

OBJECTIVES:
- Achieve a full understanding of the operational environment of the Science Payload

INPUTS:
- PHEMOS proposal concept
- Available PCW mission documentation from CSA

TASKS:
- Thorough analysis of all available documents on PCW to achieve objective.

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN1 [delivered to WP1.3-0, WP3.2-0]
- Input to CDRL EN1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0]
- Input to CDRL EN1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 3.2-0**
Work Package Title: PHEMOS/PCW Interface Requirements	**Sheet:** 1 of 1
Scheduled Start: T0+64days **Scheduled End:** T0+164days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 30 *(48c)* hours	**Resources:** Emma Spanswick, Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- Produce a list of instrument requirements for the PCW satellite

INPUTS:
- PCW Mission analysis from WP3.1-0
- Preliminary PCW-UVI concept design from proposal

▪ Instrument requirements section from initial release of CDRL SC1
TASKS: ▪ Based on the measurement requirements in the initial release of CDRL SC1 determine the associated interface requirements on PCW. These will include, but not be limited to; pointing accuracy, pointing stability, distribution of instrument suite across available satellites, and telemetry rate.
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL EN1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0] ▪ Input to CDRL EN1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WBS 4.1-0** **WP Ref: WP 4.1.1-0**
Work Package Title: Design Concept	**Sheet:** 1 of 1
Scheduled Start: T0+71days **Scheduled End:** T0+153days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 440 *(164c)*hours	**Resources:** Trond Trondsen, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers, John Pazder
OBJECTIVES: ▪ Develop a validated science payload conceptual design based on the measurement requirements of the science objectives	
INPUTS: ▪ Initial conceptual design from PCW-UVI proposal ▪ Measurement/Instrument requirements from initial release of CDRL SC1 ▪ PCW mission constraints from initial release of CDRL EN1	
TASKS: ▪ Perform conceptual design, including optics, detectors, electronics, controls, data storage and handling ▪ Define interfaces and any common resources ▪ Perform analysis given measurement requirements (from initial release of CDRL SC1) ▪ Develop preliminary Concept of Operations	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0, WP5.1-0, WP5.2-0] ▪ Input to CDRL EN2 (Final) [delivered to WP1.3-0]	

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 4.2-0**
Work Package Title: Engineering Budget	**Sheet:** 1 of 1
Scheduled Start: T0+140days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 12 *(13c)* hours	**Resources:** Blair Gordon, Ken Smith, Paul Marchand
OBJECTIVES: ▪ Determine mass, volume, power, dataflow, and thermal budgets	
INPUTS: ▪ Conceptual design from preliminary CDRL EN2 (output from WP 4.1-0)	
TASKS: ▪ Perform radiation analysis for specified orbit ▪ Estimate mass, volume, power, dataflow, and thermal budgets from refined conceptual design ▪ Iterate design if required (initial design exceeds conceivable S/C resources)	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0] ▪ Input to CDRL EN2 (Final) [delivered to WP1.3-0]	

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 4.3-0**
Work Package Title: Payload Interfaces and Compatibility	**Sheet:** 1 of 1
Scheduled Start: T0+140days **Scheduled End:** T0+149days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 12 *(15c)* hours	**Resources:** Blair Gordon, Don Asquin, Ken Smith, Paul Marchand, Donna-Lee Desaulniers

OBJECTIVES:
- Produce preliminary interface design

INPUTS:
- Conceptual design contained CDRL EN2 (output WP4.1-0)
- Data needs from initial release of CDRL SC1

TASKS:
- Determine power, command/control, data output, mechanical (mass, mounting, structural, volume), thermal requirements and characteristics

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0]
- Input to CDRL EN2 (Final) [delivered to WP1.3-0]

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 5.1-0**
Work Package Title: Programmatic	**Sheet:** 1 of 1
Scheduled Start: T0+135days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 40 *(84c)* hours	**Resources:** Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- Program Cost and schedule estimate for Phases BCD

INPUTS:
- Mission & Instrument Requirements contained in CDRL SC1
- Concept Design and analyses from WP4.1-0

TASKS:
- Prepare PHEMOS Preliminary Cost & Schedule estimate

OUTPUTS AND DELIVERABLES:
- Input to CDRL MM1 (initial release) at PCR [delivered to WP1.3-0]
- Input to CDRL MM1 (final) [delivered to WP1.3-0]

PROJECT: **PCW-UVI [PHASE 0]**	WBS Ref: **WP 5.2-0**
Work Package Title: Critical Technologies	**Sheet:** 1 of 1
Scheduled Start: T0+135days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 8 *(12c)* hours	**Resources:** Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- Identify Critical Technologies and establish initial TRL Level

INPUTS:
- Mission & Instrument Requirements contained in CDRL SC1
- Concept Design and analyses from WP4.1-0

TASKS:
- Map key instrument requirements to the performance of key technologies
- Assess Criticality of Key Technologies
- Assess current technology TRL level

OUTPUTS AND DELIVERABLES:
- Input to CDRL MM1 (initial release) at PCR [delivered to WP1.3-0]
- Input to CDRL MM1 (final) [delivered to WP1.3-0]

PhaseA Work Package Descriptions

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 3.1-A**
Work Package Title: Mission Requirements	**Sheet:** 1 of 1
Scheduled Start: T1 **Scheduled End:** T1+103days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 80 *(50c)* hours	**Resources:** Emma Spanswick, Greg Enno, Leroy Cogger, Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- To detail the mission-level requirements that will address the science objectives and measurement needs of the mission

INPUTS:
- Final CDRL EN1 from Phase 0
- Any new PCW documentation available since end of Phase 0

TASKS:
- Refine and produce mission requirements (pointing, data retrieval and distribution, ground control, etc.) requirements for the S/C to provide [based on initial figures derived in Phase 0, CDRL EN1]

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN3 (Mission Requirements Document) [delivered to WP1.3-A, WP3.2-A]
- Input to CDRL EN3 (Initial Release) is deliverable at PHEMOS Phase A MRR.
- Input to CDRL EN3 (Final) deliverable at Phase A PSRR

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 3.2-A**
Work Package Title: Instrument Requirements	**Sheet:** 1 of 1
Scheduled Start: T1+10days **Scheduled End:** T1+184days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 94 (*56C)* hours	**Resources:** Emma Spanswick, Eric Donovan, Trond Trondsen, Greg Enno, Leroy Cogger, Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- Produce measurement requirements that will address the science objectives and the measurement needs of the mission

INPUTS:
- CDRL EN1 from Phase 0
- Any new PCW documentation available since end of Phase0
- Output of WP3.1-A, mission requirements

TASKS:
- Determine/refine requirements of spatial resolution, coverage, pointing accuracy, precision, dynamic range, noise floor, external and internal scattered light rejection, max optical contamination, geometric distortion, passband separation, visible light rejection, Lyman-Alpha rejection

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN4 (Science Payload (System) Requirements Document) [delivered to WP1.3-A, WP3.3-A]
- Input to CDRL EN4 deliverable at PHEMOS Phase A MRR,
- Input to CDRL EN4 final release deliverable at PHEMOS Phase A PSRR.

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 3.3-A**
Work Package Title: PHEMOS/PCW Interface Requirements	**Sheet:** 1 of 1

Scheduled Start:T1+20days **Scheduled End:**T1+184days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 108 *(104c)* hours	**Resources:** Emma Spanswick, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers

OBJECTIVES:

- Produce list of interface requirements for mission-level work in subsequent phases

INPUTS:

- Phase 0 reports and documents
- Any new PCW documentation
- Mission and instrument requirements from Phase A (ongoing work)

TASKS:

- Produce list of interface requirements to PCW that are to be captured in the mission Requirements Document: This will include the following:
  - Optical: Sun exclusion angles, FOV, pointing direction, platform stability
  - Electrical: Power draw, command requirements, housekeeping & data volumes and rates,
  - volumes requirements and ,TT&C ; power, sun angles, FOV, exclusion angles, cooling (radiator), command, telemetry, venting (for HV)
- Update list of interfaces and interface requirements to the PCW satellite for use in the Science Payload (System) Requirements document. This will include:
  - Power Interface requirements
  - Telecommand/Telemetry/Control interface requirements
  - Data Interface Requirements
  - Mechanical & Thermal Interfaces (mounting & stability requirements, specifying thermal interface at mounting points, radiator requirements)
  - Optical Interface requirements
- Update list of power, mass, volume, EMC, thermal, pointing requirements of payload for the S/C to provide

OUTPUTS AND DELIVERABLES:

- Prepare PHEMOS/PCW mission-level interface requirement inputs to CDRL EN3 (Mission Requirements Document) [delivered to WP1.3-A]
- Prepare PHEMOS/PCW instrument-level interface requirement inputs to EN4 (Science Payload (System) Requirements Document). [delivered to WP1.3-A, WP4.1-A]
- Input to EN3 (final) at Phase A MRR [delivered to WP1.3-A]
- Input to EN4 (initial release) at Phase A MRR [delivered to WP1.3-A]
- Input to EN4 (final) at Phase A PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 4.1-A**
Work Package Title: Design Concept and Trade-off	**Sheet:** 1 of 1
Scheduled Start: T1 **Scheduled End:** T1+203days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 1082 *(444C)* hours	**Resources:** Eric Donovan, Emma Spanswick, Mike Greffen, Trond Trondsen, Greg Enno, Leroy Cogger, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers, John Pazder

OBJECTIVES:

- Perform trade-off analysis as input to later study phases

INPUTS:

- CDRLs SC1, EN1, EN2, EN4

TASKS:

- Review any updated PCW documents.
- Establish the parameters of the design concept trade study. Potential trade study elements include: Risk, cost, complexity, performance, schedule, TRL maturity, multiple sources of supply, demands on spacecraft resources
- Perform trade-off analysis of the concept design based on current and expected advancements in the key technologies and iterate design concept to reduce cost, complexity, and schedule risks against performance

and meeting science & mission objectives. Factor in the results of the Critical Technology Assessment and road mapping activity from WP 5.2. Perform design analysis to assess impact of tradeoffs, and confirm feasibility of the concept design
- Freeze design when instrument concept has met all primary scientific requirements, as well as many secondary & tertiary scientific goals as possible, balanced against a moderate level of technical/cost/schedule risk, such that the probability of mission success is high.
- Capture all aspects of final concept design (functional, external & internal interfaces, optical, electrical, software, and mechanical/thermal design requirements).
- Produce a high level architecture (block diagram) and design description identifying the subsystems and defining the external & internal interfaces
- Identify and quantify key technical, cost, schedule, and programmatic challenges and risks, and identify options to relieve or mitigate high risk/high cost drivers.
- Concept of Operations: Define normal operating modes, contingency modes. Identify concept of instrument commanding, as well as receipt, storage, and distribution of the resulting data stream, and compatibility with PCW MOC and SOC ground systems.
- The compilation of a Compliance Matrix of the concept design against the Science Objectives and User Needs, as flowed through the Mission Requirements Document (CRDL EN3) and the Science Payload (System) Requirements Document (CDRL EN4)

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN5 (initial release) prior to MRR [delivered to WP1.3-A]
- Input to CDRL EN5 (final) prior to PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 4.2-A**
Work Package Title: Engineering Budget	**Sheet:** 1 of 1
Scheduled Start: T1+80.5 days **Scheduled End:** T1+176.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 40 *(0c)* hours	**Resources:** Ken Smith, Don Asquin, Paul Marchand, Blair Gordon

OBJECTIVES:
- Refine mass, volume, power, dataflow, and thermal budgets from Phase 0

INPUTS:
- SC1 (Science Objective and User's needs Definition Document)
- EN1 (Preliminary Interface Requirements Document)
- EN2 (Science Payload Conceptual Design Document)

TASKS:
- Refine mass, volume, power, dataflow, and thermal budgets from refined conceptual design
- Adjust resource estimates to include appropriate design margins for MRR/PSRR design gate
- Verify that all required resources fall within the available PCW resource availability

OUTPUTS AND DELIVERABLES:
- Inputs of CDRL EN5 (initial release) at MRR [delivered to WP1.3-A]
- Inputs of CDRL EN5 (final) at PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 4.3-A**
Work Package Title: Payload Interfaces and Compatibility	**Sheet:** 1 of 1
Scheduled Start: T1+80.5days **Scheduled End:** T1+176days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 44 *(10c)* hours	**Resources:** Ken Smith, Paul Marchand, Blair Gordon

OBJECTIVES:
- Produce instrument failure modes and mitigation strategies, also update interface design

INPUTS:
- EN2 (Science Payload Conceptual Design Document)

TASKS:

- Perform more detailed analysis of potential and credible failure modes to determine and document effect on instrument and satellite; design instrument to minimize effects of failures
- Determine mitigation strategies to minimize failure modes on the satellite
- Update power, command/control, data output, mechanical (mass, mounting, structural, volume), thermal requirements and characteristics

OUTPUTS AND DELIVERABLES:

- Inputs to CDRL EN5 (initial release) at MRR [delivered to WP1.3-A]
- Inputs to CDRL EN5 (final) at PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 5.1-A**
Work Package Title: Programmatic	**Sheet:** 1 of 1
Scheduled Start: T1+85.5days **Scheduled End:** T1+ 101.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 122 *(22c)* hours	**Resources:** Mike Greffen, Blair Gordon, Don Asquin

OBJECTIVES:

- Update the development plan for Phase BCD output in Phase0

INPUTS:

- CDRL MM1 output from Phase0
- Concept Design and analyses from WP4.1-A (CDRL EN5)

TASKS:

- Product tree, identifying major components within the instrument package
- Identification of breadboarding or early prototyping required to derisk program
- Define the model philosophy required to incrementally retire risk, and identify which requirements will be verified on which models
- Define analyses & tests to be performed to verify functional, performance, and environmental requirements. Identify facilities to be used for testing.
- Define a Phase BCD schedule that is consistent with the defined model philosophy, and confirm that it meets PCW programmatic schedule needs. Identify major design reviews for the space hardware, as well as activities related to Ground Station equipment & Science Operations.
- Prepare cost estimate for Phases BCD including payload and associated ground support equipment, ground segment, and Science Operation Center.
- The cost and schedule estimates will factor-in the effects of the agreed PA Requirements document.
- Identify key programmatic & technical/technology risks and define avoidance/mitigation strategies

OUTPUTS AND DELIVERABLES:

- Input to CDRL MM2 (initial release) prior to MRR [delivered to WP1.3-A]
- Input to CDRL MM2 (final) prior to PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 5.2-A**
Work Package Title: Critical Technologies	**Sheet:** 1 of 1
Scheduled Start:T1+1day **Scheduled End:**T1+181.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 336 *(26c)* hours	**Resources:** Trond Trondsen, Ken Smith, Don Asquin, Donna-Lee Desaulniers, Blair Gordon

OBJECTIVES:

- Update and/or identify Critical Technologies and TRL assessments associated with the design output of WP4.1-A

INPUTS:

- CDRL MM1 from Phase0
- Concept Design and analyses from WP4.1-A (CDRL EN5)

TASKS:

▪ Investigate current and next generation developments in each of the key technology areas. ▪ Identify potential sources of manufacture (in Canada & abroad), identify current & expected TRL levels, and assess maturity relative to mission schedule requirements. ▪ Identify if any technologies would be subject to ITAR, and develop mitigation strategies for those technologies (another source, obtain TAA, etc.). ▪ Define technology roadmaps for each of the key technologies to attain desired TRL level in line with mission requirements.
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL MM2 (initial release) prior to MRR [delivered to WP1.3-A] ▪ Input to CDRL MM2 (final) prior to PSRR [delivered to WP1.3-A]

PROJECT: PCW-UVI [PHASE A]	**WBS Ref: WP 5.3-A**
Work Package Title: Product Assurance	**Sheet:** 1 of 1
Scheduled Start:T1+70.5days **Scheduled End:**T1+176.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 56 *(16c)* hours	**Resources:** Mike Greffen, Blair Gordon, Ken Smith
OBJECTIVES: ▪ Develop Product Assurance Requirements for PCW-UVI	
INPUTS: ▪ PCW Product Assurance Requirements [RD4]	
TASKS: ▪ Review CSA Product Assurance (PA) Requirements document. Categorize requirements into Categories 1-4. Recommend minimum list of PA CDRLS for Phases BCD. ▪ Negotiate with applicability and verification of safety PA clauses with CSA Safety and Mission Assurance Directorate	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL MM2 (initial release) prior to MRR [delivered to WP1.3-A] ▪ Input to CDRL MM2 (final) prior to PSRR [delivered to WP1.3-A]	

6.2.2 Personnel Allocation

WP #	PHASE 0 Work Pack Title	Eric Donovan		Emma Spanswick		Michael Greffen		Trond Trondsen		Greg Enno		Leroy Cogger		Blair Gordon		Ken Smith		Don Asquin		Paul Marchand		Donna-Lee Desaulniers		John Pazder		Total	
1.1-0	Project Planning, Control and Monitoring						65							P	16											0	81
1.2-0	Meetings and Reviews	P	44				56							P	42	P	34	P	34	P	5	P	5			0	220
1.3-0	Project Documentation	P	22	A	40		102							P	4	P	5	P	49		4	P	4			44	230
2.1-0	Science Objectives	A	16	P	10																					15	26
2.2-0	Measurement Needs			A	20									P	1	P	8	P	2			P	2			32	33
2.3-0	Data Needs			A	20																					60	20
3.1-0	PCW Mission Analysis			A	20											P	24	P	24							24	68
3.2-0	PHEMOS/PCW Interface Requirements			A	30									P	2		8	P	8							30	48
4.1-0	Design Concept							P	80					A	4	P	160	P	160	P	40	P	80		80	440	164
4.2-0	Engineering Budget													A	1	P	4	P	12	P	8					12	13
4.3-0	Payload Interfaces and Compatibility													A	1	P	4	P	12	P	8	P	2			12	15
5.1-0	Programmatic					P	64							A	40 4	P	4	P	12							40	84
5.2-0	Critical Technologies													A	2	P	8	P	8			P	2			8	12
	Phase 0 Total:	**0**	**82**	**205**	**140**	**0**	**287**	**0**	**80**	**0**	**0**	**0**	**0**	**40**	**77**	**160**	**99**	**192**	**129**	**40**	**25**	**80**	**15**	**0**	**80**	**717**	**1014**

A: Accountable P: Participant Contributed hours at no cost to contract

Phase 0 Responsibility Allocation Matrix (RAM). Level of Effort is indicated in hours.

WP #	PHASE A Work Pack Title	Eric Donovan		Emma Spanswick		Michael Greffen		Trond Trondsen		Greg Enno		Leroy Cogger		Blair Gordon		Ken Smith		Don Asquin		Paul Marchand		Donna-Lee Desaulniers		John Pazder		Total	
1.1-A	Project Planning, Control and Monitoring					A 26	50							P	24											26	74
1.2-A	Meetings and Reviews	P	56			A	18							P 10	51	P 38	16	P 46	16			P 12				106	157
1.3-A	Project Documentation	P	40	A 138	80	P 32	51	P	20					P 20	8	P 16	16	P 80	16	P 12		P 8				306	231
3.1-A	Mission Requirements			A 60	30					P 8		P 24		P 4	4	P 8	8	P 8	8							80	50
3.2-A	Instrument Requirements	P	12	A 36	20			P 8		P 8		P 24		P 2	4	P 36	10	P 12	10							94	56
3.3-A	PHEMOS/PCW Interface Requirements			P 30										A 8	8	P 12	36	P 12	44	P 32	8	P 14	8			108	104
4.1-A	Design Concept and Trade-off	P	16	P 56	20	P 20		P 64	60	P 64		P 92		A 12	14	P 406	26	P 214	82	P 84	22	P 226	54	P	150	1082	444
4.2-A	Engineering Budget													A		P 12		P 12		P 16						40	0
4.3-A	Payload Interfaces and Compatibility															P 28				P 16	10					44	10
5.1-A	Programmatic					P 10	22							A 64				P 48								122	22
5.2-A	Critical Technologies							P 28	16							P 40		P 208				P 60		P	10	336	26
5.3-A	Product Assurance					P 12	12							A 40	4	P 4										56	16
	Phase A Total:	**0**	**124**	**320**	**150**	**100**	**153**	**100**	**96**	**80**	**0**	**140**	**0**	**160**	**117**	**600**	**112**	**640**	**176**	**160**	**40**	**320**	**62**	**0**	**160**	**2620**	**1190**

A: Accountable P: Participant Contributed hours at no cost to contract

Phase A Responsibility Allocation Matrix (RAM). Level of Effort is indicated in hours.

Some of the contributed level of effort associated with Trond Trondsen and Michael Greffen and detailed in the RAM will be completed, in scope and on budget, under the current UVAMC Pre-phase A contract (9F007-080324) held by Eric Donovan at UofC.

6.2.3 Managerial Risk Assessment

MR1	**Poor communications between stakeholders [Phase 0 and Phase A]**
Definition	**Condition:** There are three major stakeholders (Prime (UofC), the major subcontractor (Routes) and the CSA), all of whom have significantly different enterprise environments. **Consequence:** MEDIUM. Poor communications among stakeholders can lead to scope, timeline and quality issues, chiefly the inability to complete the work detailed in the proposal to a satisfactory degree of quality (since the budget and timeline are fixed). A duplication of effort could waste resources and time.
Impact	**Probability:** LOW. All three major stakeholders have extensive experience working with each other. **Assessment:** LOW. $1500-$3000 per Phase. Small schedule delays (inside the float) and possible duplication of effort (10-20 hours at an average hourly rate of $150/hr).
Strategy	**Mitigation:** The Project Manager (Greffen) will manage communications with particular attention to information distribution, performance reporting and stakeholder management. **Contingency:** Personnel from Prime will travel to Routes and/or the CSA at no cost to the contract to participate in face to face meetings.
MR2	**Performance of work outside the project scope [Phase 0 and Phase A]**
Definition	**Condition:** In the early stages of design it can be very difficult to constrain activities to match the defined scope of a project. **Consequence:** MEDIUM. Due to the relatively short timelines and moderate budgets of Phase 0 and A any out of scope work will have a proportionally large impact on the project. Out of scope activities will negatively impact the required deliverables
Impact	**Probability:** LOW. There are detailed Work Package definitions for both Phase 0 and A. **Assessment:** LOW. $1500-$3000 per Phase (10-20 hours of out of scope work at an average hourly rate of $150/hr).
Strategy	**Mitigation:** An up to date Work Breakdown Structure will be maintained by the Project Manager (Greffen). Greffen will also host bi-weekly meeting with UofC and Routes personnel to access the work in progress and confirm that it is in scope. All scope change requests will be processed by Greffen. **Contingency:** UofC and Routes employees will perform incomplete in-scope tasks at no cost to the contract.
MR3	**Inability to complete work on schedule [Phase 0 and Phase A]**
Definition	**Condition:** There is a significant amount of work to complete in Phase 0 and A. Of particular concern is the trade-off analysis in Phase A. **Consequence:** HIGH. Failure to stay on schedule, to end the Trade of analysis in Phase A on schedule for example, could lead to significant schedule delays and possibly the inability to complete the work outlined in the proposal. The resulting budget and schedule overruns may negatively impact the ability of the PHEMOS mission to integrate with the PCW timeline.
Impact	**Probability:** LOW. Innovative design work is intrinsically hard to schedule accurately, however Routes (which has significant experience in this area) has been consulted extensively on the schedule estimates and the schedule contains float. **Assessment:** MEDIUM. A slippage in schedule of 2 months could cost a s much as $45,000 in contributed effort.
Strategy	**Mitigation:** The progress of each Work Package, with special attention to WP 4.1-A, will be closely monitored. A freeze of the concept trade-off analysis will be called prior to the introduction of negative float in the schedule. **Contingency:** If the trade-off analysis is not resolving as anticipated UofC personnel will be assigned full time to re-examine the trade-off parameters (ultimately derived from the Science Objectives) as well as the list of Critical Technologies.
MR4	**Poor communications between stakeholders [Phase 0 and Phase A]**

Definition	**Condition:** There are three major stakeholders (Prime (UofC), the major subcontractor (Routes) and the CSA), all of whom have significantly different enterprise environments. **Consequence:** MEDIUM. Poor communications among stakeholders can lead to scope, timeline and quality issues, chiefly the inability to complete the work detailed in the proposal to a satisfactory degree of quality (since the budget and timeline are fixed). A duplication of effort could waste resources and time.
Impact	**Probability:** LOW. All three major stakeholders have extensive experience working with each other. **Assessment:** LOW. $1500-$3000 per Phase. Small schedule delays (inside the float) and possible duplication of effort (10-20 hours at an average hourly rate of $150/hr).
Strategy	**Mitigation:** The Project Manager (Greffen) will manage communications with particular attention to information distribution, performance reporting and stakeholder management. **Contingency:** Personnel from Prime will travel to Routes and/or the CSA at no cost to the contract to participate in face to face meetings.
MR5	**Key personnel unavailable [Phase 0 and Phase A]**
Definition	**Condition:** Key personnel listed in proposal are not available to perform the work outlined. **Consequence:** MEDIUM. Backups for all key personnel have been identified. Requiring an subcontractor not included in the current plan for 10 days could cost ~$12,000.
Impact	**Probability:** LOW. The relatively short timelines of both Phases result in accurate availability estimates. **Assessment:** LOW. $5000 of contribution (no cost to contract).
Strategy	**Mitigation:** Backups for all key personnel have been identified and there availability has been confirmed. **Contingency:** If work arises that can not be performed by available personnel listed in the proposal, a subcontractor will be hired at no additional cost to the contract to perform the work.
MR6	**Over budget [Phase 0 and Phase A]**
Definition	**Condition:** The work is not completed within the available budget. **Consequence:** MEDIUM. The level of contribution by UofC and Routes would increase to complete the required work. This can become an issue if either organization is not capable of providing the required contribution.
Impact	**Probability:** MEDIUM. The budget presented is realistic but conservative. Past experience indicates that budget overruns are common. **Assessment:** MEDIUM. $40,000 of contributed effort, no cost to the contract.
Strategy	**Mitigation:** The schedule will be closely monitored by the Project Manager (Greffen). Any potential overruns will be identified early and dealt with as appropriate (modify scope, reassign resources etc.). **Contingency:** UofC will secure extra personnel and/or funding (possibly at the provincial level) to bridge any gap.

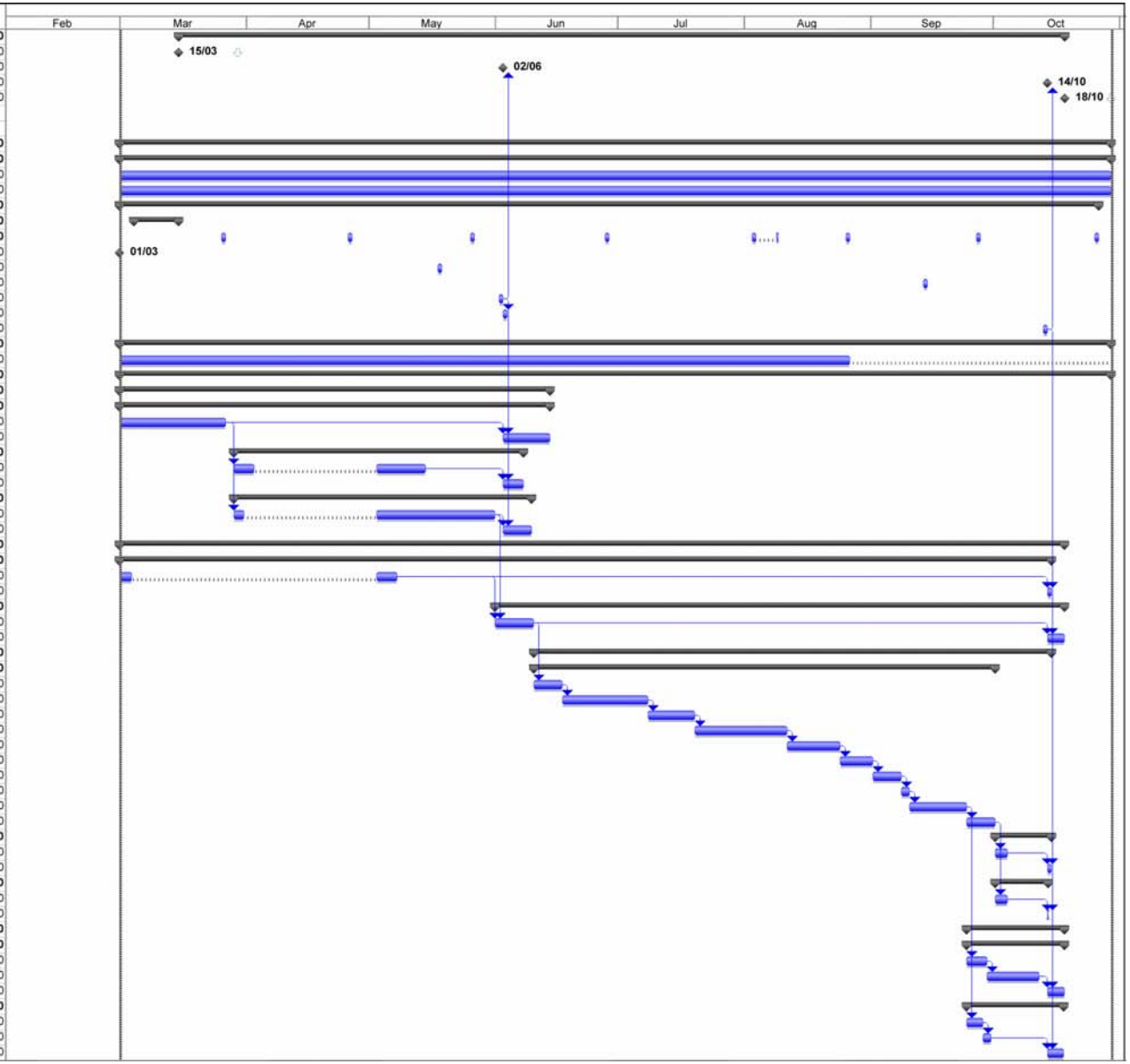
6.2.3 Milestones and Deliverables

	Milestone	Date	Deliverables
Phase 0	Kick off Meeting	15/03/2010	Project Management Plan (CDRL PM1, F) CWBS and Work Package Descriptions (CDRL PM2, IR) KoM Agenda (CDRL PM3) KoM Minutes (CDRL PM4)
	Monthly Progress Meetings	Monthly	Monthly Progress Reports (CDRL PM8)
	Mid-Term Review	02/06/2010	Mid-term Review Data Package (CDRL PM6, IR) Science Objective and User's needs Definition Document (CDRL SC1, IR) MTR Agenda (CDRL PM3) MTR Minutes (CDRL PM4)
	Science Payload Concept	14/10/2010	Science Objective and User's needs Definition Document (CDRL SC1,

	Review		F) Preliminary Interface Requirements Document (CDRL EN1, IR) Science Payload Conceptual Design Document (CDRL EN2, IR) PHEMOS Mission Preliminary Cost & Schedule Estimates (CDRL MM1, IR) PCR Agenda (CDRL PM3) PCR Minutes (CDRL PM4)
	Phase Closure	29/10/2010	Action Items Log (CDRL PM5) Phase Closure Report (CDRL PM9, F) Crown Assets List (CDRL PM10, IR) Preliminary Interface Requirements Document (CDRL EN1, F) Science Payload Conceptual Design Document (CDRL EN2, F) PHEMOS Mission Preliminary Cost & Schedule Estimates (CDRL MM1, F)
Phase A	Kick off Meeting	15/11/2010	Project Management Plan (CDRL PM11, F) CWBS and Work Package Descriptions (CDRL PM12, IR) KoM Agenda (CDRL PM13) KoM Minutes (CDRL PM14)
	Monthly Progress Meetings		Monthly Progress Reports (CDRL PM18)
	Mission Requirements Review	14/03/2011	MRR Data Package (CDRL PM16, IR) Mission Requirements Document (CDRL EN3, IR) Science Payload (System) Requirements Document (CDRL EN4, P) Science Payload Conceptual Design and Trade-off Document (CDRL EN5, P) MRR Agenda (CDRL PM13) MRR Minutes (CDRL PM14)
	Preliminary System Requirements Review	13/07/2011	PSRR Data Package (CDRL PM17) Mission Requirements Document (CDRL EN3, F) Science Payload (System) Requirements Document (CDRL EN4, IR) Science Payload Conceptual Design and Trade-off Document (CDRL EN5, IR) PHEMOS Mission Development Plan (CDRL MM2, IR) PSRR Agenda (CDRL PM13) PSRR Minutes (CDRL PM14)
	Phase Closure	31/08/11	Action Items Log (CDRL PM15) Phase Closure Report (CDRL PM19, F) Crown Assets List (CDRL PM20, F) Science Payload (System) Requirements Document (CDRL EN4, F) Science Payload Conceptual Design and Trade-off Document (CDRL EN5, F) PHEMOS Mission Development Plan (CDRL MM2, F)

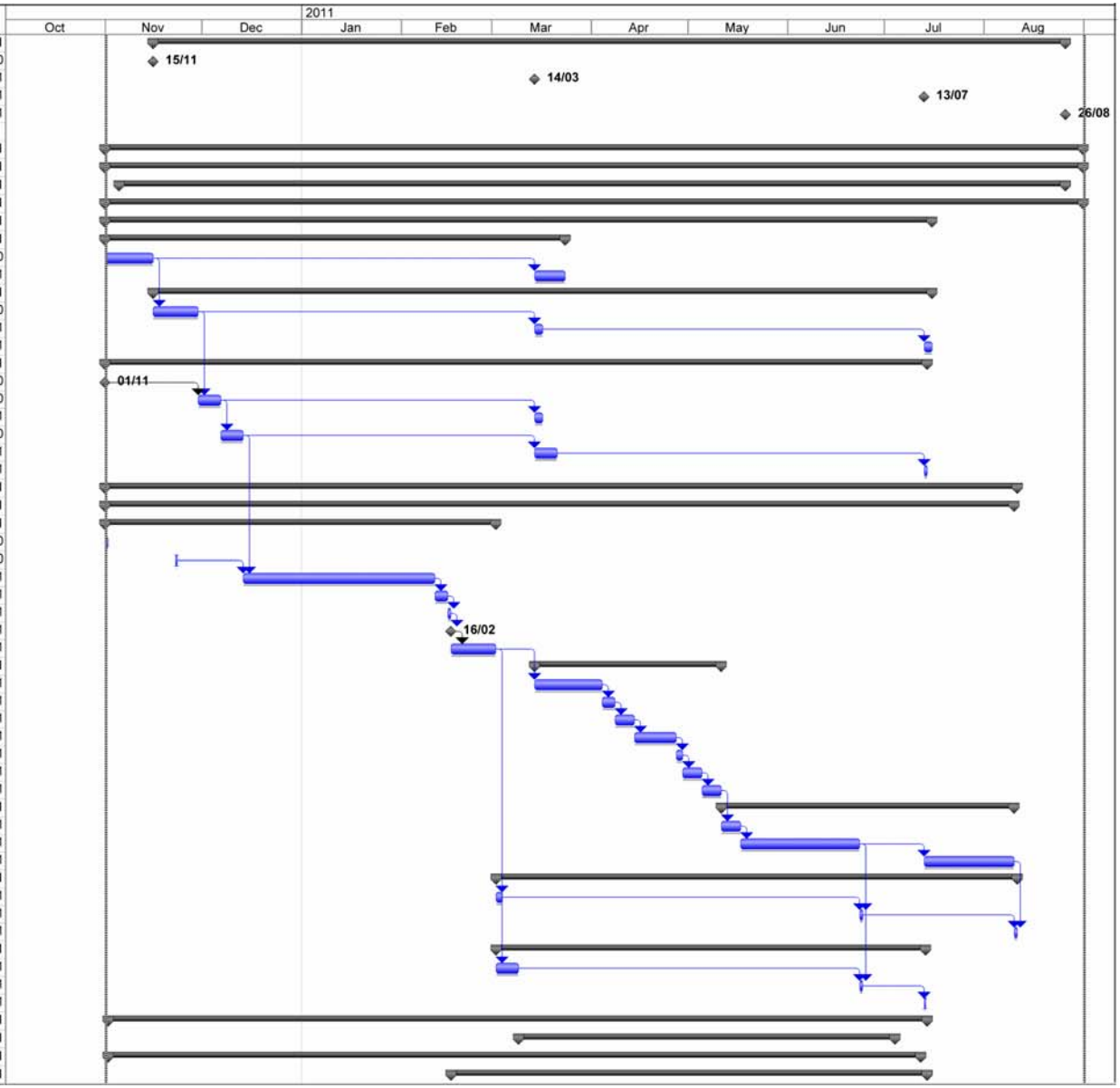
6.2.3.1 Schedule

ID	Task Name	Start	Finish
1	**Milestones**	**15/03/2010**	**18/10/2010**
2	Kick-off Meeting	15/03/2010	15/03/2010
3	MTR	02/06/2010	02/06/2010
4	PCR	14/10/2010	14/10/2010
5	End/Closure of Phase 0	18/10/2010	18/10/2010
6			
7			
8	**WBS 1-0: Project Management**	**01/03/2010**	**29/10/2010**
9	**WBS 1.1-0: Project Planning, Control and Monitoring**	**01/03/2010**	**29/10/2010**
10	CWBS (Scope) and Schedules (Time)	01/03/2010	29/10/2010
11	Cost, Quality, Risk and Communications Manageme	01/03/2010	29/10/2010
12	**WBS 1.2-0: Meetings and Reviews**	**01/03/2010**	**26/10/2010**
13	**Kick-off Meeting (proposed location Ottawa)**	**04/03/2010**	**15/03/2010**
16	**Monthly Progress Meeting**	**26/03/2010**	**26/10/2010**
25	*PCW Phase A MRR*	01/03/2010	01/03/2010
26	PCW U&ST #1 (location - Ottawa)	18/05/2010	18/05/2010
27	PCW U&ST #2 (location - Ottawa)	14/09/2010	14/09/2010
28	PHEMOS Mission MTR Meeting (CSA - 1 day)	02/06/2010	02/06/2010
29	Technical Interchange Meeting (Routes)	03/06/2010	03/06/2010
30	PCR Meeting (CSA - 1 day)	13/10/2010	14/10/2010
31	**WBS 1.3-0: Project Documentation**	**01/03/2010**	**29/10/2010**
32	UofC CADM	01/03/2010	29/10/2010
33	**CDLR Deliverables**	**01/03/2010**	**29/10/2010**
82	**WBS 2-0: Mission Definition**	**01/03/2010**	**14/06/2010**
83	**WBS 2.1-0: Science Objectives**	**01/03/2010**	**14/06/2010**
84	Science Objectives (input to CDRL SC1, IR for MTR	01/03/2010	26/03/2010
85	Finalize Science Objectives (input to CDRL SC1, F f	03/06/2010	14/06/2010
86	**WBS 2.2-0: Measurement Needs**	**29/03/2010**	**07/06/2010**
87	Measurement Needs (input to CDRL SC1, IR for M	29/03/2010	14/05/2010
88	Finalize Measurement Needs (input to CDRL SC1, F	03/06/2010	07/06/2010
89	**WBS 2.3-0: Data Needs**	**29/03/2010**	**09/06/2010**
90	Data Needs (input to CDRL SC1, IR for MTR)	29/03/2010	31/05/2010
91	Finalize Data Nees (input to CDRL SC1, F for PCR)	03/06/2010	09/06/2010
92	**WBS 3-0: Requirements**	**01/03/2010**	**18/10/2010**
93	**WBS 3.1-0: PCW Mission Analysis**	**01/03/2010**	**15/10/2010**
94	PCW Mission Analysis (documentation input to CDF	01/03/2010	07/05/2010
95	Finalize PCW Mission Analysis (input to CDRL EN1	14/10/2010	15/10/2010
96	**WBS 3.2-0: PHEMOS/PCW Interface Requirements**	**01/06/2010**	**18/10/2010**
97	PHEMOS/PCW Interface Requirements Document (	01/06/2010	10/06/2010
98	Finalize Interface Requirements Document (input to	14/10/2010	18/10/2010
99	**WBS 4-0: Science Payload Concept**	**10/06/2010**	**15/10/2010**
100	**WBS 4.1-0: Design Concept**	**10/06/2010**	**01/10/2010**
101	Payload Architecture, Block Diagram	10/06/2010	17/06/2010
102	Optical Design (Baffles, Mirrors, Coatings)	17/06/2010	08/07/2010
103	Mechanical Packaging	08/07/2010	19/07/2010
104	Electronic Design	20/07/2010	11/08/2010
105	Payload Performance Analyses	11/08/2010	24/08/2010
106	Orbit Analysis	24/08/2010	01/09/2010
107	Concept of Operations (nominal, contingency, mitig	01/09/2010	08/09/2010
108	Compliance Matrix against Science & Mission Requ	08/09/2010	10/09/2010
109	Payload Conceptual Design Documentation (input to	10/09/2010	24/09/2010
110	Finalize Conceptual Design (input to CDRL EN2, F)	24/09/2010	01/10/2010
111	**WBS 4.2-0: Engineering Budget**	**01/10/2010**	**15/10/2010**
112	Engineering Budget (input to CDRL EN2, IR for PCF	01/10/2010	04/10/2010
113	Finalize Engineering Budget (input to CDRL EN2, F)	14/10/2010	15/10/2010
114	**WPS 4.3-0: Payload Interfaces and Compatibility**	**01/10/2010**	**14/10/2010**
115	Develop Payload Interfaces (input to CDRL EN2, IR	01/10/2010	04/10/2010
116	Finalize Payload Interfaces (input to CDRL EN2, F)	14/10/2010	14/10/2010
117	**WBS 5-0: Development Plan**	**24/09/2010**	**18/10/2010**
118	**WBS 5.1-0 Programmatic**	**24/09/2010**	**18/10/2010**
119	Preliminary Development Plan (input to CDRL MM1	24/09/2010	29/09/2010
120	Cost & Schedule (Phase BCD, input to CDRL MM1,	29/09/2010	12/10/2010
121	Finalize Development Plan (input to CDRL MM1, F)	14/10/2010	18/10/2010
122	**WBS 5.2-0: Critical Technologies**	**24/09/2010**	**18/10/2010**
123	Critical Technologies Identification (input to CDRL M	24/09/2010	28/09/2010
124	TRL Assessment (input to CDRL MM1, IR for PCW)	28/09/2010	30/09/2010
125	Finalize Technologies Documentation (input to CDR	14/10/2010	18/10/2010



Gantt chart of the proposed Phase 0 schedule

ID	Task Name	Start	Finish
1	**Milestones**	**15/11/2010**	**26/08/2011**
2	KofM	15/11/2010	15/11/2010
3	MRR	14/03/2011	14/03/2011
4	PSRR	13/07/2011	13/07/2011
5	End/Closure of Phase A	26/08/2011	26/08/2011
6			
7	**WBS 1-A: Project Management**	**01/11/2010**	**31/08/2011**
8	**WBS 1.1-A: Project Planning, Control and Monitoring**	**01/11/2010**	**31/08/2011**
11	**WBS 1.2-A: Meetings and Reviews**	**05/11/2010**	**26/08/2011**
32	**WBS 1.3-A: Project Documentation**	**01/11/2010**	**31/08/2011**
91	**WBS 3-A: Requirements**	**01/11/2010**	**15/07/2011**
92	**WBS 3.1-A: Mission Requirements**	**01/11/2010**	**23/03/2011**
93	Mission Level Science and Measurment Requirements (inpu	01/11/2010	15/11/2010
94	Finalize Science and Measurment Requirements (input to CI	14/03/2011	23/03/2011
95	**WBS 3.2-A: Instruments Requirements**	**16/11/2010**	**15/07/2011**
96	Instrument Measurement Requirements (input to CDRL EN4	16/11/2010	29/11/2010
97	Revise Instrument Measurement Requirements (input to CDI	14/03/2011	16/03/2011
98	Finalize Instrument Measurement Requirements (input to CD	13/07/2011	15/07/2011
99	**WBS 3.3-A: PHEMOS/PCW Interface Requirements**	**01/11/2010**	**14/07/2011**
100	Receive updates to PCW mission documents (date TBC)	01/11/2010	01/11/2010
101	Mission Level Interface Requirements (input to CDRL EN3, I	30/11/2010	06/12/2010
102	Finalize Mission Level Interface Requirements (input to CDR	14/03/2011	16/03/2011
103	Instrument Interface Requirements (input to CDRL EN4, P f	07/12/2010	13/12/2010
104	Revise Instrument Interface Requirements (input to CDRL E	14/03/2011	21/03/2011
105	Finalize Instrument Interface Requirements (input to CDRL E	13/07/2011	14/07/2011
106	**WBS 4-A: Payload Concept**	**01/11/2010**	**11/08/2011**
107	**WBS 4.1-A: Design Concept and Trade-off**	**01/11/2010**	**10/08/2011**
108	**Trade-off analysis**	**01/11/2010**	**02/03/2011**
109	Define initial Trade-Off Parameters to Guide WP activiti	01/11/2010	01/11/2010
110	Refine Trade-Off Parameters as a result of Critical Tech	23/11/2010	23/11/2010
111	Perform Concept Design trades to improve design for lo	14/12/2010	11/02/2011
112	Compliance Matrix against Science & Mission Objective	11/02/2011	15/02/2011
113	Internal Design Review	15/02/2011	16/02/2011
114	Freeze of Concept Trade-off Analysis	16/02/2011	16/02/2011
115	Initial Conceptual Design and Trade-offs (input to CDRL	16/02/2011	02/03/2011
116	**Conceptual Design**	**14/03/2011**	**11/05/2011**
117	Optics (Baffles, Mirrors, Coatings)	14/03/2011	04/04/2011
118	Image Intensifier, Detector, HVPS	04/04/2011	08/04/2011
119	Readout Electronics, image processing, data storage &	08/04/2011	14/04/2011
120	Command, Control, Telemetry (incl Software & Elec Inte	14/04/2011	27/04/2011
121	Power Supply (Low Voltage)	27/04/2011	29/04/2011
122	Mechanical Packaging & Thermal Design	29/04/2011	05/05/2011
123	Mechanisms (e.g. aperture covers, filters)	05/05/2011	11/05/2011
124	**Conceptual Design and Tradeoffs Documentation**	**11/05/2011**	**10/08/2011**
125	Design Review and Compliance Matrix check	11/05/2011	17/05/2011
126	Revision of Conceptual Design and Tradeoffs (input to (	17/05/2011	23/06/2011
127	Finalization of Concept Design (input to CDRL EN5, F)	13/07/2011	10/08/2011
128	**WBS 4.2-A: Engineering Budget**	**02/03/2011**	**11/08/2011**
129	Initial Engineering Budgets (input to CDRL EN5, P for MRR)	02/03/2011	04/03/2011
130	Revise updates to Engineering Budgets (input to CDRL EN5	23/06/2011	24/06/2011
131	Finalization to Engineering Budget (input to CDRL EN5, F)	10/08/2011	11/08/2011
132	**WBS 4.3-A: Payload Interfaces and Compatibility**	**02/03/2011**	**13/07/2011**
133	Initial Updates to Payload Interfaces & Compatibilit (input to (	02/03/2011	09/03/2011
134	Revise Payload Interfaces & Compatibility (input to CDRL EN	23/06/2011	24/06/2011
135	Finalization of Payload Interfaces & Compatibility (input to CI	13/07/2011	13/07/2011
136	**WBS 5-A: Development Plan**	**02/11/2010**	**14/07/2011**
137	**WBS 5.1-A Programmatic**	**09/03/2011**	**04/07/2011**
140	**WBS 5.2-A: Critical Technologies**	**02/11/2010**	**12/07/2011**
145	**WBS 5.3-A: Product Assurance**	**16/02/2011**	**14/07/2011**



Gantt chart of the proposed Phase A schedule

6.2.3.2 Project Control System

The work outlined in this proposal ("the project") will be managed by the Prime (UofC) Project Manager (PPM, Greffen). The PPM is placed in the Organizational Chart (Figure 6.1) to facilitate effective project management. Six key project management knowledge areas have been identified as especially critical for the work outlined in this proposal: project cost, scope, schedule, quality, communications and risk. The methods and systems to be used to control these parameters are addressed below.

Cost: The submitted Financial Bid contains a detailed cost breakdown by WP. The Actual Cost of the project will be reviewed on a monthly cadence. It will be compared to the Planned Value as well as Earned Value (Earned Value Management, EVM), which will be calculated using a simple technical performance model. Due to the fact that Phase 0 is Fixed Price and Phase A is to a Ceiling Price, cost overruns will impact other identified project parameters and will be largely dealt with using the appropriate tools (for example, a projected cost overrun may impact the scope and/or the schedule of the project but will not affect the total budget). The Contract Plan and Report Form (Appendix XI) will be used to track and report costs to the CSA.

Scope: A Work Breakdown Structure (WBS) is a standard Scope Management tool that plays a key role in the Project Management Plan (PMP). A detailed WBS has been developed for both Phase 0 and A in heavy consultation Routes AstroEngineering. The WBS will be updated on a monthly cadence throughout the lifetime of the project. All change requests will be directed to the PMP who will seek appropriate approval and access the impact on the project (most critically cost and schedule).

Schedule: Details of the project schedule are recorded in Microsoft Project, and updated monthly (the schedules for Phase 0 and A contain positive float). EVM and/or PERT analysis will be used to access variances from the planned schedule and monitor the critical path. Formal performance reviews will act as milestone opportunities to analyze schedule performance. In the event of negative schedule variance fast tracking will be employed to correct the issue (due to the fixed project budget crashing the schedule will only be done in an extreme case). Do to the nature of the work there are several good candidate Work Packages for fast tracking.

Quality: In order to achieve the goals of the project it is critical that output quality is satisfactory. Specifically this section addresses the quality of the conceptual design and resulting requirement documents that will be used as inputs to Phase BCD. The quality of the deliverables will be assessed by determining their compliance with the instrument and mission requirements. To this end it will be the job of the PPM to facilitate the creation, documentation, and communication of the instrument requirements as well as closely monitor the WPs associated with PCW mission requirements. An internal design review will be held as part of the trade-off analysis in Phase A to check the compliance of the candidate design against the instrument requirements and ultimately the Science Objectives.

Communications: The three major stakeholders in the project are separated by geography and each has a unique enterprise environment. Clear communication between these diverse organizations (and all other stakeholders) will play a critical role in the successful conclusion of the project. Information distribution will occur through the scheduled meetings and required deliverables. It will be the job of the PPM to access if further information distribution tools are required and put them in place. The PPM will also work with stakeholders to meet their needs and address issues as they occur.

Risk: Risk management is the primary job of the PPM. All techniques listed above ultimately reduce project risk. It is important to note that project risk and business (science/technical) risk are separate entities. It is possible to complete a project on schedule and budget but have a non-functional product at the end. The PPM will be primarily responsible for managing project risk, but will also facilitate the management of technical risk.

Preliminary management and technical risk assessments have been accomplished as part of the proposal process. The risk assessment (and reassessment) process consists of identifying risks, analyzing and prioritizing, and developing a response to them. Risk reassessment will occur extremely early in Phase 0 and on a regular basis throughout the project (continuous risk management). The PPM will participate in technical risk reviews and work closely with the Technical Lead (Trondsen) to monitor and control technical risks. The PPM will also work with the Deputy PI (DPI) to manage science risks that is risks that threaten the Science Objectives. The project manager will be responsible for managing reserves as part of the risk response strategy.

Appendix I – References

I.1 Section 4 References

- Acuña, M. H., K. W. Ogilvie, D. N. Baker, S. A. Curtis, D. H. Fairfield and W. H. Mish, The Global Geospace Science Program and its Investigations, Space Science Rev., 71, 5, 1995.

- Amm, O., E.F. Donovan, H. Frey, M. Lester, R. Nakamura, J.A. Wild, A. Aikio, M. Dunlop, K. Kauristie, A. Marchaudon, I.W. McCrea, H.J. Opgenoorth, and A. Strømme, Coordinated studies of the Geospace environment using Cluster, satellite and ground-based data: An interim review, Ann. Geophys., 23, 2129, 2005.

- Angelopoulos, V., McFadden, J. P., Larson, D., Carlson, C. W., Mende, S. B., Frey, H., Phan, T., Sibeck, D. G., Glassmeier, K.-H., Auster, U., Donovan, E., Mann, I. R., Rae, I. J., Russell, C. T., Runov, A., Zhou, X.-Z., and Kepko, L.: Tail Reconnection Triggering Substorm Onset, Science, 321, 931–935, doi:10.1126/science.1160495, 2008.

- Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433, 1961.

- Baker, D. N., R. E. Ergun, J. L. Burch, J.-M. Jahn, P. W. Daly, R. Friedel, G. D. Reeves, T. A. Fritz, and D. G. Mitchell, A telescopic and microscopic view of a magnetospheric substorm on 31 March 2001, Geophys. Res. Lett., 29(18), 1862, doi:10.1029/2001GL014491, 2002.

- Basu, S., E. MacKenzie, and S. Basu (1988), Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum periods, Radio Sci., 23(3), 363–378.

- Belian, R. D., T. E. Cayton, and G. D. Reeves, Quasi-periodic global substorm-generated variations observed at geosynchronous orbit, in Space Plasmas: Coupling Between Small and Medium Scale Processes, Geophysics Monograph Series, volume 86, 143–148, 1995.

- Biskamp, D., Magnetic reconnection in plasmas, Cambridge University Press, ISBN 0 520 58288 1, 2000.

- Borg, A. L., et al., Simultaneous observations of magnetotail reconnection and bright X-ray aurora on 2. October 2002., J. Geophys. Res., 112(A6), A06215, doi: 10.1029/2006JA011913, 2007.

- Brandt, P. C., R. DeMajistre, E. C. Roelof, D. G. Mitchell, and S. Mende, IMAGE/HENA: Global ENA imaging of the plasmasheet and ring current during substorms, J. Geophys. Res., 107, 1454, 2002.

- Brandt, P. C., Y. Zheng, T. S. Sotirelis, K. Oksavik, and F. J. Rich, The Linkage Between the Ring Current and the Ionosphere System, Geophysics Monograph. Series, volume 181, 135-143, 2008.

- Burch, J. L., Magnetospheric imaging: Promise to reality, Rev. Geophys., 43, doi: 10.1029/ 2004RG000160., 2005.

- Chapman, S., and J. Bartels, Geomagnetism, Clarendon Press, Oxford, UK, 1967.

- Donovan, E., Trondsen, T., Spann, J., Liu, W., Spanswick, E., Lester, M., Tu, C.-Y., Ridley, A., Henderson, M., Immel, T., Mende, S., Bonnell, J., Syrjäsuo, M., Sofko, G., Cogger, L., Murphree, J., Jayachandran, P. T., Pulkkinen, T., Rankin, R., Sigwarth, J., Global auroral imaging, system level science, and ILWS, Adv. Space Res., 40, pp 409-418, 2007.

- Dungey, J. W., Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., 6, 47, 1961.

- Funke, B., M. Lopez-Puertas, S. Gil-Lopez, T. von Clarmann, G. P. Stiller, H. Fischer, and S. Kellmann, Downward transport of upper atmospheric NOx into the polar stratosphere and lower mesosphere during the

Antarctic 2003 and Arctic 2002/2003 winters, J. Geophys. Res. – Atmospheres, 110 (D24), D24308, doi:10.1029/2005JD006463, 2005.

- Funke, B., M. Garcia-Comas, M. Lopez-Puertas, N. Glatthor, G. P. Stiller, T. Von Clarmann, K. Semeniuk, and J. C. McConnell, Atmos. Chem. Phys., 8, 3805–3815, 2008.

- Germany, G., M. Torr, , P. Richards, and D. Torr, The dependence of modeled OI 1356 and N2 LBH auroral emissions on the neutral atmosphere, J. Geophys., Res., 95, 7725, 1990.

- Germany, G., G. Parks, M. Brittnacher, J. Cumnock, D. Lummerzheim, J. F. Spann, L. Chen, P. Richards, and F. Rich, Remote determination of auroral energy characteristics during substorm activity, Geophys. Res, Lett., 24, 995, 1997

- Germany, G., G. Parks, M. Brittnacher, J. Spann, J. Cumnock, D. Lummerzheim, F. Rich, and P. Richards, Energy characterization of a dynamic auroral event using GGS UVI images, AGU Monograph 104, page 143, 1998.

- Goldstein, J., J. Burch, B. Sandel, S. Mende, P. Brandt, and M. Hairston, Coupled response of the inner magnetosphere and ionosphere on 17 April 2002, J. Geophys. Res., 110, doi:10.1029/ 2004JA010712, 2005.

- Henderson, M., E. Donovan, J. Foster, I. Mann, T. Immel, S. Mende, and J. Sigwarth, Start-to-end global imaging of a sunward propagating, SAPS-associated giant undulation event, J. Geophys. Res., doi:10.1029/ 2009JA014106, in press, 2010.

- Hosokawa, K., J.-P. St-Maurice, G. Sofko, K. Shiokawa, Y. Otsuka, and T. Ogawa, Reorganization of polar cap patches through shears in the background plasma convection, J. Geophys. Res., 115, doi:10.1029/ 2009JA014599, 2010.

- Ieda, A., et al., Plasmoid ejection and auroral brightenings, J. Geophys. Res., 106, 3845, 2001

- Kepko, L., E. Spanswick, V. Angelopoulos, E. Donovan, J. McFadden, K. H. Glassmeier, J. Raeder, and H. J. Singer, Equatorward moving auroral signatures of a flow burst observed prior to auroral onset, Geophys. Res. Lett., 36, doi:10.1029/2009GL041476, 2009.

- Klobuchar, J.A., Ionospheric Effects, in Global Positioning System: Theory and Applications, Vol. I, American Institute of Aeronautics and Astronautics, Washington, D.C., 1996.

- Knudsen, D. J. (1996), Spatial modulation of electron energy and density by nonlinear stationary inertial Alfvén waves, J. Geophys. Res., 101(A5), 10,761–10,772

- Liang, J., Vadim Uritsky, Eric Donovan, Binbin Ni, Emma Spanswick, Trond Steinar Trondsen, John Bonnell, Alain Roux, Ulrich Auster, Davin Larson, THEMIS observations of electron cyclotron harmonic emissions, ULF waves, and pulsating auroras, Submitted to Journal of Geophysical Research – Space Physics.

- Lopez-Puertas, M, B. Funke, S. Gil-Lopez, T. von Clarmann, G. P. Stiller, M. Hopfner, S. Kellmann, H. Fischer, and C. H. Jackman, Observation of NOx enhancement and ozone depletion in the Northern and Southern Hemispheres after the October-November 2003 solar proton events, J. Geophys. Res. – Space Physics, 110 (A9), A09S43, doi:10.1029/2005JA011050, 2005.

- McWilliams et al., Annales Geophysicae, volume 19, pages 707-721, 2001

- Moen, J., Y. Rinne, H. C. Carlson, K. Oksavik, R. Fujii, and H. Opgenoorth, On the relationship between thin Birkeland current arcs and reversed flow channels in the winter cusp/cleft ionosphere, J. Geophys. Res., 113, A09220, doi:10.1029/2008JA013061, 2008.

- Mozer, F., T.D. Phan, S.D. Bale, The complex structure of the reconnecting magnetopause, Phys. Plasmas, 10, 2480, 2003.

- Ni et al., 2008 B. Ni, R.M. Thorne, Y.Y. Shprits and J. Bortnik, Resonant scattering of plasma sheet electrons by whistler-mode chorus: contribution to diffuse auroral precipitation, Geophys. Res. Lett. 35 (2008), p. L11106.

- Østgaard, N., R. R. Vondrak, J. W. Gjerloev, and G. Germany, A relation between the energy deposition by electron precipitation and geomagnetic indices during substorms, J. Geophys. Res., 107(A9), 1246, doi:10.1029/2001JA002003, 2002.

- Randall, C.E., V. L. Harvey, C. S. Singleton, S. M. Bailey, P. F. Bernath, M. Codrescu, H. Nakajima, and J. M. Russell,. Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992-2005. J. Geophys. Res. – Atmospheres, 112 (D8), D08308, doi:10.1029/2006JD007696, 2007.

- Rankin, R., K. Kabin, J. Y. Lu, I. R. Mann, R. Marchand, I. J. Rae, V. T. Tikhonchuk, and E. F. Donovan, Magnetospheric field-line resonances: Ground-based observations and modeling, JGR, 110, doi:10.1029/2004JA010919, 2005.

- Ravishankara, A. R., J. S. Daniel, and R. W. Portmann, Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century, Science, 326(5949), 123, doi:10.1126/science.1176985, 2009.

- Roelof, E., D. Mitchell, and D. Williams, Energetic Neutral Atoms (E 50 keV) from the Ring Current: IMP 7/8 and ISEE 1, J. Geophys. Res., 90(A11), 10991-11008, 1985.

- Runov, A., V. Angelopoulos, N. Ganushkina, R. Nakamura, J. McFadden, D. Larson, I. Dandouras, K.-H. Glassmeier, and C. Carr, Multi-point observations of the inner boundary of the plasma sheet during geomagnetic disturbances, Geophys. Res. Lett., 35, doi:10.1029/2008GL033982, 2008.

- Samson, J. C., L. R. Lyons, P. T. Newell, F. Creutzberg, and B. Xu Proton aurora and substorm intensifications, Geophys. Res. Lett.,19(21), 2167–2170., 1992.

- Sarris, T. E., et al. (2009), Characterization of ULF pulsations by THEMIS, Geophys. Res. Lett., 36, L04104, doi:10.1029/2008GL036732.

- Semeniuk, K., J. C. McConnell, J. J. Jin, J R. Jarosz, C. D. Boone, and P. F. Bernath, N_2O production by high energy auroral electron precipitation, J. Geophys. Res., 113, doi:10.1029/2007JD009690, 2008.

- Sergeev, V. A., Kubyshkina, M. V., Baumjohann, W., Nakamura, R., Amm, O., Pulkkinen, T., Angelopoulos, V., Mende, S. B., Klecker, B., Nagai, T., Sauvaud, J.-A., Slavin, J. A., and Thom- sen, M. F.: Transition from substorm growth to substorm expan- sion phase as observed with a radial configuration of ISTP and Cluster spacecraft, Ann. Geophys., 23, 2183–2198, 2005.

- Skone, S., K. Knudsen, and M. de Jong, Limitations in GPS receiver tracking performance under ionospheric scintillation conditions, Phys, Chem. Earth, 26, 613-621, 2001.

- Skone, S., The impact of magnetic storms on GPS receiver performance, J. Geodesy, 75, 457-468, 2001.

- Skone, S. and V. Hoyle, Canadian GPS network for ionosphere monitoring (CANGIM), GPS Solutions, 9, 59-62, 2005.

- Skone, S. and R. Yousuf, Performance of satellite-based navigation for marine users during ionospheric disturbances, Space Weather Journal, 5, 9 pages, doi:10.1029/ 2006SW000246, 2007.

- Smith, A. M., C. N. Mitchell, R. J. Watson, R. W. Meggs, P. M. Kintner, K. Kauristie, and F. Honary, GPS scintillation in the high arctic associated with an auroral arc, Space Weather, 6, doi: 10.1029/2007SW000349, 2008.

- Strickland, D., J. Jasperse, and J. Whalen, Dependence of auroral FUV emission on the incident electron spectrum and neutral atmosphere, J. Geophys. Res., 88, 8051, 1983.

- Uritsky, V. M., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K. H. Glassmeier (2009), Longitudinally propagating arc wave in the pre-onset optical aurora, Geophys. Res. Lett., 36, L21103, doi:10.1029/2009GL040777.

- Uritsky, V., Eric Donovan, T. Trondsen, D. Pineau and B. Kozelov, Data-derived spatio-temporal resolution constraints for global auroral imagers. Submitted to J. Geophys. Res, 2010.

- Watkins, N., M. Freeman, S. Chapman, and R. Dendy, J. Atmos. Solar-Terr. Phys., 63, 1435-1445, 2001.

- Yahnin, A., M. V. Malkov, V. A. Sergeev, R. J. Pellinen, O. Aulamo, S. Vennerström, E. Friis-Christensen, K. Lassen, C. Danielsen, J. D. Craven, C. Deehr, and L. A. Frank, Features of steady magnetospheric convection, J. Geophys. Res., 99, 4039-4051, 1994.

I.2 Section 5 References

- Carbary J.F., Sotirelis T., Newell P.T., Meng C.-I. Correlation of LBH intensities with precipitating particle energies, Geophys. Res. Lett. V. 31. L13801, doi:10/1029/2004GL019888. 2004.

- Frey, H. U., S. B. Mende, C. W. Carlson, J. C. Gérard, B. Hubert, J. Spann, R. Gladstone, and T. J. Immel, The electron and proton aurora as seen by IMAGE-FUV and FAST, Geophys. Res. Lett., 28, 1135, 2001

- Frey, H. U. et al. Summary of quantitative interpretation of IMAGE Far Ultraviolet auroral data. Space Sci. Rev. 109, 255–283 (2003)

- Gérard, J.-C., B. Hubert, M. Meurant, V. I. Shematovich, D. V. Bisikalo, H. Frey, S. Mende, G. R. Gladstone, and C. W. Carlson, Observation of the proton aurora with 155IMAGE FUV imager and simultaneous ion flux in situ measurements, J. Geophys. Res., 106(A12), 28,939–28,948, 2001.

- Germany, G. A., M. R. Torr, D. G. Torr, and P. G. Richards, Use of FUV auroral emissions as diagnostic indicators, J. Geophys Res., 99,383, 1994.

- Germany, G. A., D. G. Torr, P. G. Richards, M. R. Torr, and S. John, Determination of ionospheric conductivities from FUV auroral emissions, J. Geophys. Res., 99, 23297, 1994.

- Hubert B., J.C. Gérard, D.S. Evans, M. Meurant, S.B. Mende, H.U. Frey and T.J. Immel, Total electron and proton energy input during auroral substorms: remote sensing with IMAGE-FUV, J. Geophys. Res., 107, doi: 10.1029/2001JA009229, 2002.

- Lummerzheim, D., M. H. Rees, J. D. Craven, and L. A. Frank, Ionospheric conductances derived from DE-1 auroral images, J. Atmos. Terr. Phys., 53, 281, 1991.

- Monchick, L., M. J. Linevsky, C. I. Meng and S. Favin S. Chakrabarti and F. Paresce, Some auroral properties from far ultraviolet observations, Planetary and Space Science, Volume 33, Issue 2, p. 175-181, 1985.

- Torr, M. R., D. G. Torr, M. Zukic, B. Johnson, J. Ajello, P. Banks, K. Clark, K. Cole, C. Keffer, G. K. Parks, B. Tsurutani, J. F. Spann, Jr., A far ultraviolet imager for the International Solar-Terrestrial Physics Mission, Space Science Reviews, 71, 329-383, 1995.

- Wanliss, J. A., and K. M. Showalter, High-resolution global storm index: Dst versus SYM-H. J. Geophys. Res.., 111, doi:10.1029/2005JA011034, 2006

- Zukic, M., D. G. Torr, J. F. Spann, Jr., M. R. Torr, Vacuum Ultraviolet Thin Films. 2: Vacuum Ultraviolet All-Dielectric Narrowband Filters, Appl. Opt., 29, 4293, 1990.

- Zukic, M., D. G. Torr, J. Kim, J. F. Spann, Jr., M. R. Torr, Filters for the International Solar Terrestrial Physics Mission for Far Ultraviolet Imager, Opt. Engrg., 32, 3069, 1993.

Appendix II – List of Acronyms

ADC	Analog to Digital Converter
ADEx	Auroral Dynamic Explorer
AG	Annales Geophysicae
AGU	American Geophysical Union
AI&T	Assembly Integration & Test
AIF	Atlantic Innovation Fund
AIG	Auroral Imaging Group
AIL	Action Item List
A/O	Adaptive Optics
ASI	All-Sky Imager
ASR	Advance in Space Research
ASTRA	Automated Spectrophotometric Telescope Research Associates
ATS	Acquisition and Tracking Sensor
AUGO	Athabasca University Geophysical Observatory
AURIO	Auroral Imaging Observatory
BBF	Bursty Bulk Flow
BPSK	Binary Phase Shift Keying
CAD	Computer Aided Design
CADM	Configuration and Data Management
CAL	Canadian Astronautics Ltd
CANGIM	Canadian GPS Network for Ionospheric Monitoring
CANOPUS	Canadian Auroral Network for the OPEN Program Unified Study
CASSIOPE	CASCADE Smallsat and Ionospheric Polar Explorer
CCD	Charge-Coupled Device
CCGP	Canadian Controlled Goods Program
CCSDS	Consultative Committee for Space Data System
CD	Current Disruption
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CEDAR	Coupling Energetics and Dynamics of Atmospheric Regions
CFHT	Canada-France-Hawaii Telescope
CFI	Canada Foundation for Innovation
CGI	Common Gateway Interface
CGSM	Canadian GeoSpace Monitoring
CHAIN	Canadian High Arctic Ionospheric Network
CISR	Climate Impacts of Space Radiation
CJP	Canadian Journal of Physics
CMAM	Computational Methods in Applied Mathematics
CMOS	Complementary Metal-Oxide Semiconductor (transistor type)
CNSR	Canadian Network of Centres of Excellence
COSPAR	Committee on Space Research
CPA	Cold Plasma Analyzer
CPR	Cardiopulmonary Resuscitation
CPS	Central Plasma Sheet
CPU	Central Processor Unit
CRC	Communications Research Centre Canada

CSA	Canadian Space Agency
CTI	Critical Technology Items
CWBS	Contract Work Breakdown Structure
CWDM	Coarse Wavelength Division Multiplexing
DAC	Digital to Analog Converter
DARN	Super Dual Auroral Radar Network
DASP	Division of Aeronomy and Space Physics
DE-1	Dynamic Explorer-1
DFL	David Florida Laboratory
DFM	Design for Manufacture
DHU	Data Handling Unit
DID	Data Item Description
DGC	Dynamic GeoSpace Coupling
DND	Department of National Defence
DPI	Deputy PI
DRDC	Defense Research and Development Canada
EAGLES	Energy and Acceleration GLobal Explorers
EGSE	Electronic Ground Support Equipment
EISCAT	European Incoherent Scatter
EMC	Electromagnetic Compatibility
EMI	Engineering Ministries International
ENA	Energetic Neutral Atoms
EOL	End-of-Life
EPO	Early Orbit Phase
EPO	Education and Public Outreach
ePOP	Enhanced Polar Outflow Probe
ESA	European Space Agency
ESD	Electrostatic Discharge Association
eSOC	e-POP Science Operations Center
EUV	Extreme Ultra-Violet
EVM	Earned Value Management
FAI	Fast Auroral Imager
FCC	Federal Communications Commission
FDAM	Facility for Data Assimilation and Modelling
FEA	Finite Element Analysis
FMECA	Failure Modes and Effects Analysis
FORTRAN	Formula Translating System
FOV	Field of View
FPGA	Field Programmable Gate Array
FRR	Flight Readiness Review
FTS	File Transfer (Sub-)System
FUV	Far Ultra-Violet
GAIA	Global Auroral Imaging Access
GBO	Ground Based Observatory
GC	Government of Canada
GCI	Generic Channel Interface
GEM	GeoSpace Environment Modelling

GEODESIC	Geoelectrodynamics and Electro-Optical Detection of Electron and Suprathermal Ion Currents
GFSU	Guide and Focus Sensor Unit
GLAO	Ground Layer Adaptive Optics
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRL	Geophysical Research Letters
HEPT	High Energy Proton Telescope
HERO	Hyperspectral Environment and Resource Observer
HIA	Herzberg Institute of Astrophysics
HQP	Highly Qualified Personnel
HV	High Voltage
IASTED	International Association of Science and Technology for Development
IAGA	The International Association of Geomagnetism and Aeronomy
IC	Integrated Circuit
ICS	International Conference on Substorms
IDL	Interactive Data Language
IIA	Indian Institute of Astrophysics
ILWS	International Living With a Star program
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAKA	Imaging from MAuna KeA
INO	National Optics Institute
IR	Infrared
ISAS	Institute of Space and Aeronautics Sciences
ISIS	Institute for Space Imaging Science
ISR	Institute for Space Research
ISRO	Indian Space Research Organization
ISS	International Space Station
ISTP	International Solar Terrestrial Physics
ITRES	"Innovative imaging Technology and leading edge Research to meet the needs of customers with emphasis on scientific Excellence and Service"
ITAR	International Traffic in Arms Regulations
JASTP	Journal of Atmospheric and Solar-Terrestrial Physics
JGR	Journal of Geophysical Research
JWST	James Webb Space Telescope
KoM	Kick Off Meeting
LANL	Los Alamos National Laboratory
LBH	Lyman-Birge-Hopfield
LEO	Low Earth Orbit
LWIR	Long-Wave Infrared
MCP	Microchannel Plate
MCR	Mission Concept Review
MDA	MacDonald, Dettwiler and Associates Ltd.
MDR	Mission Definition Review
MET	Meteorological
Mfg.	Manufacturer
MGSE	Mechanical Ground Support Equipment

MHD	Magneto Hydrodynamic
MIDEX	Medium Explorer
MLT	Magnetic Local Time
MMS	Magnetospheric Multi-Scale
MOC	Mission Operations Centre
MOST	Microvariability & Oscillations of Stars
MRR	Mission Requirements Review
MSP	Meridian Scanning Photometer
MSSL	Mullard Space Science Laboratory, College London
MTR	Midterm Review
NASA	National Aeronautics and Space Administration
NEOSAT	Near Earth Object Surveillance Satellite
NORSTAR	Northern Solar Terrestrial Array
NRC	National Research Council
NRT	Near Real Time
NSERC	National Science and Engineering Research Council
NSF	National Science Foundation
OEDIPUS	Observations of Electric-Field Distributions in an Ionospheric Plasma – a Unique Strategy
OFE	Optical Front End
OI	Atomic Oxygen
OISL	Optical Inter-Satellite Link
ORBITALS	Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite
OSIRIS	Optical Spectrograph and InfraRed Imager System
PA	Product Assurance
PASP	Publications of the Astronomical Society of the Pacific
PCB	Printed Circuit Board
PCO	Preliminary Concept of Operations
PCR	Project Closeout Review
PCU	Power Control Unit
PCW	Polar Communications and Weather
PDF	Post-Doctoral Fellow
PERT	Program Evaluation and Review Technique
PFISR	Poker Flat Incoherent Scatter Radar
PHEMOS	Polar Highly Elliptical / Molniya Orbit Science
PI	Principal Investigator
PM	Pulse Modulation
PMP	Project Management Plan
PoCa	Polar Camera
POES	Point of Entry Spreadsheet
PPM	Prime Project Manager
PRA	Probabilistic Risk Assessment
PRR	Preliminary Requirements Review
PSU	Power Supply Unit
PSRR	Preliminary System Requirements Review
PUEO	Probing the Universe with Enhanced Optics
PWGSC	Public Works Government Services Canada
QPSK	Quadrature Phase Shift Keying

RA	Research Assistant
RAM	Resource Allocation Matrix
RBSP	Radiation Belt Storm Probes
Re	Earth Radii
RF	Radio Frequency
RFP	Request for Proposal
RISR	Resolute Bay Incoherent Scattering Radar
RLSSC	Royal Life Saving Society of Canada
ROM	Rough Order of Magnitude
RT	Real Time
S/C	Spacecraft
S&T	Science & Technology
SAI	Spin-Scan Auroral Imager
SDP	Standard Data Product
SEM	Space Environment Micro-satellite
SFC	Space Flight Center
SFF	Small Form Factor
SFP	Small Form-Factor Pluggable
SMC	Surface-Mount Component
SMS	Supra-Thermal Mass Spectrometer
SNR	Signal to Noise Ratio
SOC	Science Operations Centre
SONET	Synchronous Optical Network
SORCE	Solar Radiation and Climate Experience
SOW	Statement of Work
SPIE	International Society for Optical Engineering
SRR	System Requirements Review
ST7	Speech from the Throne 7 (2008)
ST9	Speech from the Throne 9 (2008)
STDP	Space Technologies Development Program
STK	Satellite Tool Kit
SUT	S-Band User Transponder
SWPC	Space Weather Prediction Centre
TAA	Technical Approval Authority / Team Assignment Agreement
TBC	To Be Confirmed
TBD	To Be Determined
TCL	Tool Command Language
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Total Irradiance Monitor
TPA	Thermal Plasma Analyzer
TRA	Technology Readiness Assessment
TRIUMF	Tri-University Meson Facility
TRL	Technology Readiness Level
TRR	Test Readiness Review
TVAC	Thermal Vaccum
TT&C	Telemetry, Tracking and Command
UARS	Upper Atmosphere Research Satellite
UBC	University of British Columbia

UHF	Ultra High Frequency
UofC	University of Calgary
URD	User Requirements Document
U&ST	PCW User & Science Team
UT	Universal Time
UV	Ultra-Violet
UVAI	Ultra-Violet Auroral Imager
UVAMC	Ultra-Violet Auroral Monitoring Cameras
UVI	Ultra-Violet Imager
UVIT	Ultra-Violet Imaging Telescope
VCO	Voltage-Controlled Oscillator
VIS	Visible (range of electromagnetic spectrum)
VHF	Very High Frequency
VLOT	Very Large Optical Telescope
WBS	Work Breakdown Structure
WFOS	Wide Field Optical Spectrograph
WHIMIS	Workplace Hazardous Materials Information Systems Course
WIC	Wide-angle Imaging Camera
WINDII	WIND Imaging Interferometer
WP	Work Package
XMM	X-ray Multi Mirror Mission

Appendix III – Résumés

Eric Donovan (PI)

Science/Technical Key Personnel

UCalgary

1) Leroy Cogger
2) Greg Enno
3) Mike Greffen
4) Emma Spanswick
5) Trond Trondsen
6) Vadim Uritsky

Routes AstroEngineering Ltd.

7) Don Asquin
8) Donna-Lee Desulniers
9) Blair Gordon
10) Paul Marchand
11) Ken Smith

Herzberg Institute of Astrophysics

12) John Pazder

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

FORM 100
Personal Data Form
PART I

Date: 2010/02/11

Family name	Given name	Initial(s) of all given names	Personal identification no. (PIN)
Donovan	Eric	EF	**Valid** 101620

☐ I hold a faculty position at an eligible Canadian college (complete Appendices B1 and C)

☐ I do not or will not hold an academic appointment at a Canadian postsecondary institution

Place of employment other than a Canadian postsecondary Institution (give address in Appendix A)

APPOINTMENT AT A POSTSECONDARY INSTITUTION

Title of position: Associate Professor

Department: Physics and Astronomy

Campus:

Canadian postsecondary institution: Calgary

Tenured or tenure-track academic appointment — Yes [X] No [ ]

Part-time appointment [ ] Full-time appointment [X]

- For all non-tenured or non tenure-track academic appointment and Emeritus Professors, complete Appendices B & C
- For life-time Emeritus Professor and part-time positions, complete Appendix C

ACADEMIC BACKGROUND

Degree	Name of discipline	Institution	Country	Date yyyy/mm
Bachelor's	Physics	University of Western Ontario	CANADA	1986 / 06
Master's	Physics	University of Western Ontario	CANADA	1988 / 06
Doctorate	Physics	University of Alberta	CANADA	1993 / 06

TRAINING OF HIGHLY QUALIFIED PERSONNEL

Indicate the number of students, fellows and other research personnel that you:

	Currently		Over the past six years (excluding the current year)		
	Supervised	**Co-supervised**	**Supervised**	**Co-supervised**	**Total**
Undergraduate	5		4		9
Master's	1		4		5
Doctoral	1		1		2
Postdoctoral	3		5		8
Others	4		1		5
Total	14		15		29

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Not Completed

ACADEMIC, RESEARCH AND INDUSTRIAL EXPERIENCE (use one additional page if necessary)

Position held (begin with current)	Organization	Department	Period (yyyy/mm to yyyy/mm)
Associate Professor	Calgary	Physics and Astronomy	2002/06
Assistant Professor	University of Calgary	Physics and Astronomy	1997/06 to 2002/05
Research Associate	University of Calgary	Physics and Astronomy	1996/02 to 1997/06
Sessional Instructor	University of Calgary	Physics and Astronomy	1996/01 to 1997/04
Post Doctoral Fellow	University of Calgary	Physics and Astronomy	1995/01 to 1996/01
Post Doctoral Fellow	Swedish Institute of Space Physics	Space Physics	1994/02 to 1995/01
Post Doctoral Fellow	University of Alberta	Physics	1993/05 to 1994/01

Personal identification no. (PIN)	Family name
Valid 101620	Donovan

RESEARCH SUPPORT

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.			
a) Support held in the past 4 years			
E. F. Donovan	NORSTAR Canadian Space Agency CGSM 20 hours/month	275,000(100%) 340,000(100%)	2006 2007
E. Donovan	Ravens: An Imaging Mission for ILWS - Mission Definition Study Canadian Space Agency Space Science (Concept Studies) 10 hours/month	10,000(100%)	2006
Eric Donovan	THEMIS-Canada Implementation & Operations CSA Unsolicited Proposal 20 hours/month	320,000(100%) 320,000(100%)	2006 2007
E.Donovan + 29 Others	The Resolute Bay Incoherent Scatter Radar: A Space Science Initiative in Nunavut Canadian Foundation for Innovation Round 6 40 hours/month	22,797,479(100%) 802,857(100%) 743,045(100%)	2010 2011 2012

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Personal identification no. (PIN)	Family name
Valid 101620	Donovan

RESEARCH SUPPORT

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)

List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.

b) Support currently held

E. F. Donovan	Remote Sensing of the Magnetosphere	35,000(100%)	2006
	NSERC	35,000(100%)	2007
	Discovery (Individual)		
	30 hours/month		
Eric Donovan + 19 others	Multi-Spectral Auroral Imaging Network	200,000(100%)	2008
	Operations	200,000(100%)	2009
	Canadian Space Agency	200,000(100%)	2010
	Canadian GeoSpace Monitoring	200,000(100%)	2011
	20 hours/month	200,000(100%)	2012
Eric Donovan + 4 others	CGSM Riometer Network Operations	60,000(100%)	2008
	Canadian Space Agency	60,000(100%)	2009
	CGSM	60,000(100%)	2010
	5 hours/month	60,000(100%)	2011
		60,000(100%)	2012
Brian Jackel + 7 others	Quantitative Multi-Spectral Auroral Photometry -	60,000 (0%)	2008
	MSP Network Operations	60,000 (0%)	2009
	Canadian Space Agency	60,000 (0%)	2010
	CGSM	60,000 (0%)	2011
	5 hours/month	60,000 (0%)	2012

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Personal identification no. (PIN)	Family name
Valid 101620	Donovan

RESEARCH SUPPORT

List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
b) Support currently held			
E. Donovan	THEMIS-C Operations Phase: Ground Based Observatory (GBO) operations, maintenance and data management Canadian Space Agency Space Science 20 hours/month	300,000(100%) 100,000(100%) 400,000(100%) 400,000(100%)	2008 2009 2010 2011
E. Donovan	Ultraviolet Monitoring Cameras (UVAMC) Pre-Phase A Study Canadian Space Agency Space Science 10 hours/month	204,800(100%) 345,825(100%)	2009 2010
E. Donovan	Rankin Inlet MSP Refurbishment Canadian Space Agency Space Science 10 hours/month	206,600(100%) 154,775(100%)	2009 2010
E Donovan	Global Evolution of the Substorm Injection Region Canadian Space Agency	46,650 93,900 46,650	2009 2010 2011

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Personal identification no. (PIN)	Family name
Valid 101620	Donovan

RESEARCH SUPPORT

Family name and initial(s) of applicant	Title of proposal, funding source and program, and time commitment (hours/month)	Amount per year	Years of tenure (yyyy)
List all sources of support **(including NSERC grants and university start-up funds)** held as an applicant or a co-applicant: a) support held in the past four (4) years but now completed; b) support currently held, and c) support applied for. For group grants, indicate the percentage of the funding directly applicable to your research. Use additional pages as required.			
b) Support currently held			
E Donovan	The Relationship between Auroral Type, Auroral Physics and Magnetospheric Dynamics Canadian Space Agency	66,667 66,667 66,667	2010 2011 2012

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Highly Qualified Personnel (HQP)

Provide personal data about the HQP that you currently, or over the past six years, have supervised or co-supervised.

Personal identification no. (PIN)	Family name
Valid 101620	Donovan

Name	Type of HQP Training and Status	Years Supervised or Co-supervised	Title of Project or Thesis	Present Position
Miller, Luke	Undergraduate (In Progress)	Supervised 2010 -	Instrument Development	
Reiher, Justin	Undergraduate (In Progress)	2010 -	Instrument Development	
Laing, Jun	Postdoctoral (In Progress)	Supervised 2009 -	Auroral and Magnetospheric Dynamics	
Boesen, Mari	Technician (In Progress)	Supervised 2008 -	Skymap Generation for very large ASI data sets	
McGuffin, Neil	Undergraduate (In Progress)	Supervised 2008 -	Operation of THEMIS GBO Array	
Uritsky, Vadim	Res. Associate (In Progress)	Supervised 2008 -	THEMIS Data Handling Tools	Research Associate, Auroral Imaging Group
Wilson, Cody	Technician (In Progress)	Supervised 2007 -	Operation and Maintenance of the THEMIS Canada GBO Array	THEMIS Site Coordinator, Auroral Imaging Group
Baker, Greg	MSP Lead (In Progress)	Supervised 2006 -	Ops and Data management Meridian Scanning Photometer	Photometer/Data Management Specialist, Auroral Imaging Group
Kryzanowsky, Zane	Technician (In Progress)	Supervised 2005 -	Operation and Maintenance of CGSM Riometer Array	Riometer Specialist, Auroral Imaging Group
Prosolin, Victor	Doctoral (In Progress)	Supervised 2004 -	Inner Magnetosphere in Substorms	In Doctoral Program
Greffen, Mike	Manager (In Progress)	Supervised 2003 -	Long Term Operation of Over 45 Ground Based Instruments	Program Manager, Auroral Imaging Group
Trondsen, Trond	Res. Associate (In Progress)	Co-supervised 2001 -	Multi Spectral Auroral Imaging	Research Associate (AIG) and CEO of Keo Scientific
Boesen, Mari	Undergraduate (Completed)	Supervised 2008 - 2010	Riometer Baselining and Imager Skymap File Creation	Skymap Specialist, Auroral Imaging Group
Barnetson, Kathleen	Undergraduate (Completed)	Supervised 2008 - 2009	Operation and Data Management of THEMIS GBO Array	Coop Student, Auroral Imaging Group
Little, Jarrett	Undergraduate (Completed)	Supervised 2008 - 2009	Merridian Scanning Photometer Refurbishment and Deployment	3 year Engineering at University of Victoria
Moores, Korwin	Master's (Completed)	Supervised 2007 - 2009	Diffuse Aurora	extended vacation
Spanswick, Emma	Doctoral (Completed)	Supervised 2004 - 2009	Data Specialist on THEMIS Project	Data Specialist on THEMIS Project
Marple, Steven	Res. Associate (Completed)	Supervised 2007 - 2007	GAIA Software Development	Research Scientist Lancaster University
Meurant, Matthieu	Postdoctoral (Completed)	Supervised 2005 - 2007	Proton Aurora Dynamics	Industry
Noora Partamies	Postdoctoral (Completed)	Supervised 2004 - 2007	THEMIS Auroral Observations	National Graduate Program Coordinator in Finland

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Highly Qualified Personnel (HQP)

Provide personal data about the HQP that you currently, or over the past six years, have supervised or co-supervised.

Personal identification no. (PIN)	Family name
Valid 101620	Donovan

Name	Type of HQP Training and Status	Years Supervised or Co-supervised	Title of Project or Thesis	Present Position
Voronkov, Igor	Res. Associate (Completed)	Co-supervised 2004 - 2007	THEMIS Science	On hiatus
Olivier, Hercules	Technician (Completed)	Supervised 2003 - 2007	Design of Optical & Radio Sensors	Professional Engineer at Bantral in Calgary
Syrjasuo, Mikko	Postdoctoral (Completed)	Supervised 2002 - 2007	Machine Vision in Auroral Research	Satellite Instrument Project Manager in Finland
Jackel, Brian	Res. Associate (Completed)	Supervised 2000 - 2007	THEMIS and NORSTAR Imaging and Science	Assistant Profressor (Tenure Track) U. Calgary
Pon, Andrew	Undergraduate (Completed)	Supervised 2006 - 2006	Riometer data analysis	Graduate student U Vic
Hiebert, Tara	Master's (Not Completed)	Supervised 2003 - 2006	N/A - withdrew for health reasons	Retail
Ball, Mark	Master's (Completed)	Co-supervised 2002 - 2005	Auroral Pulsations	Department of National Defence
Spanswick, Emma	Master's (Completed)	Supervised 2002 - 2004	Substorm Associated High Energy Precipitation	PhD Student - U. Calgary
Hiebert, Tara	Undergraduate (Completed)	Supervised 2003 - 2003	Substorm Onset Statistics	Retail

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Most Significant Contributions

a) Supply of Ionospheric Ions to the CPS: C. Cully (then my MSc student) and I used Akebono SMS data to characterize <70 eV H^+ & O^+ outflow at 8000 km as a function of location (ie, cusp, auroral zone, etc.), solar wind parameters, and activity. We developed an empirical model of outflow and a particle tracer to map the fluxes to the CPS. We found that this flux is ever-present and a sudden decrease in convection (e.g., due to a northward turning) will cause an *instantaneous* decrease of flux to the CPS. **We therefore elucidated *for the first time* a credible scenario for these ions to play a role in substorm onset**. This work was published in two papers [*Cully et al.*, *JGR*, *108*(A2), 2003].

b) Optical b2i: I developed an algorithm to identify the equatorward boundary of CPS proton precipitation (the *b2i*) in Meridian Scanning Photometer (MSP) data, demonstrated that this *optical b2i* correlates well with the inner CPS B-field topology, and developed a proxy (analogous to Sergeev's "MT-index") for the B-field inclination at geosynchronous orbit based on the optical b2i [see *Donovan et al.*, *JGR*, *108*(A3), 2003]. This allows us to track the B-field inclination in the inner CPS on a continuous basis on meridians away from those of GOES. We went on to demonstrate use of this technique with data from multiple MSPs, global SI12 images, and the equatorward boundary of SuperDARN E-region echoes [see papers 26, 37]. **With appropriate caveats, the ability to continuously track the magnetic topology in the inner CPS has important implications for research into magnetotail dynamics** (see next contribution).

c) Until recently, **Dispersionless Injections (DEs)** have been studied almost exclusively with near-geosynchronous *in situ* measurements. Emma Spanswick and I developed a method for remote sensing DEs with riometer data, and proved they *typically* start as an azimuthally extended disturbance beyond geosynchronous, but within 10 Re [11, 28, 24, and 29]. **Given the optical b2i, the riometer data, and new SuperDARN coverage over our MSPs and riometers, we now can track the 2D ionospheric projection of the magnetic field inclination, DE, and convection in the inner CPS during dynamic magnetotail events (including BBFs and the substorm)**.

d) GeoSpace Imaging: I have dedicated myself to creating new capabilities in auroral imaging. Together with S. Mende I was an architect of the THEMIS-ASI program [20,27,32]. My group has installed >25 ASIs over the last eight years, and now operates a network of >55 instruments. I initiated GAIA-VxO to facilitate accessing auroral images. I came up with the concept of a two-satellite mission that would provide continuous global auroral imaging (Ravens), allowing the first-time continuous imaging spanning storms and SMCs. Ravens led directly to my involvement in the Chinese KuaFu project, which includes two satellites with orbits/payload specified in my Ravens concept study [21]. This concept is now being developed as a proposal for a secondary science payload on the planned Canadian Polar Communications and Weather (PCW) satellites. Throughout, I have developed the ground- and space-based imaging programs with specific science objective, and to utilize new technologies to allow for new capabilities to meet them. **I assert that I am now an internationally recognized leader in geospace imaging, as evidenced by my accomplishments, my invited review in Advances of Space Research [25], two invited reviews I am presently working on (one for JASTP and the other for an IAGA monograph), and the nature of some of my invited talks (see section 2)**.

e) Magnetospheric Modelling: My PhD work involved development and testing global magnetospheric B-field models [*Donovan and Rostoker*, *GRL*, *18*(6), 1991; *Donovan et al.*,, *JGR*, *97*(A6), 1992; *Donovan*, *JGR*, *98*(A8), 1993; *Skone et al.*, *JGR*, *100*(A12), 1995]. In *Donovan* [1993], I presented the first-ever quantitative estimates of the effects of field-aligned currents on magnetic mapping. In the months after my PhD, I developed a method to numerically solve the MHD wave equation in a non-axially symmetric B-field (using a formulation of *H. Singer*). This work enabled C. Waters to use ground-based magnetometer measurements of frequencies of ULF field line resonances to infer radial profiles of inner-magnetospheric plasma density. This work was published in two papers [*Waters et al.*, *JGR*, *100*(A5), 1995; *Waters et al.*, *JGR*, *101*(A11), 1996]. My contribution to this work was essential to utilizing the magnetometer data for remote sensing, and is still leading to involvement by me in magnetoseismology studies [see e.g., 30, 31].

2. Research Contributions (2004-2010)

Over the past six years I have had 80 publications in refereed journals and conference proceedings, with five more more submitted and in review (not listed below), and 11 papers in nonrefereed conference procedings (not listed below). Mikko Syrjäsuo and I edited the Proceedings of the 8th International Conference on Substorms. I underline the names of my students and underline the names of myself and my PDFs/RAs. To save space I abbreviate author lists and titles, and have not included "doi" numbers for GRL and JGR articles (in those cases I indicate issue number or month of issue in brackets after the italicized volume number). GRL, JGR, AG, ASR, CJP, and JASTP refer to Geophys. Res. Lett., J. Geophys. Res., Ann. Geophys., Adv. Space Res., Can. J. Phys., and J. Atmos. Solar-Terr. Phys., respectively.

My contributions to the majority of the publications were significant, usually some combination of suggesting the study, providing critical data/interpretation, or writing/dealing with reviewer comments. Many of these studies were led by students or PDFs of mine. In a few cases (∼10) my contribution was either small (involving provision of data with minimal interpretation), or I was included as a member of the project development team (e.g., some recent THEMIS papers).

2.1b) Papers Published or Accepted for Publication in Refereed Journals

1 Klimas, A., V. Uritsky, and E. Donovan, Multiscale Auroral Emission Statistics as Evidence of Turbulent Reconnection in Earth's Midtail Plasma Sheet, *JGR*, doi:10.1029/ 2009JA014995, in press, 2010.

2 Henderson, M., E. Donovan, and five others, Start-to-end global imaging of a sunward propagating, SAPS-associated giant undulation event, *JGR*, in press, 2010.

3 Shiokawa, K., A. Nakajima, A. Ieda, K. Sakaguchi, R. Nomura, T. Aslaksen, M. Greffen, and E. Donovan, Rayleigh-Taylor type instability in auroral patches, J. Geophys. Res., doi:10.1029/2009JA014273, in press, 2010.

4 Liu, W., J. Liang, and E. Donovan, Electrostatic Field and Ion Temperature Drop in Thin Current Sheets: A Theory, J. Geophys. Res., doi:10.1029/2009JA014359, in press, 2010.

5 L. Kepko, E. Spanswick, V. Angelopoulos, E. Donovan, J. McFadden, K.-H. Glassmeier, J. Raeder, and H. J. Singer, Equatorward moving auroral signatures of a flow burst observed prior to auroral onset, *GRL*, 2009.

6 V. Uritsky, J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K. H. Glassmeier, Longitudinally propagating arc wave in the pre-onset optical aurora, *GRL*, 2009.

7 J. Liang, W. Liu, and E. Donovan, Ion temperature drop and quasi-electrostatic electric field at the current sheet boundary minutes prior to the local current disruption, *JGR*, 2009.

8 K. Sakaguchi, K. Shiokawa, and E. Donovan, Azimuthal structures of ray auroras at the beginning of auroral substorms, *GRL*, 2009.

9 Uritsky, V., E. Donovan, A. Klimas, and E. Spanswick, Collective dynamics of bursty particle precipitation initiating in the inner and outer plasma sheet, *AG*, 2009.

10 Shiokawa, K., Ieda, A., Nakajima, A., Sakaguchi, K., Nomura, R., Aslaksen, T., Greffen, M., Spanswick, E., Donovan, E., Mende, S. B., McFadden, J., Glassmeier, K.-H., Angelopoulos, V., and Miyashita, Y.: Longitudinal development of a substorm brightening arc, Ann. Geophys., 27, 1935-1940, 2009.

11 Spanswick, E., E. Donovan, W. Liu, J. Liang, J. Blake, G. Reeves, R. Friedel, B. Jackel, C. Cully, and A. Weatherwax, Global observations of substorm injection region evolution: 27 August 2001, *AG*, 2009.

12 Liang, J., W. Liu, E. Donovan, and E. Spanswick, In-situ observation of ULF wave activities associated with substorm expansion phase onset and current disruption, *AG*, 2009.

13 Uritsky, V., A. Klimas, E. Donovan, and E. Spanswick, Scale-free and scale-dependent modes of magnetotail dynamics, *GRL*, 2008.

14 Liu, W., J. Liang, and E. Donovan, Interaction between kinetic ballooning mode and thin current sheet, *GRL*, 2008.

15 Partamies, N., E. Donovan, and D. Knudsen, Statistical study of inverted-V structures in FAST data, *AG*, 2008.

16 Lui, A., and 12 others (E. Donovan 6th), Determination of the substorm initiation region from a major conjunction interval of THEMIS satellites, *in press in JGR*, 2008.

17 Angelopoulos, V., and 15 others (E. Donovan 10th), Tail reconnection triggering of substorm expansion onset, *Science*, 2008.

18 Donovan, E., *and 20 others*, including E. Spanswick, B. Jackel, M. Syrjäsuo, T. Trondsen, and G. Baker, Simultaneous in situ and ground-based observations of a small substorm, *GRL*, *35*, 2008.

19 Liang, J., E. Donovan, W. W. Liu, B. Jackel, M. Syrjäsuo, S. Mende, H. Frey, V. Angelopoulos, M. Connors, Intensification of preexisting auroral arc at substorm expansion onset: wave-like disruption during the first tens of seconds, *GRL*, *35*, 2008.

20 Mende, S., S. Harris, H. Frey, V. Angelopoulos, E. Donovan, B. Jackel, M. Greffen, C. Russell, and L. Peticolas, The THEMIS array of ground based observatories for the study of substorms, *SSR*, 2008.

21 Tu, C.-Y., R. Schwenn, E. Donovan, E. Marsch, Y.-S. Wang, L.-D. Xia, and Y.-W. Zhang, Space Weather Explorer - The KuaFu Mission, *ASR*, 2008.

22 Liu, W., J. Liang, E. Donovan, G. Sofko, B. Jackel, and 4 others, An isolated high-speed auroral streamer and its interpretation as optical signature of Alfvenic fronts generated by BBFs, *GRL*, 2008.

23 Liu, W., E. Donovan, J. Liang, I. Voronkov, E. Spanswick, P. Jayachandran, B. Jackel, and M. Meurant, Equatorward motion & fading of proton aurora during growth phase, *JGR*, *112*(A10), 2007.

24 Liang, J., W. Liu, E. Spanswick, and E. Donovan, Azimuthal structures of substorm electron injection and their signatures in riometer observations, *JGR*, *112*(A9), 2007.

25 Donovan, E., *and 19 others, including* T. Trondsen, E. Spanswick, M. Syrjäsuo, and B. Jackel, Global auroral imaging, system level science, and ILWS, *ASR*, *40*, pp 409-418, 2007.

26 Meurant, M., C. Blockx, E. Spanswick, E. Donovan, B. Hubert, J.-C. Gérard, V. Coumans, and M. Connors, EL - a possible indicator to monitor magnetic field stretching during substorm expansive phase: statistical study, *JGR*, *112*(A5), 2007.

27 Mende, S., V. Angelopoulos, H. Frey, S. Harris, E. Donovan, B. Jackel, M. Syrjäsuo, C. Russell, and I. Mann, Substorm onset location and timing using the THEMIS GBOs, *GRL*(September), *34*, 2007.

28 Spanswick, E., E. Donovan, R. Friedel, and A. Korth, Ground based identification of dispersionless electron injections, *GRL*, *34*(January), 2007.

29 Liu, W., J. Liang, E. Spanswick, and E. Donovan, Remote-Sensing Magnetospheric Dynamics With Riometers: Observation and Theory, *JGR*, *112*(A5), 2007.

30 Kabin, K., R. Rankin, C. Waters, R. Marchand, E. Donovan, and J. Samson, Different models for field line resonances in cold plasma: effect on magnetospheric density estimates, *Planet. Space Sci.*, *55*(6), 820, 2007.

31 Waters, C., K. Kabin, R. Rankin, E. Donovan, and J. Samson, ULF wave polarization and magnetic field model effects on the estimation of proton number densities in the magnetosphere using field line resonances, *Planet. Space Sci.*, *55*(6), 809, 2007.

32 Donovan, E., S. Mende, B. Jackel, H. Frey, Syrjäsuo, I. Voronkov, T. Trondsen, L. Peticolas, V. Angelopoulos, S. Harris, M. Greffen, and M. Connors, The THEMIS All-Sky Imager Array - System design and initial results from the prototype imager, *JASTP*, doi:10.1016/j.jastp.2005.03.27, 2006.

33 Jayachandran, P., J. MacDougall, and E. Donovan, Ground-based radar detection of the equatorward boundary of ion aurora in the dusk-midnight sector and its association with substorms, *Adv. Polar Upper Atmos. Res.*, *20*, 63-75, 2006.

34 Amm, O., E. Donovan, *and 11 others*, Coordinated geospace studies using Cluster, and ground-based data: An interim review, *AG*, *23*, pp 2129-2170, 2005.

35 Rae, I., E. Donovan, *and 10 others*, Evolution and characteristics of global Pc5 waves during a high solar wind speed interval, *JGR*, *110*(A12), 2005.

36 Spanswick, E., E. Donovan, and G. Baker, Pc5 modulation of high energy electron precipitation: particle interaction regions and scattering efficiency, *AG*, *23*, pp 1533-1542, 2005.

37 Jayachandran, P., E. Donovan, *and 5 others*, Global and local growth-phase equatorward expansion of the ion oval, *JGR*, 110(A5), 2005.

38 Liang, J., G. Sofko, and E. Donovan, On the spatial & temporal relationship between auroral intensification and flow enhancement in a pseudosubstorm, *JGR*, *109*(A6), 2004.

39 Syrjäsuo, M., and E. Donovan, Diurnal Auroral Occurrence Statistics Obtained Via Machine Vision, *AG*, *22*, pp 1103-1113, 2004.

40 Frey, H., Mende, Angelopoulos, and E. Donovan, IMAGE-FUV substorm observations, *JGR*, 109, 2004.

41-74 **Plus an additional 34 papers in refereed journals between 2004 and 2010**

2.2) Other Refereed Contributions (referred conference procedings and AGU monographs)

75 Syrjäsuo, M., and E. Donovan, Using relevance feedback in retrieving auroral images, *Proc. of the IASTED Int. Conf. on Computational Intelligence (CI 2005)*, 420-425, 2005.

76 Syrjäsuo, M. and E. Donovan, Content-based retrieval of auroral images - thousands of irregular shapes, Proc. of the IASTED Conf. on Visualization, Imaging and Image Processing, 224-228, 2005.

77-80 **Plus an additional 4 papers in refereed procedings between 2004 and 2008**

2.3b) Non-refereed Contributions - Selected Invited Presentations

I have given >40 invited talks, seminars, and colloquia over the last six years, some of which I list here. Of particular note was my hour-long plenary "Interdisciplinary Lecture" at COSPAR (July, 2008). There were only five interdisciplinary lectures at this major international meeting. I was the only Canadian scientist giving one of these prestigious lectures, and mine was the only one on geospace science.

- ▷ The future of global auroral imaging, *Invited Talk*, ILWS Annual Meeting, Brazil, October, 2009 (presented by J. Spann).
- ▷ Imaging the aurora, *Invited Plenary Interdisciplinary Lecture*, COSPAR, Montreal, July, 2008.
- ▷ Why substorm onset is so difficult to understand, *Invited Tutorial*, GEM, Midway, Utah, June, 2008.
- ▷ The Diffuse Aurora, *Invited Tutorial*, GEM, Midway, Utah, June, 2007.
- ▷ DASI Mission Overview, *"kickoff" talk for the CEDAR-DASI Workshop*, Santa Fe, June, 2007.
- ▷ Magnetic Storms, *UBC Department of Physics & Astronomy Colloquium*, October 2006.
- ▷ Global auroral imaging: geospace remote sensing in ILWS, *Invited talk at WPGM*, Beijing, 2006.
- ▷ High energy electron precipitation during substorms, *AGU Invited talk*, December 2004.
- ▷ The Future of Passive Remote Sensing of Auroral Precipitation in Canada, *Invited talk at the NSF DASI "Blue Sky" Visioning Workshop*, Boulder, April, 2004.

3. List of Evidence of National and International Leadership

- ▷ **PI:** Resolute Bay CFI proposal for Canadian Resolute Bay AMISR (Awarded summer/fall 2009).
- ▷ **PCo-Proposer (with A. Keiling):** Chapman Conference on the Magnetospheric Drivers of Aurora (result pending).
- ▷ **NSERC Discovery Accelerator Supplement:** 2008-2011.
- ▷ **Canada Research Chair (Tier II) in Auroral Studies:** renewed in October 2008.
- ▷ **Co-Proposer (with M. Lester):** ISSI "System-Level Science" Study Group
- ▷ **Member:** ISSI "Cluster Ground-Based Science" Study Group
- ▷ **Member:** ESA Swarm Mission Advisory Group (membership awarded by competitive process).
- ▷ **Founder:** Global Auroral Imaging Access (GAIA) Virtual Observatory program.
- ▷ **CoI:** *THEMIS* (5 spacecraft NASA MIDEX mission; V. Angelopoulos, PI).
- ▷ **CoI:** *KuaFu* (proposed 3 spacecraft Chinese mission; C.-Y. Tu, PI).
- ▷ **Chair:** International Living With a Star Ground-Based Task Group.
- ▷ **Member:** Canadian Association of Physicists Committee on Science Policy.

- ▷ **Member:** NSERC GSC-17 (2005-2007).
- ▷ **Member:** EISCAT Science Advisory Committee (2004-2007).
- ▷ **International Liaison:** US NSF GEM Steering Committee (2003-).
- ▷ **Member:** US NSF CEDAR Steering Committee (2005-2007).
- ▷ **Convenor:** 8th International Conference on Substorms (March 2006).
- ▷ **Convenor:** 2nd International Workshop on Riometry (March 2006).
- ▷ **Chair:** Canadian Geospace Monitoring Program Supervisory Group (2002-2008).
- ▷ **PI:** NORSTAR, a CSA, NSERC, & CFI funded array MSPs, riometers, and ASIs (2001-).
- ▷ **PI:** THEMIS-Canada CSA Contract for Operations of GBO Network in Canada (2003-).
- ▷ **PI:** Ravens, a CSA concept study to explore a Canadian imaging mission for ILWS.
- ▷ **PI:** Operations contract for all CANOPUS instruments from 2001-2004.
- ▷ **Co-wrote:** CANOPUS-2000 science plan (with J. Samson and I. Voronkov).

4. Contributions to Training of HQP

It is my objective to provide outstanding opportunities for students and PDFs. I try, for example, to give students first crack at unique data sets, and science questions that can be addressed best with those data sets in hand. For PDFs I have always focussed on their science projects, but also have tried to allow them to take advantage of interesting and often unusual career opportunities. As a result, I have what I consider to be a very high success rate in terms of outcomes, meaning my students and PDFs have done very well during their time with me, and more importantly, afterwards. Some specific examples are listed below:

- ▷ **Two PDF/RAs working for me have found permanent positions**. Brian Jackel was hired as an Assistant Professor in our department, starting July 2007. Noora Partamies returned to her native Finland in July 2007 as the coordinator of the Finnish national graduate program in space physics. I have handed over PI-ship of the MSP program to Brian Jackel as of January 2008.
- ▷ **Since 1999, my students have been awarded a total of eight awards for talks or posters at international and national conferences**: four AGU Outstanding Student Paper Awards (Cully, two for Spanswick, and Hiebert); two DASP Outstanding Student Paper Awards (Nicholson, Spanswick); two ICS Outstanding Student Poster Awards (Hiebert and Prosolin).
- ▷ Early in her PhD, Emma Spanswick demonstrated that the dispersionless injection can be identified in riometer data. She used this to demonstrate that the dispersionless injection *likely* starts in the 8-9 Earth radii region and subsequently expands tailward and Earthward. **She is now internationally regarded as an expert in the scientific use of riometer data, and is involved in numerous collaborations, many not involving me. Now one year out of her PhD program, she has been offered five PDF positions, has been awarded an NSERC PDF, and is the Deputy PI of the proposal to CSA for auroral imaging on PCW**.
- ▷ **Students working with me have been granted a total of 4 NSERC PGS awards, 2 AIF Scholarships, and 1 Deans Silver Anniversary Graduate Fellowship, 1 Killam Memorial Scholarship, and 1 NSERC PDF. As well, I have attracted three PDFs who were successful in competing for AIF Fellowships**.
- ▷ **Trond Trondsen started a high-tech imaging company based on early work done on NORSTAR**. This company got its start by acquiring the assets of Keo Consulting (Robert Eather's company), and now has CFI, US NSF, and US Air Force contracts. The new company, Keo Scientific, is now posting profits.
- ▷ **I work through the U. Victoria Coop Program to employ students for work terms. My research programs is increasingly offering hands-on experience in instrument design, and these students gain unusually good experience in technical work. An example is Jarret Little, and undergraduate Computer Science student, who over two work terms played an integral role in the refurbishment of a Meridian Scanning Photometer, and now has the expertise to troubleshoot problems on our existing and new photometers in the field.**

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SEND ONE ORIGINAL ONLY DO NOT PHOTOCOPY

APPENDIX A
Personal Data
(Form 100)

Complete this appendix (i) if you are an applicant or co-applicant applying for the first time; (ii) if you need to update information submitted with a previous application; or (iii) if you do not hold an appointment at a Canadian postsecondary institution. For updates, include only the revised information in addition to the date, your name and your PIN.

This information will be used by NSERC primarily to contact applicants and award holders. It may also be used to identify prospective reviewers and committee members, and to generate statistics. It will not be seen or used in the adjudication process.

Date: 2010/02/11

Family name	Given name	Initial(s) of all given names	Personal identification no. (PIN)
Donovan	Eric	EF	**Valid** 101620

Position and complete mailing address if your primary place of employment is not a Canadian postsecondary institution or if your current mailing address is temporary

2500 University Drive N.W.

Calgary AB T2N1N4
CANADA

If address is temporary, indicate:

Starting date

Leaving date

Telephone number	Facsimile number	E-mail address
(403) 220-6337	(403) 282-5016	edonovan@ucalgary.ca

Telephone number (alternate)

Give an alternate telephone number only if you can be reached at that number during business hours.

Gender (completion optional): [X] Male [ ] Female

LANGUAGE CAPABILITY

English	Read [X]	Write [X]	Speak [X]
French	Read [ ]	Write [ ]	Speak [ ]

I wish to receive my correspondence: in English [X] in French [ ]

AREA(S) OF EXPERTISE

Provide a maximum of 10 key words that describe your area(s) of expertise. Use commas to separate them. If you have expertise with particular instruments and techniques, specify which one(s).

aurora, plasma physics, ion isotropy boundary, bursty bulk flows, ionospheric outflows, mapping, storms and substorms, space weather, magnetospher, ionosphere

Research subject code(s)

Primary: 3250

Secondary: 3252

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APPENDIX B (Form 100)
Eligibility Questionnaire for University Faculty

Complete this appendix if you are an applicant or co-applicant holding a position at a Canadian university that is not a tenured, tenure-track or life-time professor emeritus position at the time of application. **The information you provide must be for the position you will hold at the time the grant is awarded.** If you are not currently in that position, you must have a written firm offer. You may append any relevant information. See the eligibility criteria in the *Program Guide.*

The information will be used by NSERC staff to determine your eligibility to hold an NSERC grant. It will not be seen or used in the adjudication process.

Date: 2010/02/11

Family name	Given name	Initial(s) of all given names	Personal identification no. (PIN)
Donovan	Eric	EF	**Valid** 101620

Title of position at Canadian university

Associate Professor

Is this an academic appointment?

[X] Yes [ ] No

If you currently have a firm written offer of a tenured or tenure-track position, but have not taken up the position at the time of application, specify the expected start date of the appointment. The offer must meet the requirements stated in the NSERC *Program Guide*

Expected start date of the appointment (yyyy/mm)

If you currently hold, or have a firm offer of, a non-tenured or non-tenure-track position, complete the following information. The offer must meet the requirements stated in the NSERC *Program Guide,* under eligibility.

Is this a position of a limited duration?

[ ] Yes [ ] No

If yes, specify the period of the appointment (yyyy/mm)

From To

If you answered no, explain the terms of your appointment.

If your position offer is not yet confirmed by the university, provide an explanation

CERTIFICATION AND SIGNATURES

We attest that during tenure of the grant:

- the position will require the applicant to engage in research that is not under the direction of another individual, and authorize the applicant to supervise or co-supervise students registered in an undergraduate or graduate degree program or postdoctoral;
- if the applicant lives abroad or holds a position of any kind outside of Canada, he/she must spend a minimum of six months per year at an eligible Canadian institution;
- the applicant's salary will not be paid out of NSERC (or other federal granting council) grant funds and the applicant will not hold a federal granting council fellowship or scholarship (for exceptions, see eligibility in the NSERC *Program Guide);*
- the applicant will not be enrolled in a graduate program in the natural sciences or engineering.

Applicant

Head of department

President of university (or representative)

Appendix D (Form 100)
Consent to Provide Limited Personal Information About Highly Qualified Personnel (HQP) to NSERC

NSERC applicants are required to describe their contributions to the training or supervision of highly qualified personnel (HQP) by providing certain details about the individuals they have trained or supervised during the six years prior to their current application. HQP information must be entered on the Personal Data Form (Form 100). This information includes the trainee's name, type of HQP training (e.g., undergraduate, master's, technical etc.) and status (completed, in-progress, incomplete), years supervised or co-supervised, title of the project or thesis, and the individual's present position.

Based on the federal *Privacy Act* rules governing the collection of personal information, applicants are asked to obtain consent from the individuals they have supervised before providing personal data about them to NSERC. In seeking this consent, the NSERC applicant must inform these individuals what data will be supplied, and assure them that it will only be used by NSERC for the purpose of assessing the applicant's contribution to HQP training. To reduce seeking consent for multiple applications, applicants will only need to seek consent one time for a six-year period. If the trainee provides consent by e-mail, the response must include confirmation that they have read and agree to the text of the consent form.

When consent cannot be obtained, applicants are asked to not provide names, or other combinations of data, that would identify those supervised. However, they may still provide the type of HQP training and status, years supervised or co-supervised, a general description of the project or thesis, and a general indication of the individual's present position if known.

An example of entering HQP information on Form 100 (with and without consent):

Name	Type of HQP Training and Status	Years Supervised or Co-supervised	Title of Project or Thesis	Present Position
Consent Received from Marie Roy				
Roy, Marie	Undergraduate (Completed)	Supervised 1994 - 1997	Isotope geochemistry in petroleum engineering	V-P (Research), Earth Analytics Inc., Calgary, Alberta
Consent Not Obtained from Marie Roy				
(name withheld)	Undergraduate (Completed)	Supervised 1994 - 1997	Isotope geochemistry	research executive in petroleum industry - western Canada

Consent Form

Name of Trainee	
Applicant Information	
Name Donovan, Eric EF	
Department Physics and Astronomy	Postsecondary Institution Calgary

I hereby allow the above-named applicant to include limited personal data about me in grant applications submitted for consideration to NSERC for the next six years. This limited data will only include my name, type of HQP training and status, years supervised or co-supervised, title of the project or thesis and, to the best of the applicant's knowledge, my position title and company or organization at the time the application is submitted. I understand that NSERC will protect this data in accordance with the *Privacy Act*, and that it will only be used in processes that assess the applicant's contributions to the training of highly qualified personnel (HQP), including confidential peer review.

Trainee's signature _____ Date _____

Note: This form must be retained by the applicant and made available to NSERC upon request.

Resumé

January 2010

Leroy L. Cogger
Birthdate: May 20, 1937
Citizenship: Canadian

Academic History

BA. (Magna cum Laude) 1960, University of Saskatchewan, Saskatoon
M.A. 1963, University of Saskatchewan, Saskatoon
Ph.D. 1968, University of Saskatchewan, Saskatoon

Employment History

1962-1963 High School Teacher, Winnipeg, Manitoba
1968-1971 Employed by Cornell University as a Research Associate at the Arecibo Observatory, Puerto Rico
1971-1975 Assistant Professor of Physics, University of Calgary, Calgary
1975-1982 Associate Professor of Physics, University of Calgary, Calgary
1982-1997 Professor of Physics, University of Calgary, Calgary
1989-2002 Director, Institute for Space Research, University of Calgary, Calgary
1997-pres. Faculty Professor and Emeritus Professor of Physics and Astronomy, University of Calgary, Calgary

Teaching Experience

High school level, 1962-1963
Undergraduate and graduate courses in Physics, 1971-1997
Graduate student supervision, 9 M.Sc. and 3 Ph.D. students, 1971-1998

Research Areas

-The physics and chemistry of the Earth's atmosphere above 85 km
-Development of instruments to image the aurora from rockets, satellites and the ground
-The study of global and local auroral processes
-Measurement of neutral winds in the thermosphere

Science Team Memberships in Space Projects

-Co-investigator, Auroral Scanning Photometer experiment on the ISIS2 satellite (C.D. Anger, Principal Investigator), 1971-1980
-Imaging team leader, CSA CANOPUS array, 1983-2002
-Co-investigator, UV Imager experiment on Sweden's Viking satellite (J.S. Murphree, Principal Investigator), 1980-1990
-Principal Investigator, UV Auroral Imager experiment on Russian Interball-2 satellite, 1987-2000
-Co-investigator, WINDII experiment on NASA's Upper Atmosphere Research Satellite (G.G.

Shepherd, Principal Investigator), 1984-1997
-Co-investigator, UV Imager experiment on Sweden's Freja satellite (J.S. Murphree, Principal Investigator), 1989-1993
-Member, Science Team, Far Ultraviolet Imager experiment on NASA IMAGE satellite (S.B. Mende, Principal Investigator), 1995-2002
-Principal Investigator, Fast Auroral Imager on CSA CASSIOPE/E-POP satellite, 2004-present

Professional Service

-Member of Advisory Board, Herzberg Institute of Astrophysics, 1992-1996
-Member of Solar Terrestrial Relations Advisory Committee (CSA), 1989-1994
-Director and Scientific Leader, Canadian Network for Space Research, a network in Canada's NCE program, 1989-1995
-Member of selection panels for CSA, NASA and National Science Foundation
-Journal referee for Journal of Geophysical Research, Geophysical Research Letters, Journal of Atmospheric and Solar-Terrestrial Physics etc.
-Chairman, Division of Aeronomy and Space Physics, Canadian Association of Physicists, 1985-1986
-Member of NSERC Grant Selection Committee for Space Physics and Astronomy, 1981-1984; Chairman, 1984
-Member of Science Advisory Committee to Canada Centre for Space Science (NRC), 1981-1984
-Member of Associate Committee on Space Research (NRC), 1975-1978
-Member, Regional Advisory Committee to the American Geophysical Union, North American Region, 2000-2004
-Member, Science Coordination Committee, CEDAR, National Science Foundation, 2000-2002
-Convenor and/or organizer for 8 national and international conferences and workshops

Dissemination of Scientific Knowledge

Over 120 published papers in refereed journals and over 140 conference presentations

Professional Awards

Recipient of 1991 Alberta Science and Technology Leadership Award for Innovation in Science
Recipient of 1994 Award of Excellence in Research, Faculty of Science, University of Calgary
Recipient of 2002 W. Rupert Turnbull Lecture Award, Canadian Aeronautics and Space Institute

Professional Organizations (current)

Canadian Association of Physics
American Geophysical Union
Canadian Aeronautics and Space Institute

CURRICULUM VITAE

Gregory Allan Enno
217 Tuscany Valley Way N.W.
Calgary, Alberta
T3L 2A7

Born: November 1, 1962
Location: Winnipeg, Manitoba, Canada
Citizenship: Canadian
Marital Status: Married (June, 1990)

Education:

School	Degree Awarded	Date
University of Calgary	BSc Astrophysics & Physics	June, 1985

Academic Experience:

Position	Dates	Department	Location
Science Operations & Analysis	Jan, 1985 - Present	Physics & Astronomy	U of Calgary

Projects:

Optical Filter Calibration and Inventory. (1983) Spectral calibration of low, high & bandpass filters, including peak wavelength, transmittance, and bandwidth.

ISIS-II Auroral Scanning Photometer. (1984- 1993) Image archive, data analysis and figure preparation for publications and conferences.

VIKING UV Imager. (1985 - 1995) Instrument operations/programming, image archive, data analysis *(which included satellite attitude determination, position and timing corrections)*, figure preparation for publications and conferences, and interpretive support for visiting scientists.

CANOPUS Auroral All-sky Imager. (1985 - 1989) Image display software, and figure preparation for publication.

The Institute For Space Research (ISR). (1986 - 2006) Computer administration support, world wide web pages creation and maintenance, figure preparation for publications, conferences, grant proposals and for public relations under the Major Facilities Grant.

Canadian Network of Centres of Excellence (CNSR). (1989 - 1994) Computer administration support, and figure preparation for publications, conferences and for public relations.

FREJA UV Imager. (1991 - 1996) Instrument ground station shipment, setup, and configuration, GSE programming, instrument operations/programming, image archive, data analysis *(which again included satellite attitude determination, position and timing corrections)*, figure/text preparation for publications and conferences, and interpretive support for visiting scientists.

INTERBALL-2 UV Imager. (1994 - 1998) Flight software debugging and testing, instrument ground station shipment, setup, and configuration, instrument operations/programming, image archive, data analysis *(which again included satellite attitude determination, position and timing corrections)*, figure preparation for publications and conferences, and interpretive support for visiting scientists.

NOZOMI (PLANET-B) Thermal Plasma Analyzer. (1998 - 2004) Computer administration support, and figure preparation for publications, conferences and for public relations. Pre and post launch simulation. Design and implementation of TPA Martian operations.

ACTIVE Sounding Rocket. (1998) Preflight testing of both the Thermal Plasma Analyzer Demonstration Model *(TPA/DM)* and the Global Positioning System *(MGR)* receivers. GSE configuration, flight software debugging,

payload assembly and test, launch support, data archival and analysis.

GEODESIC Sounding Rocket. (1999 - 2000) Preflight testing of the SII/TEI Instrument GSE configuration and programming, flight software debugging, and data archival.

SS520-2 Sounding Rocket. (1999 - 2000) Preflight simulation and testing of the Thermal Suprathermal Analyzer *(TSA)*. GSE configuration and programming, flight software debugging, data archival and analysis.

Space Environment Micro-satellite (SEM). (2000 - 2001) Preliminary design of instrument and data handling unit GSE's and the planning and layout of the Science Operations Center (*SOC*).

CUSP Sounding Rocket. (2001 - 2002) Preflight GSE configuration, programming and testing of the SII/SEI Instrument.

JOULE Sounding Rocket. (2002 - 2003) Preflight GSE configuration, programming and testing of the SII Instrument, instrument AI&T specialist at payload integration.

JOULE II Sounding Rocket. (2006) Consultant on GSE configuration and programming for the SII Instrument.

Cassiope Satellite (e-POP Payload). (2003 - Present) Project and systems engineering for the 8 instruments of the e-POP Payload, including, liaison with CSA, the mission integrator, international partners and subcontractors. Design of MGSE/EGSE and instrument test and operations configurations. Design and development of the e-POP Science Operations Center (*eSOC*). Design and implementation of the e-POP payload integration and test plan for S/C AI&T. Production of scientific satellite operation scenarios and on-orbit video simulations.

Publications/Talks:

Fox, N.J., M. Lockwood, S.W.H. Cowley, V.N. Davda, G.A. Enno, E. Friis-Christensen, R.A. Greenwald, M.G. Kivelson, M. Lester, H. Luhr, D.K. Milling, J.S. Murphree, M. Pinnock, and G.D. Reeves, **A Comparison of Freja Auroral Images with Substorm Cycle Observations**, Proceedings of the Second International Conference on Substorms, Fairbanks, USA, Geophysical Institute, March, 1994.

Fox, N.J., M. Lockwood, S.W.H. Cowley, V.N. Davda, G.A. Enno, R.A. Greenwald, M.G. Kivelson, M. Lester, H. Luhr, D.K. Milling, J.S. Murphree, M. Pinnock, and G.D. Reeves, **Observations of an Expanding Auroral Bulge and Current System Far Poleward of the Main Substorm Electrojet**, *J. Geophys. Res*, 1997.

Fox, N.J., M. Lockwood, S.W.H. Cowley, V.N. Davda, G.A. Enno, E. Friis-Christensen, R.A. Greenwald, M.R. Hairston, M. Lester, M. Lockwood, H. Luhr, D.K. Milling, J.S. Murphree, M. Pinnock, and G.D. Reeves, **A Multipoint Study of a Substorm Occurring on 7 December 1992 and Its Theoretical Implications**, *Ann. Geophysicae*, Vol 17, pp 1369+, 1999.

Lester, M., N.J. Fox, V.N. Davda, G.A. Enno, M.R. Hairston, G.D. Reeves, and T. Yamamoto, **Ionospheric Convection, Optical Signatures and Particle Precipitation in the Dusk Local Time Sector During a Magnetospheric Substorm**, *Ann. Geophysicae*, submitted, 1998.

G.P. Garbe, A.W. Yau, G.A. Enno, M. Greffen, C. Davis, and M. Chitroda, **Preliminary Results from the ACTIVE Sounding Rocket Flight**, Talk, DASP Proceedings, Feb, 1999.

A.W. Yau, P.V. Amerl, K. Berg, T. Cameron, M. Chitroda, G.A. Enno, E.P. King, I. Wevers, **Imaging Thermal Suprathermal Ion Mass Energy Angle Analyzer**, Poster Paper Fall AGU, Dec, 1999.

Weygand, J.M., J.S. Murphree, M.G. Henderson, and G.A. Enno, **Simultaneous Closed Magnetic Field Line Polar Arcs and Substorms**, *JASTP* Vol 63, 2001.

E. Zesta, E. Donovan, L. Lyons, G. Enno, J.S. Murphree, and L. Cogger, **The Two-dimensional Structure of Auroral Poleward Boundary Intensifications (PBI)**, *J. Geophys. Res*, Vol 107, No. A11, Nov, 2002.

Knudsen, D. J., J. K. Burchill, K. Berg, T. Cameron, G.A. Enno, E.P. King, C.G. Marcellus, I. Wevers, and R.A. King, **A low-energy charged particle distribution imager with a compact sensor for space applications**, *Rev. Sci. Inst.*, Vol 74 No 1, Jan, 2003.

Teaching Experience:

Position	Dates
Marker/Tutorial Instructor for Astronomy 205, 211, 213	Fall/Winter 1985

Special Skills:

Course	Governing Body	Date
RLSSC Life Saver	The Royal Life Saving Society of Canada	May 1979
	Re-certified	Nov 1991
Senior Resuscitation	The Royal Life Saving Society of Canada	May 1979
	Re-certified	Feb 1990
Standard First Aid	The Canadian Red Cross Society	Nov 1990
	Re-certified	Feb 1996
Basic Rescuer (1st Aid/CPR)	Hearth & Stroke Foundation of Canada	May 1993
	Re-certified	Apr 2007
Heart Saver (CPR)	Hearth & Stroke Foundation of Canada	Jan 1995
	Re-certified	Apr 2007
Workplace Hazardous Materials Information Systems Course (WHIMIS)	The University of Calgary Safety Services	Feb 2000
Advanced STK Training Course (Satellite Tool Kit)	Analytical Graphics Inc.	Apr 2002
Canadian Controlled Good Program (CCGP) Registered and Approved	Government of Canada	Jul 2004
Canadian Security Clearance 'Reliable' Standing	Government of Canada	Mar 2009

Volunteer Work:

Position	Location	Date
Ski Jumping Results Calculator/Recorder for local competitions	ALTIUS Nordic Ski Club	Nov 2009 to Present
Board Member Director of Operations	Calgary West Soccer Club	Sep 2009 to Present
Ski Jumping Judge (non_Cert.) for local competitions	ALTIUS Nordic Ski Club	Dec 2008 to Present
Soccer Referee Liaison for Children Ages 7 - 16.	Calgary West Soccer Club	Mar 2008 to Present
Soccer Equipment Coordinator for Children Ages 7 - 16.	Calgary West Soccer Club	Sep 2007 to Present
Ski Jumping Hill Marker for local competitions	ALTIUS Nordic Ski Club	Feb 2007 to Present
Soccer First Aider for Children Ages 8 - 9.	Tuscany Residents Association	Apr 2007 to Jun 2007
Soccer Coach for Children Ages 3 - 4.	Tuscany Residents Association	Apr 2002 to Jun 2003
Assistant Soccer Coach for Children Ages 5 - 9.	Tuscany Residents Association	Apr 2002 to Jun 2006
School Class Volunteer.	Marion Carson Elementary School	Sept. 2001 to Present
Pre-School Class Volunteer for Children Ages 3 - 4.	Kids Come First, Ranchlands Community Centre	Sep 1999 to May 2003
Coach of Recreational Speed Swimming Team for Children Ages 5 - 18.	South YMCA	Sep 1989 to Jun 1996
Treasurer;	Braxton Brae	
Board Member	Condo Assoc.	Apr 1991 to Mar 1993
Board Member	Condo Assoc.	Feb 1995 to Jul 1995

Michael John Greffen

63 MacEwan Glen Rd, NW
Calgary, AB, T3K 2J3
403.275.3267
mgreffen@ucalgary.ca

Education

B.Sc. (Physics), University of Victoria [1993]

Work Experience

Auroral Imaging Group (AIG) Program Manager, University of Calgary [2007-Present]

- Ultimately responsible for the construction, operation, maintenance and refurbishment of over forty ground based instruments (All Sky Imagers, Riometers and Meridian Scanning Photometers, an Advanced Modular Incoherent Scatter Radar) engaged in the study of the Northern Lights
- Manage a group of approximately ten full time employees, ranging from cooperative education students to engineers and PhD's
- Participate in maintenance field trips to remote northern locations
- Oversee multiple federal government contracts totaling roughly thirty million dollars
- Attend international science meetings and participate in research strategy sessions
- Co-wrote six successful funding applications to the Canadian Space Agency, Space Sciences Division
- Co-wrote successful Canadian Foundation for Innovation proposal for $25M ('The Resolute Bay Incoherent Scatter radar: A Space Science Initiative in Nunavut')

THEMIS Canada Operations Manager, University of Calgary [2003-2007]

- Located sites for, and subsequently deployed, sixteen THEMIS Ground Based Observatories (GBOs) across Canada
- Operated and maintained the sixteen THEMIS GBOs located in Canada
- Worked closely with the team at the Space Sciences Laboratory at University of California, Berkeley to design and build GBOs for the THEMIS mission
- Wrote Common Gateway Interface (CGI) software (in TCL) to display THEMIS GBO near real time monitoring and science data on the GBO monitoring website
- Participated in THEMIS Canada public relations activities, including on-air radio interviews and on-camera television interviews
- Led the re-design and refurbishment of a Meridian Scanning Photometer, including the hands-on fabrication and assembly of novel hardware and electronic components

Research Assistant, University of Calgary [1995 – 1998]

- Wrote the Electronic Ground Support Equipment (EGSE) software (C and Perl) for the Thermal Plasma Analyzer (TPA which flew on the Japanese Nozomi satellite to Mars)
- Participated in calibration, testing and final integration of TPA on to the Nozomi satellite at the Institute for Space and Astronautical Science (ISAS) in Japan
- Adapted the simulation code (Fortran and C) from the Cold Plasma Analyzer (CPA which flew on the Swedish Freja satellite) to TPA

Research Assistant, National Research Council [1993-1994]

- Wrote simulation code (in C) for the Cold Plasma Analyzer (CPA which flew on the Swedish Freja satellite) and ran the code to parameterize the instrument response function
- Produced summary plots for the Supra-Thermal Mass Spectrometer (SMS which flew on the Japanese Akebono satellite) and wrote computer code to access the data (in IDL)

Publications

Peterson, W. K., T. Abe, H. Fukunishi, M. J. Greffen, H. Hayakawa, Y. Kasahara, I. Kimura, A. Matsuoka, T. Mukai and T. Nagatsuma, On the sources of energization of molecular ions at ionospheric altitudes, *Journal of Geophysical Research*, 99 (A12), pp 23,257-23,274, 1994.

Knudsen, D. J., B. A. Whalen, A. W. Yau, M. J. Greffen, A. I. Eriksson, N. Lloyd, M. Boehm, J. Clemmons and L. G. Blomberg, Sub-kilometer thermal plasma structure near 1750 km altitude in the polar cusp/cleft, *Geophysical Research Letters*, **21 (17)**, 1907-1910, 1994.

Yau, A. W., T. Abe, M. J. Greffen, R. E. Horita, D. J. Knudsen, T. Mukai, K. I. Oyama, W. K. Peterson, E. Sagawa, S. Watanabe and B. A. Whalen, Akebono observations of the polar wind and suprathermal auroral ions: an overview, *Journal of Geomagnetism and Geoelectricity*, **48**, 45, 1996.

Yau, A. W., E. Drakou, M. J. Greffen, D. J. Knudsen and E. Sagawa, Radio-frequency ion mass spectrometer measurements of ion composition, velocity and temperature: the EXOS-D suprathermal mass spectrometer, *Geophysical Monograph*, **102**, 307-312, 1998.

Yau, A.W., G. P. Garbe, M. J. Greffen, W. Miyake and E. Sagawa, Planned observations of thermal plasma drifts and solar wind interactions in the Martian ionosphere, *Earth Planets Space*, **50**, 195-198, 1998.

Knudsen, D. J., T. D Phan, M. D. Gladders, M. J. Greffen and B. A. Whalen, Thermal electrical temperature measurements from the Freja Cold Plasma Analyzer, *Geophysical Monograph*, **102**, 91-96, 1998.

Syrjasuo, M. T., B. J. Jackel, E. F. Donovan, T. S. Trondsen and M. Greffen, Low-cost multi-band ground-based imaging of the aurora, *Solar Physics and Space Weather Instrumentation, Proceedings of SPIE*, **Vol. AM133**, 59010F-1-11, 2005.

Donovan, E., S. Mende, B. Jackal, H. Frey, M. Syrjasuo, I. Voronkov, T. Trondsen, L. Peticolas, V. Angelopoulos, S. Harris, M. Greffen and M. Connors, The THEMIS all-sky imaging array—system design and initial results from the prototype imager, *Journal of Atmospheric and Solar-Terrestrial Physics*, **68**, 1472-1487, 2006.

Harris, S. E., S. B. Mende, V. Angelopoulos, W. Rachelson, E. Donovan, B. Jackel, M. Greffen, C. T. Russell, D. R. Pierce, D. J. Dearborn, K. Rowe and M. Connors, THEMIS Ground Based Observatory System Design, *Space Science Reviews,* **141,** 213-233, 2008.

Donovan, E., W. Liu, J. Liang, E. Spanswick, I. Voronkov, M. Connors, M.
Syrjäsuo, G. Baker, B. Jackel, T. Trondsen, M. Greffen, V. Angelopoulos, C.T. Russell, S. B. Mende, H. U. Frey, A. Keiling, C. W. Carlson, J. P.

McFadden, K.-H. Glassmeier, U. Auster, K. Hayashi, K. Sakaguchi, K.
Shiokawa, J. A. Wild and I. J. Rae, Simultaneous THEMIS in situ and auroral observations of a small substorm, *Geophysical Research Letters*, **35**, L17S18, 2008

Mende, S., S. Harris, H. Frey, V. Angelopoulos, E. Donovan, B. Jackel, M. Greffen, C. Russell, and L. Peticolas, The THEMIS array of ground based observatories for the study of substorms, *Space Sci. Rev*., doi:10.1007/s11214-008-9380-x, 2008.

Sakaguchi, K., K. Shiokawa, A. Ieda, R. Nomura, A. Nakajima, M. Greffen, E. Donovan, I. R. Mann, H. Kim and M. Lessard, Fine structures and dynamics in auroral initial brightening at substorm onsets, *Annales Geophysicae*, **27**, 623-630, 2009

Shiokawa, K., Ieda, A., Nakajima, A., Sakaguchi, K., Nomura, R., Aslaksen, T., Greffen, M., Spanswick, E., Donovan, E., Mende, S. B., McFadden, J., Glassmeier, K.-H., Angelopoulos, V., and Miyashita, Y.: Longitudinal development of a substorm brightening arc, *Annales Geophysicae*, **27**, 1935-1940, 2009.

Shiokawa, K., A. Nakajima, A. Ieda, K. Sakaguchi, R. Nomura, T. Aslaksen, M. Greffen, and E. Donovan, Rayleigh-Taylor type instability in auroral patches, J. Geophys. Res., in press, doi:10.1029/2009JA014273, 2009.

Emma Spanswick – Curriculum Vitae

Present Position:	Visiting Scientist, Space Science and Applications, Los Alamos National Laboratory
Contact:	35 Tuscany Reserve Court, Calgary, AB, T3L 0A7 +1-403-826-6695(M); elspansw@ucalgary.ca, elspansw@lanl.gov
Short History:	Research Scientist, Auroral Imaging Group, University of Calgary, 2009-present Ph.D. (Physics), University of Calgary, 2004-2009 M.Sc. (Physics), University of Calgary, 2002-2004 B.Sc. (Physics, Minor in App. Math), University of Calgary, 1998-2002

Research Interests

The overall theme of my research is system-level views of magnetospheric processes, applied specifically to the high-energy (>30keV) particle population. Currently, my work is focused on the global monitoring of precipitation (through ground-based techniques) and connecting these measurements to specific magnetospheric processes. By learning how to identify and interpret the ionospheric footprint of magnetospheric processes, we can follow a phenomena/instability from the source population (the Geospace plasma environment) to the sink (the ionosphere). Ultimately this will help elucidate the plasma physics driving particle precipitation and its overall effect on the geospace system.

Most Significant Research Contributions

a) Ground-Based Identification of Dispersionless Electron Injections: A ”substorm” is a magnetospheric process which involves the stretching of the Earth’s magnetic topology due to enhanced electric currents (energy storage), a disruption of those currents due to a large-scale plasma instability, and a reconfiguration to a more dipolar configuration (energy release). During this cycle, high-energy particles (>30keV) appear in a restricted region of space called the ”injection region”. This region was discovered with (and is defined by) energy resolved in situ particle data and develops at roughly the same time as the magnetic field reconfiguration. Until recently, the injection has been studied almost exclusively with in situ particle measurements in the vicinity of geosynchronous orbit. Through work with satellite data, I was able to show that ground-based riometers provide a proxy for direct particle measurements under certain conditions [14] and can be used to identify this specific particle signature. Although they lack any kind of energy information, an array of riometers provides a comprehensive method for monitoring the evolving 2D ionospheric projection of the dispersionless injection region. Measurements that are impossible with current satellite configurations. This work started a line of research that I am actively pursuing (see papers [14], [21], [14]) and allows us to answer questions about the spatio-temporal evolution of the injection region which are not possible with satellite measurements (see (b) below for example).

b) Localization of Injection Region Onset: Ionospheric measurements of the injection region (from (a) above) show that onset occurs in a radially thin region and expands equatorward and poleward. Current thinking is at odds with these results, and typically views the injection as the inward transport of a particle population from the mid-tail (15Re) in a “convection-surge” type model [Sarris et al. 2002, Li et al. 1998]. To solve this discrepancy, I worked with scientists at Los Alamos National Laboratory and carried out a survey of in situ data from serendipitous satellite radial alignments (Polar/Geotail with LANL). We found that the injection region (as seen with in situ data) appears to start at 8Re downtail and does indeed expand radially in the magnetotail. These results confirm the ionospheric picture of the injection region and imply that there must be some localized particle energization at substorm onset. Adiabatic processes/transport cannot solely produce the signatures seen in the geosynchronous region. These are the first direct observations of the localization of injection region formation and expansion outside of geosynchronous orbit. This work is currently being written up.

Papers Published or In Press in Refereed Journals

1. Spanswick, E., G. Reeves, E. Donovan, R. Friedel, Injection region propagation outside of geosynchronous orbit, in review, J. Geophys. Res., 2010.
2. Morley, S., R. Friedel, E. Spanswick, G. Reeves, J. Steinberg, J. Koller, T. Clayton and E. Noveroske, Dropouts of the outer electron radiation belt in response to solar wind stream interfaces: Global Position System observations, submitted, Proceedings of the Royal Society A, 2010.
3. Clilverd, M., C. Rodger, T. Moffat-Griffin, E. Spanswick, P. Breen, F. Menk, R. Grew, K. Hayashi, and I. Mann, Energetic outer radiation-belt electron precipitation during recurrent solar activity, in review, J. Geophys. Res., 2010.
4. Liang, J., V. Uritsky, E. Donovan, B. Ni, E. Spanswick, T. Trondsen, J. Bonnell, A. Roux, U. Auster, and D. Larson, THEMIS observations of electron cyclotron harmonic emissions, ULF waves, and pulsating auroras, in review, J. Geophys. Res, 2010.
5. Lui, A., E. Spanswick, E. Donovan, J. Liang, W. Liu, V. Uritsky, O. LeContel, and Q. –G. Zong, An active auroral streamer and the concurrent magnetotail activity, in review, J. Geophys. Res., 2010.
6. Kepko, L., E. Spanswick, V. Angelopoulos, E. Donovan, J. McFadden, K.-H. Glassmeier, J. Raeder, and H. J. Singer, Equatorward moving auroral signatures of a flow burst observed prior to auroral onset, Geophys. Res. Lett., 36, 24, doi:10.1029/2009GL041476, 2009
7. Uritsky, V., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K.H. Glassmeier, Longitudinally propagating arc wave in the pre-onset optical aurora, Geophys. Res Lett., 36, 21, doi:10.1029/2009GL040777, 2009.
8. Liang, J., W. Liu, E. Donovan, and E. Spanswick, In-situ observation of ULF wave activities associated with substorm expansion phase onset and current disruption, Ann. Geophys., 27, 2191-2204, 2009.
9. Spanswick, E., E. Donovan, W. Liu, J. Liang, J.B. Blake, G. Reeves, R. Friedel, B. Jackel, C. Cully and A. Weatherwax, Global observations of substorm injection region evolution: 27 August 2001, Ann. Geophys., 27, 2019-2025, 2009.
10. Shiokawa, K., A. Ieda, A. Nakajima, K. Sakaguchi, R. Nomura, T. Aslaksen, M. Greffen, E. Spanswick, E. Donovan, S. B. Mende, J. McFadden, K.-H. Glassmeier, V. Angelopoulos, and Y. Miyashita, Longitudinal development of a substorm brightening arc, Ann. Geophys., 27, 1935-1940.
11. Uritsky, V., E. Donovan, A. Klimas, and E. Spanswick, Collective dynamics of bursty particle precipitation initiating in the inner and outer plasma sheet, Ann. Geophys., 27, 745-753, 2009
12. Morioka, A., Y. Miyoshi, F. Tsuchiya, H. Misawa, K. Yumoto, R.R, Anderson, J.D. Menietti, E. Donovan, G.K. Parks, F. Honary and E. Spanswick (2008), AKR breakup and auroral acceleration at substorm onset, J. Geophys. Res, 113, A09213, doi:10.1029/2008JA013322, 2008.
13. Donovan, E., W. Liu, J. Liang, E. Spanswick, I. Voronkov, M. Conners, M. Syrj□asuo, G. Baker, B. Jackel, T. Trondsen, M. Gre_en, V. Angelopoulos, C. Russel, S. Mende, H. Frey, A. Keiling, C. Carlson, J. McFadden, K.-H. Glassmeier, U. Auster, K. Hayashi, K. Sakaguchi, K. Shiokawa, J. Wild, and J. Rae, Simultaneous THEMIS in situ and auroral observations of a small substorm, Geophys. Res Lett., doi:10.1029/GL033794, 2008.
14. Liang, J., W. Liu, E. Spanswick, and E. Donovan, Azimuthal structures of substorm electron injection and their signatures in riometer observations, J. Geophys. Res., doi:10.1029/2007JA012354, 2007.
15. Liu W. W., E. F. Donovan, J. Liang, I. Voronkov, E. Spanswick, P. T. Jayachandran, B. Jackel, and M. Meurant, On the equatorward motion and fading of proton aurora during substorm growth phase, J. Geophys. Res., 112, A10217, doi:10.1029/2007JA012495, 2007.
16. Clilverd M. A., C. J. Rodger, R. M. Millan, J. G. Sample, M. Kokorowski, M. P. McCarthy, T. Ulich, T. Raita, A. J. Kavanagh, E. Spanswick, Energetic particle precipitation into the middle atmosphere triggered by a coronal mass ejection, J. Geophys. Res., 112, A12206, doi:10.1029/2007JA012395, 2007.
17. Donovan, E., J. Spann, W. Liu, T. Trondsen, A. Ridley, T. Immel, E. Spanswick, R. Rankin, P. Jayachandran, D. Knudsen, B. Jackel, L. Cogger, J. Murphree, G. Sofko, and K. McWilliams, Global auroral imaging, system level science, and ILWS, Adv. Space Res., 40, 409-418, 2007.
18. Meurant, M., C. Blockx, E. Spanswick, E. Donovan, B. Hubert, J.-C. G_erard, V. Coumans, and M. Connors, EL - a possible indicator to monitor magnetic field stretching during substorm expansive phase: statistical study, J. Geophys. Res., 112, doi:10.1029/2006JA012126, 2007.

19. Rae, J., I. Mann, Z. Dent, D. Milling, E. Donovan, and E. Spanswick, Multiple Field Line Resonances: Optical, Magnetic and Absorption Signatures, Planet. Space Sci., 55(6), 701, 2007.
20. Spanswick, E., E. Donovan, R. Friedel, and A. Korth, Ground based identification of dispersionless electron injections, Geophys. Res. Lett., 34, L03101, doi:10.1029/2006GL028329, 2007.
21. Liu, W., J. Liang, E. Spanswick, and E. Donovan, Remote-Sensing Magnetospheric Dynamics With Riometers: Observation and Theory, J. Geophys. Res., 112, doi:10.1029/2006JA012115, 2007.
22. Partamies, N., K. Kauristie, E. Donovan, E. Spanswick, and K. Liou, Meso-scale aurora within the expansion phase bulge, Annales Geophysicae, Vol. 24, pp 2209-2218, 13-9-2006.
23. Aminaei, A., F. Honary, A. Viljanen, and E. Spanswick, A Statistical Study of Substorm Related Absorption Events, Vol. 24, pp 1871-1885, Annales Geophysicae, 2006.
24. Spanswick, E., E. Donovan, and G. Baker, Pc5 modulation of high energy electron precipitation: particle interaction regions and scattering efficiency, Annales Geophys., 23:1533-1542, 2005.

Refereed Conference Proceedings

25. Spanswick, E., E. Donovan, W. Liu, A. Aasnes, T. Hiebert, and D. Wallis, Substorm spikes in high-energy e- precipitation, AGU Monograph 155 (Physics of the Inner Magnetosphere), pp 227-236, 2005.

Nonrefereed Conference Proceedings

26. Meurant, M., C. Blockx, E. Spanswick, E. Donovan, B. Hubert, J.-C. G_erard, T. Trondsen, and M.Connors, EL a possible indicator to monitor the magnetic _eld stretching at global scale during substorm expansive phase: case study, ICS-8 Proc., 181, 2007.
27. Spanswick, E., E. Donovan, R. Friedel, and D. Danskin, The macroscale evolution of the substorm injection, ICS-8 Proc., 303, 2007.
28. Voronkov, I., A. Runov, A. Koustov, K. Kabin, M. Meurant, E. Donovan, C. Bryant, and E. Spanswick, Features of magnetosphere-ionosphere coupling during breakups and substorm onsets inferred from multi-instrument alignment, ICS-8 Proc., 319, 2007.
29. Partamies N., K. Kauristie, E. Donovan, E. Spanswick, and K. Liou, Meso-Scale Structures Within the Auroral Bulge, Preceedings of the 7th International Conference on Substorms, Sept 2004.

Invited Talks, and Seminars

- Spanswick E., E. Donovan, G. Reeves, R. Friedel, ,Tenth International Conference on Substorms, Invited Talk, CA, March 2010.
- Spanswick E., E. Donovan, D. Knudsen, K. Barnetson, G. Baker, and T. Trondsen, Quantitative Investigations of MI Coupling Using SWARM in Coordination with Optical Observations of the Aurora, Invited Talk, ESA Second SWARM International Science Meeting, Postdam, July 2009.
- Spanswick E., E. Donovan, G. Reeves, and R. Friedel, Evolution of the dispersionless injection region, Invited Talk, COSPAR, Montreal, July 2008.
- Spanswick E., E. Donovan, G. Reeves, and R. Friedel, Two Satellite Observations of Dispersionless Injections, Invited Talk, Ninth International Conference on Substorms, Graz, May 2008.
- Spanswick E., M. Meurant, High Energy Precipitation in Dipolarizations, Invited talk, Western Pacific Geophysics Meeting, Beijing CN, July 2006.

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PERSONAL DATA

Date of Birth: <withheld> ● Sex: Male ● Visa Status: Landed Immigrant, Canada ● Citizen of the Kingdom of Norway ● Language Skills: English, German, Norwegian, Swedish, Danish ● Driver's Licenses: Alberta Class 5 license and EU International Driver's License ● Industry Canada licensed ham radio operator (VE6NOR).

AREAS OF EXPERTISE, EXPERIENCE, AND CAPABILITIES

Remote sensing ● space plasma physics ● academic and technical writing ● charge-coupled device (CCD) imaging systems ● optical and electro-optical systems ● low light-level imaging in visible and IR ● optical design using Zemax ● calibration and characterization of optical instrumentation ● knowledge of RF systems and circuits, wireless (radio) communications ● radar techniques and spectral analysis ● scientific programming (several languages including assembler code) ● writing Linux device drivers ● scientific image/data acquisition, processing, and analysis ● digital and analog control theory ● computer interfaces to real-world ● real-time software programming ● basic FPGA programming ● digital and analog electronic design, microprocessors, and embedded applications ● functional definition and system design of scientific instrumentation ● space flight systems, radiation environment ● video editing ● graphic design ● photography ● arctic winter field-work.

EDUCATION

PH.D. COSMIC GEOPHYSICS, UNIVERSITY OF TROMSØ, NORWAY — 1998

Developed a portable intensified imaging system (optics, electronics, hardware, software) and applied it to auroral studies in the Canadian arctic, publishing findings in refereed scientific journals (*Journal of Geophysical Research, Geophysical Research Letters, Annales Geophysicae*).

M.SC. APPLIED PHYSICS/ELECTRICAL ENGINEERING, UNIVERSITY OF TROMSØ — 1988

Developed a novel, practical method for determining signal losses (the “System Constant”) in waveguides and filters for calibration purposes at the UHF/VHF European Incoherent Scatter Radar Facility EISCAT near Tromsø, Norway. The method relies on precise ionospheric plasma-line frequency measurements using a charge-coupled device based spectrum analyzer.

B.SC. PHYSICS, UNIVERSITY OF TROMSØ — 1986

PROFESSIONAL EXPERIENCE

PRESIDENT, KEO SCIENTIFIC LTD — 2003-PRESENT

Keo Scientific Ltd. designs and builds highly sensitive scientific instrumentation, capable of wavelength-resolved imaging of sub-visual emissions from the upper atmosphere, for defense and research institutions worldwide.

RESEARCH ASSOCIATE, UNIVERSITY OF CALGARY, INST. FOR SPACE RESEARCH — 1998-PRESENT

NORSTAR/CGSM/MSI Program Scientist/Engineer, responsible for a network of multispectral imagers across Canada ● Lead Investigator on the ePOP (Enhanced Polar Outflow Probe) Fast Auroral Imager ● ePOP Science Team member ● Co-Principal Investigator on KuaFu Project Ultra-Violet Auroral Monitoring Cameras (UVAMC) ● Principal Investigator on the Meridian Scanning Photometer Design Project ● Member of NASA THEMIS Mission Team ● Optical Designer on U of Calgary H-Beta Photometer Project

IMAGING SPECIALIST, UNIVERSITY OF CALGARY, INSTITUTE FOR SPACE RESEARCH — 1997-1998

Principal Investigator on the The Portable Auroral Imager project ● Research Scientist/Programmer, Canadian Space Agency's CANOPUS Project ● Technical consultant/liaison on Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), the first NASA medium-class satellite explorer (MIDEX) project ● Participating Scientist on the IMAGE project ● Participating scientist on the NORSTAR project.

RESEARCH ENGINEER, UNIVERSITY OF CALGARY, INSTITUTE FOR SPACE RESEARCH — 1993-1996

Responsible for the design, implementation, and calibration of a compact and portable imaging system that is now being used for high-resolution video imaging of the Northern Lights. The system is based on state-of-the-art intensified charge-coupled device video camera technology and high-resolution video recording technology. The design was dictated by requirements as to angular and temporal resolution and light-gathering power given by scientific objectives. Made several field-trips into the Canadian arctic to apply the imager to auroral studies in conjunction with instrumentation permanently installed at the site. Data were subsequently analyzed, and several important findings published in international scientific journals.

RESEARCH SCIENTIST, RESEARCH COUNCIL OF NORWAY — 1988-1993

Designed, implemented, and characterized a computer controlled digital all-sky camera system for the observation of the Northern Lights from the Ramfjordmoen research station outside Tromsø, Norway. Wrote all real-time control software as well as a complete image processing suite ● Took part in the design of the AURIO visible and ultra-violet auroral CCD imagers that is to fly on the European Space Agency's Polar Platform, part of the then U.S.-commissioned Space Station Freedom project ● Participated in the preliminary design phase of the ultra-violet auroral imagers on the Swedish satellite Freja that was successfully launched in October 1992 ● Assisted in the design of the Polar Camera (PoCa), a set of imagers for ground based observations of the aurora in polar cap regions (Ellesmere Island). This work included research into image compression algorithms and recommendation of preferred option based on certain design criteria, writing low-level software handling data communication between computer and cameras, writing an ephemerides software package, as well as doing the complete mechanical design of the camera units using the CADKey Computer Aided Design package (under the SGI IRIX O/S) ● Designed an electronic testbed intended for the development of microprocessor, transputer, and charge-coupled device clocking applications..

RESEARCH ASSISTANT, UNIVERSITY OF TROMSØ, NORWAY — 1987-1988

Operated and maintained an ionospheric "Partial Reflection" (MF) radar system used for real- time determination of dynamic parameters of the upper atmosphere ● Responsible for converting the Tromsø Ionosonde FORTRAN data presentation software for use on a new computer system.

ELECTRONICS TECHNICIAN, UNIVERSITY OF TROMSØ, NORWAY — 1987

Designed and implemented a dedicated digital controller and mechanical interface for controlling exposure time and frame rate of a 35 mm news-reel (*Filmavisen*) Eyemo motion picture camera. The camera had to be rebuilt slightly, as the camera had no accessible 1:1 axes; the most exact axis was one that rotated once per eight frames. A Nikon lens mount was fitted, and a Nikkor f/2.8, 8 mm fisheye was mounted. The camera was used to acquire color footage of the Aurora Borealis for a movie commissioned for the then-newly-opened Tromsø Northern Lights Planetarium.

LABORATORY ASSISTANT, UNIVERSITY OF TROMSØ, NORWAY — 1986

Assisted students in performing laboratory experiments in an introductory Analog and Digital Electronics course run by Dr. Ove Harang.

SCHOLARSHIPS, AWARDS, RECOGNITION

Faculty of Science Fellowship for Physics and Astronomy 2000 (CAD 6,000) ● University Technologies International Inc. Fellowship in Science for 1999-2000 (CAD 15,000) ● Norwegian Space Centre's Scholarship for promising young Norwegian research scientists, October 1989 (NOK 50,000) ● Outstanding Student Presentation award received for an invited talk at the American Geophysical Union (AGU) Fall Meeting 1997, San Francisco, in a section on Alfvénic Structures and their relation to the Discrete Aurora.

Dr. Vadim M. URITSKY

Curriculum Vitae

Affiliation

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Summary

Dr. Vadim M. Uritsky received his **Ph.D. in Space Physics** from St. Petersburg State University, Russia in 1998. In 1999-2001, he held a postdoctoral research position at NASA / Goddard Space Flight Center, Greenbelt, MD. In 2002-2005, he continued his research as a senior staff scientist at the Institute of Physics of St. Petersburg State University. In 2005, Dr. Uritsky defended his post-doctorate habilitation thesis and was granted the title of *Doktor Nauk* (**Grand Ph.D.**), the highest academic degree in Russian Federation. Since 2006, Dr. Uritsky is a senior research associate and an adjunct (research) professor in the Department of Physics and Astronomy of the University of Calgary, Canada.

Dr. Uritsky is a recipient of several **professional awards**, including the National Research Council Resident Research Associateship Award from the U.S. National Academies. Dr. Uritsky is an expert reviewer for major scientific journals and funding agencies. He participated in international research programs involving CIS, Japan, Germany, Greece, Italy, USA, and has contributed to the organization of international scientific meetings as a session chair/convener and an invited lecturer.

Dr. Uritsky's main **scientific interests** are in the areas of experimental space physics, space instrument design, theory of complexity, and statistical mechanics of turbulent media. He is the first author on 25 peer-reviewed scientific papers (about 70 publications in total). Over the past ten years, Dr. Uritsky's research has been **funded** by the Russian Foundation or Basic Research, the European Union's INTAS program, the U.S. National Research Council, NASA science programs, Canadian Space Agency, and Canada Foundation for Innovation.

Dr. Uritsky has taught university **lecture courses** for physics majors, engineers, and interdisciplinary students, including electricity and magnetism, special relativity, subatomic physics, quantum mechanics, scientific programming, digital image processing, experimental space physics, statistical mechanics of complex systems, and other subjects.

Education

2005	*Doktor Nauk* [1] degree in Space Physics, awarded by the Higher Attestation Commission of the Ministry of Education and Science of Russian Federation. Thesis title: "*Multiscale processes in Earth's magnetosphere*". Scientific consultants: V.A. Sergeev, V.N. Troyan, and L.M. Zelenyi.
2001	Completion of 2-year postdoctoral tenure at NASA / Goddard Space Flight Center (Laboratory for Extraterrestrial Physics), Greenbelt, MD supported by the U.S. National Academies of Sciences. Project title: "*Analysis and modeling of multiscale magnetospheric disturbances*". Research advisor: A.J. Klimas.
1998	Ph.D. with honors in Space - and Geophysics, St. Petersburg University, St. Petersburg, Russia. Thesis title: "*Fractal analysis and modeling of catastrophic phenomena in geophysical systems*". Supervisors: M.I. Pudovkin and V.N. Troyan.
1992	M.S. with honors in Statistical Physics and Electronics, St. Petersburg Polytechnic University, St. Petersburg, Russia.
1990	B.S. in Physics, St. Petersburg Polytechnic University, St. Petersburg, Russia.

Employment history

2009 – present	Senior Research Scientist, Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada.
2006 – 2009	Adjunct Assistant Professor, Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada.
2001 – 2006	Senior Staff Scientist and Research Professor, Department of Geophysics, St. Petersburg State University, St. Petersburg, Russia.
1999 – 2001	National Research Council Resident Research Associate, Laboratory for Extraterrestrial Physics, NASA / Goddard SFC, Greenbelt, MD, USA.
1998 – 1999	Research Associate, Laboratory for Magnetospheric Physics, St. Petersburg State University, St. Petersburg, Russia.
1995 – 1997	Postgraduate Research Associate, Department of Geophysics, St.Petersburg State University, St. Petersburg, Russia.
1992 – 1994	Research Assistant and Scientific Programmer, V. M. Bekhterev Psychoneurological Research Institute, St. Petersburg, Russia.
1989 – 1992	Graduate Research Assistant, Condensed Matter Department of St. Petersburg Nuclear Physics Research Institute, St. Petersburg, Russia.

[1] Highest academic degree in Russia, analogous to *Habilitation* in Germany and *Doctor of Science* in the UK.

Professionals awards

2005	*Best Research Work in Physics* award from St. Petersburg State University, Russia.
1999	*Resident Research Associateship Award* from the National Research Council of the U.S. National Academies.
1998	*Leonhard Euler Award* for the outstanding postgraduate project from the German Academic Exchange Service (DAAD).
1998	*Young Scientist Contest* award and stipend from the Board of Education of the Government of Russian Federation.

Other activities and achievements

2009 – present	Peer reviewer for the *National Sciences and Engineering Research Council of Canada*.
2008 – present	Peer and Panel Reviewer for the *Research Council of Norway*.
2001 – present	Referee for the *U.S. National Science Foundation*.
1998 – present	Peer reviewer for *Physical Review Letters*, *Journal of Geophysical Research – Space Physics*, *Geophysical Research Letters*, and 7 other professional journals.
2007 – 2009	Science Team member at the *International Space Science Institute*, Bern, Switzerland.
2002 – 2008	Consulting appointments at *NASA / Goddard Space Flight Center*, Greenbelt, MD.
2008 – 2009	Scientific organizer of a regular seminar series on Space Physics (*University of Calgary*).
2006 – 2007, 2009	Convener and chair of special sessions at *Fall AGU meetings* (SPA and NG sections).
2004 – present	Member of the *Committee on Space Research* of the International Council for Science.
1999 – present	Member of the *American Geophysical Union* (AGU) and the American Physical Society.

Research experience

Scientific interests

- **Magnetospheric physics:** auroral observations of transient magnetospheric processes; substorm breakup triggers and precursors; intermittent turbulence in solar wind - magnetosphere – ionosphere system; waves and instabilities in optical auroral arc; cross-scale coupling in turbulent magnetotail plasma; conjugate signatures of localized magnetic reconnection in thin current sheets; analysis and theory of low-frequency plasma sheet oscillations; global predictive models of geomagnetic activity for space weather applications.
- **Plasma turbulence and the theory of complexity:** scaling and universality in resistive MHD turbulence; self-organized criticality and energy avalanching in spatially distributed systems; dynamics and statistics of short-living intermittent dissipative structures in space plasmas.
- **Solar physics:** statistical models of solar flares and nanoflares; multiscale topology of photospheric magnetic network its relation to coronal heating.
- **Data analysis and visualization:** advanced algorithms of image processing; spatiotemporal pattern recognition; data-derived recommendations for satellite instrumentation design.

Recent invited presentations

1. Waves and turbulence in optical auroral arcs, *UCLA – Space Physics*, Los Angeles, LA, 2010.
2. Low-frequency waves in auroral arcs: optical echo of magnetotail dynamics, *Fall AGU Meeting*, San Francisco, USA, 2009.
3. Longitudinally Propagating Arc Wave in the Pre-Onset Optical Aurora, *NASA / Goddard Space Flight Center – Heliophysics*, Greenbelt, MD, USA, 2009.
4. Reconciling Self-Organized Criticality and Intermittent Turbulence in Space Plasmas, *International Workshop on Geocomplexity*, Toronto, Canada, 2009.
5. Substorm onset in multiscale auroral complexity as seen by THEMIS imaging observatories, *Nonlinear Magnetosphere*, Vina del Mar, Chile, 2009.
6. Multiscale Intermittency and Avalanching in Nature and Simulations, *NASA / Goddard Space Flight Center – Heliophysics*, Greenbelt, MD, USA, 2008.
7. Scaling and universality in earth's magnetosphere, *37th COSPAR Scientific Assembly*, Montréal, Canada, 2008.
8. Multiscale complexity in Earth's magnetosphere, *International Conference on Problems of Geocosmos*, St.Petersburg, Russia, 2008.
9. Spatiotemporal analysis of flaring activity in solar corona, *Big Bear Solar Observatory – videoconference*, Big Bear, CA, USA, 2008;
10. Spatiotemporal analysis of solar flares event decomposition (STED) for solar and magnetospheric physics, *JHU / Applied Physics Laboratory*, Laurel, MD, USA, 2008.
11. Event decomposition of intermittent spatiotemporal patterns in nature and simulations, *National Center for Atmospheric Research*, Boulder, CO, USA, 2008.

Ongoing collaboration projects

- Conjugate observations of bursty bulk flows and flapping magnetotail motion using ground based and in situ THEMIS instrumentation (with V. Angelopoulis and A. Runov, UCLA).
- Numerical models of intermittency in Earth's magnetosphere (with P.Charbonneau, University of Montreal and W. Liu, Canadian Space Agency).
- Intermittent MHD turbulence (with A. Pouquet and D. Rosenberg, NCAR).
- Multiscale reconnection and avalanching in Earth's magnetosphere (with A. Klimas, NASA / GSFC).
- Spatiotemporal analysis of flaring activity in solar corona (with J.M. Davila, NASA / GSFC, and V. Abramenko, Big Bear Solar Observatory).

Previous and current funding

2010 – 2015	Co - Investigator & Project Theme leader, grant from Canada Foundation for Innovation to construct and operate RISR-C (*Resolute Bay Incoherent Scatter Radar, south face*). Project Theme (led by V.M. Uritsky): "*Turbulence and instabilities in solar-terrestrial plasmas*". Amount: ~$10M.
2008 – present	Senior Research Scientist and Data Specialist on contracts from the Canadian Space Agency: THEMIS ASI (*THEMIS all-sky imagers*), UVAMC (*Ultraviolet Monitoring Cameras*), CGSM (*Canadian GeoSpace Monitoring*). Amount: CAD 75,000 / year (base salary).
2005 – 2007	Co – Investigator, grants SMD-06-0288 and SRT03-0026 from NASA Geospace Science Program. Project title: "*Localized reconnection and scale-free avalanching in driven current-sheet models*".
2004 – 2006	Co - Principle Investigator, grant 04-05-64938 from the Russian Foundation for Basic Research. Project title: "*Dynamics of fractal characteristics of ultra low frequency geomagnetic fields related to seismic and magnetospheric activity*". Amount: RUB 140,000.
2003 – 2004	Co - Principle Investigator, grant from the *Intergeofizika* international research program run by the Russian Ministry of Education. Project title: "*Study of the ULF electromagnetic phenomena related to earthquakes and geomagnetic disturbances*". Amount: RUB 40,000.
2001 – 2002	Co - Investigator, grant from the "Universities of Russia" collaborative research program. Project title: "*Developing phenomenological models of earthquakes based on the self-organized criticality concept*". Amount: RUB 40,000.

2004	Travel grant from the International Committee on Space Research (COSPAR). Amount: USD 2,000.
2000 – 2002	Co - Principle Investigator, grant 98-05-65554 from the Russian Foundation for Basic Research. Project title: "*Analysis and modeling of magnetospheric and lithospheric signals in the frequency range of geomagnetic pulsations*." Amount: RUB 160,000.
1999 – 2003	Co - Investigator, grant 99-1102 from the European Union's International Association for the promotion of co-operation with CIS countries (INTAS). Project title: "*Study of the ULF electromagnetic phenomena related to earthquakes*". Amount: EUR 30,000.
1999 – 2001	Principle Investigator, individual research associateship award from the U.S. National Research Council. Project title: "*Analysis and modeling of multiscale magnetospheric disturbances related to substorm activity*" Amount: USD 110,000.
1997 – 1998	Postgraduate fellowship from the German Academic Exchange Service (DAAD) Amount: DM 4,000.

List of publications

International refereed journals

1. Klimas, A.J., V.M. Uritsky, and E. Donovan, Multiscale auroral emission statistics as evidence of turbulent reconnection in Earth's midtail plasma sheet, *Journal of Geophysical Research – Space Physics*, doi:10.1029/2009JA014995, 2010 (in press).
2. Uritsky, V.M., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K.H. Glassmeier, Longitudinally propagating arc wave in the pre-onset optical aurora, *Geophysical Research Letters*, 36, L21103, 2009.
3. Lovejoy, S. et al., Nonlinear geophysics: why we need it, *Eos*, 90(48), p. 455-456, 2009.
4. Uritsky, V.M., J. Davila, and E.I. Jones, Coexistence of self-organized criticality and intermittent turbulence in the solar corona – reply to comment, *Physical Review Letters*, 103 (3): Art. 039502, 2009.
5. Uritsky, V. M., E. Donovan, A. J. Klimas, and E. Spanswick, Collective dynamics of bursty particle precipitation initiating in the inner and outer plasma sheet, *Annales Geophysicae*, 27 (2): 745-753, 2009.
6. Uritsky, V.M., E. Donovan, A.J. Klimas, and E. Spanswick, scale-free and scale-dependent modes of energy release dynamics in the nighttime magnetosphere, *Geophysical Research Letters*, 35 (21): Art. L21101, 2008.
7. Serletis, A., O.Y. Uritskaya, and V.M. Uritsky, Detrended fluctuation analysis of the US stock market, *International Journal of Bifurcation and Chaos*, 18 (2): 599-603, 2008.
8. Uritsky, V.M., M. Paczuski, D. Davila, and S. I. Jones, Coexistence of self-organized criticality and intermittent turbulence in the solar corona, *Physical Review Letters*, 99 (2), Art. No. 025001, 2007.
9. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, Critical finite-size scaling of energy and lifetime probability distributions of auroral emissions, *Geophysical Research Letters*, 33, L08102, 2006.
10. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, Analysis and prediction of high-latitude geomagnetic disturbances based on a self-organized criticality framework, *Advances in Space Research*, 37 (3), 539-546, 2006.
11. Pulkkinen A, A.J. Klimas, D. Vassiliadis, and V.M. Uritsky, Role of stochastic fluctuations in the magnetosphere-ionosphere system: A stochastic model for the AE index variations, *Journal of Geophysical Research – Space Physics*, 111 (A10), p.A10218 1 - 20, 2006.
12. Pulkkinen A, A.J. Klimas, D. Vassiliadis, V.M. Uritsky, and E. Tanskanen, Spatiotemporal scaling properties of the ground geomagnetic field variations, *Journal of Geophysical Research – Space Physics*, 111 (A3), p.A03305 1 - 15, 2006.
13. Uritsky, V.M. and A.J. Klimas, Hysteresis-controlled instability waves in a scale-free driven current sheet model, *Nonlinear Processes in Geophysics*, 12, p.827-833, 2005.
14. Klimas, A.J., V.M. Uritsky, D. Vassiliadis, and D.N. Baker, A mechanism for the loading-unloading substorm cycle missing in mhd global magnetospheric simulation models, *Geophysical Research Letters*, 32 (14), L14108, 2005.
15. Valdivia, J.A. , J. Rogan, V. Munoz, L. Gomberoff, A. Klimas, D. Vassiliadis, V.M. Uritsky, S. Sharma, B. Toledo, and L. Wastavino. The magnetosphere as a complex system. *Advances in Space Research*, 35 (5), p.961-971, 2005.

16. Klimas, A.J., V.M. Uritsky, D. Vassiliadis, and D.N. Baker, Reconnection and scale-free avalanching in a driven current-sheet model, *Journal of Geophysical Research – Space Physics*, 109 (A2), p.A02218 1 - 14, 2004.

17. Uritsky, V.M., Smirnova, N., Troyan, V. and Vallianatos, F., Critical dynamics of fractal fault systems and its role in the generation of electromagnetic emissions before major earthquakes, *Physics and Chemistry of Earth*, 29 (4-9), p.473-480, 2004.

18. Kozelov, B.V., V.M. Uritsky, and A.J. Klimas, Power law probability distributions of multiscale auroral dynamics from ground-based TV observations, *Geophysical Research Letters*, 31 (20), L20804, 2004.

19. Valdivia, J.A., A.J. Klimas, D. Vassiliadis, V.M. Uritsky, and J. Takalo, Self-organization in a current sheet model, *Space Science Reviews*, 107 (1-2), 515-522, 2003.

20. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, Evaluation of spreading critical exponents from the spatiotemporal evolution of emission regions on the nighttime aurora, *Geophysical Research Letters*, 30 (15), p.1813-1816, 2003.

21. Uritsky, V.M., A.J. Klimas, D. Vassiliadis, D. Chua, and G. Parks, Scale-free statistics of spatiotemporal auroral emissions as depicted by POLAR UVI images: Dynamic magnetosphere is an avalanching system, *Journal of Geophysical Research – Space Physics*, 107 (A12), p.1426-1436, 2002.

22. Kamenskaya V.G., V.M.Uritsky, N.I.Muzalevskaya, S.V.Zvereva and L.V.Tomanov. Fractal characteristics of heart rate variability in adolescents at verbal testing. *International Journal of Psychophysiology*, 45 (1-2), p.161, 2002.

23. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, Multiscale dynamics and robust critical scaling in a continuum current sheet model, *Physical Review E*, 65 (4), p.046113-1 - 046113-5, 2002.

24. Uritsky, V.M., A.J. Klimas, J.A. Valdivia, D. Vassiliadis, and D.N. Baker, Stable critical behavior and fast field annihilation in a magnetic filed reversal model, *Journal of Atmospheric and Solar - Terrestrial Physics*, 63 (13), p.1425-1433, 2001.

25. Uritsky, V.M., M.I. Pudovkin, and A. Steen, Geomagnetic substorms as perturbed self-organized critical dynamics of the magnetosphere, *Journal of Atmospheric and Solar - Terrestrial Physics*, 63 (13), p.1415-1424, 2001.

26. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, Comparative study of dynamical critical scaling in the auroral electrojet index versus solar wind fluctuations, *Geophysical Research Letters*, 28 (19), p.3809-3812, 2001.

27. Uritsky V.M., V.B. Slezin, E.A. Korsakova, S.K. Khorshev, and N.I.Muzalevskaya, Fractal diagnostics of alpha-rhythm malfunctions in epileptic patients. *Biophysics*, 44 (1), p. 33-37, 1999.

28. Khorshev S.K., E.A. Korsakova, V.M. Uritsky, and V.B. Slezin, Diagnostics of epilepsy and its preclinical stage by the method of fractal EEG analysis. *Epilepsy*, 40 (suppl. 2x), p.279, 1999.

29. Uritsky, V.M. and M.I. Pudovkin, Fractal dynamics of AE-index of geomagnetic activity as a potential manifestation of self-organized criticality in magnetosphere, *Geomagnetism and Aeronomy*, 38 (3), 17-28, 1998.

30. Uritsky, V.M. and M.I. Pudovkin, Low Frequency 1/f-like fluctuations of the AE-index as a possible manifestation of self-organized criticality in the magnetosphere, *Annales Geophysicae*, 16 (12), p.1580-1588, 1998.

31. Muzalevskaya N.I. and V.M. Uritsky, Antiblastomic effect of weak extremely low frequency stochastic magnetic field with a 1/f power spectrum. *Biophysics*, 42 (4), p.961-970, 1997.

32. Uritsky V.M. and N.I. Muzalevskaya, Fractal stochastic electromagnetic background as a factor stabilizing processes of vital activity. *Fractals*, 1 (3), p.321-325, 1993.

Russian refereed journals

33. Uritsky, V.M. Critical exponents of a turbulent plasma sheet model, *Bulletin of St.Petersburg State University (Ser.4)*, 1 (4), p.67-69, 2004.
34. Muzalevskaya, N.I. and V.M. Uritsky, Analysis of stability and reliability of large interactive systems and its application in medical diagnostics. *Bulletin of St.Petersburg State University (Ser.4)*, 2 (12), p.3-19, 2000.
35. Slezin, V.B, N.I. Muzalevskaya, V.M. Uritsky, and I.Y. Rybina, Change of functional status of human brain during Christian prayer, *Psychology and Psychophysics*, 1, p.132-136, 2000.
36. Uritsky, V.M. and V.N. Troyan, Fractal algorithm for detecting first arrival time in noisy seismic records. *Bulletin of St.Petersburg State University (Ser.4)*, 1, p.14-20, 1999.
37. Uritsky, V.M. and V.N. Troyan, Estimation of characteristic changes in fractal geometry of regional seismicity before strong earthquakes. *Voprosy Geofiziki*, 35, p.39-42, 1998.
38. Uritsky, V.M. and M.I. Pudovkin, Modeling of non-stationary chaotic processes in the magnetosphere using cellular automata. *Voprosy Geofiziki*, 35, p.317-326, 1998.
39. Muzalevskaya, N.I., A.M. Reschikov, and V.M. Uritsky, Investigation of the electromagnetic channel in inter-cell interactions using the ultra-low frequency spectroscopy method, *Izvestija Vuzov (Russian Academy of Science), Ser. Priborostrojenije*, 6, p. 47-54, 1993.
40. Uritsky, V.M., N.I. Muzalevskaya, and V.P. Belousov, Study of conditions of extra-weak energy exchange in open heterogeneous system influenced by a low frequency magnetic field, *Izvestija Vuzov (Russian Academy of Science), Ser. Priborostrojenije*, 6, p.85-89, 1993.

Book chapters

41. Wanliss, J., D. Liu, V.M. Uritsky, and M. Wuergler, Fractal modeling of human psychomotor skills acquisition process, in: *Digital Human Modeling (Lecture Notes in Computer Science)*, Berlin: Springer, p. 474-482, 2007.
42. Klimas, A.J., V.M. Uritsky, D. Vassiliadis, and D.N. Baker, Simulation study of SOC dynamics in driven current-sheet models, in: *Nonequilibrium Phenomena in Plasmas*, edited by A.S. Sharma and P.K. Kaw, New York: Kluwer Academic Publishers, p.71-90, 2005.
43. Muzalevskaya, N.I and V.M. Uritsky. Application of stochastic methods of functional diagnostics and therapy in medicine, in: Telemedicine: *Informational Technologies of 21st Century*, St.Petersburg: Anatolia Press, 1998, p.209-243.
44. Uritsky, V.M. and N.I. Muzalevskaya, Fractal patterns and processes in biological systems (a review), in: *Biomedical Informatics*, edited by R.I. Polonnikov and F.G. Korotkov, St.Petersburg: Institute of Informatics Press, p.84-129, 1995.

Conference proceedings and e-prints

45. Klimas, A.J. and V.M. Uritsky, Self-organized criticality and intermittent turbulence in an MHD current sheet with a threshold instability, *arXiv:astro-ph/0701486v4*, 2009.
46. Uritsky, V.M. and N.I. Muzalevskaya. Multiscale intermittency in physics and physiology, in: *Proc. 7th Int. Conf. on Problems of Geocosmos*, St. Petersburg, Russia, p. 349-354, 2008.
47. Muzalevskaya N.I. and V.M. Uritsky, Extra low frequency fluctuations of heart rate variability as a signature of adaptation dynamics of human homeostasis, in: *Fluctuations and Noise in Biological, Biophysical and Biomedical Systems*, edited by N.G. Stocks et al., p. 9-16, 2005.

48. Uritsky, V.M. and N.I. Muzalevskaya, Modeling and prediction of self-organized adaptation dynamics in complex interactive systems, in: *Longevity, Aging and Degradation Models in Relability, Public Health, Medical Care and Biology*, edited by V. Antonov et al., SPbSPU, St.Petersburg, p. 283-297, 2004.

49. Uritsky, V.M., N.A. Smirnova, V.N. Troyan, A. Tzanis and F. Vallianatos. Modelling pre-seismic electromagnetic emissions using` self-organized criticality approach, in: *Proc. 5th International Conference on Problems of Geocosmos*, edited by. A.A. Kovtun, M.V. Kubyshkina, V.S. Semenov et al., p. 263-266, 2004.

50. Vallianatos, F., V. Troyan, N. Smirnova, V.M. Uritsky, D. Kiyashchenko, N. Makarenko, V. Lapenna, L. Telesca, A. De Santis, V. Korepanov, Y. Yampolski, Study of seismic hazard anomalies recognition possibilities: strategy of the SHARP project, in: *Proc. 5th International Conference on Problems of Geocosmos*, edited by. A.A. Kovtun, M.V. Kubyshkina, V.S. Semenov et al.,, St. Petersburg University, Russia, p. 104-120, 2004.

51. Kozelov B.V. and V.M. Uritsky, Scale-free statistics of spatiotemporal auroral emissions observed by ground-based scanning photometers, in: *Proc. 7th International Conference on Substorms (ICS-7)*, edited by N. Ganushkina, and T. Pulkkinen, Finnish Meteorological Institute, Levi, Finland, p. 160-163, 2004.

52. Klimas, A.J., V.M. Uritsky, and D.N. Baker, Scale-free avalanching and loading-unloading cycle in a driven current-sheet model, in: *Proc. 7th International Conference on Substorms (ICS-7)*, edited by N. Ganushkina, and T. Pulkkinen, Finnish Meteorological Institute, Levi, Finland, p. 15-22, 2004.

53. Uritsky, V.M. and A.J. Klimas, Scaling and predictability of complex geospace disturbances, in: *Proc. 7th International Conference on Substorms (ICS-7)*, edited by N. Ganushkina, and T. Pulkkinen, Finnish Meteorological Institute, Finland, p. 51-54, 2004.

54. Uritskaya, O.Y. and V.M. Uritsky, Fractal analysis and modeling of currency exchange rate dynamics in countries with different types of monetary systems, in: *Proc. 4th International Conference on Soft Calculations and Measurements (v.2)*, St. Petersburg, p.188-191. 2001.

55. Uritskaya, O.Y, V.M. Uritsky, and A.V.Fedotov, Fractal analysis of stability of revenue flows in St.Petersburg's administrative districts, in: *Proc. 4th International Conference on Soft Calculations and Measurements (v.2)*, St.Petersburg, p. 184-187, 2001.

56. Klimas, A.J., V.M. Uritsky, J.A. Valdivia, D. Vassiliadis, and D.N. Baker, On the compatibility of the coherent substorm cycle with the complex plasma sheet, in: *Proc. 5th International Conference on Substorms (ICS-5)*, edited by A. Wilson, ESA, St.Petersburg, Russia, p.165-168, 2000.

57. Uritsky, V.M., A.J. Klimas, and D. Vassiliadis, On a new approach to detection of stable critical dynamics of the magnetosphere, in: *5th International Conference on Substorms (ICS-5)*, edited by A. Wilson, ESA, St.Petersburg, Russia, p. 213-216, 2000.

58. Troyan V.N. and V.M. Uritsky, Fractal clustering of seismic events in northern Chile, in: *Proc. Int. Conf. of Soft Computing and Measurements (v.1)*, p. 61-65, 1999.

59. Muzalevskaya, N.I. and V.M.Uritsky, Assessing cardiac risk by the two-parametrical stability analysis of 1/f fluctuations of R-R Interval, in: *Proc. 15th International Conference on Noise in Physical Systems and 1/f Fluctuations*, Ed. C. Surya, London: Bentham Press, p. 203-206, 1999.

60. Uritsky, V.M. and V.S. Semenov, A sandpile model for global statistics of the reconnection events in the magnetotail, in: *The Solar Wind - Magnetosphere System 3*, edited by H.K. Biernat, C.J. Farrugia, and D.F. Vogl, Austrian Academy of Scince, Graz, Austria, p. 299-308, 1998.

61. Patzig, R., M. Sobiesiak, and V.M. Uritsky, CINCA 95: Laufzeit-Tomographie und Nachbebenanalyse, in: *Deformationprozesse in den Anden*, Freie Universitaat Berlin Press, p.452-463, 1998.

62. Uritsky V.M. and N.I. Muzalevskaya. Self-organized criticality as a possible mechanism of controlling 1/f fluctuations, in: *Proc. 14th Int. Conf. on Noise in Phys. Systems and 1/f Fluctuations*, edited by C. Claeys and E. Simoen, Singapore: World Scientific, p. 649-652, 1997.

63. Muzalevskaya N.I., V.M. Uritsky, and A.M. Reschikov. Malignant cells controlled by 1/f stochastic magnetic field, in: *Proc. 13th Int. Conf. on Noise in Physical Systems and 1/f Fluctuations*, Singapore: World Scientific, p.639-642, 1995.

64. Muzalevskaya N.I., V.M. Uritsky, E.V.Korolyov, A.M.Reschikov, and G.P.Timoshinov. Stochastic control of living systems: normalization of physiological functions by 1/f magnetic field, in: *Proc. 12th Int. Conf. on Noise in Physical Systems and 1/f Fluctuations*, edited by P.H. Handel and A.L. Chung, Woodbury: AIP Press, p.724-727, 1993.

65. Uritsky V.M., N.I. Muzalevskaya , E.V.Korolyov, and G.P.Timoshinov, Analysis of 1/fb- fluctuations in an interphase region as a possible tool for characterization of highly diluted solutions, in: *Proc. 12th Int. Conf. on Noise in Physical Systems and 1/f Fluctuations*, edited by P.H. Handel and A.L. Chung, Woddbury: AIP Press, p.145-146, 1993.

66. Muzalevskaya N.I., E.V.Korolyov, V.M. Uritsky, and A.I. Sibilyov, Conductivity fluctuations of an electrode system in the extra-weak electromagnetic field, in: *Annual Research Report of the St.Petersburg Nuclear Physics Institute (1990-1991)*, St.Petersburg: NPRI press, p.139-140, 1992.

67. Uritsky, V.M. and N.I. Muzalevskaya, Information function of slow variations of stochastically organized environment, in: *Contemporary Problems in Investigation and Conservation of the Biosphere*, edited by N.V.Krasnogorskaya, St.Petersburg: Gidrometeoizdat press, p. 244-253, 1992.

68. Muzalevskaya N.I., V.M. Uritsky, E.V.Korolyov, and G.P.Timoshinov, Conductivity fluctuations in an electrode system exposed to weak extra low frequency magnetic field, in: *Proc. 11th Int. Conf. on Noise in Physical Systems and 1/f Fluctuations*, edited by T.Musha, S.Sato, and M.Yamamoto. Tokyo: Ohmsha, p.465-467, 1992.

69. Uritsky, V.M., Muzalevskaya N.I., Korolyov E.V., Timoshinov G.P. Weak extra low frequency magnetic field and conductivity fluctuations in an electrode system, in: *Proc. 6th Scientific Conf. on Fluctuation Phenomena in Physical Systems*, Vilnius: Vilnius Univ. Press, p.208-209, 1991.

Manuscripts under review

70. Vallieres-Nollet, M.-A., P. Charbonneau, V.M. Uritsky, E. Donovan, and W. Liu, Dual scaling for self-organized critical models of the magnetosphere, *Journal of Geophysical Research – Space Physics*, 2010.

71. J. Wanliss and V.M. Uritsky, Understanding bursty behavior in mid-latitude geomagnetic activity, *Journal of Geophysical Research – Space Physics*, 2009.

Teaching experience

Courses

- **University of Calgary, Canada:** undergraduate courses for physics major, minors, and engineers (electricity and magnetism, modern physics (special relativity, subatomic physics), quantum mechanics, research project in physics).
- **St. Petersburg State University, Russia:** optional graduate lecture courses for physics majors (scaling, complexity and pattern formation in nature and simulations; seismic electromagnetic phenomena; nonequilibrium phase transitions; plasma turbulence; advanced methods of data analysis and visualization).
- **Free University of Berlin, Germany:** lecture series for undergraduate and graduate students (fractals and self-organization in geophysical systems).

Teaching history

2008 – 2009	PHYS 598, "*Research Project in Physics*" – 4th year practicum for Physics majors (University of Calgary, Canada).
2008	PHYS 443, "*Quantum Mechanics*" – 3rd year lecture course for Physics majors (University of Calgary, Canada).
2007	PHYS 301, "*Modern Physics*" – 2nd year lecture course for Physics majors & minors (University of Calgary, Canada).
2007	PHYS 259, "Electricity and Magnetism" – 1st year lecture course for Engineering (University of Calgary, Canada).
2001	"*Self-organized criticality in models and observations*" – optional lecture course for graduate students (St. Petersburg State University, Russia).
2001	"*Chaos and pattern formation in dynamical systems*" – popular lecture series (Omsk Polytechnic University, Russia).
2001 – 2002	"*Methods of scientific programming*" – high school advanced placement practicum (St. Petersburg, Russia).
1997	"*Fractals and self-organization in geophysical systems*" – lecture series for graduate and postgraduate students (Free University of Berlin, Germany).

Student supervision

2009 – 2010	Research supervisor, pre-graduation project (University of Calgary, Canada). Project title: "*Low-frequency waves in auroral arcs: optical echo of magnetotail dynamics*".
2009	Research supervisor, undergraduate co-op project (University of Calgary / University of Victoria, Canada). Project title: "*Data-derived resolution requirements for global auroral imagers*".
2009	Scientific consultant, M.S. project (University of Montreal, Canada). Thesis title: "*Self-organized critical models of the magnetosphere*".
2008 – 2009	Research supervisor, B.S. project (University of Calgary, Canada). Degree earned. Project title: "*Multiscale complexity in the solar wind – magnetosphere coupling and its impact on the space weather predictability*"
2006 – 2007	Scientific consultant, M.S. project (University of Maryland, USA). Degree earned. Project title: "*Self-organized criticality and intermittent turbulence in solar corona*".
2003 – 2005	Co-supervisor, M.S. project (St. Petersburg State University, Russia). Degree earned. Thesis title: "*Influence of geomagnetic activity on fractal characteristics of ultra low frequency seismic electromagnetic emissions*"
2002 – 2004	Scientific consultant, Ph.D. project (St. Petersburg Polytechnic University, Russia). Degree earned. Thesis title: "*Forecasting economic crises based on fractal analysis of currency exchange rate fluctuations*".
2002 – 2004	Scientific consultant, M.D. project (St. Petersburg Psycho-Neurological Research Institute, Russia). Degree earned. Thesis title: "*Fractal analysis of heart rate variability as a tool of clinical studies*"
1998 – 1999	Scientific consultant, M.D. project (St. Petersburg Medical Academy of Postgraduate Studies, Russia). Degree earned. Thesis title: "*Extra-low frequency fluctuations of heart rate variability in patients with cardiac rhythm disorders*"

Don Asquin

Education

- Graduate Class Audit - Spacecraft System Design
  University of Colorado, Boulder, Colorado 2000

- Graduate Classes in Astrophysics, 11 hours
  University of Denver, Denver, Colorado 1994-96, 4.0 GPA

- B.Sc., Electrical Engineering, 1985
  University of Calgary, Calgary, Alberta
  - Engineering Deans List 1984, 1985
  - Natural Sciences and Engineering Research Council, Undergraduate Research Award, 1984
  - Electrical Engineering Students Society, Technical Coordinator, 1984-85

Publications

Hutchings J.B., Postma J., Asquin D., and Leahy D. 2007. Photon Event Centroiding with UV Photon-counting Detectors. Publications of the Astronomical Society of the Pacific Vol 119, No. 860 Oct 2007

Experience

Senior Systems Designer, **April 2004 – Present**
Routes AstroEngineering, Ottawa, Ontario

Developing instrument for joint Canadian Space Agency (CSA) Department of National Defense (DND) spacecraft

- Sapphire Charge Coupled Device (CCD) PreAmplifier Design
  - Testing and Verifying PreAmplifier Engineering and Flight Printed Circuit Board (PCB)
  - Designed and Implemented PreAmplifier PCB
  - Specified Subsystem interface cabling for Electromagnetic Compliance
  - Specified components to National Aeronautics and Space Administration (NASA)guidelines

Developed instrumentation for joint Canadian and Indian spacecraft

- Ultraviolet Imaging Telescope (UVIT) Detector Subsystem for the CSA and Indian Space Research Organization (ISRO), System Engineering, Design Engineer
  - Delivered Flight Model (FM) hardware to University of Calgary for Calibration
  - Tested and verified FM hardware, including Vibration and Thermal Vacuum Testing
  - Delivered Flight Model (EM) hardware to ISRO for integration
  - Led Vibration, Thermal Vacuum and Electromagnetic Compliance testing at CSA David Florida Laboratory (DFL) for EM cycle
  - Designed and Implemented camera head PCB
  - Specified components to Military guidelines
  - Worked with the Indian Space Agencies (ISRO and IIA) and subcontractors to define system specifications and interfaces
  - Wrote BCD proposal to CSA

- Fast Auroral Imager (IR and Visible) on the e-Pop payload for the University of Calgary, System

Engineering, Project Management
  - Led a small team to design mechanical enclosures for camera and electronics units
  - Guided electrical design subcontractor in details of requirements for spacecraft instrument design
  - Wrote Phase CD proposal for mechanical design
- Data Storage Unit for the Cassiope / Cascade payload for MDA Radiation sensitivity testing
  - Worked with manufacturer of Flash based storage unit and MDA to specify test methodology
  - Led small team to build EGSE and support software
  - Led proton SEE and TID testing at University of British Columbia, TRIUMF
  - Led Cobalt 60 TID testing at DRDC

Senior Hardware Designer, **October 2001 – April 2004**
Meriton Networks, Ottawa, Ontario

Developed an integrating fiber optic add-drop multiplexer for the telecommunications market

- Led a collaborative signal integrity investigation with manufacturer of a 2.5 Gbps clock and data recovery I.C.
- Purchased laboratory test equipment at bankruptcy auctions resulting in significant cost savings
- Coordinated company patent activities, including, writing, editing and collaborating with patent lawyer
- Specified component requirements for optical component suppliers to meet specialized system requirements
- Designed and implemented a 2.5 Gbps CWDM fiber optic transceiver module
- Investigated and solved crosstalk issues in a 16 channel 2.5 Gbps data retime and switch card
- Developed control and synchronization plane for SONET based optical switch
- Integrated and system tested fiber optic add-drop multiplexer
- Investigated feasibility of 10 Gbps midplane
- Designed optical interface card utilizing SFF and SFP optical transceivers, optical power monitors, and optical multiplexers and demultiplexers

Manager, RF Development, **January 2001 – September 2001**
Spacebridge Semiconductor, Hull, Quebec

Managed a SiGe RF IC design team, developing components for the satellite based broadband wireless market.

- Created a project management plan for development of an L-band modulator and demodulator for the terminal equipment in a satellite-based, broadband access product
- Developed a “Design Flow” for RF IC development including project planning and tracking
- Motivated a group of new designers into an efficient team
- Contracted university experts to act as mentors to designers
- Demonstrated end to end functionality of an S-Band modulator, with integrated I & Q DACs, baseband amplifiers, mixers, VCO, phase shifter and IF output amplifier
- Led failure analysis study of shorted metal-metal capacitors in RF IC die
- Organized characterization and volume testing of RF ICs
- Oversaw tape-out of an L-band broadband wireless demodulator, including Monte Carlo Analysis and “corner” verification

- Coordinated and provided technical input into the layout of evaluation PCBs for modulator and demodulator RF ICs

Senior Engineer, **June 1999 – November 2000**
University Of Colorado, Laboratory For Atmospheric And Space Physics, Boulder, Colorado

Developed electronic circuitry for a NASA-funded satellite (SORCE), which is monitoring spectral changes in the sun

- Developed analog circuitry for a solar Total Irradiance Monitor (TIM) and Generic Channel Interface (GCI)
- Designed and tested circuitry elements including: transconductance amplifiers, precision voltage references, H-Bridge motor drivers, Wheatstone bridges, and temperature controllers
- Specified electronic parts, to NASA guidelines, to perform reliably in harsh space environment
- Created schematics, simulated circuitry, laid out and tested surface mount PCBs
- Coordinated design and implementation of interface unit between scientific instruments and spacecraft microprocessor
- Integrated mechanical and electrical design early in development cycle to optimize instrument design
- Collaborated with University Professors to meet scientific requirements and engineering compromises
- Thermal vacuum tested electromechanical mechanisms to ensure on-orbit reliability
- Reviewed instrument design with international scientists
- Mentored university students in electronic design and testing

Manager, Gates Planetarium & Imax Theater **August 1993 – May 1999**
Denver Museum Of Natural History**,** Denver, Colorado

Managed a $1.5 million annual budget and a team of 10 full-time and 15 part-time employees providing programming for an annual audience of 800,000 visitors.

- Reorganized staff structure from two separate groups into one efficient team
- Negotiated and monitored external contracts
- Co-authored and reviewed governmental grants
- Served as the astronomy and technology lead for the conceptual development of a $20 million space science exhibit
- Oversaw development of a wide range of special events and planetarium shows
- Collaborated with astronomy and space science resources (University of Denver, University of Colorado, Lockheed Martin, NASA) to ensure accurate information from experts in the field
- Created a strong working relationship with the local media to increase impact of special events and became a key public resource of astronomy information
- Evaluated new technologies for a $5 million upgrade of the planetarium facility
- Ensured reliable operation of 50 ft. computerized planetarium dome and IMAX theater
- Coordinated planetarium show production through creation of scripts, computer animation, narration, slides, and video
- Utilized telecommunications systems to link public with scientists and experts to witness and participate in astronomical events and discoveries

Senior Engineer, **September 1992 – February 1993**
Multi/Point Inc., Denver, Colorado

Designed and tested an avalanche beacon for backcountry skiers in a small start-up company.

- Evaluated the mechanical and electronic feasibility of proposed designs
- Debugged and optimized existing op amp-based design
- Developed and constructed a new prototype unit using FM radio IC and ceramic filters

Senior Engineer, **May 1985 – June 1992**
Bell Northern Research (Nortel), Ottawa, Ontario

Developed advanced telecommunications products from paper design to manufacturable products.

- Designed, tested and implemented analog and digital circuits for fiber optic and microwave radio transmission systems
- Served as team leader of a five-person design group managing a $150,000 laboratory equipment budget
- Negotiated and coordinated circuit card production with the manufacturing group
- Recovered slipped program schedules to deliver high-quality products on time and within cost objectives
- Tested transmission systems for compliance with FCC EMI and ESD regulations
- Designed triple-input, 140 MHz, low-noise, IF receiver and signal combiner
- Prototyped low-cost 435 Mb/s fibre optic transmitter
- Implemented synchronous 108 MHz clock divider chain
- Developed 570 Mb/s data switch and retime

M. Donna-Lee Desaulniers

EDUCATION: B. Sc. (Physics) McGill University 1975
M. Sc (Electrical Eng.) Queen's University 1978
Thesis: A Comparison Study of Four Image Reconstruction Techniques for Atmospherically Degraded Images

EXPERIENCE:

2006 to present **COM DEV Canada**
JWST Contamination Engineer-part time/term

Design integrity specialist providing technical expertise as required:

- Contamination control guidelines for hardware cleaning and handling
- Clean room procedures and practices including contamination monitoring and measurements
- Instrument contamination budgeting (both particulate and molecular)
- Analysis of impact of contamination on optical performance
- Recommendations on selection of materials
- Contamination control guidelines for vacuum operations to minimize contamination including hardware thermal vacuum bake out guidelines

1992 to present **Consultant/Optical Engineering**
Optics Specialist

Ceravolo Optical Systems

Optical Specialist providing baffle design recommendations

Routes AstroEngineering

Optical Specialist providing technical expertise as required:

- General proposal support for Routes on optical space instrumentation
- Optical systems analysis and design expertise for the proposed CATs and Ravens Project
- Systems engineering, optical testing and baffle design for the E-POP Project
- Stray Light Control System optical design and stray light analysis for the NEOSSat and the Sapphire Projects
- Analysis of calibration errors for the Hyperspectral HERO spectrometer
- Supported the Insect Habitat project as an optical engineering consultant and specialist for video camera imaging .including lens designs and technical management of sub-contractor

- The CSA hyperspectral imager study of radiometric calibration errors
- Optical specialist for OSIRIS IR Imager and UV/Visible Spectrograph. Duties include optical analysis, component specifications, liaison between Routes and optical sub – contractors, baffle design, evaluation and component testing as well as overall system performance testing.
- Project Manager for Optical Sensors for Earth Observation study, for CSA Space technology branch.

University of British Columbia

Space Materials Specialist, resource to PI on the MOST Project as required

Hymark Corporation

Optical Specialist providing tolerancing and optical specifications for a laser range finder system

Cal Corporation

Optical Specialist on an Acousto-Optically Tunable Filter Technology Development Study and general technical support for CAL personnel on project

1985 to 1992 **CAL Corporation**
Senior Optical Engineer

Optical Group Leader Space Division

- supervision and performance reviews
- responsible for overall optical group technical performance
- involved in marketing and proposals activities

Lead Optical Engineer WINDII Project

- Responsible for all optical aspects of instrument including detail design, implementation of design and component and assembly testing
- Performed detail design and test of the WINDII Michelison Interferometer, the WINDII OH compound filter and Fabry-Perot filter/interforometer,
- Performed optical redesign of WINDII inner baffle assembly and straylight analysis of instrument
- Monitor optical build sub-contracts
- Performed systems optical engineering
- Responsible for general costing, scheduling of activities and optical personnel on WINDII Project
- Support WINDII Project and Technical Managers at customer meetings; made

presentations to Project Science Team, Principal Investigator and CSA/NASA; liaison with CNES participants on project

Lead Optical Engineer ISL Project

- monitored junior optical staff optical on project
- Performed baffle performance analysis; thin film performance analysis; general systems analysis
- Support Project Manager at customer meetings

1981 to 1985 **MacDonald Detwiller & Associates**
Research Analyst

- Applications software team member on MSRS, a dual meteorological satellite ground station and imaging processing project
- MSRS systems test leader;responsible for system software and customer factory level acceptance test plans
- research analyst on various IRAP projects involving geocoding of satellite and airborne remote sensing imagery and post-processing SAR speckle noise reduction techniques
- general technical marketing support

1977 to 1981 **Defence Research Establish Ottawa**
Defence Scientist

- Research into real-time optical techniques to deblur motion-smeared and out-of-focus images
- Research into the properties of film in regards to spatial resolution
- General support for ground truth exercise ,including programming support on the Sarsat Project

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BLAIR GORDON

EDUCATION & QUALIFICATIONS

1983 B.A.Sc. Electrical Engineering, Management Sciences option, University of Waterloo
1986 P.Eng. - Professional Engineer designation, Professional Engineers of Ontario.
2000 PMP - Project Management Professional certification, Project Management Institute
2005 Executive Development Program, Queens University

EXPERIENCE

ROUTES ASTROENGINEERING LTD
2009 to 2010 President, and Director - Business Development
2007 to 2008 Director – Programs, and Business Development
2002 to 2006 Director – Programs

General Duties:
- Chart the direction of the Company relative to corporate Strategic Plan
- Provide liaison between company and external program collaborators & stakeholders for existing and future programs.
- Responsible for development of future business opportunities, preparation of proposals
- Responsible to the customer for overall satisfaction in execution of in-house programs
- Mandate and direct process improvement initiatives within the company.
- Perform project management and technical leadership/guidance activities as required to support the needs of in-house projects.

Selected Project Activities:

ORBITALS/HEPT Phase A Studies: Provided support to University of Alberta in the conceptual development of a High Energy Proton Telescope (HEPT) instrument as part of the ORBITALS Phase A Mission study.
- Provided technical review & comment of instrument requirements and interface documents.
- Provided technical review of technology risk areas
- Provided detailed cost & schedule estimates for Phase B-D instrument development

Ravens Phase 0 Concept Study: Lead a multi-disciplinary team in developing a concept design for a ultra-violet auroral imager that would operate on a spinning satellite, based on technical requirements developed by the University of Calgary. Identified potential technological and manufacturing challenges in the concept design

2001 to 2002 DISTINCTIVE MANAGEMENT SOLUTIONS
President, Consultant: Technical & Management solutions for the space industry.
Client: Routes AstroEngineering Ltd.
- THM Hyperspectral pre-Phase A Study: Retained to lead a technical team in the evaluation of the ground and in-orbit calibration requirements of a hyperspectral optical imaging payload, addressing

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the sensitivities, instabilities and drift of the payload over the planned 5-7 year mission life. Delivered study report to MDA/CSA.

- SciSat-1 Power Control Unit (PCU): Retained as Technical/Systems Engineer & Project Manager for the completion of the Engineering Development Model and ProtoFlight Model development activities. Delivered the EDM and PFM equipment and associated documentation to Bristol Aerospace Limited. Managed contractual & technical performance of satellite solar panel subcontractor during Flight Model development/manufacture phase.
- Corporate Infrastructure Development: Initiated a number of facility, training, and process improvement initiatives concurrent with SciSat PCU development. These improvements were timed to be ready "just-in-time" for the ProtoFlight PCU MAIT activities.

Sept 2002 - Oct 2001

ZENASTRA PHOTONICS INCORPORATED
Product Engineer

Held responsibility for the development, deployment and technical performance of assigned optical telecom component products. Delivered on the following corporate milestones:

- Nov 2000 - Developed and delivered Zenastra's first functional prototypes (VOA4 – Nortel Qtera, 8 week turnaround)
- Mar 2001 - Developed and delivered Zenastra's first corporate marketing samples (VOA8, TOS 2x2 products)
- July 2001 - Developed products for delivery to first customer (VOA8/10). Achieved best-in-class insertion loss performance in addition to product performance improvements in power consumption, voltage, and package size relative to the samples produced in March 2001.

1983-2000

EMS TECHNOLOGIES CANADA

(formerly CANADIAN ASTRONAUTICS LIMITED)

Senior Project Manager:
Project Manager in Space Systems group, managing multidisciplinary technical teams in the development of complex space science instruments and satellite bus components. Also managed technology development initiatives for optical inter-satellite communications applications.

1997-1999 Optical Front End (OFE) for OISL Communications
Customer: Communications Research Centre Canada (CRC)
Technology Development – Optical Satellite Telecommunications
Responsible for development of key technologies to enable future satellites to communicate via lasers (OISL-Optical InterSatellite Link systems). The Optical Front End subsystem of an OISL terminal gimbals the optical antenna, acquires & tracks the partner satellite, and separates the Tx/Rx signals

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into the modulation/demodulation subsystem.
- Derived system requirements, system architecture, and specified key technical and interface requirements
- Developed proof-of-concept model to evaluate key technical issues & evaluate alternate technologies.

1996-1999 Acquisition & Tracking Sensor (ATS) for OISL Communications

Customer: European Space Agency (ESA)

The ATS is a highly integrated, high speed optical sensor, and is a key optical technology enabling a satellite to acquire its partner, lock-on, and then track it as the satellite moves across the sky.
- Performed tradeoff evaluations wrt optical architectures and detector performance characteristics.
- Developed working prototype and evaluated accuracy and speed performance.
- Satellite Bus Equipment – Optical Equipment

1999-2000 CALTRAC™ GEO Star Tracker

Responsible for development of satellite optical ACS equipment.

Customer Base: GEO Satellite Bus Manufacturers (Alcatel Space Industries, etc.)

The CALTRAC™ GEO Star Tracker is an attitude sensor product targeted for satellites operating in GEOstationary orbit.
- Prepared Project Plan (all phases), and Technology Development Plan.
- Performed cost reduction analyses, and risk mitigation activities.
- Evaluated design & process improvements for increased reliability, manufacturability & testability.
- Conducted successful Preliminary Design Review with Alcatel Space Industries.

1998-1999 CALTRAC™ Star Tracker

Customer Base: Satellite Bus Manufacturers, including Alcatel Space Industries, Lockheed Martin Astronautics, Matra Marconi Space (now Astrium), Alenia Space.

The CALTRAC™ Star Tracker is an attitude sensor product targeted for Low Earth Orbit (LEO) satellites. First launched May 2000.
- Coordinated day-to-day operations of engineering & support teams during product design and verification phases.
- Set and communicated team goals & priorities. Managed design, procurement, manufacturing, and test logistics.

Space Instruments - Optical Equipment

Responsible for development of a number of optical space science instruments, designed to observe the auroral borealis.

1998 Wide-angle Imaging Camera (WIC)

Customer: Canadian Space Agency (CSA)

Delivered one flight model camera for integration onto NASA's IMAGE spacecraft. Provided post delivery technical support. Launched May 2000.

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1991-1992 Project: FREJA Auroral Imager (FAI)
Customer: Canadian Space Agency (CSA)
Manufactured two flight model cameras and one flight spare camera for Sweden's FREJA spacecraft. Integrated flight cameras onto spacecraft in Sweden. Launched October 1992.

1987-1990 Project: Ultra Violet Auroral Imager (UVAI)
Customer: Canadian Space Agency (CSA)
Manufactured flight model equipment (two cameras, gimbal system, electronics pkg.) for integration onto Russian INTERBALL spacecraft. Also delivered full-up engineering model, ground support equipment, and flight spares. Performed system tests in Russia and supported satellite integration activities. Provided in-orbit operations support. Launched August 1996.

Satellite Bus Equipment - RF Equipment
Responsible for development of satellite bus RF equipment.

1995-1997 Project: S-Band User Transponder (SUT)
Customer: European Space Agency (ESA)
The SUT is a highly integrated dual mode transponder for use aboard satellites for Telecommand/Telemetry/Control (TT&C) functions. The transponder can be configured in orbit for BPSK/PM operation or for spread spectrum/QPSK mode.

- Developed an Engineering Model to validate the technology and the manufacturing/production techniques.

Space Instruments – RF Equipment
Responsible for development of RF space science instruments

1993-1995 Project: High Frequency Transmitter/Receiver Experiment (HEX/REX)
Customer: Canadian Space Agency/Communications Research Centre
The HEX/REX equipment consisted of a transmitter/receiver operating in the 25 kHz to 8 MHz frequency range. Launched onboard a two part ballistic rocket as part of the OEDIPUS-C mission, the transmitter emitted sequences of pulses from the forward payload which were received by the synchronized receiver on the aft payload. Launched in January 1996.

- Responsible for technical coordination of project team spanning three companies and four sub-consultants.
- Manufactured flight model equipment and performed initial system tests. Provided technical support to rocket integration team.

SECURITY CLEARANCE: Level II - Secret

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PAUL MARCHAND, P. Eng.

Education

University of Ottawa – Ottawa, Ontario

Master of Applied Science (Mechanical Engineering) **2007**

- Graduate courses (A+ in all courses)
  Orbital Mechanics, Finite Element Analysis, Mechatronics, Stability Analysis
  Advanced Vibration Analysis, Space Mission Analysis and Design
- Thesis on Force Limited Vibration Testing nominated for best thesis in science

Bachelor of Applied Science degree in Mechanical Engineering, CO-OP **1993**

Experience Summary

Over 15 years of experience in the analysis, design, and testing of space instruments for use on satellites, the space shuttle, and the international space station.

Recent Professional Experience

Routes AstroEngineering – Ottawa, Ontario **1995 - present**

Senior Mechanical Engineer

- Responsible for ensuring the structural and thermal performances of space instruments
- Experienced in the design, analysis, assembly, and test of flight hardware
- Design Experience
  - Space imagers
    - OSIRIS, POSSEX/MOZE, ePOP-FAI, UVIT, MOST Door
  - Scientific instruments for shuttle and space station
    - MIM-II, MVIS, ARF-II, Insect Habitat, PMDIS/TRAC, Laser Camera System
  - Electronics assemblies
    - OSIRIS, ePOP-FAI, SAPPHIRE, NEOSSAT
  - Ground support equipment
    - JWST Fine Guidance Sensor, Star Tracker, Mini-MIM
  - Space Solar Panels
    - M3MSAT, NEOSSAT, AISSAT-1, NANOSAT
  - Passive and active thermal control system design
    - OSIRIS, ePOP-FAI, Insect Habitat, UVIT
- Analysis experience
  - Load Analyses (Heat Loads, Statics, Dynamics, Orbital Mechanics)
  - Structural Analyses (Vibration, Stress, Fracture, Fatigue)
  - Thermal Analyses (Heat Transfer, Fluid Flow, Thermodynamics)
  - Solar Cell Power Generation (M3MSAT, NEOSSAT, AISSAT-1, NANOSAT)
- Environmental Testing (TVAC, Thermal Chamber, Vibration)
- Studies (Ultra-Violet telescope study, ISS Furnace Study)
- Software
  - CAD (SolidWorks)

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- FEA (NISA, SINDA, SolidWorks Simulation)
- Numerical Analyses (MATLAB, SIMULINK, Excel)

Previous Work Experience

Biokinetics and Associates Limited – Ottawa, Ontario **Apr 1994 – Dec 1994**

- Involved in the design, test, and manufacture of helmets
- Performed seat-belt measurements using a Hybrid-III automotive dummy

SPAR Aerospace Limited – Ottawa, Ontario **Jun 1993 – Dec 1993**

- Designed and assembled support equipment and participated in the testing RADARSAT 1 and MSAT satellites

SPAR Aerospace Limited – Ottawa, Ontario **May 1992 – Aug 1992**

- Designed ground support equipment for the Radarsat and MSAT satellites

National Research Council – Ottawa, Ontario **Sep 1991 –Dec 1991**

- Aided in performing full size crash tests on prototype trains.
- Analyzed feasibility of major modification to equipment

National Energy Board – Ottawa, Ontario **Jan 1991 –Apr 1991**

- Evaluated fluid flow software
- Performed a fluid flow analysis of gas flowing in pipelines across Canada

OC Transpo – Ottawa, Ontario **May 1990 –Aug 1990**

- Assisted in the duties of engineers
- Performed minor design projects

Associations

Professional Engineers Ontario
Ontario Society of Professional Engineers

Publications

Marchand, P., O'Grady, M, Singhal, R., "Relating the Value of C^2 of the Semi-Empirical Method of Force Limited Vibration to a 2-DOF System", Proceedings of the 22nd Aerospace Testing Seminar, Manhattan Beach, Ca, March 22 – 24, 2005

Marchand, Paul, Redekop, David, "Free Vibration Analysis of a Crankshaft using FEA", Proceedings of the 20th Canadian Congress of Applied Mechanics, McGill Montreal, May 30 to June 2 2005

Leroy Cogger, et. al, "The Fast Auroral Imager Experiment to Investigate the Dynamics

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of Nighttime Optical Aurora as part of the CASSIOPE/EPOP Mission", CASI, 2006

Llewellyn, E. J., et al., "The OSIRIS Instrument on the Odin Spacecraft", Canadian Journal of Physics, 82, pp. 411-422, 2004

KENNETH WALTER SMITH

EDUCATION

M.Eng., McMaster University, 1980
B.Eng., McMaster University, 1977

EXPERIENCE

1990 to Present ROUTES ASTROENGINEERING LTD
Director, Technology

The design lead of the imaging and power electronics for the Sapphire surveillance satellite being built for DND. This is a CCD-based imaging system. Also assisting with the imaging electronics for the NEOSSAT microsatellite, a joint CSA and DND mission.

Involved with the Ravens UV auroral imager study, trading-off implementation and realization of instrument performance parameters and science requirements.

The electronics design lead for the UVIT (Ultra Violet Imaging Telescope) detector readout and power electronics for Phases B, C, and D. This utilizes a 14-bit A/D converter and a CMOS technology image sensor, plus real-time digital image processing in an FPGA. Involved with the development of photon event detection and centroiding (accurate position determination) algorithm for data from the image sensor. The UVIT electronics is part of the UVIT Canadian and Indian ultra-violet telescope to be flown on the Indian Astrosat astronomy satellite.

Was involved with a Phase 0 study of the UVIT electronics, to be flown on an Indian astronomy satellite called AstroSat. This instrument involves the use of an intensified image sensor and a digital signal processor for imaging using photon-counting. The work involved design simulation and hardware and software breadboarding of the image sensor readout and processing electronics, including EGSE.

Also was involved in a series of past studies for the design of digital signal processing electronics for the CUVIT instrument, a Canadian UV Imaging Telescope which uses photon-counting techniques for imaging and attitude stabilization. This was the predecessor instrument concept to UVIT.

Developed low-noise CCD and infrared detector (linear NIR InGaAs) readout electronics for OSIRIS, an optical spectrograph and NIR imager flown on the

Swedish Odin satellite.

Technical manager for Freja Ultraviolet Imager. Designed and tested both digital and analog radiation-hardened electronics, including CCD readout electronics, in addition to systems design, hardware and software interface definition, all levels of test, and interaction with the Science Team and CSA.

Also involved with numerous designs and also concept studies for several other space-based imaging payloads.

1979-1990 CANADIAN ASTRONAUTICS LIMITED (now Com Dev Limited, Ottawa)

Responsible for the electrical design and implementation of the UVAI instrument flown on the Russian Interball satellite, an ultraviolet imager similar to the VIKING instrument, for the NRCC (now part of CSA). Also involved in the systems level design and interface with the Science Team.

Electrical design manager and lead on WINDII project, a Wide Angle Michelson Imaging Interferometer used for measuring upper atmospheric winds on the Upper Atmospheric Research Satellite (UARS).

Project leader for the ultraviolet imaging camera electronics flown on the Swedish VIKING Spacecraft, for imaging the aurora in low level far ultraviolet light. This instrument and spacecraft was successfully flown. The UV imager electronics contained a radiation-hardened processor and CCD camera video processing and digitizing electronics. Responsible for the design, implementation and test of the UV camera digital electronics. Performed radiation testing for various ICs. Also involved with the pre-launch testing and post-launch scientific ground operations and support.

Also involved with numerous designs and also concept studies for several other space-based imaging payloads, as well as many types of ground-based instrumentation.

1977-1979 COMMUNICATIONS RESEARCH LAB
McMaster University, Hamilton, Ontario

Responsible for the design and implementation of a colour image display system, computer interface and software for analysis of optical satellite and ground-based radar imagery.

Investigated the implementation of digital image processing techniques for satellite and radar imagery.

Studied communication satellite modulation and synchronization techniques, also satellite-based earth observation techniques.

Security clearance: Level II - secret (valid until the end of 2012)

Curriculum Vitae
John Pazder

Optical Team Leader
Herzberg Institute of Astrophysics
National Research Council of Canada
5071 West Saanich Road
Victoria, BC V9E 2E7
Canada

John.Pazder@nrc-cnrc.gc.ca
t: 250. 363. 0058
f: 250. 363. 0045

Employment history:
2004-present : Optical Team leader, HIA, NRC
2002-2004 : Optical Designer, HIA, NRC
1996-2002 : Optical Designer, CREO Products, Burnaby B.C.

Education:
MASc, Mechanical Engineering, University of Victoria, (1996);
Thesis: "The Optical Design of an Adaptive Optics System Imaging Two Selectable Layers"

BASc, Physics, University of Victoria (1991)

Expertise:
Optical design, Optical System Modeling, Stray Light Analysis

Major Projects:
Optical Systems Engineer, Thirty Meter Telescope (www.tmt.org)
Optical Systems Engineer, WFOS Feasibility Study.
Lead optical designer, MOST space telescope and ASTRA spectrograph.
Lead optical modeling on HIA VLOT/TMT Integrated model.
Contributor to: JWST FGS, UVIT, CFHT GLAO feasibility study, Gemini GLAO feasibility study, VLOT 20m study (error budget, telescope models, segment manufacture studies), Gemini Altar A/O optical design,

Awards:
2008: **Alouette Award**, awarded to MOST team for success of MOST.

Selected Publications:
John S. Pazder; J. Christopher Clemens. *VPH grating technology for the Thirty Meter Telescope instrumentation*. Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, Eli Atad-Ettedgui; Dietrich Lemke, Editors, Proceedings of the SPIE, 70184U (2008)

John S. Pazder; Konstantinos Vogiatzis; George Z. Angeli., *Dome and mirror seeing estimates for the Thirty Meter Telescope*, Modeling, Systems Engineering, and Project Management for Astronomy III, George Z. Angeli; Martin J. Cullum, Editors. Proceedings of the SPIE, 70170R

Olivier Lai; Mark Chun; Jean Charles Cuillandre; Ray Carlberg; Harvey Richer; David Andersen; John Pazder; John Tonry; René Doyon; Simon Thibault; Jim Dunlop; Chris Pritchet; Jean Pierre Véran; Christ Ftaclas; Peter Onaka; Klaus W. Hodapp; Robert A.

McLaren; Emmanuel Bertin; Yannick Mellier; Pierre Astier; Reynald Pain. *IMAKA: imaging from Mauna KeA with an atmosphere corrected 1 square degree optical imager*, Adaptive Optics Systems, Norbert Hubin; Claire E. Max; Peter L. Wizinowich, Editors, . Proceedings of the SPIE, 70154H (2008)

Adelman, S. J.; Gulliver, A. F.; Smalley, B.; Pazder, J. S.; Younger, P. F.; Boyd, L. J.; Epand, D.; Younger, T. *The ASTRA Spectrophotometer: Design and Overview. The Future of Photometric*, Spectrophotometric and Polarimetric Standardization, ASP Conference Series, Vol. 364, Proceedings of a conference held 8-11 May, 2006 in Blankenberge, Belgium. Edited by C. Sterken. San Francisco: Astronomical Society of the Pacific, 2007., p.255

Szeto, Kei; Andersen, David; Crampton, David; Morris, Simon; Lloyd-Hart, Michael; Myers, Richard; Jensen, Joseph B.; Fletcher, Murray; Gardhouse, W. Rusty; Milton, N. Mark; Pazder, John; Stoesz, Jeff; Simons, Doug; Véran, Jean-Pierre, *A proposed implementation of a ground layer adaptive optics system on the Gemini Telescope*. Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, pp. 626958 (2006)

Pazder, John S.; Fletcher, Murray; Morbey, Chris, *The optical design of the wide field optical spectrograph for the Thirty Meter Telescope*. Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, pp. 626932 (2006)

Pazder, John S.; Roberts, Scott; Abraham, Roberto; Anthony, Andre; Fletcher, Murray; Hardy, Tim; Loop, David; Sun, Simon, *WFOS: a wide field optical spectrograph for the Thirty Meter*, Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, pp. 62691X (2006)

Pazder, John S.; Roberts, Scott C.; Smith, Malcolm J.; Lavigne, Jean-Francois; McKenzie, Hannah. *The optical modeling tools for the Canadian Very Large Optical Telescope integrated model.* Proc. SPIE, Volume 5382, pp. 404-412 (2004).

Walker, Gordon; Matthews, Jaymie; Kuschnig, Rainer; Johnson, Ron; Rucinski, Slavek; Pazder, John; Burley, Gregory; Walker, Andrew; Skaret, Kristina; Zee, Robert. *The MOST Asteroseismology Mission: Ultraprecise Photometry from Space.*PASP Volume 115, Issue 811, pp. 1023-1035.

Roberts, Scott C.; Morbey, Christopher L.; Crabtree, Dennis R.; Carlberg, Ray; Crampton, David; Davidge, Timothy J.; Fitzsimmons, Joeleff T.; Gedig, Michael H.; Halliday, David J.; Hesser, James E.; Herriot, Glen; Oke, J. Beverly; Pazder, John S.; Szeto, Kei; Veran, Jean-Pierre. *Canadian very large optical telescope technical studies.* Proc. SPIE Vol. 4840, p. 104-115 (2003).

E.H. Richardson, J.M. Fletcher, C.L. Morbey, J.M. Oschmann, J.S. Pazder. *Optical design of Gemini "Altair"*. Proc. SPIE Vol. 3353, p. 600-610 (1998).

Appendix IV – Relevant Technical Papers

The follow section is comprised of technical papers of relevance to this proposal published by members of the key personnel. Key Personnel are underlined.

- **Intensified charge-coupled-device imager for auroral studies,** S.K. Babey, J.S. Murphree, E.P. King, L.L. Cogger, and C.D. Anger, *Opt. Eng.* 25, 1149–1154 (1986).

- **An ultraviolet auroral imager for the Viking spacecraft,** Anger, C. D., S. K. Babey, A. L. Broadfoot, R. G. Brown, L. L. Cogger, R. Gattinger, J. W. Haslett, R. A. King, D. J. McEwen, J. S. Murphree, E. H. Richardson, B. R. Sandel, K. Smith and A. Vallance Jones, Geophys. Res. Lett., 14, pp. 387-390, 1987.

- **The Application of CCD Detectors to UV Imaging from a Spinning Satellite,** Murphree, J. S. and Cogger, L. L., Ultraviolet Technology II, *Proc. Soc. Opt. Eng.* 932, 42, 1988.

- **The Freja Ultraviolet Imager,** Murphree, J. S., R A. King (U of C), T. Payne, K. Smith, D. Reid (Routes), J. Adema (DEP), B. Gordon (CAL), and R. Wlochowicz (CSA), *Space Sci. Rev.* 70, 421-446, 1994.

- **Ultraviolet Auroral Imager (UVAI),** Cogger, L. L., D. J. Hearn, J. S. Murphree, R. A. King, E. P. King, Y. I. Galperin, B. Gordon and J. Matsushita, In *Interball Mission and Payload*, RSA - IKI - CNES, 382 - 400, 1995. Edited by Y. Galperin, T. Muliarchik and J. P. Thouvenin. Russian Space Agency, Space Research Institute and French Space Agency.

- **Far ultraviolet imaging from the IMAGE spacecraft. 2. Wideband FUV imaging,** Mende S.B.; Heetderks H.; Frey H.U.; Lampton M.; Geller S.P.; Abiad R.; Siegmund O.H.W.; Tremsin A.S.; Spann J.; Dougani H.; Fuselier S.A.; Magoncelli A.L.; Bumala M.B.; Murphree S.; Trondsen T., Space Science Reviews, Volume 91, Numbers 1-2, January 2000 , pp. 271-285(15)

- **Auroral imaging in Canada: Past, present, and future,** Cogger, L., E. Donovan,. D. Knudsen, J. S. Murphree, and T. Trondsen, *Canadian aeronautics and space journal,* ISSN 0008-2821, 2002, vol. 48, no 1, pp. 107-113

- **"Ravens" – The Far Ultra-Violet Auroral Monitoring Iimagers on the Chinese KuaFu-Mission,** Trond S. Trondsen, Eric F. Donovan, Leroy L. Cogger, Jing-Song Wang, Chuan-Yi Tu, *Proceedings of the 13th Canadian Astronautics Conference, ASTRO 2006*, Montreal, QC, Canada, organized by CASI (Canadian Astronautics and Space Institute), April 25-27, 2006

- **The Fast Auroral Imager Experiment to Investigate the Dynamics of Nighttime Optical Aurora as part of the CASSIOPE/ePOP Mission,** Cogger, S. Murphree, T. Trondsen, A. Yau, D. Asquin, B. Gordon, P. Marchand, D. Ng, G. Burley, M. Lessard, Proceedings of the 13th Canadian Astronautics Conference, ASTRO 2006, Montreal, QC, Canada, organized by CASI (Canadian Astronautics and Space Institute), April 25-27, 2006

- **Global auroral imaging, system-level science,** Donovan, E., and 19 others, including T. Trondsen, and E. Spanswick, , and ILWS, Adv. Space Res., 40, pp 409-418, 2007.

- **Data-derived spatio-temporal resolution constraints for global auroral imagers**, Uritsky, V., E. Donovan, T. Trondsen, D. Pineau, and B. Kozelov, submitted, J. Geophys. Res., Feb. 2010.

Intensified charge-coupled-device imager for auroral studies

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Abstract. A 100×100 pixel charge-coupled-device (CCD) area detector combined with an image intensifier, all-sky optics, and a filter wheel has been developed to provide quantitative monochromatic images of the aurora. The design of the instrument provides for a variable exposure rate to accommodate the large dynamic range of auroral intensities, from a minimum of 20 ms up to several minutes. Standard auroral emission features are monitored by four selectable filters, normally at 6300, 5577, 3914, and 4278 Å. Depending on the filter utilized, sensitivity can be from 180 to 250 $R \cdot ADU^{-1} \cdot s^{-1}$. The instrument has been used successfully in support of balloon, rocket, and satellite campaigns.

Subject terms: charge-coupled device; image intensifier; monochromatic imaging; all-sky camera; area detector.

Optical Engineering 25(10), 1149-1154 (October 1986).

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1. INTRODUCTION

The aurora, as it manifests itself in various emission features, provides a fascinating glimpse of complex solar wind/magnetosphere/ionosphere interactions. Historically the aurora has been of widespread interest because of its bewildering spatial and temporal variations, which can be readily observed with the unaided eye. Significant effort has been expended since the turn of the century to understand the sources of the aurora. As auroral theory has developed, there has been a corresponding requirement for more sophisticated measurement techniques. The development of the all-sky camera[1] was an important initial step in acquiring qualitative optical information on a routine basis. Progress in measurement techniques made possible the invaluable scientific contributions of satellite-borne optical detectors capable of monitoring the auroral emissions over large regions of the high latitude ionosphere.[2-5]

Satellite observations have shown that, even on a global scale, the aurora is an extremely dynamic phenomenon. Though such observations will continue to be important, there is a requirement to provide measurements on a smaller spatial scale and with increased sensitivity and temporal resolution. However, the very characteristics that are most interesting, that is, the rapid spatial/temporal/brightness variations of the aurora, considerably complicate the rapid acquisition of data over extended regions of space.[6] Fortunately, with the recent advances in microcircuit technologies, devices have become available that can detect optical emissions simultaneously over a two-dimensional grid, thereby eliminating the need to mechanically or electrically scan a detector over the emission region. These photoelectric array detectors for low light level measurements have been used successfully for a number of years in astronomical observations.

In this paper we describe an all-sky camera (ASC) that utilizes such an array detector for ground-based measurements of the aurora. The instrument has been successfully used to provide support measurements for a number of balloon and rocket experiments as well as to provide useful optical images in its own right.

2. CRITERIA FOR INSTRUMENT DESIGN

The scientific goals of the auroral researcher to a large degree determine the criteria that affect the design of any particular instrument. In the case of the ASC, basic operating and analysis modes provided initial design constraints: auroral data were to be obtained from a single instrument that could be easily operated from any site where power could be obtained. Data were to be analyzed on separate image processing equipment, and this dictated the utilization of digital storage techniques.

The primary objective in data acquisition is to obtain two-dimensional monochromatic data of auroral emissions. From a single site this implies the use of some form of all-sky imaging to within a few degrees of the horizon in all directions. Though the spatial resolution at a fixed altitude in the ionosphere will vary with angle from the zenith, some criterion is necessary for determining the minimum acceptable resolution. Recognizing that auroral scale sizes range at least

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from 1 m to 1000 km, we chose a central scale size of 1 km as the objective for the ASC.

Emphasis in optical auroral data collection is more and more focused on obtaining monochromatic data leading toward analysis of auroral energetics rather than simply wide-scale morphologic observations. The ASC therefore was designed to monitor selectively a variety of auroral emission lines and bands. The number of photons/s available for any emission feature depends on a variety of factors. At the most common auroral wavelengths (3914 Å, 5577 Å), intensities below 100 R and up to several hundred kR must be allowed for. Some method of integration can be used to acquire data when intensities are low; however, auroral forms can exhibit rapid fluctuations that are also of interest. The goal of high sensitivity must therefore be balanced against rapid temporal resolution. Auroral fluctuations have been measured on the order of 10 Hz, and thus integration times shorter than 100 ms are desirable.

3. INSTRUMENT DESCRIPTION

The instrument consists of an outdoor tripod-mounted camera head, together with an indoor, Z-80-based microcomputer system, CRT terminal, image display unit, time code reader, and nine-track tape drive for data storage (Fig. 1).

Within the camera head are the optics, image intensifier, CCD detector, and associated electronics. The optical system is shown in Fig. 2. A fisheye conversion lens with 165° field of view acts as a field widener. Following the fisheye, incoming light passes through one of six 1.25-in.-diameter bandpass interference filters located in the bidirectional motorized filter wheel. Emissions that are monitored include 5577 Å (O^1S), 6300 Å (O^1D), 3914 Å (N_2^+), and 4278 Å (N_2^+). One filter position is opaque for use in taking dark current measurements and for protection of the intensifier when the instrument is not in use. The doublet lens forms a 14-mm-diameter image, which is reduced to a 6 mm f/1.47 image on the intensifier photocathode by the 25 mm relay lens.

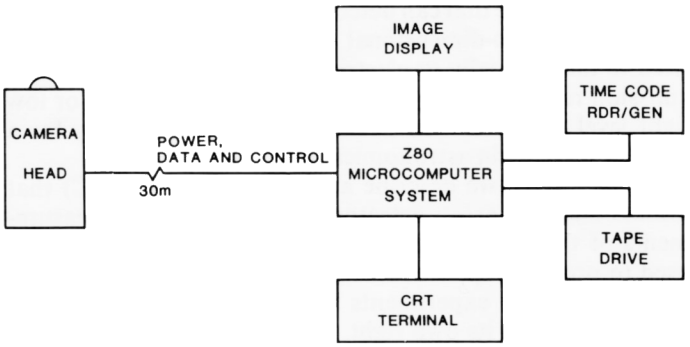


Fig. 1. Schematic of the basic components of the all-sky camera (ASC).

Because a convergent beam through the filter is unavoidable in such an imaging system, the attendant effects of reduced peak transmission, increased effective bandwidth, and downward-shifted peak transmittance wavelength must be considered in the filter selection process. In the ASC the maximum cone half-angle through the filter is 10.5°. The bandwidth of the filters is specified as a relatively broad 30 Å to minimize the effects of nonnormal incidence. A disadvantage of the present design is that the range of angles through the filter is not the same for each image point; a uniform range of angles could be achieved by including a lens one focal length from an aperture stop to satisfy the telecentric condition.

The electrostatically focused image intensifier is a Varo 3603-1 25 mm, second-generation microchannel plate with an S20 extended red photocathode and a nominal luminous gain of 25,000. The intensifier has built-in dc-dc high voltage power supply converters and requires only a 2.5 V external power supply (which can be switched under computer control).

Initially the intensifier output phosphor was proximity-focused onto the detector by means of a fiber-optic block bonded to the CCD. However, after the failure of two detectors it became apparent that the supplier's technique of cementing the fiber bundle directly to the array surface resulted in damage to the CCD during cooling, owing to unequal thermal expansion of the fiber and the CCD array. A lens-coupling approach was consequently adopted in which an 8 mm f/1.4 camera lens forms a 4 mm image of the intensifier phosphor on the detector. Recently A. L. Broadfoot at the Lunar and Planetary Laboratory of the University of Arizona has developed a fiber-optic coupling technique in which the CCD and fiber bundle are oil-coupled and mounted on a common ceramic carrier. This approach is being utilized in the UV auroral imager aboard the Viking satellite launched Feb. 22, 1986.[6] We have measured the coupling efficiency of the fiber-optic approach and found it to be about 0.60. This compares with an efficiency (obtained from geometric considerations) of about 0.02 for a lens-coupled system.

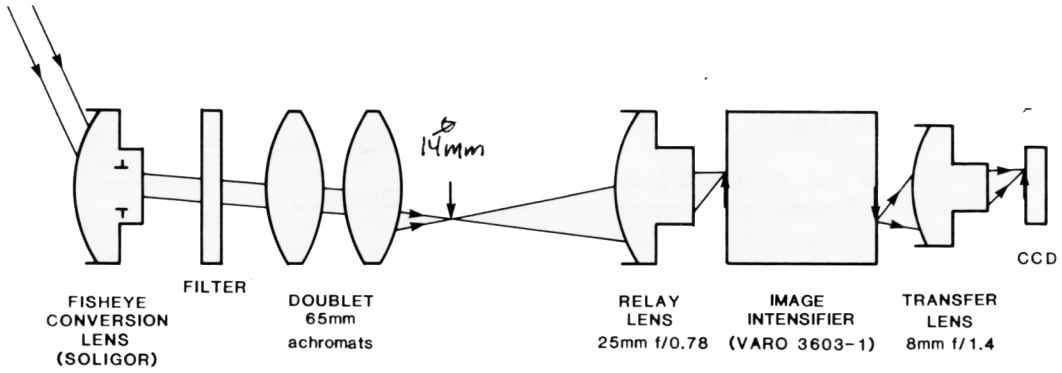


Fig. 2. Design of optical system. The image is optically coupled from the output of the image intensifier and matched in size to the photosensitive area of the CCD.

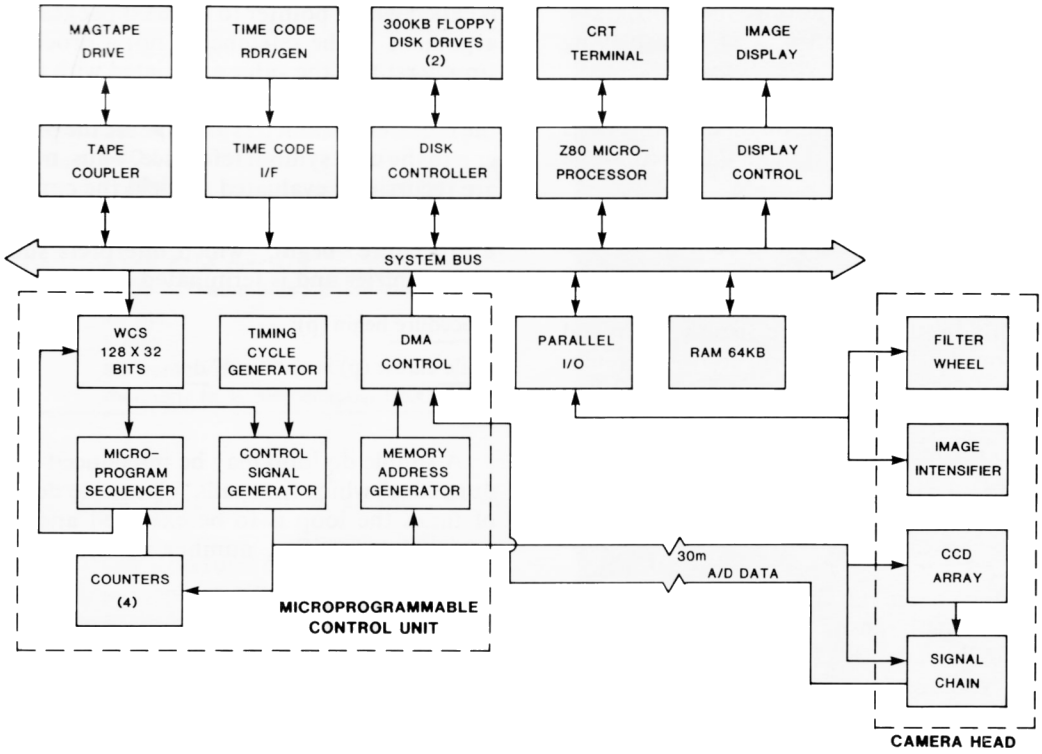


Fig. 3. Schematic of the instrument control system.

The detector is a Fairchild CCD 202 solid-state image sensor consisting of an array of 100×100 pixels. Each pixel is 18 μm by 30 μm, and the dimensions of the total image sensing area are 4 mm by 3 mm. Image photons incident upon the array generate electron-hole pairs in each photosite. The total charge accumulated is a linear function of the incident irradiance at the photosite during the integration period. Unfortunately there are also thermally produced electron-hole pairs, and since exposure times on the order of several seconds are required to detect faint auroras, the CCD must be cooled to reduce this dark current. A two-stage thermoelectric cooler is located in the thermal conduction path between the CCD and a reservoir of crushed dry ice. The CCD temperature can be regulated by controlling the cooler current; in practice a sufficiently stable temperature is obtained with a constant current setting. The CCD operating temperature is typically 233 K. The dark current rate at this temperature is about 2 ADU $\cdot$ pixel$^{-1} \cdot$ s^{-1}. The camera head is purged with dry nitrogen to prevent internal condensation, and a blower prevents frost formation on the exterior lens surface during cold weather.

Details of the instrument control hardware are illustrated in Fig. 3. The CCD video signal is buffered on a small circuit board that also has the sensor socket mounted in it. A separate chamber houses several circuit cards that contain the analog signal chain, A/D converter, filter wheel control, and line driver/receiver circuitry. The CCD video signal is amplified and undergoes correlated double sampling (CDS)[8] before digitization by an 8-bit flash converter. CDS involves sampling both the reset level and the video signal for each pixel and then producing an analog difference between these levels. This improves the noise performance by removing the uncertainty associated with the reset level and removes the effects of long-term offset drift. The system gain is set such that the CCD full-well signal (3×10^5 e$^-$) is matched to the dynamic range of the A/D converter; hence the conversion gain is 1170 e$^-$/ADU. The combined effect of the various non-signal-related noise sources (CCD read noise, amplifier noise, quantization noise, etc.) is below 1 ADU.

The microcomputer system (Zilog MCZ-1/25) performs the system controller and data acquisition functions. The system includes dual 300 Kbyte floppy disk drives and uses the Zilog RIO operating system. A 100 ft ribbon cable connects the camera head to the microcomputer system. All CCD clocking and control signals are generated by a special-purpose microprogrammable control unit (MCU) interfaced to the microprocessor bus. The MCU consists of a writable control store (WCS), control sequencing logic, direct memory access (DMA) address generator, and interface logic to the camera head and to a local image display unit.

The MCU is triggered by the CPU to initiate a CCD readout. The MCU then requests control of the system bus. When the CPU is tristated, the MCU begins cycling through microinstructions in the WCS. Bits in the microinstruction are allocated for CCD clocking and A/D control, counter control (permits looping), memory address control, and display control. As the CCD is scanned out, the image is transferred by DMA into the processor memory and stored as a raster array. Control of the system bus is restored to the CPU when the readout is finished.

A counter/timer interrupts the processor every 20 ms so that a microprogram can be run. Typically, one of three resident microprograms is run following a timer interrupt. One microprogram clocks out the CCD and writes the image into memory. A second microprogram, used during integration, holds the CCD clocks static while reading image data out

from memory to refresh the display. The third microprogram, used in the idle mode, clears out the CCD while displaying image data from memory.

The experimenter specifies an integral number of 20-ms increments to obtain the desired integration time. Frame rates up to 50 Hz can thus be achieved (although data cannot be recorded at this high a rate).

The display circuits contain line and column counters whose outputs undergo D/A conversion to control an X-Y display. The stream of 8-bit pixel values from memory or from the CCD are converted to an analog video signal that modulates the Z-axis (amplitude channel) of the display. Gain and threshold controls allow the user to perform contour stretching to enhance the displayed image.

Image data can be stored on floppy disk or nine-track tape, although limited storage capacity and transfer rate make the former less desirable. A header record associated with each image contains a sequence identifier along with parameters for the exposure. About 2.5 s are required to store a full image on tape.

Also interfaced to the system is a time code reader/generator that can receive the signal transmitted by a WWV station. The universal time is delivered in BCD form to a port on the microcomputer and recorded in the header for each image.

4. CONTROL SOFTWARE

For maximum instrument usefulness and ease of operation, a flexible and interactive control interface is desirable. A novel command line interpreter, ZI, has been developed to meet these requirements, based on the principles outlined by Trail.[9] The ZI interpreter achieves structured programming capability and efficient execution while maintaining the interactivity of an interpreter environment.

A command line is executed in two steps: (1) construction of a program vector, pv[], with pointers to entries in a symbol table for each token in the command line and (2) recursive interpretation of the program vector. The input command line format consists of alphanumeric symbols separated by one or more nonalphanumeric characters. This permits a free source format and choice of delimiter characters to improve readability. Upon receipt of a carriage return character, the command line is scanned and separated into tokens. The symbol table is searched and an entry for each token, consisting of a pointer to its entry in the symbol table, is created in the program vector.

The heart of the interpreter is the procedure "clause," which recursively interprets the program vector:

```
procedure clause (p);
   s = pv[p];
   p = p + 1;
   if s is a procedure reference then clause = s(p)
                              else clause = s;
end;
```

Here p is the current position in the program vector pv, and s is the symbol table entry referenced by pv[p]. This syntax is not intended to conform to a particular language but is presented only to illustrate the algorithm. The interpretation is initiated by calling clause [0]. The reference in the program vector is examined, and if it is a procedure, then the procedure is called with a pointer to the next program vector entry as an argument. If the reference is not a procedure, then "clause" simply returns the value associated with that symbol. When a procedure is called, it makes recursive calls to "clause" to yield the required parameters and update the program vector pointer p to the next symbol reference. Thus, nested procedure calls are recursively evaluated to yield the correct result.

Structured programming capability is achieved by defining a procedure "begin," which interprets subsequent program vector entries and is terminated by an entry "end":

```
procedure begin (p);
while clause (p) is not "end" do;
end;
```

A simple do loop may be introduced by defining a procedure "do," which first calls "clause" to determine the number of times the loop is to be executed and then calls "clause" again the specified number of times but without incrementing p:

```
procedure do;
n = clause (p);
for i = 1 to n do begin p = localp;
                        clause (p);
                  end;
end;
```

The above constructs can be used in conjunction with defined procedures that effect instrument control to implement complex sequences of operations in a compact, readable format. For example, suppose one has a procedure "x" that initiates acquisition into memory of an exposure of duration specified by a single argument, a procedure "fw" that changes the filter wheel position to that specified by a single argument, and a procedure "wt" that writes the most recently acquired image onto tape. Then, to acquire 100 sets of images at two wavelengths (filters 1 and 3) with integration times of 10 and 20 units, respectively, one could enter a command line as follows:

```
do 100 begin fw = 1 x = 10 wt fw = 3 x = 20 wt end
```

The delimiter characters are arbitrary and could in practice be blanks.

We have implemented a variety of procedures to allow similar control over all aspects of ASC operation, including the "xeq" command, which causes input to the interpreter to be taken from a named disk file. This feature is useful for implementing initialization and other preprogrammed sequences.

5. INSTRUMENT PERFORMANCE

Details of the operating characteristics of the ASC are given in Table I. The instrument has been field tested under a variety of conditions in support of balloon, rocket, and satellite missions. Examples of the acquired data are shown in Fig. 4. Each individual image consists of the full 100×100 pixel output of the CCD and is corrected for dark counts (see below). When the ASC is being positioned at an observing site, the column orientation is set along the local geomagnetic meridian because auroral features are best ordered in a magnetic coor-

TABLE I. Operating characteristics.

Optics	f/1.4 lens coupled
Intensifier	second-generation microchannel plate 25 mm image intensifier (Varo 3603-1)
gain	25,000
photocathode	S20-ER
phosphor	P-20-AL
Sensor	100×100 element CCD (Fairchild CCD 202)
Digital conversion	8 bits, 615K pixels/s
Image	100×100 elements×8 bits/pixel
Minimum exposure	20 ms
Maximum exposure	5 min
Maximum frame rate	50 frames/s
Mass storage	magnetic tape, 350 images/1200 ft tape

100×100×8×350 = 28 Mbits

dinate system. Thus, geomagnetic north is at the top in the images.

The images reveal marked structural changes in the aurora over large regions of the ionosphere (100 pixels corresponds to approximately 600 km in the horizontal direction at typical auroral altitudes). The intensity of each pixel is represented in a gray-scale manner from black (low intensity) to white (high intensity). Figure 5 illustrates the variations that can occur in the aurora over a period of a few minutes, especially in the more intense features. Here 16 images taken 60 s apart reveal significant intensity changes as well as the motion of some discrete auroral forms (four images of second row through first image of third row).

For the acquired data to be interpreted quantitatively, the instrument must be characterized so that digital output values obtained for any given pixel can be converted to intensities. The first step in this process is to separate the signal generated by incident photons due to auroral features from the signal due to the internally generated background level, primarily dark current in the CCD itself. Even though the CCD is cooled, each pixel accumulates charge, depending on the temperature and the integration time. Because the resulting output for any given integration period at the same temperature is reasonably consistent, dark images are accumulated that can then be subtracted from the appropriate images of actual auroral emissions.

Computation of the auroral source brightness B_L for any pixel i,j utilizes the relation

$$\int_0^\infty B_L T_\lambda d\lambda = C_\lambda * [S_{ij}(\tau,T) - D_{ij}(\tau,T)] * U_{ij} , \quad (1)$$

where T_λ is the transmission of the filter utilized (which is a function of wavelength), C_λ is the wavelength-dependent conversion factor from output digital value to kilorayleighs, S_{ij} is the observed count rate for exposure time τ and temperature T, D_{ij} is the corresponding dark level contribution, and U_{ij} is a normalization factor that accounts for nonuniformity in the intensifier photocathode and detector. The latter correction factor is obtained by filling the field of view of the camera with light of uniform intensity and normalizing all pixels to the maximum pixel response. This type of measurement is greatly facilitated by using an automated optical calibration system.[10]

Knowledge of the filter characteristics and of the source brightness at specific wavelengths from a low brightness

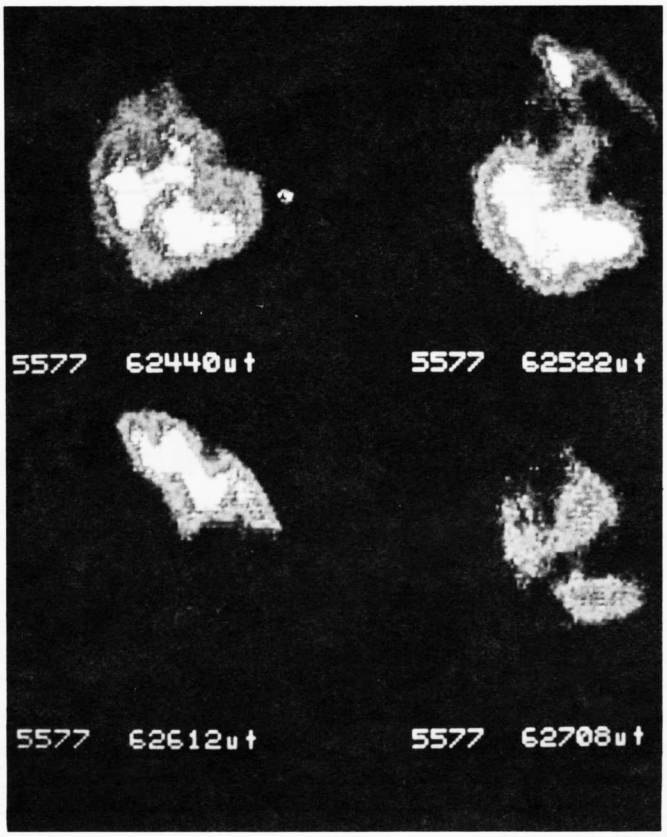


Fig. 4. ASC images of 5577 Å auroral emission taken 3 March 1984 between 062440 and 062708 UT from Fort Churchill, Manitoba. The sequence of four images illustrates the spatial variations that can be encountered in auroral observations and also the dynamic intensity changes (compare 062612 and 062708 UT). The data are oriented with geomagnetic east to the right; intensities are represented in gray scale with white corresponding to higher intensities.

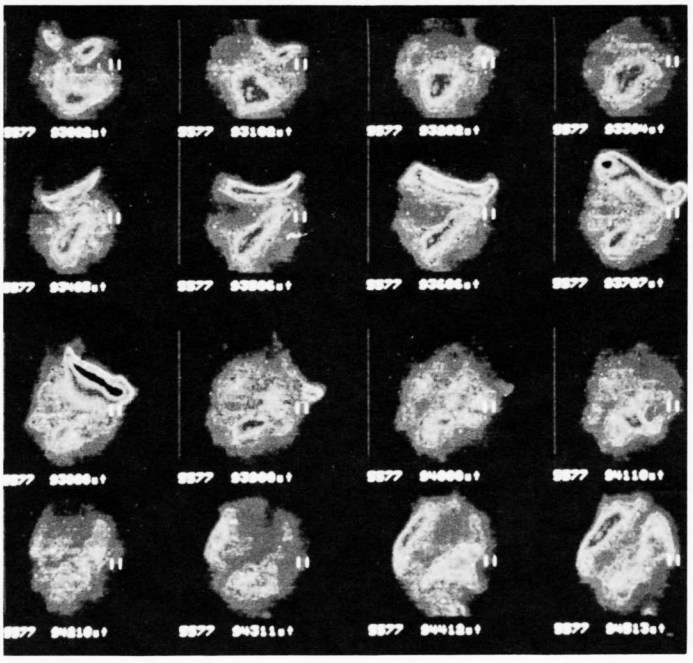


Fig. 5. A series of 16 images at 5577 Å taken 14 October 1982 in support of a balloon flight. The two vertical bars in each figure denote the balloon position with respect to the observed emissions.

TABLE II. Calibration constants.

Wavelength, Å	C_λ, $R \cdot ADU^{-1} \cdot s^{-1}$
3914	4470
4278	1430
5577	178
6300	236

source allows the computation of C_λ, the results of which are shown in Table II. The instrument sensitivity is inversely proportional to C_λ. Clearly the instrument is most sensitive at the atomic oxygen wavelengths, 5577 Å and 6300 Å, primarily due to the responsivity of the intensifier photocathode.

6. CONCLUSION

Utilization of the ASC during a variety of campaigns has shown its versatility in obtaining monochromatic all-sky images of auroral emissions.

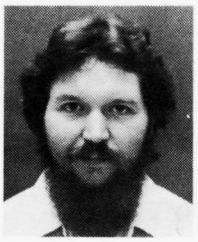
Though the instrument is very flexible in the manner in which data can be acquired, it is simple to use and responds rapidly to changing auroral conditions. Its all-sky capability has proven particularly useful in relating in situ measurements to the two-dimensional distributions of the aurora. Given a desired set of coordinates, it is straightforward to compute a pixel position and, because of the digital nature of all the stored data, to retrieve quantitative information about the actual intensity.

7. ACKNOWLEDGMENT

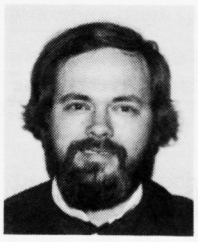
This work has been supported by the Natural Sciences and Engineering Research Council of Canada through Operating Grants A-7 and A-6762.

8. REFERENCES

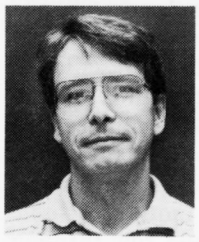
1. W. Stoffregen, "All-sky camera auroral research during the Third Geophysical year 1957–58," Tellus 7, 509–517 (1955).
2. C. D. Anger, J. Fancott, J. McNally, and N. S. Kerr, "ISIS-2 scanning auroral photometer," Appl. Opt. 12, 1753–1766 (1973).
3. E. H. Rogers, D. F. Nelson, and R. C. Savage, "Auroral photography from a satellite," Science 183(4128), 951–952 (1974).
4. L. A. Frank, J. D. Craven, K. L. Ackerson, M. R. English, R. H. Eather, and R. L. Carovillano, "Global auroral imaging instrumentation for the Dynamics Explorer mission," Space Sci. Instrum. 5, 369–393 (1981).
5. C.-I. Meng and R. E. Huffman, "Ultraviolet imaging from space of the aurora under full sunlight," Geophys. Res. Lett. 11(4), 315–318 (1984).
6. C. D. Anger, "Advances in auroral imaging from space," Adv. Space Res. 2(7), 97–105 (1982).
7. S. B. Mende, R. H. Eather, and E. K. Aamodt, "Instrument for the monochromatic observation of all-sky auroral images," Appl. Opt. 16, 1691–1700 (1977).
8. M. H. White, D. R. Lampe, F. C. Blaha, and I. A. Mack, "Characterization of surface channel CCD image arrays at low light levels," IEEE J. Solid-State Circ. SC-9, 1–13 (1974).
9. I. A. Trail, "A concept for interactive high-level languages: theory and application," in *European Computing Conference on Interactive Systems,* Online Conferences Ltd., Uxbridge, pp. 201–215 (1975).
10. L. Smith, "A computer controlled optical calibration system," M. Sc. Thesis, The University of Calgary (1981).



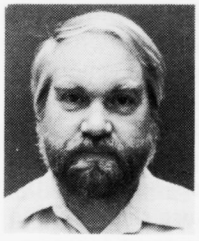
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AN ULTRAVIOLET AURORAL IMAGER FOR THE VIKING SPACECRAFT

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Abstract. The V5 ultraviolet auroral imager is one of a complement of experiments launched into polar orbit aboard the Swedish spacecraft Viking in February of 1986. The imager consists of two intensified wide-angle f/1 cameras, identical except in passband, with electronic despinning providing exposure times of one second. Critical to electronic despinning is the use of tapered fiber optic bundles to remove distortions generated when the spherical focal surface of the Burch configuration camera is projected onto the plane of the charge coupled detector. Data acquired by V5 are telemetered to a ground station in Kiruna, Sweden for archiving and real time display using a VAX11/750 system.

Introduction

In 1980 the Swedish Space Corporation decided to proceed with the development of its first scientific satellite aimed at a comprehensive study of the processes responsible for the Aurora Borealis. For this purpose a highly eccentric orbit over the north pole was selected in order that the satellite would pass regularly through the region near 15,000 km altitude where the charged particles responsible for the aurora may receive their kinetic energy. Since global observations of optical aurora were considered to be of great importance in interpreting the other measurements made on the spacecraft and since the orbit chosen provides an extended viewing opportunity at high altitudes over the polar regions, it was decided to include some form of optical instrument in the payload complement, preferably one which could detect auroral emissions in daytime as well as nighttime conditions. The design of this instrument was influenced by the following considerations:

1. Experience gained from previous imagers such as ISIS-II Anger[1973], DMSP Rogers[1974], Kyokko Hirao[1978], Dynamics Explorer Frank[1981], and Hilat Meng[1984].

2. Under the viewing conditions provided by the satellite, auroral observations in the visible part of the spectrum would be ruled out on the dayside of the earth by the intense background coming from the earth and sunlit atmosphere. Even on the nightside, the proximity of the sunlit part of the earth to the field of view would inevitably produce so much scattering in the instrument optics as to virtually rule out high resolution imagery with a compact camera. This led to the conclusion that observations would need to be made in the vacuum ultraviolet part of the spectrum where solar flux and low reflectivity of the atmosphere permit auroral observations to be made in both the dark and sunlit hemispheres.

3. A fast reflecting optical system with a 25° field of view and the minimum number of optical elements was needed. These objectives were satisfied with an f/1 inverse Cassegrain Burch camera involving two spherical mirrors. The resulting focal surface was spherical with a radius of curvature of 22.4 mm.

4. It was desired to image separately at the two most prominent UV auroral emissions (LBH and OI) in order to derive from their relative intensities and spatial distributions, information on the precipitating electrons responsible for their emission.

5. Curved microchannel plate (MCP) intensifiers were required to conform to the spherical focal surface. A number of considerations led to the decision to use open intensifiers, with the photocathode material deposited directly on the front surface of the MCP. The cesium iodide and potassium bromide cathodes required for the chosen wavelength ranges meant that the intensifier assemblies had to be maintained in a vacuum or dry nitrogen environment at all times.

6. Gain from a single stage MCP was more than adequate and avoided the resolution and lifetime problems of multistage MCP's. Good transfer efficiency was accomplished by directly coupling the intensifier to the detector with fiber optic blocks. The fiber blocks also provided the desired mapping of the spherical surface of the intensifier to the plane of the CCD.

7. In order to achieve the desired sensitivity, exposures of one second were necessary from a spinning satellite. This was accomplished by synchronously stepping the charge accumulating in the CCD with the image motion due to satellite spin. This required that the CCD columns be aligned with the spacecraft equatorial plane to within ±0.2°.

8. Interactive control of the instrument pointing and image size was needed in order to make effective use of the available telemetry bandwidth and to meet varied scientific objectives. The CCD exposure was triggered at any desired point in the spacecraft spin using a reference pulse from the spacecraft limb or sun sensors. Flexible CCD readout electronics made it possible to shrink or enlarge the effective image dimensions and to shift the field of view within the bounds of the optical system. All of the above could be accomplished in near-real-time by the instrument operator, but necessitated having an extensive viewing and planning capability at the ground telemetry site in Kiruna, Sweden. A summary of the instrument characteristics is given in table 1.

Optics and Image Mapping

The layout of the camera, a concentric spherical optical system originally used by Burch[1947] (Fraser[1953], Rosin[1968], and Wynne[1969]) as a reflecting microscope objective, is shown in Figure 1. Components of the system are anchored inside a graphite fiber epoxy composite tube (GFEC) which is sealed with a dust cover. The camera was kept under a dry nitrogen purge until a few hours prior to launch at which time the purge was removed leaving the camera sealed with a

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TABLE 1. Instrument Characteristics

Characteristics	Value
focal length, f/no.	22.4mm, f/1
field of view	20° by 25°
ccd format	288 by 385 pixels
effective pixel size	30 μm square
angular resolution	0.076° by 0.076°
time resolution	20 seconds
dynamic range	256 (8-bits)
photocathodes	CsI (0), KBr (1)
filters	BaF_2 (0), CaF_2 (1)
passbands (0.1 of peak)	1340–1800Å (0), 1235–1600Å (1)
sensitivity	0.1–0.4 dn per photoelectron

slight positive pressure. The dust cap was not released until several hours after orbit had been achieved.

With a field of view of 25° and reflecting surfaces throughout, this compact f/1 system yields good optical throughput and sensitivity in the UV. The arrangement gives excellent correction for spherical aberration while off-axis aberrations are minimized by the concentric design. The image surface is a section of a sphere having the same centre of curvature as the mirrors. The overall resolution of the system is limited by the image intensifier to approximately 0.076° .

The concentric design of the optics, including the conformal microchannel plate and phosphor screen, ensures that the image formed is free of angular distortion in the sense that the external field is accurately mapped onto the spherical image surface. If this surface is projected onto the CCD by a parallel bundle of fibers, the image will be distorted in the same way that the latitude-longitude grid on the spherical earth is distorted in an orthogonal projection onto a flat map surface. This leads to a point spread function of several pixels at the edges of an image formed from a spinning platform.

This degradation can be removed by introducing a tapered fiber optic assembly between the MCP and the CCD. The entrance and exit surfaces of the assembly are figured to match the corresponding surfaces of the MCP and the CCD, while the interior surfaces are figured to compensate for the distortions due to projection. Image transformation using fiber optic bundles was examined by Truscott and Tosswill at the Galileo Electro-Optics Corporation (technical memorandum). A discussion of the V5 image corrector is given by King et al. (in preparation).

Thermal Effects on the Optics

The camera must operate down to temperatures as low as −30° C but final focusing adjustments are conveniently made only at room temperature. It was therefore desirable that it should stay in focus over this temperature range. The sensitivity of the Burch design to the separation of the primary and secondary mirrors was minimized because the GFEC housing has a near zero thermal expansion coefficient along the optic axis of the camera and because the mirrors are made from Zerodur which also has a very low expansion coefficient. As a consequence of this choice of materials the camera should stay in focus through the operating temperature range.

Camera Passbands

The imager comprises two separate cameras with passbands respectively from about 1235–1600Å and from 1340–1800Å. The shorter wavelength camera (Camera 1) transmits the strong 1304Å and 1356Å OI multiplets as well as some N_2 LBH bands while the other (Camera 0) cuts off the OI lines but passes the LBH bands as well as some contribution from the 1493Å NI line. The passbands were achieved by combining:

Camera 0. a BaF_2 filter and CsI photocathode

Camera 1. a CaF_2 filter, KBr photocathode, and reflective coatings on the secondary mirror

The CaF_2 and BaF_2 filters provide the short wavelength cutoff to the passbands. These filters were placed in the central hole of the secondary mirrors. In this location the filters which were specifically polished for low UV scattering do not affect the image quality. The photocathodes provide the long wavelength cutoff for the camera passbands and in particular confer very low sensitivity for visible light scattered from the terrestrial atmosphere and surface. This is important if the imager is to be able to image aurora in the daylit portion of the polar cap. The residual quantum efficiency of CsI and KBr photocathodes is poorly known in the critical region at wavelengths longer than 3000Å but according to tube manufacturer's data it should not exceed 2.0×10^{-6} percent at 3000Å and should fall by a factor 10 for every 290Å. For such quantum efficiencies the signal from the sunlit earth and lower atmosphere could be comparable with the expected signal from IBC2 aurora for Camera 1 and consequently it was thought wise to introduce some extra attenuation at longer wavelengths. This was achieved by overcoating the secondary mirror of Camera 1 with a selectively reflecting coating supplied by Acton Research Corporation. The mirror of Camera 0 was not overcoated because it was more important to maintain maximum sensitivity in the far UV rather than to minimize response in the visible. It does not appear likely that useful information on incident electron energy is obtainable from the ratio of the camera signals under daylit conditions because of the important contribution of 1304Å dayglow to the signals of Camera 1. The remaining mirror surfaces were overcoated with aluminum by Acton Research Corporation for maximum reflectivity in the 1250–1500Å region.

Preliminary estimates of V5's sensitivity indicate that sub kilo-rayleigh aurora would be detectable in a 1 second exposure. This is consistent with expected sensitivities of a few photoelectrons per pixel-spin and electro-optic gains in the range 0.1–0.4 dn per photoelectron. (One dn is a unit of 8-bit digitized video signal from the cameras.) Visible light rejection in the dayglow region of the spectrum is provided by the photocathode response, by attenuation through multiple scattering in the channels of the MCP, and by an aluminum overcoating on the fiber optic tapers. Preliminary observations of dayglow at 1304Å are consistent with expected fluxes.

The Baffle System

The cameras must frequently operate when the vector to the sun lies at an angle of less than 90° to the camera axis and consequently it is necessary to use a baffle system to prevent the scattering of ultraviolet light into the detector from illuminated surfaces in the optical path. The most vulnerable surfaces would be those of the CaF_2 and BaF_2 filters and the mirrors which can scatter directly into image space. The baffle system employed prevents the sun from directly illuminating the filter, the mirrors, or the stop at the edge of the filter. This greatly reduces the level of stray light. However light could still scatter from the interior of the baffle tube onto the

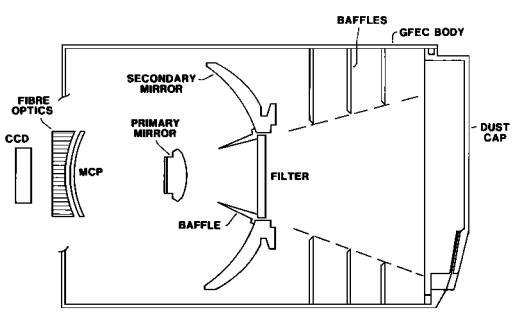


Fig. 1. A schematic cross section of one camera detailing the GFEC housing, inverse Cassegrain optics, baffles, dust cover, filter, curved intensifier, fiber optic tapers, and the CCD.

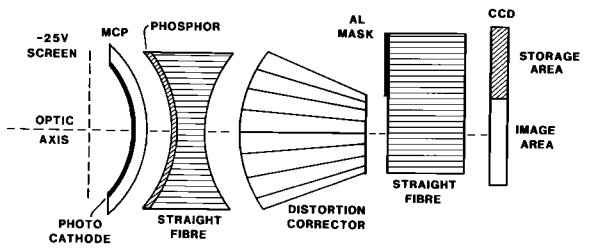


Fig. 2. A schematic cross section of the intensifier assembly detailing the electron screen, the curved mcp and photocathode, the phosphor screen, sections of the fiber optic distortion corrector, and the CCD.

filter. The level of scattered light from the baffle is reduced by a series of vanes provided with knife edges. The vanes eliminate direct scattering paths from the walls of the baffle to the filter. The residual scatter arises from two sources:

1. scatter from the tips of the knife edges and
2. multiple scatter from the fronts of the vanes to the back surfaces of preceding vanes.

As pointed out by Breault[1977] these two sources can be comparable. The diffuse and specular reflectance of the vane and baffle tube surfaces are important in controlling the amount of scatter. Analysis of the baffle system indicated that provided the surface diffuse reflectance of the baffle system surfaces is less than 3 percent, then the contribution from multiple scatter should be less than that from the knife edges. The total baffle scatter, with all the vane knife edges directly illuminated (except for the innermost edge at the filter), and for a diffuse reflectance at the knife edge of 5 percent, should be less that 20 percent of the IBC2 signal for Camera 1. For Camera 0 the predicted signal from scatter under this most unfavourable condition may be comparable to that of the signal.

The critical sun angle for the baffle system is about 45°. Baffle scatter will be most serious when the spacecraft orbit approaches the noon-midnight sector and will probably introduce some limitations in the viewing time of the midnight sector of the auroral oval under this condition.

The Image Intensifiers

The intensifiers which were fabricated specifically for the V5 imager are shown in Figure 2. They are windowless and are curved to conform to the curved focal surface of the camera. The intensifier housing, of Macor machinable ceramic, holds the MCP and other components in position using a series of ceramic rings. Electrical contact to the phosphor and MCP is through flat circular electrodes touching the outside edges of their surfaces. The housing is completely demountable except for the output faceplate, which is permanently bonded in place.

The photocathode material is deposited directly on the front surface of the MCP. Photoelectrons from the photocathode initiate an electron cascade in a channel of the MCP with the resulting electron image collected on a phosphor screen deposited on a concave depression in the fiber-optic output faceplate. This concavity matches the curvature of the back surface of the MCP, so that good proximity focusing can be maintained over the full field. Incorporated in the faceplate is the fiber optic bundle which transmits the visible light generated at the phosphor screen to the CCD and also serves as a distortion corrector. In front of the MCP is a screen held at −25 V. In combination with a +25 V potential on the front surface of the MCP, this screen provides a modest barrier against low-energy charged particles. The potential also pushes photoelectrons back toward the MCP.

The custom MCP's needed to conform to the spherical focal surface of the optics were made by Galileo Electro-Optics Corporation. They are 24.8 mm in diameter, with a spherical radius of curvature of 22.4 mm, giving them a pronounced dome-like appearance. The 12 μm channels are parallel to the optic axis of the camera. Because rays forming the image cannot be parallel to the optic axis at the focal surface, visible light from the image undergoes multiple scattering in the channels of the MCP, reducing its intensity by approximately 5000. The measured gains are typical of MCP channels having a length-diameter ratio of 40. Current gains of approximately 20,000 at 1000 V agree well with gains inferred from pulse-height distributions. Deposition of the photocathodes did not affect the gain.

Electrons from the MCP are accelerated to the phosphor by a potential difference of about 3500 V, and the light produced there is conducted to the CCD by the fiber-optic output faceplate. The P-20 phosphor is deposited over a transparent layer of tin oxide for good electrical contact, and overcoated with approximately 200 Å of aluminum. Testing showed that this overcoat was necessary to prevent visible light scattered through the channels of the MCP from reaching the CCD, where it could compete with the UV-stimulated light from the phosphor. About 2000 eV is lost by each electron in penetrating the aluminum layer. Deposition of the tin oxide, phosphor, and aluminum were performed by Galileo Electro-Optics Corporation.

The hygroscopic nature of the KBr and CsI photocathode materials imposed special requirements on the handling of the MCP's once the cathodes had been deposited. To avoid exposure of the cathodes to water vapor, the coated MCP's were never exposed to air. They were stored in vacuum, and transported and handled in containers purged by dry nitrogen gas. For coating and vacuum testing, the plates were held in a sealed, purgeable fixture having an electrically-actuated door. The same fixture held the completed intensifier for vacuum testing. Special carrying containers were fabricated for transporting the coated plates. These vacuum-tight containers were loaded in a nitrogen atmosphere, purged with nitrogen, and then sealed. For assembly into the intensifiers, the MCP's were removed from vacuum storage to a nitrogen-purged bag, installed in the intensifier housing, and the assembly was returned to vacuum storage or placed in vacuum test. After installation in the camera, the windowless intensifier is protected by a purge of dry nitrogen.

The Detectors

The cameras use English Electric Valve P8602 CCD array detectors to sense the visible image produced at the phosphor. The CCD is a three-phase frame transfer device having 288 rows and 385 columns in both the image and storage regions. The CCD's were procured without windows and bonded to fiber optic blocks. When projected onto the MCP, the CCD pixels have an apparent size of 30 μm square. An opaque layer of aluminum was deposited on part of the fiber block to mask the storage region of the CCD. The CCD's used in the flight instruments were selected from a large number of candidate CCD's that underwent optical and electrical testing.

Spin compensation is achieved electronically by stepping the charge in the CCD from row to row in synchronism with the motion of the image. Moving the charge in this manner is a normal part of the CCD readout process. Normally this is done rapidly at the end of an exposure to minimize smearing due to the accumulation of additional photoelectrons as the charge steps through the image region enroute to the dark storage area. However, in this case the image itself is moving, and it is only necessary to keep the moving charge pattern matched to the image in order to achieve an effective exposure time of 1 second for each element in the scene. The optical design must be such that each element moves in a straight line down a column at a uniform rate if smearing is to be avoided; hence the emphasis on distortion-free optics.

The Electronics

The electronics divide into five primary blocks: spacecraft interfacing and control, central processing unit (CPU), random access memory, CCD clock drivers and video signal chain, and the power supply. These blocks are closely aligned to the actual board configuration in the electronics enclosure, a magnesium housing which was potted with Eccofoam FPH to secure the electronics against launch vibrations.

The spacecraft interface receives and processes commands from the telemetry uplink and transmits the downlink telemetry stream at an effective bit rate of 5.1 kbps. Data can also be transmitted down via V4 (when that experiment has spare channel capacity) increasing the bit rate to 30.7 kbps. The spacecraft interface also detects pulses from the limb and sun sensors, which provide a reference for triggering image acquisition.

The CPU is a bit-slice type architecture with dual ported registers and 1024 32-bit words of microcoded program that can be uploaded from the ground station. A reduced instruction set CPU minimizes program size and speeds execution. Ease of programming was sacrificed to simplify hardware requirements.

The instrument software maintains five imaging parameter lists, one of which is a default (power-up) list. Each list contains information to define an image: ID tag, high voltage setting (intensifier gain), camera select (either or both), camera video gain, spin rate correction factor for synchronous stepping (vertical clock frequency), vertical and horizontal size, viewing angle, pixel binning factors, earth limb or sun time delay (rotational viewing angle), and an image repeat factor. The instrument steps through the command lists, executing each one at its repeat factor. The command lists may be loaded from the ground station during a pass.

In addition to the program store, there are 48 kBytes of data memory that are used for storing image sequence parameters, variables, and the image header and image data before telemetry transmission. It is implemented using radiation hardened Harris 8 kByte CMOS RAM modules.

The CCD analog circuitry develops the necessary horizontal and vertical clocking pulses and processes the video signal from the CCD's. Correlated double sampling is used to reduce noise. The amplifier gain is selectable. An 8-bit analog to digital converter digitizes the multiplexed video signals from each camera as well as the outputs from temperature sensors.

The low voltage power supply generates several voltages for the analog and digital electronics. It is an efficient switching supply synchronized to the spacecraft 54 kHz clock to confine switching noise to known frequencies. A special slow-start circuit minimizes the start-up current surge. When the main 28 V power is turned off at the end of a satellite pass, a low current 5 V program-memory keep-alive power is generated from the 54 kHz spacecraft clock which is always present during the experiment off period. A high voltage power supply generates a voltage selectable in eight steps from 750 V to 950 V for the MCP. A second high voltage supply generates a fixed voltage of 4500 V for the intensifier phosphor screen.

Conclusions

The V5 instrument, by realizing some of the potential inherent in the use of intensified CCD technology and fiber optic tapers, will yield images with spatial and temporal resolutions an order of magnitude beyond those currently available. One can reasonably expect future generations of auroral imagers to provide more detailed spectral information and to lessen the gap between the Image and the Reality.

References

Anger, C. D., T. Fancott, J. McNally, and H. S. Kerr, ISIS-II Scanning Auroral Photometer, *Applied Optics, 12*, 1753–1766, 1973

Breault, Robert P., Problems and Techniques in Stray Radiation Suppression, *SPIE, 107*, 2–23, 1977

Burch, C. R., Reflecting Microscopes, *Proc. Phys. Soc., 59*, 41–46, 1947

Frank, L. A., J. D. Craven, K. L. Ackerson, M. R. English, R. H. Eather, R. L. Carovillano, Global Auroral Imaging Instrumentation for the Dynamics Explorer Mission, *Space Sci. Inst., 5*, 369, 1981

Fraser, R. D. B., A 0.8 N.A. Reflecting Microscope for Infrared Absorption Measurements, *JOSA, 43*, 929–930, 1953

Hirao, K. and T. Itoh, Scientific Satellite Kyokko (EXOS-A), *Solar Terr. Env. Res. in Japan, 2*, 148–152, 1978

Meng, C. I. and R. E. Huffman, Ultraviolet Imaging From Space of the Aurora Under Full Sunlight, *GRL, 11*, 315–318, 1984

Rogers, E. H., D. F. Nelson, R. C. Savage, Auroral Photography From a Satellite, *Science, 183*, 951–952, 1974

Rosin, Seymour, Inverse Cassegrainian Systems, *Applied Optics, 7*, 1483–1497, 1968

Wynne, C. G., Two-Mirror Anastigmats, *JOSA, 59*, 572–578, 1969 (Errata, *JOSA, 60*, 143, 1970)

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The application of CCD detectors to UV imaging from a spinning satellite

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ABSTRACT

One of the instruments operated during the successful Swedish Viking satellite mission of 1986 was an Ultraviolet Imager contributed by Canada. The camera provided global images of the aurora with exposure times of about one second and repetition rates of one to three per minute. This time resolution was achieved using the combination of a fast (f/1) camera, an image intensifier and a coupled CCD detector operated in the time-delay-integration (TDI) mode to "de-spin" the instrument. Interactive control and real-time analysis of data were integral parts of the instrument design. The instrument provided approximately 45,000 images. Based upon the Viking experience, a new UV imager is being developed for the Auroral Probe satellite of the Soviet Union's multi-satellite Interball program.

1. INTRODUCTION

Although a great amount of knowledge of the Earth's atmosphere, magnetosphere and the solar wind has been acquired since the development of scientific satellites, there remains much to learn about the processes that couple energy from one region to another. These processes are not only complex in nature, but they vary dramatically with time and position. One natural indicator of magnetospheric processes is the global distribution of optical aurora; atmospheric atoms and molecules radiate in response to excitation by electrons and protons that have been accelerated to high energies in the magnetosphere. The upper atmosphere serves as a screen which provides indirect, but valuable, information about the incoming energy flux that would be impossible to acquire with point measurements either on the ground or in space; and for this reason considerable effort has been expended on obtaining global auroral images from satellites. Ideally, such images should be instantaneous views of the aurora, covering both the dayside and nightside of the earth with temporal and spatial resolution consistent with the scale size of the relevant magnetospheric processes.

The acquisition of auroral images from space poses severe technical problems, and for that reason an ideal instrument as described above does not exist. Nevertheless, there has been considerable progress towards this goal since the first auroral imager was flown on the ISIS-2 satellite[1] in 1971. Two-dimensional views of the auroral distribution were obtained at wavelengths 391.4 and 557.7 nm, corresponding to two prominent auroral emissions, by combining the orbital motion and rotation of the satellite with a 13 pixel image dissector tube. It required about 15 minutes to traverse an auroral zone, and almost two hours (the orbital period) elapsed between views of the same polar region. In spite of the obvious limitations, the experiment led to new insights concerning the nature of aurora. Shortly thereafter the series of DMSP satellites utilized white-light scanners to image segments of the auroral zones each orbit[2]. The combination of a scanning mirror and the orbital motion provided images of superior spatial resolution, but still with a low repetition rate. As with ISIS-2, useful observations were limited to the nightside of the earth. Viewing of aurora on the dayside was possible from the Kyokko (EXOS-1)[3] satellite because its image-memory tube was sensitive to the wavelength range 120 to 140 nm where there is little reflected sunlight from the earth and atmosphere. An oscillating mirror was used to "de-spin" the satellite during an exposure, providing one image every spin period (2 minutes). Instrumental difficulties have unfortunately resulted in limited scientific returns. The imager on the Dynamics Explorer satellite (DE-1)[4] has operated successfully since launch in 1981. It consists of three photometers and a wide assortment of selectable filters to provide monochromatic images at both UV and visible wavelengths. Two-dimensional images are constructed in a line- by-line manner approximately every 12 minutes from each photometer by means of a one-axis scanning mirror combined with the spacecraft rotation. Because of the large apogee, long sequences of observations are possible. Spectrometers[5] flown on the HILAT satellite, launched in 1983, and on the POLAR BEAR satellite, launched in 1986, obtained images at selected UV wavelengths; a scanning mirror combined with the orbital motion provided images of the polar region every orbit.

Experience gained from previous imagers led to the design of a CCD-based UV camera that is capable of viewing the auroral distribution every satellite rotation without the use of a scanning mirror. Two of these cameras were flown on the Swedish Viking satellite in 1986, and two others will be utilized in the Interball program being coordinated by the USSR. In the Viking application, the exposure time was extended to about one second, which is consistent with a 20 degree field of view in the scan plane for a satellite rotation period of 20 seconds. Images could be acquired at a repetition rate of up to one every 20 seconds, although due to telemetry constraints the rate was typically about one image per minute. The two cameras were designed to respond primarily to two different auroral emissions, providing the possibility of relating observed emission rate ratios to the characteristic energy of the precipitating electrons. Another unique feature of the Viking mission was real-time control and monitoring of the camera operation by scientists at the ground station. During the twelve month mission, a total of about 45,000 auroral images were acquired; these have stimulated a great deal of scientific analysis[6].

The purpose of this paper is to describe the basic design and operation of this type of imager, and to present an evaluation of its performance based upon the experience gained from the Viking mission. Modifications of the design to accommodate the Interball mission will also be outlined. Some examples of auroral observations will be included to illustrate the nature of the images that have been acquired.

2. INSTRUMENT DESCRIPTION

The design of the cameras for the Viking and Interball missions was driven strongly by the need to obtain rapid images of relatively weak auroral emissions that occur on the dayside as well as the nightside of the earth. Moreover, the images were to be taken from a spinning satellite which placed constraints on the exposure time. It was obvious that auroral observations would have to be made in the vacuum ultraviolet part of the spectrum where the solar flux is weak and the reflectivity of the atmosphere is low. A compact, fast reflecting optical system was chosen to maximize the photon collection rate per pixel of the image. The detector module consists of a microchannel plate intensifier (MCP) coupled by fiber optic blocks to a CCD array detector. This system would still be too insensitive to be used on a spinning satellite unless steps were taken to increase the exposure time from a few milliseconds (i.e. the maximum time to prevent spatial smearing greater than 20 km when the satellite is spinning at 3 revolutions per minute) to about one second. The increased exposure time is accomplished by causing the accumulated charge in the CCD pixels to move along the columns of the CCD array at the same rate as the image moves through the field of view. The clocking rate must be adjusted to match the spin rate exactly, and an initiation pulse must be obtained from either an earth limb or sun sensor. For this method of operation to be successful, the CCD columns must be closely aligned with the spacecraft equatorial plane, and fiber-optical tapers must be employed to transform the image at the intensifier onto an orthogonal grid.

The description that follows pertains to the cameras used on the Viking spacecraft because they have already been flown. The cameras for the Interball mission have not yet been completed (launch is expected in 1990), but modifications to the Viking cameras can be identified at this time.

A schematic drawing of a single camera is shown in Fig. 1, and a list of instrument parameters is given in Table I.

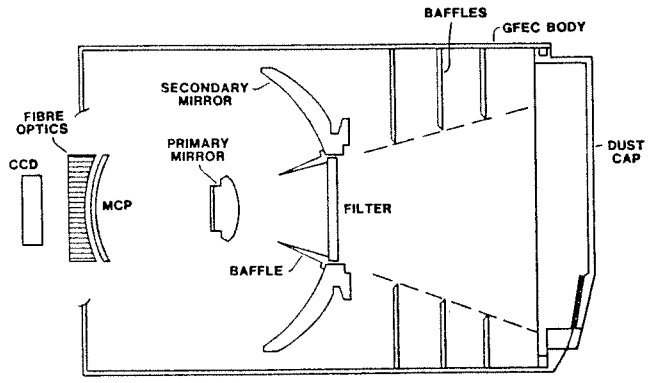


Figure 1. Schematic cross section of one Viking UV camera.

Table I. Operating Characteristics (Viking Cameras)

Parameter	Value
Focal length, f/no.	22.4 mm, f/1
Field of view	20 deg. by 25 deg.
CCD format	288 by 385 pixels
Effective pixel size	30 microns square
Angular resolution	0.077 deg by 0.077 deg
Time resolution	20 s(1 spin period)
Exposure time	1.2 s(for 20 s spin period)
Dynamic range	0 to 256 (8-bit A/D)
Photocathodes	CsI(camera 0);KBr(camera 1)
Filters	
Passbands(0.1 of peak)	134-180nm(camera 0); 124-160nm(camera 1)

The camera unit is 25 cm long and 12 cm in diameter. The body is made of a graphite fiber epoxy composite tube (GFEC) to minimize the thermal expansion of the body over the expected temperature range. A dust cover seals the camera until the planned orbit has been achieved. The inverse Cassegrain optics form a Burch-type camera[7] of 22.4 mm focal length that operates at f/1, providing UV sensitivity with good throughput over a 25 degree field of view. The filter is positioned in the central hole of the secondary mirror where it does not adversely affect the image quality. The baffle system is necessary to prevent sources outside the field of view from illuminating the filter directly, and to attenuate the level of scattering into the instrument[8].

The image formed by this type of camera conforms to a spherical surface having the same center of curvature as the mirrors. Rather than attempting to flatten the field, it was decided to incorporate a curved microchannel plate intensifier (MCP) with the photocathode material deposited directly on the surface. The open design required that special care be taken so that the photocathodes were never exposed to ambient air; they were stored either in a vacuum or under a dry nitrogen gas purge. The phosphor screen of the MCP has the same curvature as the photocathode, the channels are 12 microns in diameter and provide a current gain of about 20,000 at 1000V. Between the exit of the channels and the phosphor a potential difference of about 3500 V accelerates the electrons that strike the phosphor. The P-20 phosphor is deposited on a layer of tin oxide for good electrical contact, and overcoated with approximately 200 A of aluminum to stop visible light. The intensifier assembly was manufactured by Galileo Electro-Optics Corporation.

Light from the phosphor is transmitted to the CCD detector by a combination of fiber optic sections that match the surfaces of the CCD and curved phosphor and also removes the distortion due to the projection of the spherical focal plane onto the flat CCD detector[9]. Without this distortion corrector, images of points

on the earth would not move in straight lines as the spacecraft spins. The CCD array detector is a model P8602, made by English Electric Valve, with 288 rows and 385 columns in both the image and storage regions. Purchased without a window, the CCD was bonded to a fiber optic block. Each pixel when referred to the photocathode is about 30 microns square and subtends an angle of 0.077 degrees corresponding to about 20 km at the earth for a satellite near 15,000 km altitude.

The optical passband of the camera is determined by the photocathode material, the filter, and mirror coating. For the Viking mission, the two cameras utilized different photocathode materials and filters (see Table I). In addition, to ensure that at least one camera could detect aurora in daylight, camera 1 received a mirror coating especially designed to reject long wavelength (>2000 A) light, and its fiber optical taper was coated with aluminum. Special high reflectance aluminum coatings were applied to the remaining mirror surfaces by Acton Research Corporation.

The charge from each CCD is clocked out, synchronously sampled, amplified, and digitized (8 bits). Data storage of 48 kilobytes contains the images and other parameters assembled for direct transmission. For the Viking satellite with a spin rate of about 3 rpm and a normal telemetry rate of 5.1 kilobits per second it was not possible to transmit full resolution images from each camera every spin; it was common to use 2 by 2 pixel binning and to record images every three or four spins. On occasions when access to a higher rate (30.7 kilobits per second) was arranged, improvements in either spatial or temporal resolution were achieved. Real-time monitoring of the images at the ground station (Kiruna, Sweden), made it possible to respond to auroral conditions as they changed during a single pass over the polar region. The satellite was in an elliptical, polar orbit of period 4 hours and apogee near 13,500 km altitude.

The design of the cameras for the Interball program is based upon the Viking cameras; nevertheless, significant changes are necessary to accommodate the different satellite orbital configuration, spacecraft architecture, and telemetry. The Auroral Probe satellite of the Interball program is expected to have an inclination of 65 degrees, an apogee of 20,000 km, an orbital period of 6 hours and a spin rate of 0.5 rpm with the spin axis pointed at the sun. In order to optimize the auroral coverage, there will be two cameras with the same passband, one pointing 90 degrees to the spin axis (like Viking) and the other pointing 67 degrees from the spin axis. In this way the two 25 degree fields of view overlap to provide coverage of 46 degrees. The offset camera requires different image distortion correction which will be provided by special optical fiber tapers. Another change will be the choice of a closed rather than open intensifier to eliminate the possibility of contamination of the photocathode. The window of the intensifier, most likely made of calcium fluoride, will serve as the camera's filter.

Operational methods will also be different for the Interball mission. There will be onboard storage capacity (magnetic tape) which will permit data taking when the satellite is out of view of a ground station. This also means that access to the satellite for real-time control and monitoring will be greatly reduced, and for this reason there will be electronic and software changes introduced to minimize the dependence on ground station personnel. One obvious change is to increase the dynamic range of the cameras by using a 12-bit analog to digital converter. Another change is to implement software that can adjust the time delay for the exposures without intervention from a ground station. A major addition for Interball is a one-axis adjustment of the pointing direction to correct for a possible 2 degree offset of the spin axis from its predicted direction. This correction may be required to align the columns of the CCD detectors with the scan plane; otherwise, smearing will result.

The Interball cameras will be ready for a two-year mission beginning in late 1990. The combination of satellites (one near the earth, the other some 200,000 km away) as well as complementary ground-based observations should result in significant advances in the understanding of auroral and magnetospheric processes.

3. INSTRUMENT OPERATION

The Viking satellite was successfully launched on 22 February, 1986 and the first useful scientific data was obtained 2 weeks later. Software control of practically all instrument functions allowed considerable flexibility in obtaining the most useful view of the northern hemisphere auroral distribution. In addition the cameras were designed for real-time commanding and data acquisition. The onboard central processing unit (CPU) controls the operation of both cameras by reference to parameter lists that can be altered via the telemetry uplink. To illustrate the necessity for such flexibility Fig. 2 presents a graphical view of the earth as seen from the satellite for an arbitrary time during the mission. The rectangular field of view of a single camera is indicated along with the limits of observation perpendicular to the scan plane. The scan plane is defined as that plane perpendicular to the spin axis which should contain the optical axis of each camera. In addition (and most importantly) the charge transfer direction must be parallel to this plane.

The basic viewing conditions are of course determined by the satellite position and spin axis pointing direction which limits the field of view in the direction perpendicular to the scan plane. However, since the satellite is spinning there is complete freedom as to where to position the field of view within the 360 degree segment swept out by the satellite. In Fig. 2 the image acquisition was centered on the northern auroral distribution. The relevant parameter is denoted as angin and represents the angle of separation between row 1 of the CCD and the edge of the earth in the scan plane. In Fig. 2 therefore, angin is slightly negative. This angle is ultimately obtained from the time difference between a signal indicating an absolute reference position within the spin and the time when image readout begins. Normally the reference signal is

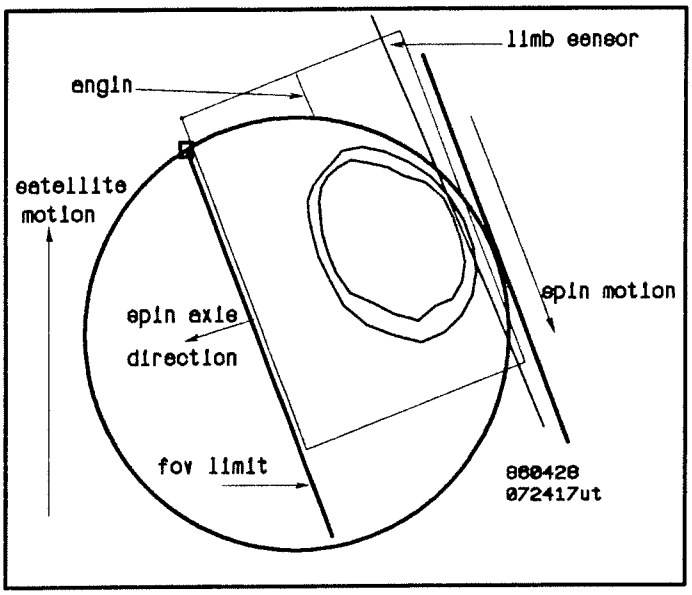


Figure 2. Schematic of viewing conditions of the Northern Hemisphere from the Viking Satellite for 860428 at 072417 UT.

Table II. Commandable Parameters Affecting Image Format

Parameter	Typical Value
Row Binning	2
Column Binning	2
Number of Rows	288
Column Offset	22
Number of Columns	344

provided by an earth limb sensor. On Viking the earth limb sensor was not coplanar with the optical axis of the cameras (see Fig. 2). Because Viking was not always in a cartwheel configuration, there were times when the earth limb sensor did not intersect the earth. At such times it was necessary to utilize a signal from the sun sensor to obtain the equivalent information.

In addition to having control over the position of the image within the spin there is considerable flexibility over how to readout the pixels from each CCD. Table I indicates the physical characteristics of each CCD and Table II presents certain commandable parameters which affect the image format. As noted above the onboard memory for the Viking imager was not large enough to contain full resolution images from both (or even one) camera. It was therefore normal to do on-chip binning in both the row and column directions. This binning is done as the CCD is read out. The remaining parameters in Table II control windowing of the image within the CCD. With reference to Fig. 2 for example, not all of the CCD columns were utilized in obtaining that image because the selected field of view is slightly smaller than the total field of view.

During the data acquisition period, parameters such as these were organized into command files and telemetered to the satellite every orbit. It was possible given the real-time commanding and data acquisition capabilities to make immediate adjustments to viewing conditions. Generally, the effects of changes could be assessed by visual inspection of the data on a color display monitor within 3 minutes of a command change. This rapid access to both data and command facilities provided assessments of global auroral conditions in support of ground-based rocket and balloon launches for the first time.

4. PERFORMANCE

The successful operation of the instrument is best demonstrated by displaying the raw images in standard two - dimensional format as shown in Fig. 3. The data for each image comprises a 72 byte header and some arbitrary number of pixels (8 bits per pixel)for each camera in column major format. Each of the four images in Fig. 3 is simply a formatted version of the raw data stream. For display the 8 bit pixel value (or data number - DN) is represented in a grey scale scheme: in Fig. 3 increasing DN corresponds to proceeding from black to white. Note that the pixel values are in fact binned CCD pixels and thus represent in this case 4 CCD pixels each. The instrument generally was operated in one of two basic modes: 1) with simultaneous readout of both cameras so that point by point comparisons of intensities acquired at exactly the same time could be made; 2) alternate camera mode where the temporal resolution was better than 1) but data from the same camera was acquired only every other image. In general images were sized so that 1 minute temporal resolution was obtained. This does not mean that it took 1 minute to acquire the image: rather every pixel in the CCD is exposed simultaneously for approximately 1 second. The temporal resolution is governed by the telemetry rate and spin rate not the exposure time.

One of the most crucial aspects of instrument performance is the determination of the alignment of the cameras. There are 3 main degrees of freedom:

1) angle of the optical axis with respect to the sensor (or sensors) providing timing pulses
2) angle of the optical axis perpendicular to the scan plane
3) angle which the charge transfer direction makes with respect to the scan plane.

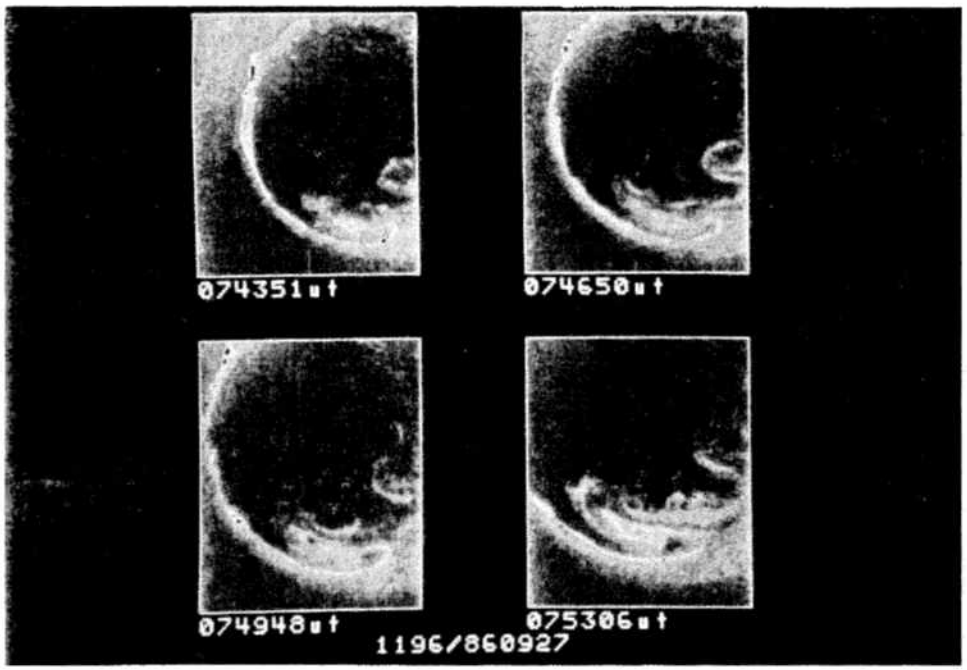


Figure 3. UV image data obtained from the Viking satellite. The four images represent views of the Northern Hemisphere dusk sector auroral distribution.

Knowledge of the first angle is necessary to establish the correct time delay between the signal pulse (typically from the earth limb sensor) and image read out. For data acquisition purposes accuracy to within a few degrees is sufficient, but for post-acquisition analysis the tolerance must be within a pixel. This includes knowing the angle out of the scan plane if it is not coplanar. For Viking the angles with respect to the earth limb sensor were 168.65 degrees for camera 0 and 169.81 degrees for camera 1. These positive angles are different ($\sim$ 15 CCD pixels), thus the images acquired from the two cameras are not exactly registered.

The second angle represents the position within the CCD imaging area that the scan plane lies. Assuming for the moment that the third angle noted above is zero, this is equivalent to saying the column within which the scan plane lies. Optimally this should be the center of the imaging area of the CCD (ie column 192), but the tolerance can be as large as a degree since it only introduces distortion in conjunction with the third angle. On Viking these angles turned out to be .23 and -.54 for camera 0 and 1 respectively. The combination of these two effects indicates that the optical axes of the two cameras differ by 1.4 degrees.

The final angle is the critical one because any misalignment between the charge transfer direction and the source as its sweeps across the instrument field of view will cause smearing of the image across columns. Thus if there is a point source, it will appear to extend into adjacent columns. The tolerance on this angle can be estimated by requiring that no more than 1 CCD pixel smear occur as a source sweeps over the field of view. This corresponds to an angle of .2 degrees. Inspection of the images obtained revealed qualitative success in this alignment. To test this quantitatively, star observations were used. The star images were artificially smeared by utilizing the wrong TDI rate. This instead of a point source, they appear elongated. By spreading them out in row extent (ie along the charge transfer direction) a cross column component could be measured. This was found to be .18 degrees for camera 0.

The cameras were designed primarily for viewing extended objects such as the auroral distribution, but they respond as well to point sources of light such as UV stars. In fact observations of UV stars are very important in both assessing instrument function and providing an inertial reference for deducing corrections to the nominal spin axis position. Most UV star emission rates are so high and localized that under normal operating conditions for the Viking imager they exceed the capacity of the individual CCD wells. Some stars however, have sufficiently low flux rates that they can be measured without saturating the CCD or A/D converter and they provide a means whereby the point spread function could be measured. During calibration the point spread function was found to be approximately 1.25 pixels in diameter after careful focusing of the cameras. The point spread function during actual flight operation can be affected by a number of factors: 1) defocusing of the cameras; 2) the binning algorithm; 3) inaccuracies in the TDI rate; and 4) misalignment of the charge transfer direction with respect to the scan plane. The effects of the latter two processes are evident when purposefully smearing the data as noted above and the effect on the point spread function can be calculated.

Under normal circumstances the TDI rate was set at the beginning of each orbit, but in fact it was found to be quite constant and it was primarily during initial checkout and attitude maneuvers that discrepancies between the TDI and actual spin rate occurred. Errors on the order of .10 degrees/second affect the columnar extension of a star by approximately .6 CCD pixels. Fortunately the satellite spin rate was quite stable and well known and the TDI rate was adjustable with a resolution of about 10 times that required. The effect of the misalignment is to smear the image of a star in the cross-column direction. As shown above the Viking cameras were aligned to just tolerance specification and so in fact the contribution to the extent of a point source due to this effect is on the order of .5 CCD pixels as long as the TDI rate is correct.

The major effect on the point spread function is due to the binning algorithm used. To assess this effect it is first necessary to establish the response in unbinned mode. Examples were found where the TDI rate contributed no smearing. The point spread function after the slight correction for misalignment was 2.5 CCD pixels in diameter using the 1/e points. This indicates that some slight defocusing has occurred. Empirically, once the data is binned, unsaturated UV stars occupy 2 to 3 binned pixels (2 by 2 CCD pixels) which is considerably more than for the calibration or unbinned data. The reason of course is that the point spread function depends on where within a given bin the star image falls. The actual point spread function will always exceed a single binned pixel and there is a 40% probability that significant contribution from a point source can affect 3 binned pixels. This is entirely analogous to the problem of deconvolving the instrument function from observations of narrow auroral features.

System response can be broken down into the contribution due to several major components. For an external source there will be a certain number of photoevents at the photocathode per (kR-pixel). This conversion efficiency will depend on the transmission efficiencies of the various optical elements in addition to the quantum efficiency of the photocathode. For both cameras the result was approximately 3 photoevents per (kR-pixel). The gain of the MCP comprises two parts: the electron gain which for the typical voltage used was 2000 and the phosphor gain ($\sim$ 28). The output phosphor photons were transmitted to the CCD by the fiber optic bundles and converted to electrons by the CCD. The output of the CCD was taken through a programmable gain stage and converted to DN. For the lowest programmable gain state this latter conversion stage required 8200 phosphor photons per DN for camera 0 and 9800 for camera 1. The overall response therefore is approximately 20 and 8 DN per (kR-pixel) respectively for emissions at the transmission peak.

Expressing the calibration factor in this manner is not particularly useful for an auroral physicist. The instrument is a broad band instrument and what is desired is to relate the overall system response to a more commonly used reference emission rate. Although there are variations in the emission rates at different wavelengths (even for the same emitting species) as a function of precipitated energy, efforts are underway to characterize this response. Initial work[10] has indicated that the LBH emissions can be related to the N_2+ 4278 band emission through the conversion factor 21 DN per (kR of 4278 - pixel) at the lowest gain state. Subsequent work using ground-based all-sky camera data has found that for quiet auroral conditions the conversion factor approaches 25 DN per (kR 4278 - pixel) which is in quite close agreement considering the variables involved.

Although qualitatively the raw images are quite useful even for cursory scientific analysis, there are several important corrections which need to be made to the data before quantitative results can be obtained. Inspection of the raw image data reveals a column dependent response to the external emissions due to a variation in transmission efficiency in the fiber optic tapers. The result is that a flat field source would produce the inverse of the response shown in Fig. 4. In the center of the image area of the CCDs the response is a maximum falling off to approximately 25% at both edges. The empirically obtained correction curve shown is consistent with the taper calibration, and various star sightings have been used to verify this variation. This type of correction is an inherent problem with two-dimensional imaging instruments that scanning instruments do not have because they utilize a common field of view to build up a two-dimensional image. On the other hand, the non-uniformity can always be corrected for (assuming that the signal in the center does not exceed the dynamic range and that at the edges does not fall below the noise level). The temporal information lost by scanning with a single field of view cannot however, be regained.

One of the primary design considerations in constructing the Viking cameras was to ensure that sufficient signal levels would be obtained in the relatively weak LBH emissions on the nightside even during periods of relative auroral quiescence. This goal coupled with some of the inherent noise problems associated with CCDs and technical limitations imposed by the project argued for ensuring that as many photoevents as possible occurred. The oxygen camera (camera 1) provides plenty of signal due to auroral emissions so it was possible to suppress the significant increase in background level with increasing wavelength when viewing the daylight regions of the earth. For LBH this extra protection was not possible so that the transmission fall off of the CsI photocathode was relied on to provide the long wavelength rejection. The result is a fortunate combination of being able to adequately monitor low intensity nightside aurora and still reject most of the atmospheric reflection at longer wavelengths. Note that the long wavelength contribution is only a concern when the total contribution due to the product of the residual transmissivity of the photocathode and the solar flux is on the order of the LBH signal. Since the transmissivity is less than 10^{-5} in the 300 to 400 nm region, there is no contribution from regions where there is no direct solar illumination. However, even on the dayside under full sunlight illumination information on the distribution of aurora can be obtained. The examples shown in Fig. 2 reveal the auroral distribution quite reasonably in the afternoon sector where full solar illumination occurs at that time of the year. One of the components of the long wavelength contamination is due to scattering by clouds in the troposphere. These appear in the dayside LBH images

(camera 0) as patchy emission patterns. This type of contamination is similar to the problem of observing in the visible wavelength region even in the night sector. In that case albedo from clouds and snow-covered ground can add a factor of two to observations from above[11] and complicates data analysis although this is not often taken into account. The contamination present in the Viking data has been compared to satellite weather photos to verify that large cloud formations can contribute to the signal. Once the cloud patterns are identified it is possible to compute the contribution. During July of 1986 when large regions of the dayside were imaged by Viking several good cases were obtained and the average result was an increase in the signal level of 16% over the surrounding dayglow.

Though offering many advantages, CCDs also have several drawbacks when it comes to signal level. The major one is the noise due to thermally generated electrons which is strongly dependent on the chip temperature. On Viking due to project constraints it was not possible to cool the CCDs low enough to reduce this to the level of other noise sources. Typically the chips operated at a temperature of -20 degrees Celsius which results in DN levels like that shown in Fig. 5 for the lowest analog gain state, and consequently 10% of the dynamic range was lost to this type of noise. Inspection of Fig. 5 reveals two other effects. The most obvious is the ramp in dark current with CCD row number, which is due to the difference in TDI rate and readout rate. Once the image is in the storage area the slower readout rate takes over and the amount of time which a row spends in the storage area is strictly a function of its distance from the horizontal transport register; hence the rows which spend longer in the storage area have more dark current generated.

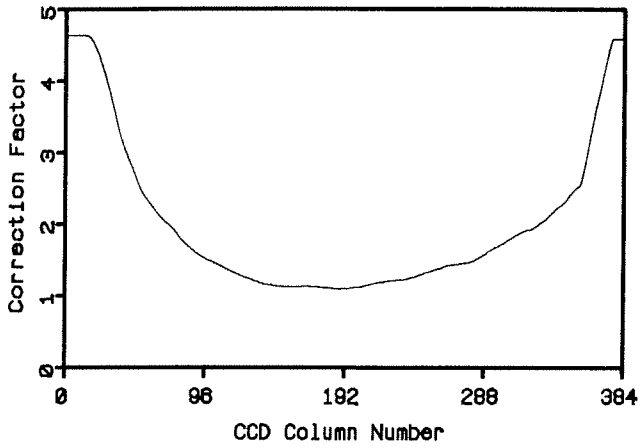


Figure 4. Graph of the columnar correction factor for the Viking LBH camera.

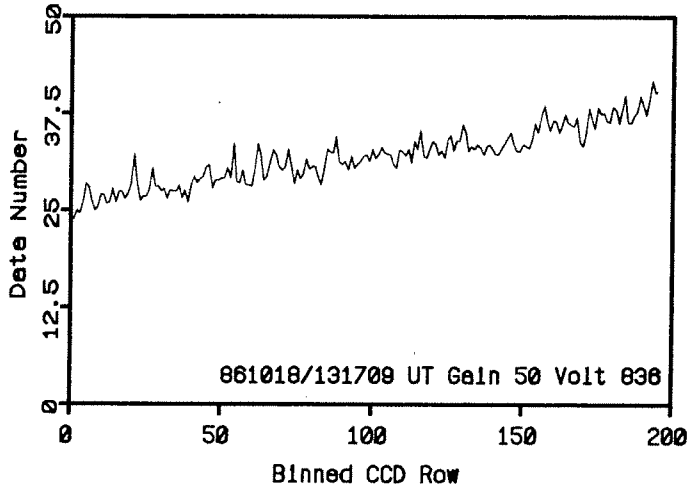


Figure 5. Illustration of the noise level variation with CCD row number.

The other effect is the noise on the ramp which is primarily due to pickup noise at the input to the analog preamplifier. It was discovered that the power supply converter circuit provided a recognizable noise signal particularly when in multiple camera mode. This was due to the necessity of switching the preamplifier back and forth between the cameras. Thus it became common practice to utilize alternate camera mode as much as possible.

5. CONCLUSION

Past experience with satellite auroral imagery has shown that in order to make sugnificant steps forward in our understanding of magnetospheric processes, improvements in temporal resolution and spatial coverage is essential. The goal of improved temporal resolution is not just to acquire more images more rapidly, but to expose the entire field of view simultaneously. Auroral physics has progressed to the point where the precise timing of events is necessary and images which take even on the order of minutes to acquire lose vital information. The successful utilization of CCD detectors in the Viking program has shown that it is possible to obtain this type of information and also to handle the vast quantities of data which result. The effects of a spinning satellite can be readily handled and with reasonably sophisticated software real-time assessment of the image quality can be made.

The Viking cameras were in many ways prototypes and their success argues for further efforts in this area. The Interball program will take what has been learned from the Viking instrument analysis and incorporate several improvements. Both Viking and Interball cameras are in many ways survey instruments, but the dynamic range limitation with Viking that required close monitoring of the instrument in order to obtain as much useful data as possible will be removed with Interball.

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7. REFERENCES

1. C.D. Anger, T. Fancott, J. McNally, and H.S. Kerr, "ISIS-II Scanning Auroral Photometer," Appl. Opt. 12, 1753-1766 (1973).
2. E.H. Rogers, D.F. Nelson, and R.C. Savage, "Auroral photography from a satellite," Science, 183, 951-952 (1974),
3. K. Hirao and T. Itoh, "Scientific satellite Kyokko (EXOS-A)," Solar Terr. Env. Res. in Japan, 2, 148-152 (1978).
4. L.A. Frank, J.D. Craven, K.L. Ackerson, M.R. English, R.H. Eather, and R.L. Carovillano, "Global auroral imaging instrumentation for the Dynamics Explorer mission," Space Sci. Inst. 5, 369-393 (1981).
5. C.I. Meng and R.E. Huffman, "Ultraviolet imaging from space of the aurora under full sunlight," Geophys. Res. Lett. 11, 315-318 (1984).
6. C.D. Anger et al., "Scientific results from the Viking Ultraviolet Imager: an introduction," Geophys. Res. Lett. 14, 383-386 (1987).
7. C.R. Burch, "Reflecting microscopes," Proc. Phys. Soc. 59, 41-46 (1947).
8. C.D. Anger et al., "An ultraviolet auroral imager for the Viking spacecraft," Geophys. Res. Lett. 14, 387-390 (1987).
9. R.A. King, A.L. Broadfoot, B.R. Sandel, and A. Vallance Jones, "Correcting image distortion with fiber optic tapers," Appl. Opt., in press.
10. A. Vallance Jones et al., "A comparison of CANOPUS ground optical data with images from the Viking UV Camera," Geophys. Res. Lett. 14, 391-394 (1987).
11. A.W. Harrison and C.D. Anger, "Earth albedo effects in satellite auroral photometry," Can. J. Phys., 55, 929-936 (1977).

THE FREJA ULTRAVIOLET IMAGER

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Abstract. Auroral images acquired by satellite instrumentation have proven to be a crucial component of the scientific equiry into the physical processes of the Earth's magnetosphere. The *Freja* mission provided an opportunity to extend these measurements into the temporal and spatial regime commonly associated with ground-based optical imagers. Employing the basic procedure used successfully in the *Viking* program allowed image repetition rates of 6 s to be achieved with simultaneous exposure of all pixels within the field-of-view. Typical exposure times of 0.3 s required development of an improved image intensifier system and operational requirements resulted in image formats covering approximately one-third of a spin. Simultaneously exposing two broad-band UV cameras, the instrument generates in its normal operational mode 264.6 kbytes per image pair. Results from initial operations confirm the design approach and suggest such imagers can be routinely included on challenging low cost missions such as *Freja*.

1. Scientific Background

The scientific value of auroral imaging became recognized worldwide as a direct consequence of the Canadian ISIS 2 spacecraft which contained two photometers (Anger *et al.*, 1973; Shepherd *et al.*, 1973) that provided for the first time a global view from above of the auroral distribution about the Earth's magnetic poles. The U.S. followed shortly after with the DMSP series of spacecraft which used photographic techniques for its data system (Rogers *et al.*, 1974). Both approaches were limited to only dark side viewing because of the use of visible wavelengths. With *Kyokko* (Hirao and Itoh, 1978), Dynamics Explorer (DE) 1 (Frank *et al.*, 1981), HILAT (Meng and Huffman, 1984) and Polar Bear dayside viewing became possible through the use of ultraviolet wavelengths. With DE 1 it further became possible using a scanning mirror to obtain time sequences of images at the rate of one image about every 12 min. The UV Imager on *Viking* (Anger *et al.*, 1987a) extended these capabilities to observe the entire auroral distribution because of its improved spatial and temporal resolution (providing 1 s exposures as fast as every

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20 s). Other recent satellite programs containing imagers such as Akebono have continued to contribute to improving knowledge of the aurora (e.g., Oguti *et al.*, 1990).

With every technological improvement have come new scientific discoveries. Auroral images mirror in space and time the processes that are taking place in the magnetosphere, and are widely used by scientists as a visual reference for specific *in situ* or groundbased measurements. The advent of ultraviolet auroral imaging from satellites provided the opportunity to obtain the auroral configuration on a near-instantaneous basis and therefore to study the auroral distribution in relation to global magnetospheric phenomena. The introduction of area detectors, specifically charge-coupled devices (CCD), allowed the design of an imager capable of imaging of large areas of the Earth with every pixel within the image exposed at the same instant of time. Installed on a spinning spacecraft images could be acquired at a repetition rate equal to the spin period. The *Viking* UV imager incorporated this type of detector and as a consequence was able to image the global auroral distribution in about 1 s with a repetition rate of up to three images per minute. This development made possible the study of the temporal variations of global auroral phenomena on the time scale of 1 min, and has led to new insights into the physical processes responsible for the aurora. Some preliminary summaries of the scientific achievements of the *Viking* UV imager can be found in Anger *et al.* (1987b) and Cogger *et al.* (1991). In the context of further instrument development it is useful to consider two areas of scientific interest. First, partly as a result of the *Viking* UV imager measurements it has become apparent that the dayside aurora is a dynamic, highly structured part of the auroral distribution. Of particular interest have been the observations of a series of vortices which appear to reflect processes which are associated with shear flows in the magnetosphere (Lui *et al.*, 1989; Murphree *et al.*, 1989). The temporal evolution of these features in conjunction with substorm periods suggests that an important link may exist with the nightside current density maximum in the magnetotail (Elphinstone *et al.*, 1991a). This is substantiated by magnetic field line mapping which links these dayside (in the ionosphere) features to the nightside magnetospheric equatorial plane (Elphinstone *et al.*, 1991b). However, while models (e.g., Wei *et al.*, 1990) have been proposed to explain such observations, considerably more constraint is required via better measurements to establish the correct theory. For example, more coordinated electric field measurements in the regime of these distortions is required in conjunction with these images. Further the temporal and spatial characteristics provided by the *Viking* measurements (1 min and approximately 30 km typically) are insufficient to limit theoretical models significantly.

An area of major interest in the nightside part of the magnetosphere is the location of substorm onset. Considerable effort has been expended over the last decade to model the substorm morphology in terms of magnetospheric processes and one important aspect of this must be the question of whether the optical effects measured in the ionosphere reflect near Earth (e.g., $<20R_E$) activity (predominantly)

or activity far down the tail at the distant neutral line. Given the vast volume of the magnetosphere it has not been possible to conclusively relate measurements made by a satellite in the magnetotail with ionospheric features although a number of important studies have been performed in this area (e.g., Lopez *et al.*, 1990). A major *Viking* result has been the observation that optical substorm expansions can occur well equatorward of the poleward extent of emissions, both during quiet and active periods (Murphree *et al.*, 1991, 1993). There is no reason to suspect that this poleward region of emissions is not on closed field lines and that the onset location is therefore unrelated to the open/closed field line boundary, a result consistent with some (but not all) near-Earth mechanisms and only under some conditions the distant tail boundary layer theory. Again however, the *Viking* UV imager measurements do not provide sufficient resolution particularly when attempting to correlate optical signatures with particle sources regions although progress has been made in this area (Sandahl *et al.*, 1990; Elphinstone *et al.*, 1992).

The *Freja* program with its low altitude, rapidly spinning satellite provided an ideal platform to improve the temporal and spatial resolution of UV imager data. A factor of 10 increase in image repetition rate is immediately possible and the spatial resolution as well could be reduced by a factor of 10 compared to *Viking*. The price of these improvements would be the elimination of truly global coverage because at the 1700 km apogee of *Freja* it is not possible to observe the entire auroral distribution on an instantaneous basis. This is illustrated in Figure 1 where an actual *Viking* image and portions of three *Freja* images are compared (in practice *Freja* images cover considerably more extent than shown in the vertical dimension of the figure). While the *Viking* and *Freja* data are clearly from different epochs, the comparison shows that *Freja* is able to provide information on smaller scale phenomena. It is toward these issues that the *Freja* UV imager instrument design was directed.

2. Instrument Overview

The design of the cameras was driven by the short development time available for the *Freja* mission and the need to obtain rapid images of relatively weak auroral emissions that occur on the dayside as well as the nightside of the Earth. Moreover, the images were to be taken from a spinning spacecraft which for the nominal 10 rpm spin rate poses severe exposure time constraints. The *Freja* UV imager (see Figure 2) consists of 3 major components: 2 cameras (denoted camera 0 and camera 1) mounted side by side on the bottom of the spacecraft (i.e., in the spacecraft shadow), an electronics unit and an IR limb sensor to provide a triggering signal. This Earth sensor is a simple fixed infrared (10 μm wavelength) sensor which generates timing pulses on each spin of the spacecraft, as the sensor scans across the Earth's limbs. The Earth sensor unit contains the IR optics, germanium bolometer, and a preamplifier while the Earth sensor electronics unit contains

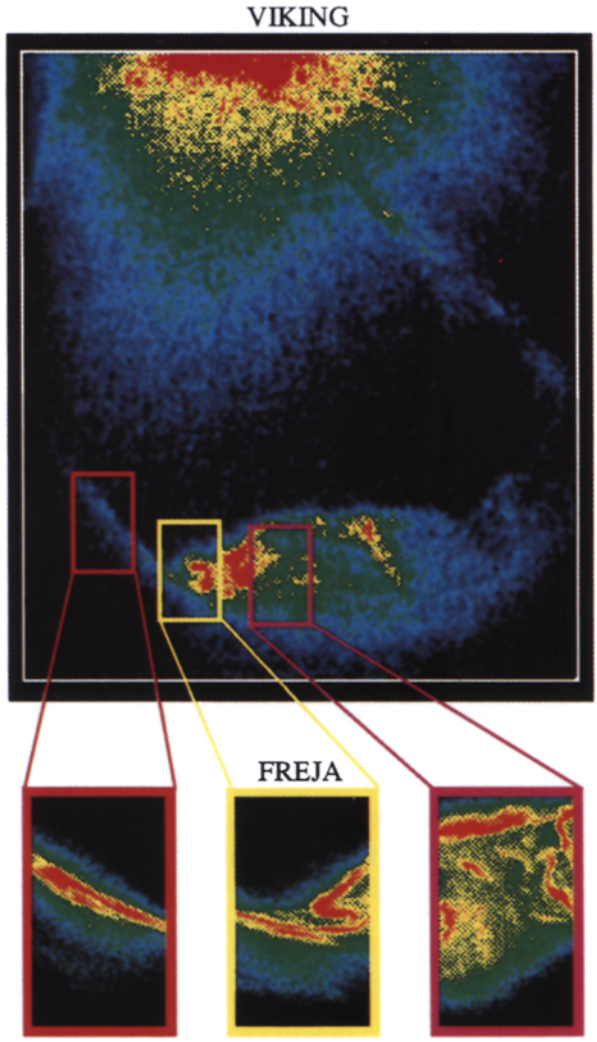


Fig. 1. Comparison of an actual *Viking* image and portions of 3 actual *Freja* images. The relative scale sizes are approximate only.

the bolometer signal processing electronics, which detect hot/cold and cold/hot transitions representing the Earth's limbs.

Conceptually the method employed to image UV emissions is straightforward. Because of the desire to produce a true image wherein all pixels are exposed at the same time an area detector is employed. This detector (a Charge Coupled Device – CCD) can be thought of as an array of row and column pixels and hence it requires a two-dimensional optic system which provides a flat focal plane. For UV measurements the input scene is first photo converted to visible light via a photocathode, electron multiplier, and a phosphor and presented as a flat image at the face of the CCD. Light incident on the CCD will build up charge in each

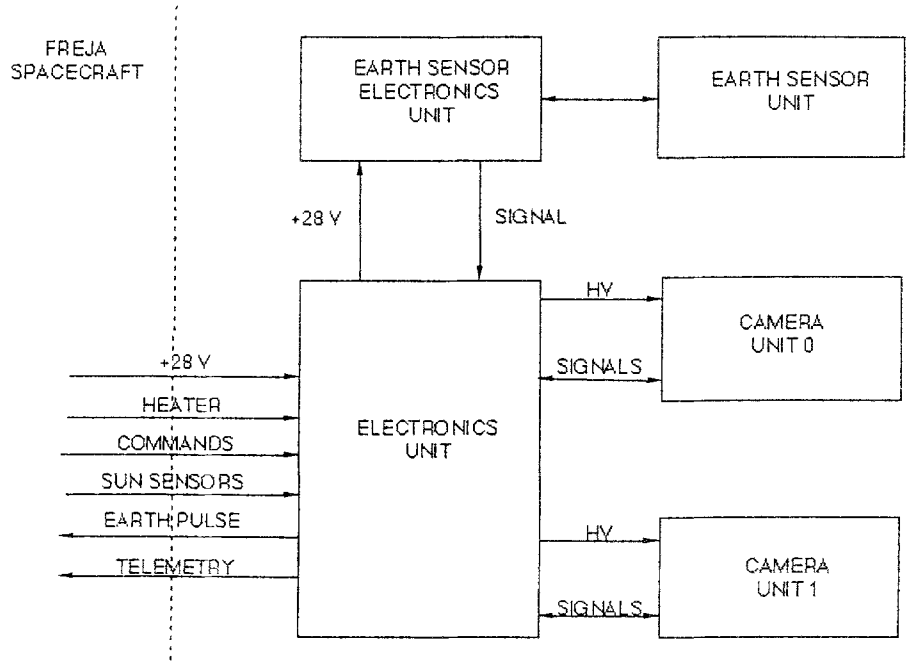


Fig. 2. Schematic showing the major *Freja* UV imager components and their interconnections.

pixel for as long as exposure is desired. In normal operation of such a detector the input is closed (e.g., via a shutter) and the charge shifted (generally along columns) to a storage area where it is subsequently read out serially producing an analog signal. This signal is then digitized and formatted appropriately for storage in image memory until telemetry to the ground. For instruments on a spinning satellite it is necessary to shift the charge in the CCD so that the scene stays in focus as long as it is in the imaging area. This means that the charge shifting rate along a column must be the same as the spin rate. Under this method (so-called Time Delay Integration – TDI) the effective exposure rate is

$$\tau = \frac{Nf}{S},$$

where N is the number of rows in the CCD, f is the angular field of view of a pixel (degrees) and S is the spin rate (deg s^{-1}). Beginning of exposure is defined in relation to the signal obtained from the Earth sensor. Application of this method has been discussed by Murphree and Cogger (1988).

While the basic design utilized was conceptually the same as for the *Viking* UV imager, a number of technical improvements/modifications were required:

– a new detector system was required to eliminate saturation problems and improve sensitivity;

– the exposure rate had to be reduced by approximately a factor of 4;

– much more image memory was required to store images acquired out of ground station range;

– the instrument had to be capable of imaging over the entire 360 deg of a spin.

The significance of the final point can be appreciated by considering the basic instrument design. The Earth sensor provides a reference point within a 360 deg spin from which decisions can be made regarding the acquisition of an image. This is necessary because the basic camera design provides auroral images taken at 2 UV passbands but the optical extent of each field of view (which are essentially overlapping) is significantly less than the width of the Earth at these altitudes. The basic field of view is governed by a number of factors one of which is the usage of a CCD. The size of CCD chosen coupled with the basic optical configuration resulted in a 22.4 deg coverage in the direction of the spin. Since from typical altitudes of *Freja* the width of the Earth corresponds to approximately 110 deg, considerable effort would be required operationally to position the field of view over interesting regions on the Earth. To overcome this the imager was designed to be able to construct images larger than the optical design. This was possible because the basic TDI capability could be extended to the CCD readout rate. Images were readout of the CCD at the same rate thereby constructing an image which has each pixel exposed for the same amount of time, but where the time period covered by the image exceeds the exposure time. Operationally this allowed producing images on the order of 110 deg extent and still retain simultaneous exposure of all pixels to within the nominal 1.8 s of spin required to acquire such a large image.

A major improvement in the *Freja* program over that for example of the *Viking* program is the high telemetry rate available to the instrument. The normal rate for the imager is 44 kbytes per second (see Table I) which is over a factor of 8 higher than *Viking*. Still this basic rate does not allow the large size images discussed above to be telemetered in one spin. To retain the 6 s image repetition rate in these situations required expanded image memory (952 kbytes). Such enhancements affect the mass and power required by the instrument which for the *Freja* mission (and of course for most others) was at a premium. Table I gives the resulting resources required by the instrument. To save power a low power mode was utilized wherein software and image data could be retained at minimal power consumption.

3. Mounting on Spacecraft

To accomplish the science noted above precise alignment of the instrument on the satellite was required. The basic image acquisition method utilizing the TDI approach requires that the charge transfer direction be parallel (or anti-parallel depending on the characteristics of the optics) to the direction of the spin. This in turn generally requires that the optical axis of each camera must be perpendicular to the spin axis. The plane swept out by the vector perpendicular to the spin axis in which the optical axis of the camera lies is denoted as the scan plane. Proper operation requires accurate knowledge of the actual scan plane and hence spin axis

TABLE I

Freja UV imager specifications

Mass	
Cameras	1.89 kg
Electronics	4.53 kg
IR sensor	0.79 kg
Total mass	9.1 kg
Power	
High	7 W
Low	2 W
Physical size	
Cameras	26 by 15 by 13 cm each
Electronics box	30 by 20 by 14 cm
Telemetry rate	
High	88.064 kbits s^{-1}
Low	44.032 kbits s^{-1}
Image storage	952 kbytes
Processor memory	32 kbytes

rotation vector. Alignment is crucial and involves primarily 3 deg of freedom as illustrated in Figure 3.

(1) Angle with respect to a fixed scan plane position. Nominally this is the position of the instrument providing the triggering signal. Accuracy on the order of a few degrees is all that is required initially, but for data analysis accuracy to within one pixel field of view will be required (denoted α).

(2) Optical axis of each camera should be within $\approx$1 deg of the scan plane (denoted θ).

(3) Charge transfer direction must be within 0.2 deg of parallel to scan plane. This is the most crucial alignment as a mismatch between charge transfer direction and spin direction will result in image smear (denoted β).

To satisfy these requirements each camera contained an alignment cube which was used in conjunction with a theodolite to align the optical axis of each camera with respect to the satellite spin axis. The alignment cubes were related to the optical axis of each camera during calibration to accuracies required above. The final results (in degrees) are given in Table II for alignment with the spin axis. It should be noted that correct alignment requires knowledge of the true satellite rotation axis which was determined during full up satellite tests.

Accuracy of these alignments can be verified during operation and in particular it is crucial to confirm that the charge transfer direction has remained aligned with the scan plane. Fortunately a simple mechanism exists to check this. Since the basic operation requires the charge transfer rate to match the spin rate to eliminate

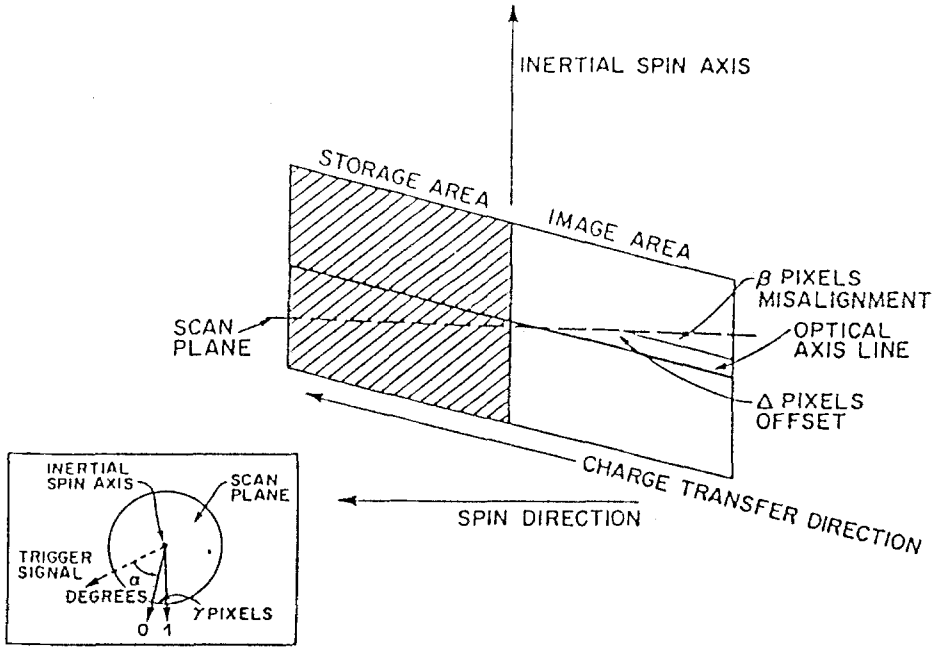


Fig. 3. Relationship of CCD orientation to the satellite spin axis. The plane of the CCD is presumed to be perpendicular to a vector from the spin axis to the CCD.

TABLE II

Optical axis alignment angles

	Camera 0	Camera 1
α	33.88	33.74
θ	90.04	89.89
β	<0.01	<0.01

smearing in the spin direction, by purposefully mismatching these rates point sources (such as stars) will be smeared out visibly in the charge transfer direction. Any misalignment would appear as the point source tracking from one column to another. The test was performed shortly after launch and no misalignment in the column direction was measurable over roughly 70 CCD rows.

4. Camera Overview

To image even relatively weak auroral emissions, it is necessary to use a fast camera. The compact, spherical design used in both the *Viking* and *Freja* missions is an inverted Cassegrain Burch type camera, operating at $f/1$ (Burch, 1947). A schematic of the optical design for a *Freja* camera is shown in Figure 4 (see

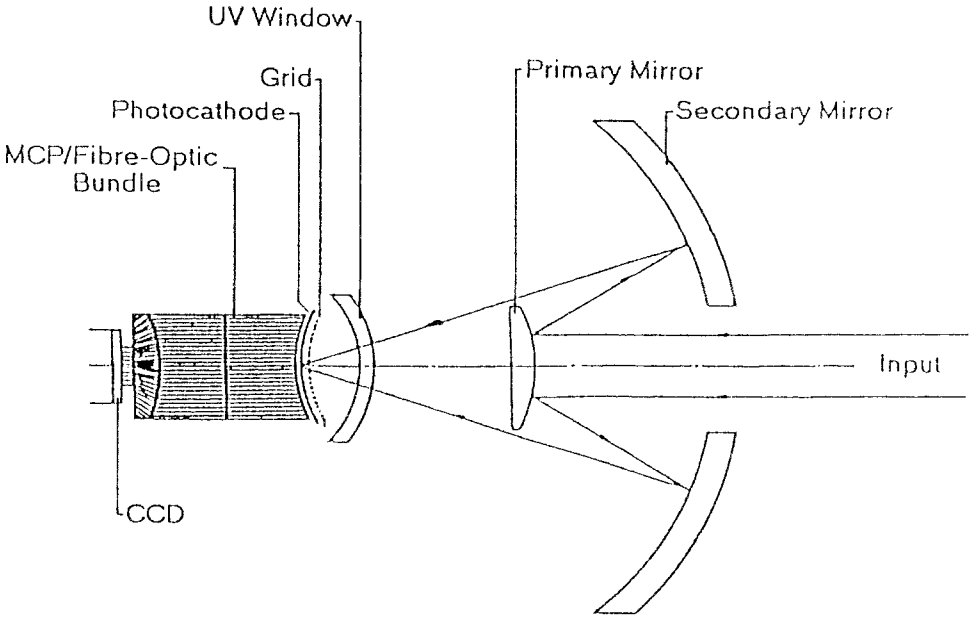


Fig. 4. Schematic of the *Freja* UV imager optical system. Light is incident from the right onto the primary mirror. After reflection from the secondary mirror the light passes through a UV high pass filter and then onto a photocathode. Electrons produced are accelerated and converted to visible light and then coupled fibre-optically to the CCD.

Anger *et al.*, 1987a, for the *Viking* design). The camera is housed inside a graphite fibre epoxy composite (GFEC) tube of wall thickness 0.06 inches, a material which has desirable thermal expansion characteristics over the expected operating temperature range. Baffles are required to prevent scattering of sources outside the field of view from contaminating the image. Operationally it is required that the instrument never be operated when the Sun vector is within 45 deg of the optical axes of the cameras. However, even when this is satisfied solar flux scattering off the camera housing into the optics must be minimized. In addition it is possible for objects on the *Freja* spacecraft itself to scatter light into the cameras; for example, there is one wire boom which is 19 deg from the optical axis of camera 0. The baffles are designed to reduce all solar flux effects by 2.5×10^{-4}.

One of the primary purposes of the camera is to select the wavelength region over which the measurements are to be made. Though characteristically over the near UV region terrestrially scattered solar flux is less of a problem than at visible wavelengths, selection within this region must take into account two other factors:

(1) availability of materials to select particular wavelength intervals,

(2) auroral emission intensities.

The most common approach (and that which was used) it to concentrate on broad band UV measurements. For 2 separate cameras these are to monitor principally the molecular nitrogen Lyman–Birge-Hopfield (LBH) emissions which extend from

130.4 nm to 200.0 nm as various vibrational and rotational transitions, and the strong line at 130.4 nm due to atomic oxygen. The technique for both cameras is to principally define the wavelength coverage by the combination of a transmission filter to provide the short wavelength cutoff and to utilize a photoemissive material to provide the long wavelength cutoff. Details of how this is done are provided below, but some comments on these two wavelength intervals should be noted:

(1) While LBH emissions are primarily optically thin, those at 130.4 nm are not with the result that considerable radiative transfer effects occur, principally broadening of narrow features.

(2) UV broad band measurements do not directly provide integrated, precipitated energy measurements such as for example, the N_2^+ visible emissions.

(3) LBH emission response to particle precipitation depends on energy (as does 130.4 nm) but less strongly. Thus the ratio (1304/LBH) could be indicative of characteristic energy with higher ratios indicating softer fluxes (Rees *et al.*, 1988; Steele *et al.*, 1992).

Returning now to the camera design, the optics system primarily defines the solid angle over which flux will be accepted. Referring to Figure 4, the primary mirror has a radius of curvature of 26.6 mm and is covered with a Al/MgF_2 coating. Incoming flux strikes this surface and is reflected onto the secondary mirror. The secondary mirror of radius of curvature of 64.8 mm has the primary mirror as a central obscuration, but is designed to focus the incoming photons onto the detector at angles greater than 15 deg. Because of concern about long wavelength contamination it is possible to coat this mirror with a special dark coating with the following properties:

(1) peak reflectance in 135.0–145.0 nm region,

(2) peak reflectance >60%,

(3) peak reflectance outside of 122.0 to 160.0 nm passband <3%.

At the heart of each camera is the Micro-Channel-Plate (MCP) intensifier and fibre optically coupled CCD (Adema *et al.*, 1992). Rather than an open intensifier as was used in the *Viking* UV Imager a closed (i.e., sealed) design is employed for several reasons:

(1) contamination of sensitive elements (e.g., photocathode) is minimized,

(2) saturation due to ambient electron fluxes eliminated,

(3) last minute access to instrument on launch pad not required.

The sealing is accomplished by placing the required filter as a window over the front of the photocathode. Because the MCP is operated with the anode at ground this means the window is at a high negative potential and to prevent space charge buildup it is coated on the inside with 2 nm of nickel. For structural reasons the windows must be relatively thick. The LBH camera utilizes 2.5 mm of BaF_2 to provide the short wavelengths cutoff for that camera while the 130.4 nm camera employs 3.5 mm of CaF_2. Once a photon passes through the window it impinges on a photocathode material (see Figure 5) designed to be photoemissive over a particular wavelength region. This photocathode (CsI or KBr) is deposited

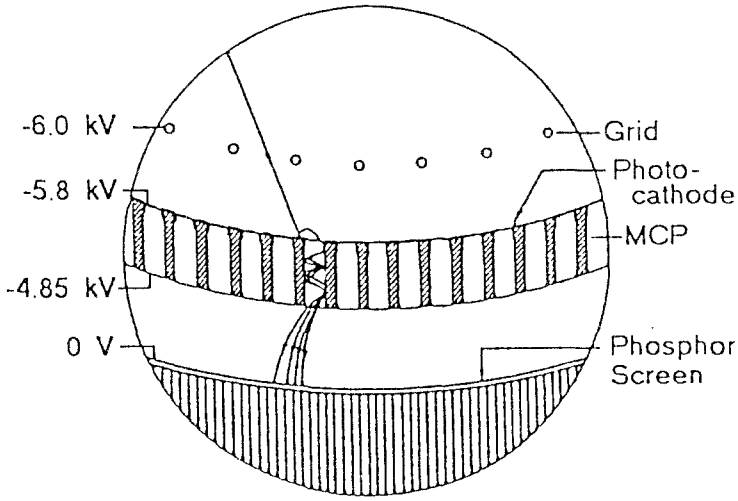


Fig. 5. Schematic of the photoconversion and electron acceleration process. An incident photon is shown hitting the photocathode. The emission of an electron results in a cascade along the pore of the MCP. Conversion to a visible light source occurs at the phosphor.

directly on the front surface of the MCP. In fact significant photoemission occurs from the photocathode material which winds up being deposited within the MCP pores themselves down to approximately 4 pore diameters (a pore diameter is 12 microns). Electrons emitted by the photocathode are subjected to the nominal −200 V (relative to the photocathode) placed on the conformal stainless steel grid. This 2 mm by 2 mm hole size, 80 micron wire grid is placed 2 mm from the photocathode to inhibit electrons from drifting laterally from their production sight. This is crucial because any such drifting greatly increases the point spread function of the instrument.

Once a photoelectron is confined to a pore it is accelerated by a variable potential (750 to 1000 V) to produce a cascade of electrons out the back of the MCP. This cascade of electrons is accelerated to the anode by a potential of typically 4850 V. This acceleration is necessary for the electrons to traverse an aluminum coating overlain on a P43 phosphor. The purpose of the coating is to shield the subsequent optical chain from light which penetrates (without photoconversion) the MCP. P43 is chosen as the phosphor in spite of its low screen efficiency (30% of P20) because of its fast decay time (>100 ns). This is required because of the high spin rate which the *Freja* spacecraft will operate under. A pixel sweeps through the field of view at a rate of approximately 780 Hz and the response of the phosphor due to one pixel must be gone before the next one arrives. Once the electrons strike the phosphor photons are produced which are then fibre-optically coupled to the CCD.

The phosphor screen is also curved, and light emitted from it must be mapped to the flat CCD. This is done using a combination of fibre optic blocks, one that matches the curved surface of the phosphor screen, and another that removes the distortion arising from projecting a curved image onto a flat surface (King *et al.*,

TABLE III

Freja UV imager optical characteristics

Camera optics	Inverse Cassegrain, speed $F/1$ Focal length 22.4 mm Field-of-view 22.4° × 30°
Spectral passband	LBH – 134 nm to 180 nm (BaF_2+CsI) 130.4 nm – 1250 nm to 160 nm (CaF_2+KBr)
Detector	Intensified CCD 228 (ROWS) 385 (COLUMNS) Pixel size 22μ × 22μ Full well potential $3 \times 10^5\ e^-$
Resolution	Angular 0.07781° Spatial (from apogee with 2 × 2 pixels) ~5 km
Exposure	0.37 s (for 6 s spin period)

1988). This allows the usage of a single charge transfer rate for all columns. As discussed above, when light is incident on a row of CCD pixels that row is clocked such that the source remains in focus. Once each row reached the output horizontal transfer register, software control allows rows of pixels to be summed if desired. Similarly as the charge is shifted to the output gate of the horizontal transport register columns can be summed. This ability helps improve the signal-to-noise ratio and as well reduce image size.

The final major component of the cameras is a preamp which takes the output of the CCD (electrons per pixel) and provides signal conditioning such that the analogue signal can be transferred with minimal noise pickup to the electronics unit. The preamp utilizes a correlated double sampling technique to get rid of noise in the output stage of the CCD. Subsequently a fast OP-37J low-noise operational amplifier provides a fixed gain of 5 to the analogue signal. Two video gains for each camera were available. The lower gain was primarily intended for situations where CCD pixel binning was used and the video levels were high (i.e., daytime). The main control of the camera gain was via the MCP voltage. Since the two MCP detector HV lines were connected in parallel, both MCP gains were controlled together. A summary of important characteristics resulting from the above camera definition is given in Table III.

5. Electronic Systems Overview

Conceptually the electronics consists of several interconnected blocks as shown in the block diagram given in Figure 6. In general, the blocks communicate via the

processor address, data and control busses. The electronics as well must interface with the *Freja* spacecraft power, command and telemetry subsystems, the Earth and Sun sensors, the camera units and the temperature sensors. Three printed circuit boards were used to organize the various electronic subsystems. One board contained the Central Processing Unit (CPU) which, in general, controls the actions and interactions of the other functional units. The CPU includes address decoding circuitry, an interrupt controller and a Direct Memory Access (DMA) controller and is based on the radiation-hardened Harris 80C86 microprocessor operating at 4 MHz. The DMA controller is used for efficient transfer of image data from the Analog to Digital Converter (ADC) units A/D0 and A/D1 to memory, from memory to the telemetry system and also for the transfer of data from the Command Telemetry Interface (CTI) to memory, e.g., during upload of a new flight program. Various system functions are controlled by the microprocessor by writing to the collection of registers which make up the Parallel Output including the amplifier gains, high voltage supply and selection of MUX status channels.

The memory consisted of 64 Kbytes of EPROM and 952 Kbytes of RAM. All digital ICs were low power static CMOS devices. It is worth noting that not all CMOS ICs have low power consumption. For such a low power design, the choice of ICs and how they are used is very important. Although many of the ICs were radiation hardened or tolerant, some ICs were not, namely the RAM, FIFOs, and interrupt controller. There are versions of RAM ICs, for example, that are made more radiation tolerant by using a special manufacturing process. Unfortunately, they are very expensive, particularly since a minimum quantity (e.g., 30) must be purchased. Such a cost was prohibitive for a low cost instrument and was not justified, considering that the *Freja* radiation environment was not as high as other missions in higher orbits, such as *Viking*. As the instrument is often turned off when the satellite is out of range of the tracking station, the radiation dose is effectively lowered since the effects of radiation are usually much less when the power is off.

The Command/Telemetry Interface (CTI) provides the link to the spacecraft telemetry unit and occupies a second printed circuit board. Due to the non-standard serial interfaces to the *Freja* spacecraft, the interface circuits had to be implemented using discrete logic ICs (e.g., gates and flip-flops). Radiation hardened logic was used; Harris HCS series of high speed CMOS, plus a few CD4000B series CMOS ICs. The digital interfaces to the satellite are opto-isolated to avoid noise caused by ground loops. The CTI receives the telemetry stream from the spacecraft and is responsible for identifying commands and data pertaining to the instrument and decoding them. These are then provided to the CPU for implementation. Certain commands are implemented discretely by the Discrete Command Decoder, i.e., interpreted by hardware instead of by the microprocessor. These include CPU Reset, Low Power Mode on/off, and High Voltage Supply on/off. The CTI is also responsible for the formatting and transmitting of the data the instrument gathers. The CTI fetches data from memory by direct memory access, determines and inserts the appropriate header, packetizes and synchronizes the data according to

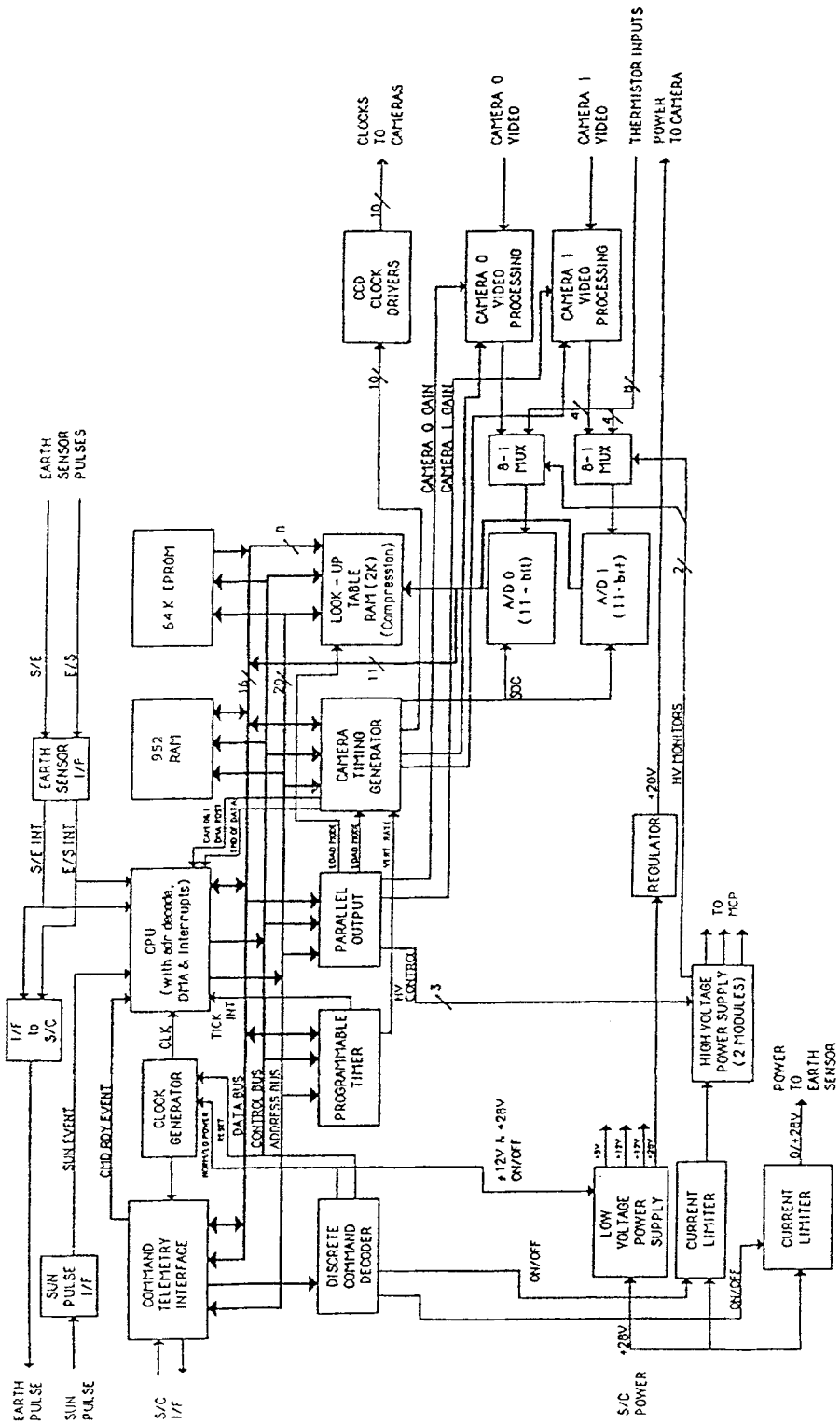


Fig. 6. Block diagram of the *Freja* UV imager electronics unit showing important interconnections.

protocol, and passes it on to the spacecraft telemetry unit. The DMA controller allows this process to be accomplished separately from the CPU, allowing the instrument to continue imaging operations.

The major activity which the electronics unit must support is the acquisition of image data from each of the cameras. Conceptually this involves two primary functions the first of which is controlling the transfer of charge in the CCDs and the second is digitizing the resulting analog signal produced by each camera detector unit. A third PCB contains the circuits for these CCD camera interfaces, called the Camera Controller. The CCD clock timing is generated by a RAM-based state machine running at a clock frequency of 4 MHz. The RAM, initialized by the Controller, contains the CCD clock and video timing waveforms. The use of RAM to store the bit patterns allowed waveforms to be changed and optimized during the development and test of the instrument. For example, a special bit pattern was used to implement the 'stare' mode imaging with long exposure times required for ground-based calibration. In orbit, TDI imaging mode is used. A programmable timer allows the CCD vertical clock rate to be changed, as required by the spacecraft spin period. The nominal line readout rate is 16.3 ms, with a pixel digitization every 3 μs. The instrument is capable of integrating and digitizing video continuously, until the Controller memory buffer was full. The clock signal for the entire system is produced by an 82C85 clock generator. The 82C85 can generate low-frequency signals or even stop the clock, so that power-saving modes could be implemented.

The Camera Timing Generator also produces signals necessary for analog to digital conversion. Within each camera an analog video signal is produced from the CCD by using a standard correlated double sampling method. This signal is then amplified by a gain of 10 video amplifier before being passed to the video processing portions of the electronics unit. Upon further programmable amplification each video signal is then, together with various status information (CCD temperatures, HV information), fed into an analog multiplexer (MUX) the output of which is passed to its own Micro Power Systems MP7685UD/883 ADC. This separation of the analog signal chain between cameras provided significantly better performance than on the *Viking* instrument by removing interference of the two analog signals at a single ADC. Each ADC is an 11 bit, 2 μs converter and additional sample-and-hold was used in front of each A/D to allow simultaneous A/D conversion and processing of the next CCD sample. A noise level of about 80 electrons RMS (referenced to the CCD) was achieved. The noise was mainly determined by the A/D converter quantization (gain of 121 electrons per DN) and noise from the power supply and digital logic. Noise on the CCD bias voltages was particularly important.

The digitized video is transferred to the processor buffer memory via a FIFO buffer and a DMA controller. A standard DMA controller IC could not be used since it was only capable of 8 bit transfers into a 64 KB memory segment. A rad-hard discrete logic DMA controller is used, capable of 1 MB transfers, in either 8 or 16 bit form. The Camera Controller has several modes; single camera 11-bit mode (using

16-bit fields), or single or dual camera 8-bit mode. The 8-bit mode compresses the 11-bit linearly encoded data into an 8-bit field. Two forms of compression are available; linear (by removing the 3 LSBs) and logarithmic, the latter useful for scenes with large dynamic range. The compression was implemented using RAM-based look-up tables, which are initialized by the Controller and hence can be modified. Dual camera linear 8-bit mode proved to be the most useful in-orbit. Single camera 11-bit mode was used mainly for calibration and performance testing.

The UV imager contained several power supplies. DC/DC converters generated the +5, +12, −12, and +30 V power for the electronics from the main *Freja* 28 V power bus. Isolation was required to prevent ground noise in the spacecraft power wiring. High voltage power supplies generated the voltages required by the MCP; −6, −5.8, and −4.7 KV. The latter voltage was in fact adjustable by the Controller in eight equal steps over a range from −4.7 to −5.0 KV, controlling the MCP gain. The power supply contained EMI noise filters and current surge limiters, important to all the experiments and the spacecraft. All power supplies could be turned off and on via command. A low power mode was available, where all power except the +5 V power to the Controller was turned off. The Controller power was reduced by setting it into a HALT mode. This would allow the UV imager instrument to retain it's memory contents and be left on continuously without discharging the *Freja* batteries.

6. Commanding

The microprocessor is controlled by a flight program stored in RAM. Upon power-up, an initial program stored in ROM is automatically loaded into RAM. This program contains enough information for basic operation. More involved programs can be uploaded from the ground station via the telemetry link. Software control of practically all instrument functions allows considerable flexibility in operating the instrument and getting the most useful view of the auroral distribution.

An important feature of the instrument is the ability to command it to enter a Low-Power mode. In this mode the power supplies to the analog signal chain, CCDs and MCPs are shut down via software command. Except for the clock to the Command and Telemetry Interface, all clocks are stopped during this mode. The Discrete Command Decoder will still be working since it does not require help from the microprocessor. If further power savings are required, it is also possible to reduce microprocessor clock frequency from software.

There are two types of commands decoded from the serial telemetry stream:

(1) Discrete commands.

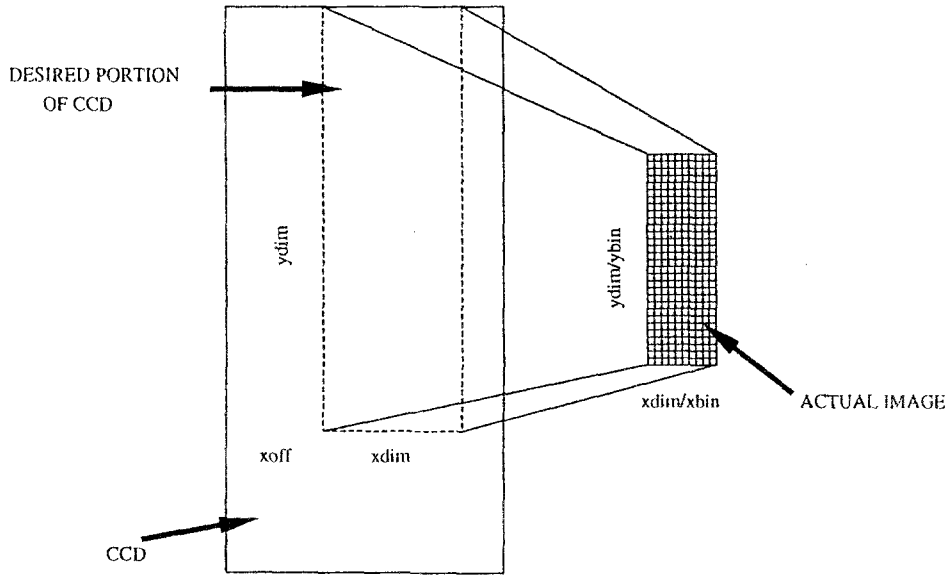


Fig. 7. Illustration of how a final image might be constructed from a subset of a CCD field of view.

(2) Processor commands.
  (a) Operational commands,
  (b) Memory access commands,
  (c) Test/maintenance commands.

Discrete commands are defined as commands that do not require decoding and execution by the microprocessor; they are implemented solely in hardware. Processor commands are defined as commands that require decoding and execution by the microprocessor (thus they are read and buffered on an interrupt basis). The subclasses of processor commands provide for changing the state of the instrument (operational), the capability to gain direct access to the instrument memory (memory access) and to enter special test modes (test/maintenance).

Upon Power-Up the ROM-stored flight program is automatically loaded into RAM and execution is started. Both onboard cameras are controlled by the CPU by referencing parameter lists that can be changed via the telemetry uplink. The parameter list can be updated several times per orbit depending on availability of down-link stations and real-time and data acquisition capabilities. In order to take advantage of the sophisticated abilities of the camera controller, a number of parameters must be set to define an image. As an illustration of the flexibility available and hence complexity involved Figure 7 shows an example of how an image might be selected from a portion of an actual CCD. Five parameters are necessary; the first three specify what part of the CCD is to actually be saved as an image. Parameter xdim specifies the extent in columns, xoff the position of the first column and ydim the extent in the row direction. The reference point in the row dimension (i.e., where in 360 deg to start the image) is defined by a separate

parameter referenced to the Earth sensor signal. Note as well ydim may exceed the physical dimensions of the CCD because the TDI rate equals the digitization rate. The remaining two parameters (xbin and ybin) specify what binning of pixels is desired to construct the actual output image. As a large number of just these 5 parameters can be envisioned to be useful, some means of minimizing storage requirements for parameters and yet retaining maximum flexibility was necessary. The method chosen was to utilize structure pointers to define the combination of parameters desired. In this way for example a single byte (i.e., a number from 0 to 7) could specify one of 8 further pointers, etc., to define the path along which to proceed to acquire the full set of parameters to define each image. Operationally then different images could be specified with a minimum of command overhead by changing a pointer high up in the path. This organizational scheme allowed predefining several hundred expected operational scenarios.

The amount of available RAM opened up possibilities not available on previous imaging missions. Data can be gathered, for example over the South Pole, stored in memory and telemetered down once the spacecraft comes into the coverage area of a ground station. Depending on compression scheme used and superpixel size, a nominal amount of 3 dual camera images can be stored in RAM awaiting download. Once the spacecraft is within reach of a ground station, it can be commanded to download stored image data. The instrument can also download images as they are gathered when the spacecraft is within the coverage area of a ground station. The received images can be used as a basis for changing imaging parameters to be able to better study a particularly interesting feature or phenomenon. For example, it may be decided that all on-board processing power be concentrated on just one of the cameras (i.e., one wavelength) to gain an increase in temporal and spatial resolution. Theoretically, the effects of changing the imaging parameters should be apparent during that same pass, depending of the real-time processing and up-link capabilities available. The instrument can also be commanded to download test patterns, various instrument status information and spacecraft time, for test purposes.

7. Calibration

A significant advantage of the technique utilized to acquire images is that the data are immediately interpretable without any preprocessing. For example, Figure 8 shows a color representation (red being higher data numbers) of the actual raw data from the instrument during an orbit on 5 December, 1993. Data from both cameras is shown with the LBH results on the right and the (primarily) 130.4 nm image on the left. In this presentation data numbers from 0 to 255 have been represented as various colors, but no other processing is required to identify the auroral region running through the upper middle of each image. At this level much interesting visualization occurs, but to proceed farther a number of instrumental effects must be accounted for. The first is obvious in comparing the images from the

two cameras. The LBH camera apparently measured a much lower emission level than the 130.4 nm camera. Part of this difference is due to differing sensitivities of the two cameras.

While a number of factors contribute to the sensitivity the major component in this case is the gain of the MCP. The voltage applied to the MCP provides the primary means whereby the instrument can be set to a reasonable sensitivity during the actual mission. The gain of the two MCP units is shown in Figure 9. The data were acquired during the test and construction phase of the image intensifiers and show the standard increase in electron gain with increasing voltage. Preliminary test during the early mission revealed that a voltage setting of 871 V provides a reasonable gain for all operating conditions. At this voltage there is roughly a factor of 2 difference between the cameras which helps explain the differing throughput. Another sensitivity difference acts in the opposite direction. As Griffioen *et al.* (1991) point out remnant photocathode emissivity at long (i.e., visible) wavelengths can contribute to the emission seen particularly when imaging the dayside portion of the Earth. The application of a dark coating to the secondary mirror of the 130.4 nm camera, while reducing that problem as well reduces throughput as shown in Figure 10. Here a typical curve of the reflectivity for the 130.4 nm camera shows the reduction in reflectivity as a function of wavelength. Because of the reduced sensitivity of the LBH camera it does not contain such a coating.

A further sensitivity affect common to both cameras, but not apparent in the data of Figure 8 is a dependence of optical throughout on position with respect to the optic axis. It is necessary to accurately correct all pixels within the field of view to the same sensitivity level. This was accomplished during calibration by illuminating each camera with a UV point source and measuring the data number output at a specific preamp and MCP gain and accurately determining the position of the point source within the field of view. Because of the usage of the TDI approach in clocking the CCDs there results only a one-dimensinal (i.e., columnar) dependence on sensitivity. This column-dependent sensitivity is the result of reduced throughput particularly of the fibre optic bundles used for correction of the distortion effects. Figure 11 shows the result of a series of point source measurements with column number for the LBH camera. The reduction in sensitivity from the center to edges corresponds to approximately a factor of 1.8. The data in the figure are the result of interpolating between points in the column direction and averaging 11 points over the row direction for several such raster scans of the UV point source. These effects at both high and low column numbers are the result of the calibration setup.

An equally important aspect of calibration for quantitatively utilizing the images is to determine the precise angular position of each pixel with respect to the optical axis. Because of the optical system there is an approximate cosine dependence on the field of view of a pixel as one proceeds away from the optical axis. Again because of the TDI approach this dependence occurs only in the column direction. During calibration data was acquired from a point source which was moved suc-

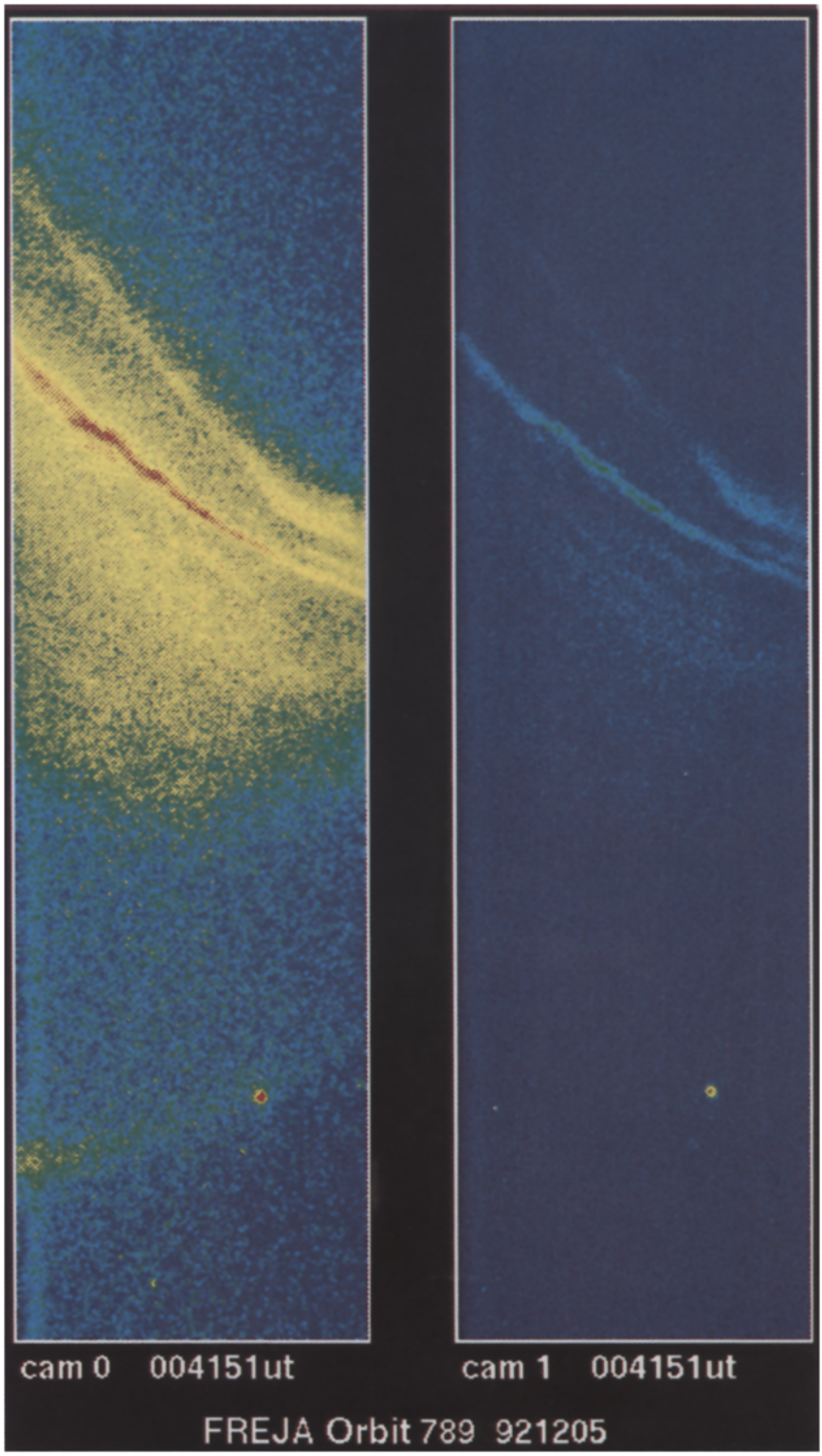


Fig. 8. A pair of *Freja* images acquired at 00:41:51 UT on 5 December, 1992. The LBH data is shown on the right and the 130.4 camera data on the left. UV intensities are represented in a pseudo-color format with red most intense and blue weakest.

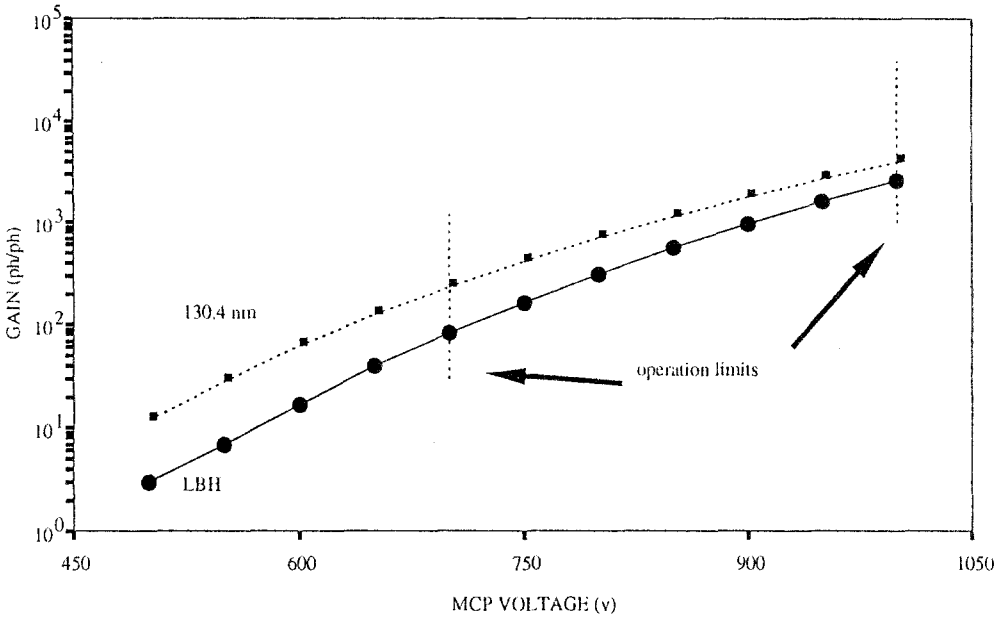


Fig. 9. Photon in photon out gain curves for the two flight MCPs. Typical operation occurs at 871 V.

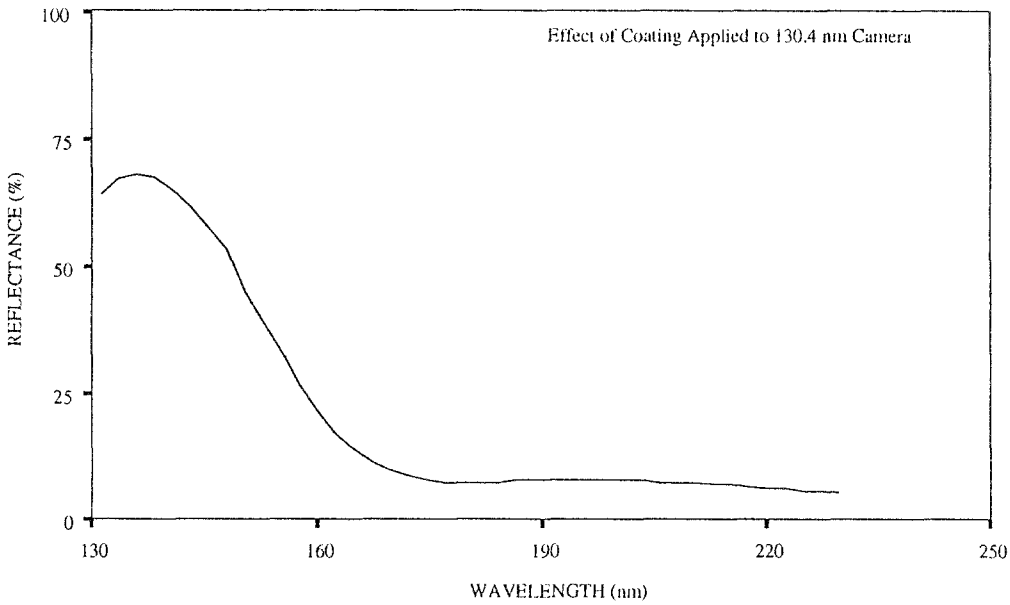


Fig. 10. Variation in reflectance of coating applied to the secondary mirror of the 130.4 nm camera.

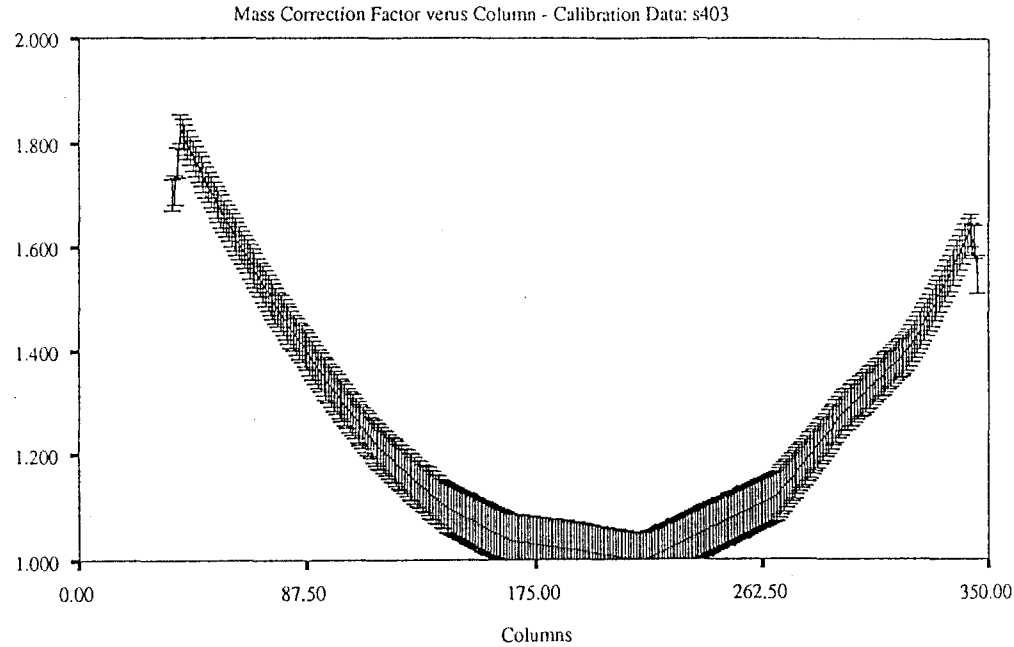


Fig. 11. Calibration results of the variation in sensitivity with CCD column for the LBH camera. The effect is largely due to the decrease in optical transmission through the fibre-optic bundles at their edge.

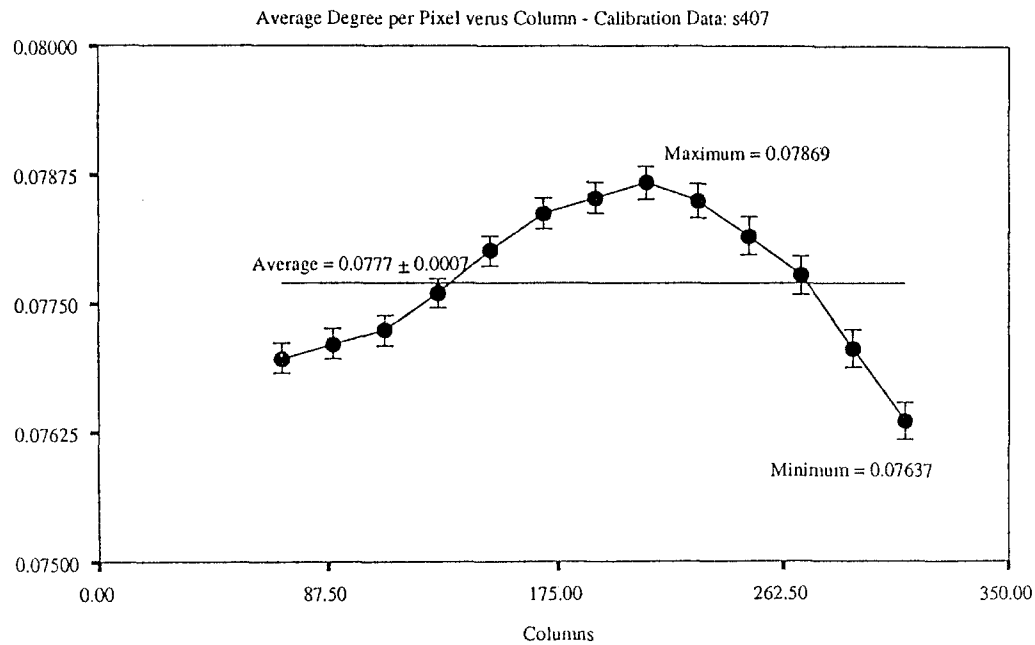


Fig. 12. Calibration results of the field of view of a pixel versus CCD column.

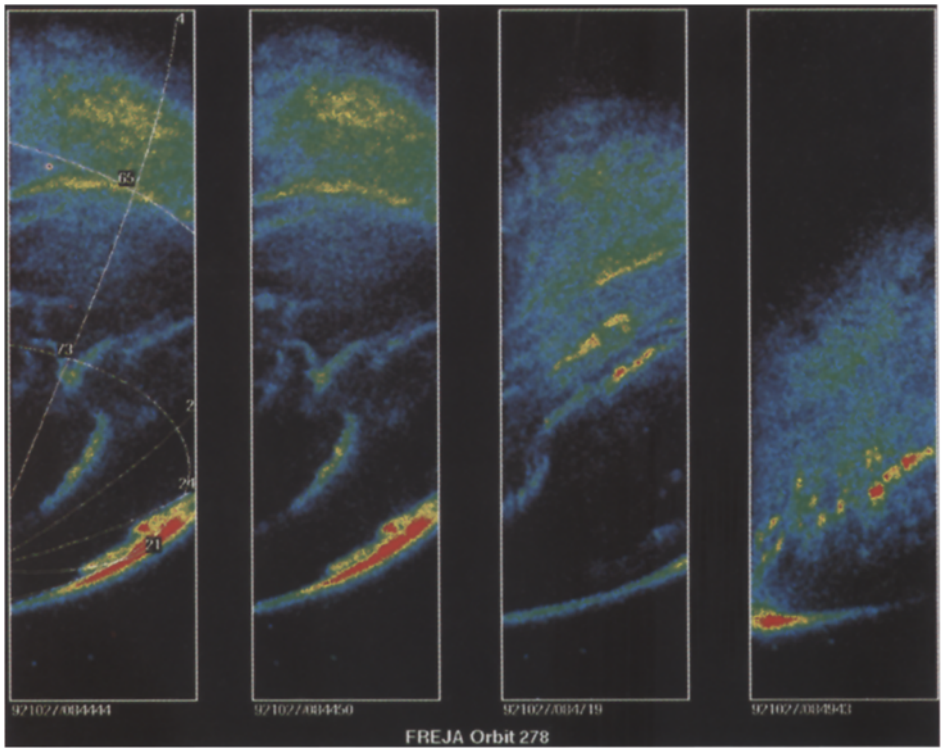


Fig. 13. Series of 4 *Freja* images acquired 27 October, 1992. The data are from the LBH camera and increasing intensities are shown in color from blue to red.

cessively in angle. The centroid of the resulting position in the CCD was obtained and from adjacent positions the nominal field of view obtained. Figure 12 shows the result for the LBH camera. The error bars result from averaging different rows together. To simplify calculations an average pixel field of view for the column direction utilized as defined by the constant line in the figure. It is not possible to use such an average value in the row direction because first the field of view covered along a column must be the same (i.e., over a spin each column must occupy 360 deg). The value for this direction turned out to be 0.0778 and 0.0787 for the LBH and 130.4 nm cameras, respectively. Though these differences are small for the LBH camera for example, such a difference over the extent of a typical image in the row direction corresponds to 0.21 deg or approximately 3 pixels.

8. Operations

Operation of the imager is handled routinely through e-mail communications with the Swedish Space Corporation. Their operations at ESRANGE in Sweden provide primary commanding and data acquisition. Imager data is available in real time

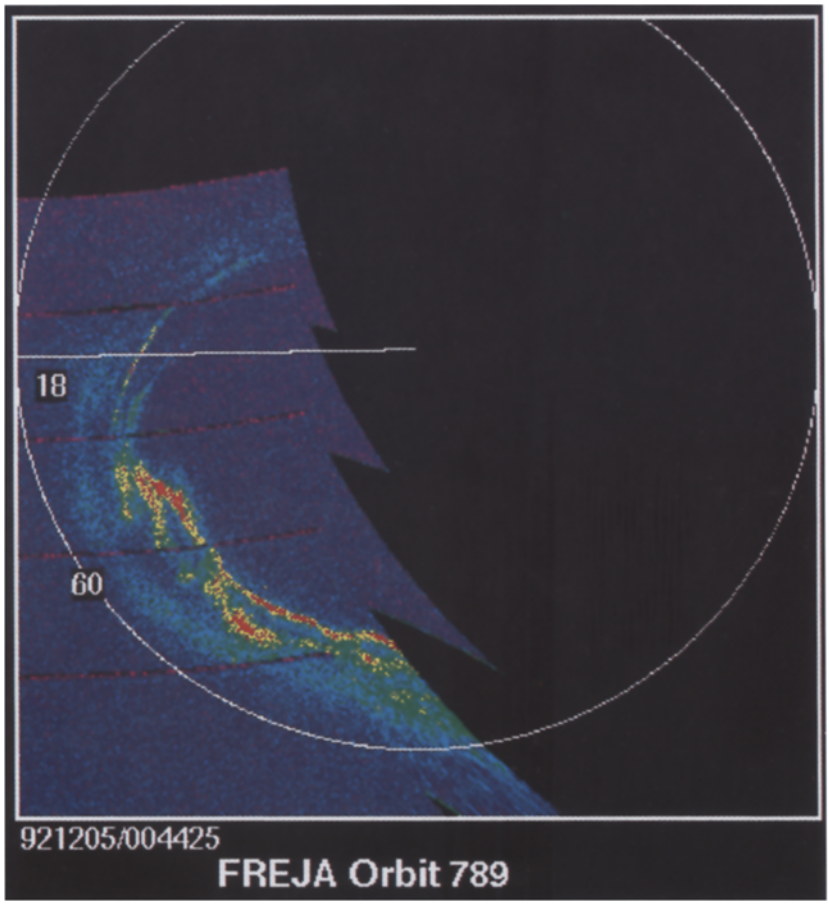


Fig. 14. A transform of 5 images acquired 5 December, 1992 onto a plane tangent to the Earth at 85 deg eccentric dipole (1990) latitude.

from that station and can be remotely accessed for display at the University of Calgary. Because of the low altitude of the *Freja* satellite ground station contact typically covers 10 to 15 min which for the imaging mode normally run yields 20 pairs of dual camera images per ground station pass. An example of the typical image repetition scenario is shown in Figure 13. Here images only 3 weeks after launch are displayed in a pseudo-color format with red representing the highest intensities. The first two images represent the data from successive spins of the satellite and the differences (difficult to identify in this presentation) represent temporal variations in the auroral distribution in the 6-s spin period level. Because the telemetry rate allocated to the imager (see Table I) is so much less than the image pixel accumulation rate typically, 3 spins of large size, dual camera images are acquired before RAM is filled at that point image acquisition halts until the memory is cleared upon which the next image is acquired. This corresponds to the

third image in the figure some 140 s later. The final image is the fourth subsequent image.

The orbital configuration of *Freja* during the fall allowed successive images to be combined into a single global view of a large fraction of the auroral distribution much as has been done in the past with line scan type systems. Figure 13 represents the result of combining a sequence of 5 images to produce such a transform in magnetic coordinates. Note that the total elapsed time between these images is less than 10 min which means it still provides a reasonable representation of the dusk sector portion of the auroral distribution.

9. Conclusions

Though constrained by time and fiscal resources the *Freja* UV imager has successfully met a number of technical difficulties. It provides an excellent extension of this type of imaging concept to satellites with severe operational constraints. It has been confirmed that high spin rate, low altitude operations can still provide useful scientific data.

Acknowledgements

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References

Adema, J., King, R. A., and Wlochowicz, R.: 1992, 'Development of an Ultra Violet Auroral Imager for the Freja Project', *Proc. of ESA Symp. on Photon Detectors for Space Instrumentation*, ESA SP-356, p. 223.

Anger, C. D., Murphree, J. S., Vallance Jones, A., King, R. A., Broadfoot, A. L., Cogger, L. L., Creutzberg, F., Gattinger, R. L., Gustafsson, G., Harris, F. R., Haslett, J. W., Llewellyn, E. J., McConnell, J. C., McEwen, D. J., Richardson, E. H., Rostoker, G., Sandel, B. R., Shepherd, G. G., Venkatesan, D., Wallis, D. D., and Witt, G.: 1987a, 'Scientific Results from the Viking Ultraviolet Imager: an Introduction', *Geophys. Res. Letters* **14**, 383–386.

Anger, C. D., Babey, S. K., Broadfoot, A. L., Brown, R. G., Cogger, L. L., Gattinger, R., Haslett, J. W., King, R. A., McEwen, D. J., Murphree, J. S., Richardson, E. H., Sandel, B. R., Smith, K., and Vallance Jones, A.: 1987b, 'An Ultraviolet Auroral Imager for the Viking Spacecraft', *Geophys. Res. Letters* **14**, 387–390.

Anger, C. D., Fancott, T., McNally, J., and Kerr, H. S.: 1973, 'ISIS–II Scanning Auroral Photometer', *Appl. Opt.* **12**, 1753–1766.

Burch, C. R.: 1947, 'Relfecting Microscopes', *Proc. Phys. Soc.* **59**, 41–46.

Elphinstone, R. D., Murphree, J. S., Cogger, L. L., Hearn, D., Henderson, M. G., and Lundin, R.: 1991a, 'Observations of Changes to the Auroral Distribution Prior to Substorm Onset', *Magnetospheric Substorms, Amer. Geophys. Un. Mono.* **64**, 257.

Elphinstone, R. D., Hearn, D. J., Murphree, J. S., and Cogger, L. L.: 1991b, 'Mapping Using the Tsyganenko Long Magnetospheric Model and Its Relationship to Viking Auroral Images', *J. Geophys. Res.* **96**, 1467.

Elphinstone, R. D., Murphree, J. S., Hearn, D. J., Cogger, L. L., Newell, P. T., and Vo, H. B.: 1992, 'Viking Observations of the UV Dayside Aurora and Their Relationship to DMSP Particle Boundary Definitions', *Ann. Geophys.* **10**, 815.

Frank, L. A., Craven, J. D., Ackerson, K. L., English, M. R., Eather, R. H., and Carovillano, R. L.: 1981, 'Global Auroral Imaging Instrumentation for the Dynamics Explorer Mission', *Space Inst. Instr.* **5**, 369–393.

Griffioen, E., McConnell, J. C., Murphree, J. S., Shepherd, G. G., Cogger, L. L., and Vallance Jones, A.: 1991, 'Viking UV Cameras: Calibration Using Model Calculations and Long Wavelength Light Leakage', *Can. J. Phys.* **69**, 1154.

Hirao, K. and Itoh, T.: 1978, 'Scientific Satellite Kyokko (EXOS-A)', *Solar Terrest. Env. Res. in Japan* **2**, 148–152.

Jones, A. V. *et al.*: 1987, 'A Comparison of CANOPUS Ground Optical Data with Images from the Viking UV Camera', *Geophys. Res. Letters* **14**, 391–394.

King, R. A., Broadfoot, A. L., Sandel, B. R., and Vallance Jones, A.: 1988, 'Correcting Image Distortion with Fiber Optic Tapers', *Appl. Opt.* **27**, 2048.

Lopez, R. E., Luhr, H., Anderson, B. J., Newell, P. T., and McEntire, R. W.: 1990, 'Multipoint Observations of a Small Substorm', *J. Geophys. Res.* **95**, 18,897.

Lui, A. T. Y., Venkatesan, D., and Murphree, J. S.: 1989, 'Auroral Bright Spots on the Dayside Oval', *J. Geophys. Res.* **94**, 5515.

Meng, C.-I. and Huffman, R. E.: 1984, 'Ultraviolet Imaging from Space of the Aurora under Full Sunlight', *Geophys. Res. Letters* **11**, 315–318.

Murphree, J. S. and Cogger, L. L.: 1988, 'The Application of CCD Detectors to UV Imaging from a Spinning Satellite', *Ultraviolet Technology II, Proc. Soc. Opt. Eng.* **932**, 42.

Murphree, J. S., Cogger, L. L., and Elphinstone, R. D.: 1989, 'Observations of Distortions of Optical Features in the UV Auroral Distribution', *IEEE Trans. Plasma Sci.* **17**, 109.

Murphree, J. S., Elphinstone, R. D., Cogger, L. L., and Hearn, D.: 1991, 'Viking Optical Substorm Signatures', *Magnetospheric Substorms, Amer. Geophys. Un. Mono.* **64**, 241.

Murphree, J. S., Elphinstone, R. D., Henderson, M. G., Cogger, L. L., and Hearn, D. J.: 1993, 'Interpretation of Optical Substorm Onset Observations', *J. Atmospheric Terrest. Phys.* **55**, 1159.

Oguti, T., Kaneda, E., Ejiri, M., Sasaki, S., Kadokura, A., Yamamoto, T., Hayashi, K., Fujii, R., and Makita, K.: 1990, 'Studies of Auroral Dynamics by Aurora-TV on the Akebono (EXOS-D) Satellite', *J. Geomag. Geoelectr.* **42**, 555.

Rees, M. H., Lummerzheim, D., Roble, R. G., Winningham, J. D., Craven, J. D., and Frank, L. A.: 1988, 'Auroral Energy Deposition Rate, Characteristic Electron Energy, and Ionospheric Parameters Derived from Dynamics Explorer I Images', *J. Geophys. Res.* **93**, 12,841.

Rogers, E. H., Nelson, D. F., and Savage, R. C.: 1974, 'Auroral Photography from a Satellite', *Science* **183**, 951–952.

Sandahl, I., Eliasson, L., Pellinen-Wannberg, A., Rostoker, G., Block, L. P., Erlandson, R. E., Friis-Christensen, E., Jacobsen, B., Luhr, H., and Murphree, J. S.: 1990, 'Distribution of Auroral Precipitation at Midnight During a Magnetic Storm', *J. Geophys. Res.* **95**, 6051.

Shepherd, G. G., Fancott, T., McNally, J., and Kerr, H. S.: 1973, 'ISIS–II Atomic Oxygen Red Line Photometer', *Appl. Opt.* **12**, 1767.

Steele, D. P., McEwen, D. J., and Murphree, J. S.: 1992, 'On the Possibility of Auroral Remote Sensing with the Viking Ultraviolet Imager', *J. Geophys. Res.* **97**, 2845.

Wei, C. Q., Lee, L. C., and Labelle-Hamer, A. L.: 1990, 'A Simulation Study of the Vortex Structure in the Low Latitude Boundary Layer', *J. Geophys. Res.* **95**, 20,793.

Ultraviolet Auroral Imager (UVAI)

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1 Scientific Objectives of the Experiment

The overall purpose of the experiment is to investigate the processes in the earth's environment that are responsible for various auroral phenomena. These processes have been the object of much study using a variety of techniques, but the complexity of the earth-sun system has continued to challenge attempts at reaching a satisfactory level of understanding. Electric and magnetic fields, current systems, waves, and particles all interact in the processes responsible for aurora, so it is necessary to undertake experimental programs that involve a variety of measurements at different points in space in order to make significant progress. The distribution of aurora in time and space in the polar regions of the earth is a key component in an attempt to achieve a cohesive interpretation of in-situ satellite measurements of waves, particles and fields. An auroral imager situated in a satellite is the only means available to achieve the necessary spatial and temporal information. Aurora is a dynamic phenomenon which can change dramatically on a time scale of minutes or less, and so must be monitored at a rate consistent with the changes.

Although the acquisition and analysis of auroral images can lead to very fruitful scientific benefits such as statistical studies of features that can be mapped into specific regions of the magnetosphere, it is clear that the major scientific achievements will come about through the close coordination of efforts by teams of scientists who are carrying out complementary experiments both on board satellites and from the ground.

The following list of specific scientific objectives is not exhaustive, but does represent what can be achieved through the utilization of an auroral imager in cooperation with other measurements:

1. To investigate the processes involved in the energization of auroral particles that give rise to auroral events;
2. To identify the optical consequences of large magnetic storms such as concurrent changes in both dayside and nightside aurora;
3. To identify the various characteristic forms of aurora seen from space and to relate these to specific processes in the magnetosphere; and
4. To investigate the relationship between auroral events and lower atmospheric phenomena, such as gravity wave propagation and stratospheric warmings.
5. To map various auroral features to their generation regions in the outer magnetosphere, especially in the magnetotail, and to experimentally confirm the linkage.

It is expected that the UVAI will be used to extend the scientific achievements realized from the UV cameras on the Swedish Viking satellite (Cogger et al., 1991).

2 Overview of the Experiment

The scientific motivation to study the global temporal and spatial distribution of aurora led to the following measurement objectives:

1. To observe aurora during both geomagnetically quiet and disturbed periods;
2. To observe the entire auroral distribution within an exposure time of a few seconds;
3. To observe aurora irrespective of sunlight conditions; and
4. To provide continuous coverage of the aurora for typical substorm lifetimes (1 to 3 hours).

These objectives can be met for the Interball program with a camera similar to that previously flown on the Swedish Viking satellite. The camera must operate in the ultraviolet part of the spectrum where solar photons are completely absorbed by the Earth's upper atmosphere which provides sufficient contrast for the aurora to be seen above the dayglow background. Suitable auroral spectral features are the Lyman-Birge-Hopfield (LBH) bands of molecular nitrogen and the atomic oxygen lines at 130.4 nm and 135.6 nm which can be included within a passband extending from 125 nm to 160 nm. This passband excludes the Lyman alpha emission at 121.5 nm which has both a proton-aurora source and a geocoronal source.

The auroral emissions within the passband are suitably strong even under quiet conditions that a very sensitive camera with an exposure time of several seconds can obtain satisfactory images. The Viking camera operated at f/1 with an instantaneous field of view of 25 degrees by 20 degrees. In order to increase the exposure time beyond a few milliseconds (necessary to eliminate image smearing) the camera utilizes a technique to electronically move the image in the array detector at the same rate as the satellite spins. The exposure time is then determined by the desired field of view and the spin period. For the Auroral Probe satellite which will have a 120 second spin period, a 20 degree field of view corresponds to an exposure time of 6.7 seconds. Selection of the specific field of view to observe the aurora requires a reference signal from a horizon sensor to provide the appropriate spin phase information. The repetition rate for images can be as rapid as one image per spin of the satellite; i.e., one image every 2 minutes.

The entire auroral distribution can be measured simultaneously with a 20 degree by 25 degree field of view when the satellite geographic position, the declination of the satellite spin axis are suitable, and the satellite altitude is above 8000 km. In order to accommodate a large range of spin axis declination two cameras are utilized: one camera (camera 0) is oriented with its optical axis perpendicular to the spin axis direction; and the other (camera 1) is oriented with its optical axis in a direction of 67.5 degrees with respect to the satellite spin axis. For certain periods of time

during the mission only one of the cameras will be required to image the aurora; at other times both will have to be utilized. Figure 1 shows a viewing situation in which both cameras are required to cover the entire auroral distribution. The 25-degree fields of view of the two cameras overlap slightly to permit position and sensitivity registration. As pointed out above, it is also necessary to position dynamically the 20-degree field in the scan direction by knowledge of the phase angle of the optical axis with respect to the earth's horizon.

For the Auroral Probe orbit it will be possible for the cameras to observe the aurora for periods as long as 3 hours under the best conditions. The actual quantity of images will in practice be determined by the allocation of data storage and/or telemetry availability. The telemetered output from the cameras will be raw images with variable array sizes. Adjustments in the operating parameters are possible so that images can be spaced in time or altered in size.

3 Technical Description

3.1 Mechanical Description

The UVAI instrument (Figure 2) is comprised of two cameras, two earth sensors, a gimbal mechanism, two radiator plates and two electronics boxes, all mounted on a baseplate which is mounted onto the spacecraft. The overall mass of the instrument is 20 kg. The baseplate size is 43 by 33 cm and the instrument height is 35 cm. Each camera consists of a camera body, a dust cover and a detector. Each camera body, which is constructed of graphite fibre epoxy composite (GFEC) to minimize the thermal expansion of the body over the expected temperature range, supports a dust cover, baffle, two mirrors, a detector and a preamplifier (Figure 3). The cameras are supported by circular clamps fitted with O-rings, and the clamps are rigidly attached to the gimbal frame to maintain the correct pointing directions (camera 0 perpendicular to the baseplate, camera 1 67.5 degrees to the baseplate).

The camera dust covers form the closure to the front end of the camera bodies. They do not form an air-tight seal because they are only required to protect against dust prior to launch. The dust covers, which are spring loaded, will be released after launch using a biphenol plug which will vaporize in the space environment.

The UVAI instrument contains two separate earth sensors, one coaligned with each camera, to provide pulses at each horizon crossing during a single rotation of the satellite. These pulses are used to measure the spin rate of the satellite, the angular width of the earth, and to provide an earth-fixed reference angle for the calculation of the initiation time of an auroral image.

The gimbal mechanism rotates the cameras about an axis in the Y,Z-plane of the satellite, i.e., normal to X, the expected spacecraft spin axis, to compensate for a possible 2 degree variation in orientation of the true spin axis with the spacecraft's X-axis. The gimbal motor and associated electronics are located adjacent to the gimbal frame. The gimbal frame is locked in place prior to launch by means of a biphenol plug.

The two radiator plates, attached to each camera body, are designed to radiate heat from the CCDs, keeping them at a constant cool temperature of approximately -35 degrees Celsius. Thermal blankets will be utilized to keep the camera bodies at an operating temperature of about -5 degrees.

UVAI has two separate but connected electronics boxes; one containing earth sensor electronics, and the other containing the operations and control electronics. The electronic boxes, like the cameras and earth sensors are thermally isolated from the instrument structure.

3.2 Optical Description

The optical design is similar to that of the UV camera that was flown on the Swedish Viking satellite (Anger et al., 1987). The inverse Cassegrain optics form a Burch-type camera of 22.9 mm focal length that operates at f/1, providing UV sensitivity with good throughput over the 20 by 25 degree field of view. Some camera parameters are given in Table 1. The general arrangement of the optical elements is shown in Figure 3. The mirrors were fabricated from Zerodur, a material with a very small coefficient of thermal expansion. The primary mirror is coated with aluminum onto which a protective coating of magnesium fluoride has been applied. The secondary mirror is coated with aluminum, but in this case a special interference coating has been added to reduce the reflectance of the mirror at wavelengths outside of the camera passband.

A significant change in the optical design for UVAI has been the development of a closed rather than open detector. The calcium fluoride window of the UVAI detector serves as an absorption filter to define the short wavelength cut-off of the camera response. The overall passband of the camera, shown in Figure 4, is determined by the combination of mirror coatings, the calcium fluoride filter and the quantum efficiency of the potassium bromide photocathode material.

The image formed by this type of camera conforms to a spherical rather than flat surface. Rather than attempting to flatten the field, the approach used in both the Viking and Interball cameras was to incorporate a curved microchannel plate intensifier (MCP) with the photocathode material deposited directly on the surface. Figure 5 shows the configuration of the detector. The UV photons strike the photocathode, where by means of the photoelectric effect, a fraction are converted to electrons that escape the potassium bromide and are accelerated and multiplied by the MCP. The current gain of the MCP can be varied in steps

over three orders of magnitude by adjustment of the MCP voltage between 750 and 1000 volts. The electrons that are ejected from the photocathode but which do not travel along the 12 micron-diameter channels are repelled by a mesh grid placed 10 mm in front of the photocathode with an electric potential of -40 volts with respect to the photocathode. There is also a thin metallic coating on the inside surface of the window that provides a path to ground for any stray electrons.

The anode screen consists of a thin layer of phosphor deposited upon a fibre block whose surface is in proximity to and conformal with the output surface of the MCP. The P-20 phosphor is coated with a thin aluminum backing which serves several purposes: it is the high-voltage terminal (approx. 4000 volts with respect to the output end of the MCP) that creates the accelerating field between the MCP and the screen; it attenuates visible light passing through the MCP to the CCD; it increases the anode collection efficiency by reflecting phosphor radiation towards the CCD; and it drains the charge collected from the MCP.

Light from the phosphor is transmitted to the CCD detector by a combination of fibre optic sections that match the surfaces of the CCD and the curved phosphor and also remove the distortion due to the projection of the spherical focal plane onto the flat CCD detector (King et al., 1988) in such a way that all points in the image move parallel to the CCD columns at a uniform rate. It is this feature that allows the charge to be shifted along the columns during an exposure without introducing significant spreading of the image across adjacent columns. With the clocking rate adjusted to match the satellite spin rate, the charge then moves along the columns at the same rate as the image moves through the field of view of the camera thus permitting the long exposure (6.7 seconds) without smearing of the image. The corrector sections are different for the two cameras because the scan planes are at different angles with respect to the spin axis of the satellite.

The CCD detector is a type EEV 8603 with a full frame format of 578 by 385 pixels. The characteristics of the CCD are given in Table 2.

3.3 Electrical Description

An electrical block diagram is shown in Figure 6. The preamplifier is located in the camera rear assembly. It connects to the main electronics unit via a 25-pin connector. The preamplifier printed circuit board (PCB) is also wired to the CCD PCB, on which is mounted the CCD detector. The preamplifier contains the following circuits: a sample-and-hold amplifier; a low noise amplifier with programmable gain (1,2,5, or 10); and a DC error amplifier for CCD output bias nulling.

The Processor PCB is one of five PCB's that plug into the UVAI electronics unit motherboard in the main electronics box. The Processor board provides the central control functions requested by the software that is stored in 2048 by 32-bit RAM with power back-up.

The CCD interface PCB contains a video analog chain (gain 2.5), a low pass filter, an 8 channel multiplexer for 2 video chains, 5 temperature channels, and one high voltage monitor. There is a single 12-bit A/D converter and a 12-bit to 8-bit translation table PROM for data compression. No compression is performed on data numbers between 0 and 49 inclusive; between 50 and 4095 logarithmic compression is utilized. Also contained on this PCB are CCD clock level reference voltage generators, CCD clock drivers, and preamplifier power supply regulators.

Another PCB contains the 48K bytes of CMOS static RAM, of which 8K bytes is backed up by the UVAI battery during main power-off periods. Included are address decoding, logic level shifters and buffers for the RAM as well as a data bus interface. Two 12-bit programmable rate timing generators are used for the CCD vertical clock control.

The spacecraft interface PCB contains the following circuits: optoisolated interfaces to the Ouks command signals; majority vote logic (three wire) for Ouks signals; optoisolated discrete command interfaces for FK1 and FK2; power-up reset circuit; clock generator for processor clock and RTC; SSNI signal interfaces and SSNI telemetry parallel to serial shift register and control logic; KBV signal interfaces and KBV serial to parallel shift register. A second interface PCB board contains the gimbal electronics and the STO telemetry interface.

Raw power at 27 volts is received from the spacecraft via two lines, one for heaters and the NiCd battery charge circuit and the other for instrument power. A synchronous converter and regulator provides the basic +/- 5 volt low-voltage power. A second supply converts from 5 volts to 4800 volts as required by the detector.

4 Modes of Operation and Camera Characteristics

The successful operation of the cameras requires the capability to alter a number of instrument parameters. To minimize the demand on the uplink, there exist in PROM three candidate parameter lists that can be altered as required. These lists contain the following:

- the camera(s) to be operated
- manual earth limb sensor selection
- the number of images to be acquired
- the number of spins between images
- the size of images in pixel pairs (horizontal and vertical offsets)
- the number of pixels to bin (between 1 and 15)
- the angular delay from the selected limb pulse to the end of the TDI image exposure
- camera gain control. The video gain can be set independently for each camera; the image intensifier gain is the same for each camera

- manual setting of vertical clock rate for each camera

The image header contains all of the parameters related to each image as well as other information such as time and date of image acquisition, thermistor readings, etc.

Table 1 provides information about the spatial resolution and camera dynamic range. It should be noted that the spatial resolution applies to apogee (20,000 km above the earth's surface); for lower altitudes the spatial resolution improves. The sensitivity can be improved at the expense of spatial resolution by on-chip summation: for example, 2 by 2 pixel summation improves the signal-to-noise ratio by a factor of 2. The range of 0.5 to 100 kR is an estimate of the equivalent OI 5577 intensity. The calculated camera signals for a 1 kilorayleigh source at the peak of the instrument passband are given in Table 3 for an MCP voltage of 850 volts and an analog circuit gain of 25. One kR produces 125 data numbers per exposure at the output of the A/D converter. It must be emphasized that the correct value for the sensitivity can be obtained with confidence only from the laboratory calibration of the flight model of the cameras. Several other critical laboratory measurements must be undertaken to ensure the proper alignments of components, to assess the image distortion, and to obtain the responsivity variation on a pixel-by-pixel basis.

There is no onboard calibration capability. During the mission, UV stars will be used to monitor the response of the cameras and to check the viewing geometry. Since there is a 2.5 degree overlap in the fields of view of the two cameras, it is possible during the mission to check the relative pointing and responsivity to aurora.

5 Mission Planning

The operations of the instrument during the mission will be determined to a large extent by data storage/telemetry capability and by the viewing geometry. Figure 7 shows the number of minutes that the auroral distribution (whole or part) can be viewed by each camera over one orbit as a function of the day of the year. Calculations have been done for two launch conditions: the top is for a summer launch leading to a local midnight apogee about two months later; the bottom is for a winter launch leading to a local midnight about two months later. It is evident that the UVAI instrument provides significantly better coverage for the case of the summer launch, which is not surprising, since the camera 1 offset angle was chosen for a summer launch and autumn midnight conjunction of the two Interball satellites. For the summer launch scenario, in contrast to the winter launch situation, there are no periods when neither camera can image the aurora and it is also evident that both the average and peak coverage per orbit are much greater. There are times when the aurora can be viewed for several hours per orbit, but for most of the orbits, the amount of available time is less than two hours.

The estimated coverage of the UVAI cameras from apogee is a helpful tool for mission planning because it is near apogee that the in-situ measurements of auroral particles and fields can be made at the same time as images are obtained. The coverage from apogee is determined by the direction of the satellite spin axis and the local time of the satellite at apogee. Figure 8 has been constructed for the simple geometrical situation that occurs at 0, 6, 12, and 18 hours and for the spin axis pointing at the sun. The table gives the range in spin axis declination (between + 23.5 and - 23.5 degrees) for which the geographic pole and the subsatellite point (65 degrees geographic latitude) can be observed by at least one camera. For the situation in which the spin axis is pointed towards the sun, these declination values can be readily converted to seasons of the year.

The second major consideration when planning the operations is the availability of SSNI and STO telemetry. For each rotation of the satellite (120 seconds), one 48Kbyte data segment corresponding to the image(s) acquired during the previous rotation of the satellite can be transferred from the instrument. The effective real-time telemetry requirement is then approximately 4 kilobits per second. When this amount of telemetry is available, every image can be telemetered to ground. For example, in an observing sequence lasting one hour, 30 complete images would be transferred to ground. For telemetry rates less than 4 kilobits per second, either smaller images must be transmitted or exposures must be made less frequently than once every spin period (120 seconds).

When direct transmission of data is not available, images can be transferred to the satellite magnetic tape recorder. The UVAI allocation of 14 megabits is sufficient to store the data from 36 rotations of the satellite (72 minutes).

During the mission, cyclograms will be designed to maximize the scientific returns from the instrument by means of prediction software (based upon knowledge of the orbital elements and the attitude of the satellite spin axis) and advance knowledge of the telemetry schedule.

6 Correlated Work With Other Experiments Along the Orbit

The UV images of the aurora provide a very useful context for the interpretation of in-situ measurements of auroral particles and fields. The periods of most interest for collaboration will be during the magnetic conjunctions when the Auroral Probe and Tail Probe satellites will be situated on or near the same flux tubes that have footprints in the auroral regions on either the dayside or nightside.

In addition to other experiments on the Interball satellites, there may be opportunities to collaborate with other scientists who have experiments on other satellites and on the ground. For example, joint measurements with the Swedish Freja satellite would provide additional auroral particle and image data taken at a lower altitude. Flights over Canada should

benefit from the presence of the CANOPUS array of magnetometers, radars and optical instruments. Similar networks will be in operation in a number of high-latitude countries.

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7.2 Contractors

Instrument: CAL Corporation, Ottawa, Canada

Detector: Delft Electronische Producten, Roden, Holland

Program support: FirstMark Technologies, Ottawa, Canada

7.3 Funding and Project Management

Instrument funding: Canadian Space Agency

Science funding: Natural Sciences and Engineering Research Council, Canada

Project Manager: Jack Matsushita, Canadian Space Agency

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8 References

Anger, C. D., S. K. Babey, A. L. Broadfoot, R. G. Brown, L. L. Cogger, R. Gattinger, J. W. Haslett, R. A. King, D. J. McEwen, J. S. Murphree, E. H. Richardson, B. R. Sandel, K. Smith and A. Vallance Jones, An ultraviolet auroral imager for the Viking spacecraft, *Geophys. Res. Lett.*, **14**, 387-390, 1987.

Cogger, L. L., J. S. Murphree, R. D. Elphinstone, D. J. Hearn, and R. A. King, The UV Imager Experiment on the Swedish Viking Satellite: Contributions to Auroral Physics, *Can. J. Phys.*, **69**, 1032-1039, 1991.

King, R. A., A. L. Broadfoot, B. R. Sandel, and A. Vallance Jones, Correcting Image Distortion with Fiber Optic Tapers, *Appl. Opt.*, **27**, 2048-2054, 1988.

Figure Captions

Fig. 1. Fields of view of the two cameras observing the earth from apogee.

Fig. 2. The UVAI instrument.

Fig. 3. Elements of a single UV camera.

Fig. 4. Calculated passband of the UVAI cameras.

Fig. 5. UVAI intensifier sub-assembly.

Fig. 6. UVAI electrical block diagram.

Fig. 7. Estimated aurora viewing time per orbit for two different launch conditions.

Fig. 8. Visibility of features for different local times of apogee and declination of the satellite spin axis.

Table 1. Interball Ultraviolet Auroral Imager (UVAI) instrument characteristics.

Camera Optics	Inverse Cassegrain, speed F/1 Focal Length 22.4mm Field of View 25° × 20°
Number of Cameras	2
Look Direction	Camera 0 - optical axis is 90° from spin axis Camera 1 - optical axis is 67.5° from spin axis
Spectral Passband	125nm to 160nm
Filter	CaF_2
Detector	Intensified CCD Photocathode KBr Image size 320 × 256 pixels Pixel size 30μ × 30μ projected onto photocathode
Resolution	Angular 0.076° × 0.076° Spatial (from apogee with 2 × 2 pixel summation): Camera 0 = ≈55 km Camera 1 = ≈80 km
Exposure	6.5 seconds (for 120 second spin period)
Repetition Rate	Typically one image every spin period
Dynamic Range	4096 digitized values compressed to 256
Intensity Range	0.5 to 100 kR equivalent OI 557.7nm

Table 2. CCD Characteristics.

Type	eev 8603/uvai
Full frame format	578 × 385 pix
Pixel size	22 × 22 μ
Image format	256 × 320 pix
Image size	5.63 × 7.04 mm
Approximate full well potential	$3 \cdot 10^5 e^-$
Approximate full well potential	201 mV

Table 3. System gain summary.

One kR source	$1 \cdot 10^9$ γ/sec/ster/cm^2
Image integration time	6.67 sec
Camera AΩ and vignetting	$3.99 \cdot 10^{-6}$ ster cm^2
Signal/pix/frame at optics	2115 γ

Theoretical Signals for 1 kilo-Rayleigh Source					
Note	Gain	Units	Signal	Sigma	Units
Optics	0.496		1049	0.0	γ
CaF_2	0.563		591	0.0	γ
Grid	0.975		576	0.0	γ
Photocathode	0.140	d^-/γ	80.7	8.98	e^-
MCP	750	e^-/e^-	60512	9527	e^-
Anode	13.8	γ/e^-	837177	131808	γ
Corrector	0.104		87276	13741	γ
CCD Fiber	0.800		69821	10993	γ
CCD qe	0.260	e^-/γ	18153	2861	e^-
CCD gate	0.670	$\mu V/e^-$	12163	1917	μV
Signal chain	25	μV/μV	304	47.9	mV
A to D	0.410	dn/mV	125	19.6	dn

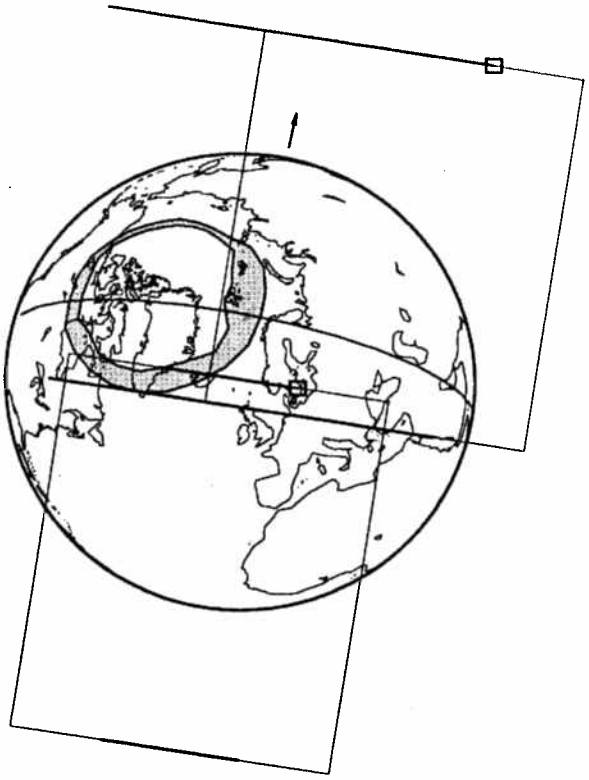


fig. 1

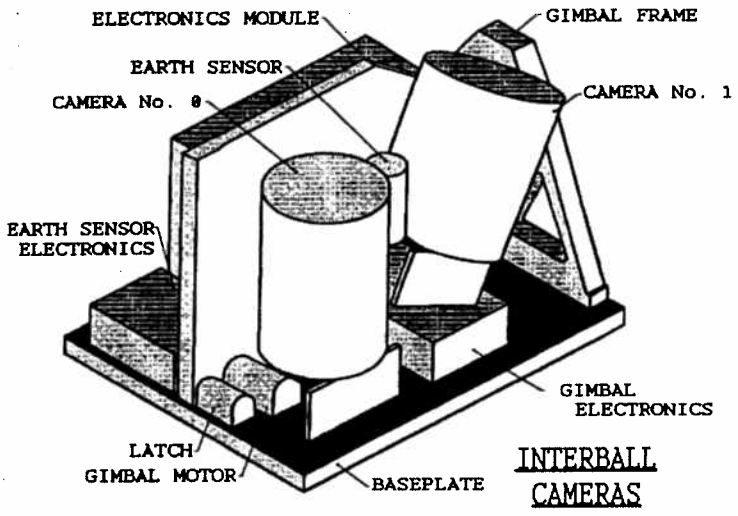

ELECTRONICS MODULE
GIMBAL FRAME
EARTH SENSOR
CAMERA No. 0
CAMERA No. 1
EARTH SENSOR ELECTRONICS
GIMBAL ELECTRONICS
LATCH
GIMBAL MOTOR
BASEPLATE
INTERBALL CAMERAS

fig. 2

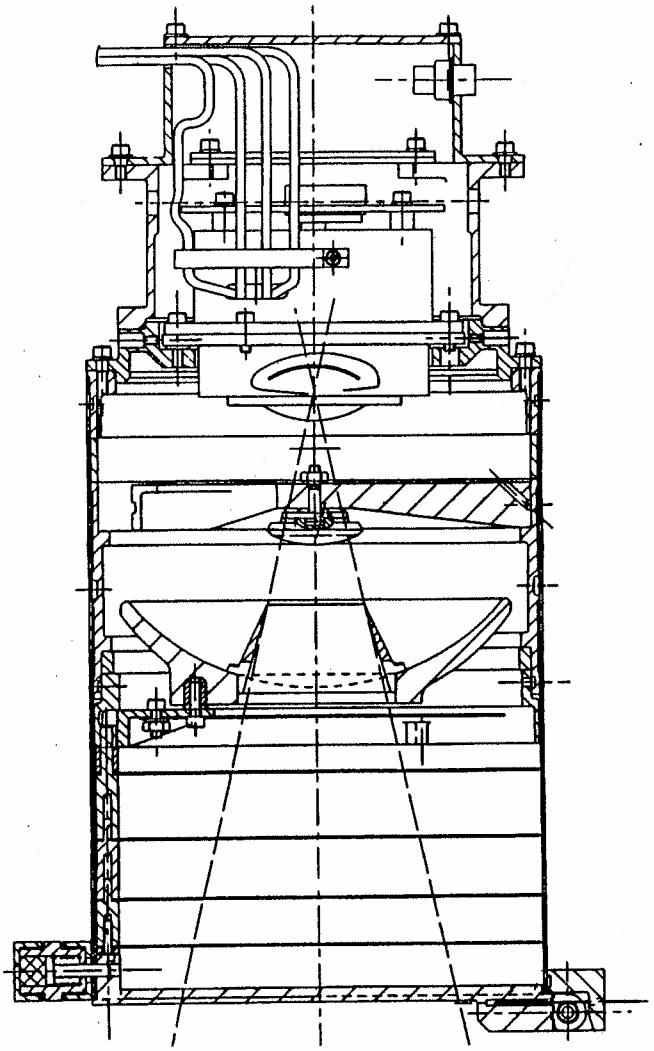


fig. 3

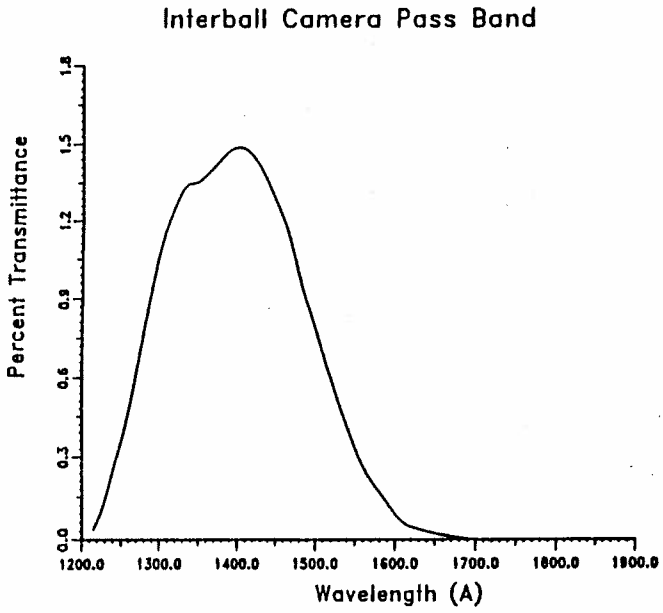

Interball Camera Pass Band
Percent Transmittance
0.0
0.3
0.6
0.9
1.2
1.5
1.8
1200.0
1300.0
1400.0
1500.0
1600.0
1700.0
1800.0
1900.0
Wavelength (A)

fig. 4

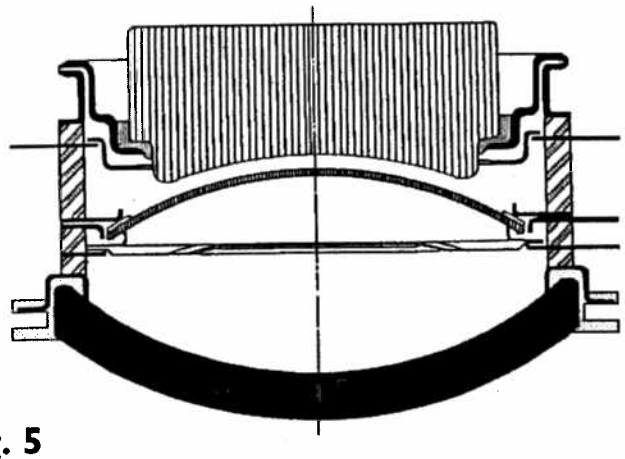


fig. 5

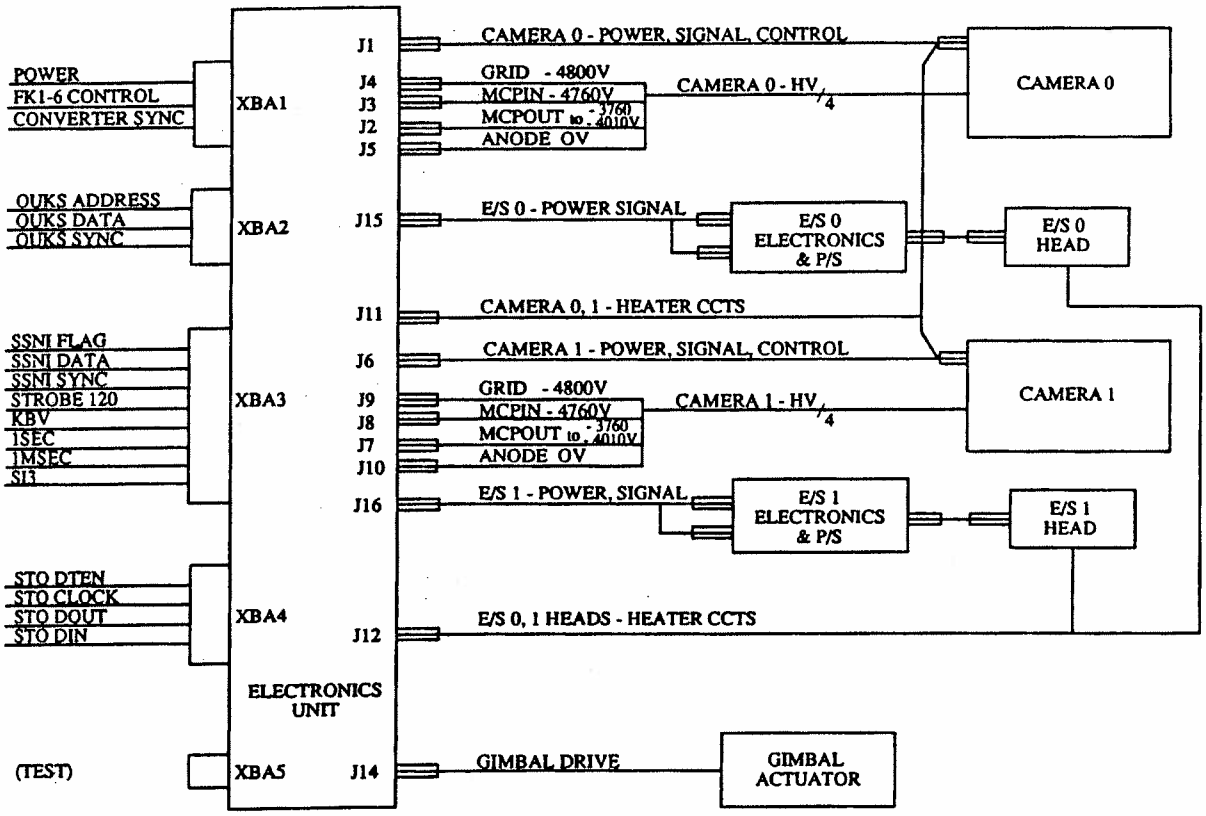
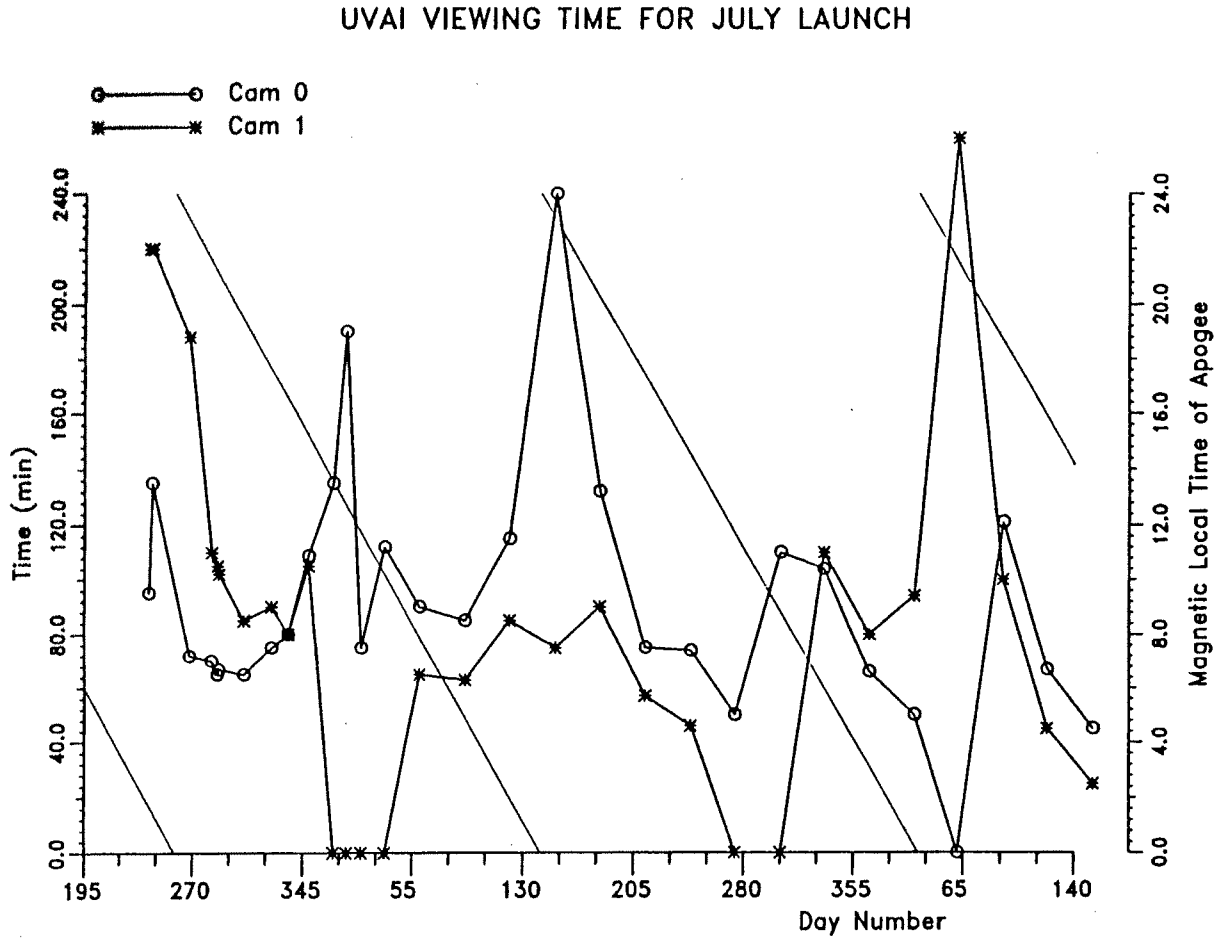

POWER
FK1-6 CONTROL
CONVERTER SYNC
XBA1
OUKS ADDRESS
OUKS DATA
OUKS SYNC
XBA2
SSNI FLAG
SSNI DATA
SSNI SYNC
STROBE 120
KBV
1SEC
1MSEC
SI3
XBA3
STO DTEN
STO CLOCK
STO DOUT
STO DIN
XBA4
ELECTRONICS UNIT
(TEST)
XBA5
J1
J4
J3
J2
J5
J15
J11
J6
J9
J8
J7
J10
J16
J12
J14
CAMERA 0 - POWER, SIGNAL, CONTROL
GRID - 4800V
MCPIN - 4760V
MCPOUT to - 3760 - 4010V
ANODE OV
CAMERA 0 - HV/4
CAMERA 0
E/S 0 - POWER SIGNAL
E/S 0 ELECTRONICS & P/S
E/S 0 HEAD
CAMERA 0, 1 - HEATER CCTS
CAMERA 1 - POWER, SIGNAL, CONTROL
GRID - 4800V
MCPIN - 4760V
MCPOUT to - 3760 - 4010V
ANODE OV
CAMERA 1 - HV/4
CAMERA 1
E/S 1 - POWER, SIGNAL
E/S 1 ELECTRONICS & P/S
E/S 1 HEAD
E/S 0, 1 HEADS - HEATER CCTS
GIMBAL DRIVE
GIMBAL ACTUATOR

fig. 6


UVAI VIEWING TIME FOR JULY LAUNCH
Cam 0
Cam 1
Time (min)
0.0
40.0
80.0
120.0
160.0
200.0
240.0
Magnetic Local Time of Apogee
0.0
4.0
8.0
12.0
16.0
20.0
24.0
195
270
345
55
130
205
280
355
65
140
Day Number

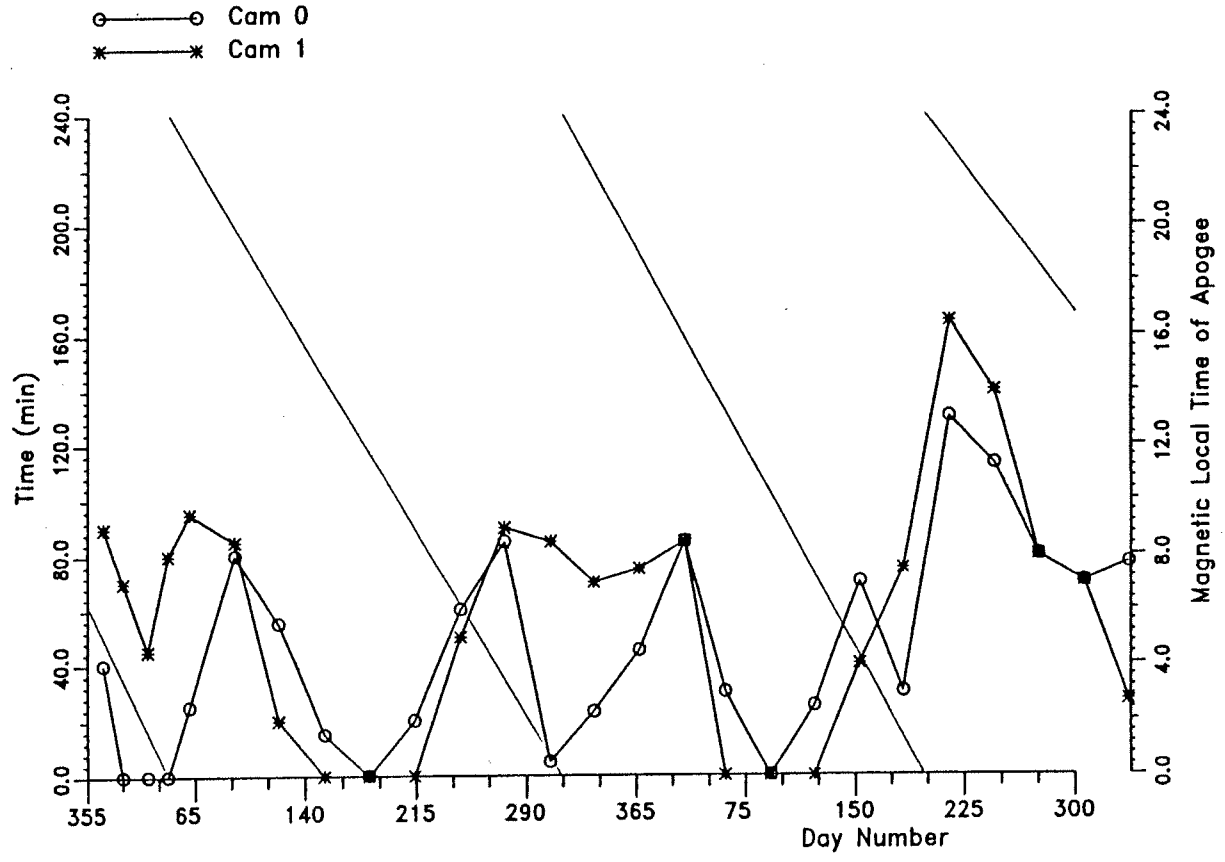

UVAI VIEWING TIME FOR DECEMBER LAUNCH
Cam 0
Cam 1
Time (min)
0.0
40.0
80.0
120.0
160.0
200.0
240.0
Magnetic Local Time of Apogee
0.0
4.0
8.0
12.0
16.0
20.0
24.0
355
65
140
215
290
365
75
150
225
300
Day Number

fig. 7

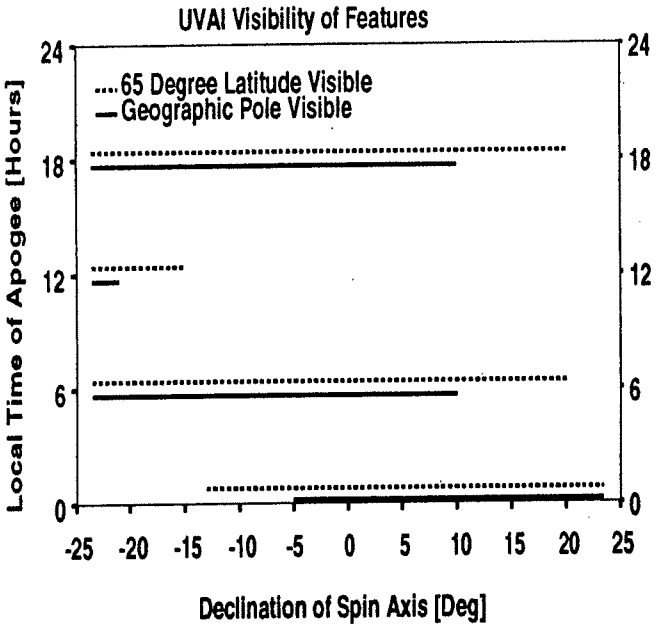

UVAI Visibility of Features
65 Degree Latitude Visible
Geographic Pole Visible
Local Time of Apogee [Hours]
24
18
12
6
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Declination of Spin Axis [Deg]

fig. 8

FAR ULTRAVIOLET IMAGING FROM THE IMAGE SPACECRAFT: 2. WIDEBAND FUV IMAGING

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Abstract. The Far Ultraviolet Wideband Imaging Camera (WIC) complements the magnetospheric images taken by the IMAGE satellite instruments with simultaneous global maps of the terrestrial aurora. Thus, a primary requirement of WIC is to image the total intensity of the aurora in wavelength regions most representative of the auroral source and least contaminated by dayglow, have sufficient field of view to cover the entire polar region from spacecraft apogee and have resolution that is sufficient to resolve auroras on a scale of 1 to 2 latitude degrees. The instrument is sensitive in the spectral region from 140-190 nm. The WIC is mounted on the rotating IMAGE spacecraft viewing radially outward and has a field of view of 17° in the direction parallel to the spacecraft spin axis. Its field of view is 30° in the direction perpendicular to the spin axis, although only a 17° x 17° image of the Earth is recorded. The optics was an all-reflective, inverted Cassegrain Burch camera using concentric optics with a small convex primary and a large concave secondary mirror. The mirrors were coated by a special multi-layer coating, which has low reflectivity in the visible and near UV region. The detector consists of a MCP-intensified CCD. The MCP is curved to accommodate the focal surface of the concentric optics. The phosphor of the image intensifier is deposited on a concave fiberoptic window, which is then coupled to the CCD with a fiberoptic taper. The camera head operates in a fast frame transfer mode with the CCD being read approximately 30 full frames (512 by 256 pixel) per second with an exposure time of 0.033 s. The image motion due to the satellite spin is minimal during such a short exposure. Each image is electronically distortion corrected using the look up table scheme. An offset is added to each memory address that is proportional to the image shift due to satellite rotation, and the charge signal is digitally summed in memory. On orbit, approximately 300 frames will be added to produce one WIC image in memory. The advantage of the electronic motion compensation and distortion correction is that it is extremely flexible, permitting several kinds of corrections including motions parallel and perpendicular to the predicted axis of rotation. The instrument was calibrated by applying ultraviolet light through a vacuum monochromator and measuring the absolute responsivity of the instrument. To obtain the data for the distortion look up table, the camera was turned through various angles and the input angles corresponding to a pixel matrix were recorded. It was found that the spectral response peaked at 150 nm and fell off in either direction. The equivalent aperture of the camera, including mirror reflectivities and effective photocathode quantum efficiency, is about 0.04 cm^2. Thus, a 100 Rayleigh LBH aurora is expected to produce 23 equivalent counts per pixel per 10 s exposure at the peak of instrument response.

1. Introduction

In a companion paper (Paper 1) we have discussed the IMAGE auroral imaging requirements. In summary, the Wideband Imaging Camera (WIC) is required to image the total intensity of the aurora in wavelength regions most representative of the auroral source and least contaminated by dayglow and other undesirable sources. It must also have sufficient field of view to cover the entire polar region from spacecraft apogee, and have resolution that is sufficient to resolve auroras on a scale of 1 to 2 latitude degrees.

After almost three decades of auroral imaging from satellites, the advantages of this observational technique have become well established. With every technological improvement have come new scientific discoveries. Initially focusing on visible auroras, it quickly became apparent that much more extended coverage could be obtained by utilizing the ultraviolet portion of the spectrum. First successfully implemented by the Dynamics Explorer program,

DE-1 utilized a combination of filters and scanning mirrors to detect UV emissions (among others) in several broad bands (Frank et al., 1981). This mission also established the importance of multiple images per satellite orbit, thereby providing for the first time reasonable temporal information on the hemispheric auroral distribution.

Two technical improvements over the DE-1 system were realized by the Viking Imager program implemented by the Canadian Space Agency (Anger et al., 1987): Exposing all regions of an image at the same time (thereby reducing uncertainties in the timing of observations), and providing the ability to image from a spinning satellite. The introduction of area detectors, specifically, charge-coupled devices (CCD), allowed the design of an imager capable of imaging large areas of the Earth with every pixel within the image exposed at the same instant of time. Installed on a spinning satellite, images could be acquired at a repetition rate equal to the spin period by implementing a method to shift the charge at the spin rate of the satellite, thereby keeping the image from blurring.

In order to provide a suitable camera system for the restricted number of photons that would be imaged on a spinning satellite, it was necessary to employ a fast camera. The design chosen was an inverted Cassegrain Burch type camera, operating at f/1 (Burch, 1947). The camera was housed inside a graphite fiber epoxy composite (GFEC) tube, a material that was intended to provide the necessary thermal expansion characteristics over the expected operating temperature range. In the Canadian program, the instrument was designed to mount on a platform that exposes the instrument to space, and the expected operating temperature range of the instrument was much larger than the environment expected in the interior of the IMAGE spacecraft. The camera had a field of view of approximately 30° x 30° and was fitted with baffles to reduce scattered light by a factor of 2.5×10^{-4}.

Subsequent to the Viking program, the opportunity to make further improvements was provided by the Freja program (Murphree et. al., 1994). In this low altitude mission, the satellite spin rate was significantly higher, resulting in effective integration times of approximately 0.3 s. In addition, the satellite altitude required extending the field of view of the camera system beyond the nominal 30° in order to observe the entire Earth. This was accomplished by matching the CCD readout rate to the satellite spin rate so that data could be continuously read into memory, theoretically allowing images of a complete spin to be acquired.

The final utilization of this design was in the Russian Interball program (Cogger et al., 1995). In this program, two identical cameras were employed. But because of the orbital configuration, one was mounted at 67.5° to the spin axis, not at 90° as is normal. This was to take advantage of the changing orbit and to allow more complete coverage of the auroral distribution. This required more sophisticated tapers connecting the MCP to the CCD.

It was established (See Paper 1) that the IMAGE satellite needed a similar Wideband Imaging Camera (WIC) with a field of view of about 20°. This imager needed to operate in the far ultraviolet spectral range. Thus, the IMAGE requirements were very similar to those of the cameras used on the Viking/Freja satellite missions and, therefore, this camera design was adopted for the IMAGE mission.

Instruments on IMAGE view radially outward away from the spin axis. The spin axis is perpendicular to the orbit plane. The orbit is truly polar (90° orbital inclination) with apogee at 44,000 km and perigee at 1000 km. For the first two years of the mission, apogee is over the Northern Hemisphere and after one year after launch, directly above the pole. The satellite will spend most of its time far away from Earth, observing at and near apogee. The FUV auroral instruments view the Earth for a brief time– once per satellite revolution (period of revolution = 2 min.). During certain seasons the sun is near the satellite orbit or spin plane and therefore it is possible for it to illuminate the IMAGE FUV optical apertures. Sun sensors are included in the FUV package that protect the instruments by reducing the high voltage to a few hundred volts to minimize damage from the high solar UV fluxes. It should be mentioned that during times when it is possible to have a solar eclipse at the satellite, by either the Earth or the Moon, the protection system is ineffective and the instrument high voltages will be turned off.

Table 1
IMAGE WIC Requirement Summary

	Wave-length (nm)	FOV (°)	Pixel size apogee (km)	Angular resolution (°)	Photon collection efficiency (exposure time) (Rayleigh^{-1} pix^{-1} cm^{-2})	Min. Aperture for 1 count pix^{-1} for 100 R source strength (cm^2)
LBH Auroral morphology	140-190	>10	100	0.13	4.1 [10 s]	0.0024
Dayglow	LBH	>10	200	0.26	16 [10 s]	0.0006

The FUV requirements applying to WIC are summarized in Table 1. The first column presents the scientific objective, the second column shows the relevant wavelength region. The field of view (FOV) is derived from the global coverage requirement of the aurora near apogee. The science objective defines the ground resolution, which translates into an angular resolution listed in column 5. As was discussed earlier, the angular resolution defines the photon collection efficiency of the imager in photons Rayleigh^{-1} pix^{-1} cm^{-2} s^{-1}. The FUV images are taken on a rotating spacecraft and the rotation rate is 3 degrees per second (one revolution in every two minutes). The field of view was chosen to be 30° for the WIC in the direction of rotation. Each auroral feature, therefore, spends 10 seconds in the WIC field of view. This consideration defines the exposure time. In the table column representing photon collection efficiency we have included the exposure time and provided the data for the photon collection efficiency for one exposure during one rotation of the spacecraft. The last column is the equivalent aperture required for the instrument to provide the equivalent signal-to-noise ratio for one significant photoelectron count per pixel for a 100 Rayleigh auroral source. These apertures look rather small but we have to realize that they are equivalent apertures and include the actual collecting aperture of the instrument multiplied by the combination of optical transmissions and the applicable efficiencies of conversion of photons into measurable electric charge units. The combined efficiencies for ultraviolet instruments are usually no more than 1 to 2%.

In addition, the various contaminant emissions contribute significantly to the minimum detectable signal. Thus, one count per pixel may be sufficient to produce an acceptable image in the absence of any background, but not in the presence of a background. In summary, we have demonstrated that we needed to optimize the instrument photon collection efficiency while making every effort to minimize the background.

2. Instrument Description

The Earth subtends about 15 degrees when viewed from apogee. In order to image the global aurora it was decided that a full Earth view from apogee would be most advantageous because that would allow full auroral oval coverage even when the satellite is at about one half of the full apogee geocentric distance. The WIC camera attempts to use the available auroral signal in the FUV wavelength band with the exception of OI 130.4 nm emission. A CsI photocathode was used to minimize contamination from the wavelength region longer than 190 nm. To reject UV from wavelengths shorter than 140 nm, we used a 2 mm thick BaF_2 window with an appropriate heater and temperature monitoring system on the window flange. BaF_2 is known to leak in the shorter wavelength region when cold. The refractive index of transparent salts such as MgF_2 vary greatly, and to avoid chromatic aberrations in the wavelength region from 140-190 nm, a reflective system is the best choice. One of the most recent spaceflight FUV cameras, the UVI on the ISTP POLAR satellite, used a three mirror reflective system (Torr, et al., 1995). The resources on IMAGE were more constrained, and since the three mirror system is relatively bulky, we have chosen a concentric two mirror camera of the Viking-Freja type. Some of the IMAGE FUV team members were part of the prior Viking-Freja programs and they were able to offer considerable help and knowledge regarding these cameras. In fact, the front optics graphite fibre epoxy composite (GFEC) tube of the IMAGE WIC flight unit is a Freja flight spare. The type of system is colloquially known as an inverted Cassegrain because the primary is a small convex mirror located in such a manner that the incoming light passes through a hole in the center of a larger, concave secondary (Figure 1). It is a concentric design and both primary and secondary mirrors are spherical and have a common center of curvature. This system is very fast (f/1) and very compact. It has a very serious disadvantage, however, in that it produces the image on a spherical surface and requires that the photocathode be on a spherical surface.

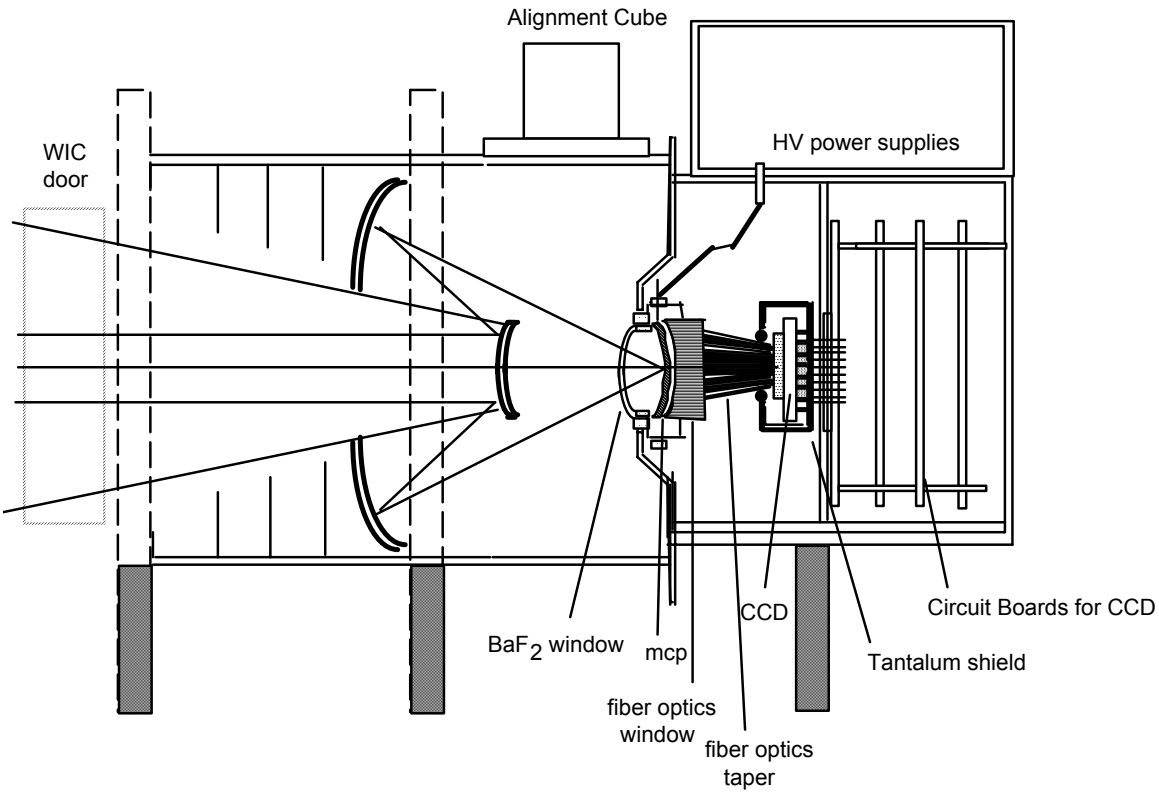


Figure 1. ***Cross sectional schematic of the WIC.***

We considered copying the entire Viking/Freja system to minimize the design risk. The Viking/Freja cameras were also on a rotating spacecraft and operated in the TDI mode. However, the image in the Viking system CCD was not read out in the conventional, fast framing manner. The charge image was integrated on the CCD, and during the integration the charge image was clocked to move in such a way as to compensate for the spacecraft rotation. In order to do this successfully it was necessary to correct the image distortion of the system before imaging on the CCD. In the Viking design this was accomplished by a special fiber optics coupling system that was specially polished and mated to another fiberoptic element. The net result was the removal of the optical distortions. On the advice of the team members who were associated with the Viking design, it was decided that we would not attempt to do this difficult task again. Rather, we would operate IMAGE WIC by digitally removing the distortion.

In the IMAGE WIC design (Figure 1), the camera head operates in a fast frame transfer mode with the CCD being read at approximately 30 full frames (512 by 256 pixel) per second with an exposure time of approximately 33 ms. The image motion is negligible during such a short exposure. Each image is electronically distortion corrected using the look up table scheme, an offset added to each memory address which is proportional to the image shift due to satellite rotation, and the charge signal is digitally summed in memory. The advantage of the electronic distortion correction is that it is extremely flexible, permitting various kinds of corrections, including x and y motions and image rotation.

One of the disadvantages of this approach is that during each spin-scan of the Earth the CCD will be read many (300) times and the resulting CCD read out noise will be added up in the integrated image, and the resultant r.m.s. noise will be larger by the square root of 300 = 17. To minimize this deficiency, the WIC intensifier had to have 17 times more gain to minimize the relative contribution of the CCD read out noise. The digitization of the WIC camera electronics was adjusted so that the peak to peak fluctuation for a single frame readout was just about 3 A-D units. Thus, for a 300 exposure integration, the peak to peak fluctuation was 50 A-D units. The image intensifier gain had to be sufficient to amplify each single photoelectron to the order of 50 A-D units to assure that, on average, a single electron incidence was competitive with the CCD read out noise.

The WIC imager is shown in Figure 2. When this photo was taken the instrument was set up with attached ground support equipment (GSE), including an ion pump to keep the image intensifier chamber under vacuum. This set up permitted the testing of the instrument in air, the application of high voltages, and the illumination of the photocathode with ultraviolet light. For flight, however, the pipes and the attached stainless steel bellows will be

removed and replaced with a purge fitting. This purge fitting allows communication between the detector and instrument cavities. The instrument will be purged with dry nitrogen during all phases of integration up to launch. The instrument has a front cover door not shown in Figure 2. This door will be closed during normal purging and will be opened on orbit, where the detector will be evacuated through the optical cavity.

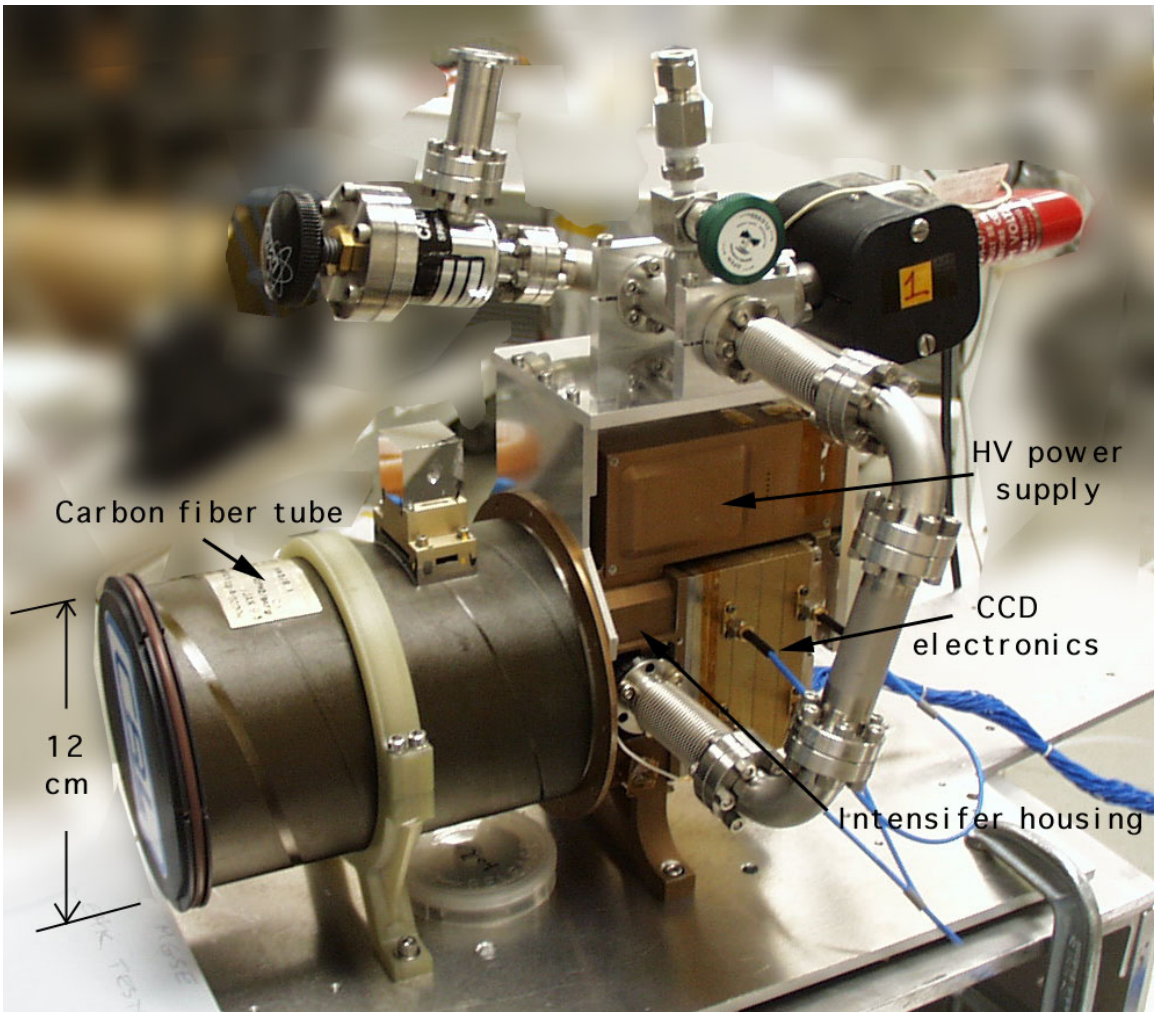


Figure 2. Photograph of the WIC camera flight unit. The stainless steel plumbing and the bare aluminum support structure are GSE. The black ion pump is also GSE. The round tube is the carbon fiber optical tube holding baffles and the primary and secondary mirrors. The alignment cube is mounted on top of the tube. Besides the carbon fiber tube body, the camera consists of alodyne coated units: top is the high voltage power supply, bottom left image intensifier housing, and bottom right the CCD electronics.

The WIC instrument is shown schematically in Figure 1. Light enters from the left and is reflected by the small primary mirror. The secondary mirror reflects the light towards the photocathode around the periphery of the primary mirror. There is a curved BaF_2 entrance window on the detector to reject radiation short of 140 nm in wavelength. Inside the detector, a curved microchannel plate is mounted and the cesium iodide photocathode is evaporated on the concave side. A photoelectron, which is emitted by the photocathode, is accelerated down into the MCP pores and will multiply through secondary emission by colliding with the walls. It has been customary to place a mesh in front of the photocathode and to apply a negative potential to the mesh. The purpose of such a mesh was to supply an additional electric field in front of the MCP to accelerate the electrons into the MCP pores, and at the same time to discourage the lateral spread of electrons on the input side. Such meshes have been shown to increase the effective quantum efficiency of MCPs. This technique was not adopted for the WIC because it was thought that any added electrode with high negative potential would contribute additional photo emissions excited

by out of band UV and visible radiation. The minimization of those emissions was considered to be of greater importance than improvement of a few percent in effective quantum efficiency. It should be noted that the application of an FUV photocathode to a surface actually reduces the near UV response when compared to bare, untreated metal such as a mesh.

At the back end of the MCP, the electron avalanche is accelerated towards the phosphor by an electric field applied between the back end of the MCP (ground) and the phosphor (+4000V), which is deposited on the concave side of the fiberoptic output window. The phosphor is coated with aluminum on the MCP side to minimize light from returning toward the MCP and to prevent light from the optics from directly reaching the CCD.

There are two high voltage supplies with remotely programmable outputs mounted on the WIC camera. One of them supplies the input end of the microchannel plate with negative voltages and provides a commandable accelerating voltage level between 900 and 1200 volts. The MCP gain depends on this voltage. The other power supply provides positive 4000 volts to the phosphor. On the back of the detector, the fiberoptic window is flat and a tapered fiberoptic plug is bonded to it. The plug transfers the image to the CCD with a demagnification of 1.75 to 1. Of the 512 x 512 pixels (pixel spacing of 15 μm), only 512 x 256 pixels of the CCD are active. The 512 direction is in the plane of rotation.

CCDs are known to be sensitive to proton bombardment because protons generate traps in the silicon that impair the charge transfer efficiency. To assure that the CCD will survive the proton exposure of the IMAGE spacecraft orbit, a proprietary, radiation-tolerant CCD, developed for the Lockheed-Martin star tracker systems was used, and a tantalum shielding cup (of 4 mm thickness weighing 450 g) was installed to surround the CCD. To minimize mechanical loading on the CCD, it is bonded to the fiberoptic taper and connection is made to the circuit board through pushpins, which minimize the force on the CCD assembly. There are several circuit boards in the front-end camera. Some of them are digital, supplying the clock wave forms for the CCD to accomplish frame transfers and subsequent read out on a line-by-line and on a pixel-by-pixel basis. Another board processes the video from the CCD using a delay line based, fast double-correlated sampler design. The camera outputs the information digitally in the form of A-D converted 8-bit bytes, one per pixel.

As was discussed before, the WIC optics was originally built as a spare for the Canadian Freja program. The housings were disassembled and the mirrors were taken out. New mirrors were fabricated to the old specifications under the supervision of Canadian Astronautics Limited (CAL), who was the original contractor for the Viking/Freja cameras. The new mirrors were coated by special multi-layer coating, which had low reflectivity in the visible and near UV region. The coatings were made using the technology developed for the ISTP/POLAR UVI imager filters (Torr et al., 1995). In parallel, sample coatings were deposited on flat substrates to evaluate them at all angles used in the WIC design. Their normal angle of incidence reflectivity is presented as Figure 3. The large fluctuations in the reflectivity are real because the measurement accuracy is better than a few percent. Note that having the two mirrors in the WIC means that the resultant reflectivity is the product of the two reflectivities. This mirror coating provides additional visible and near UV suppression.

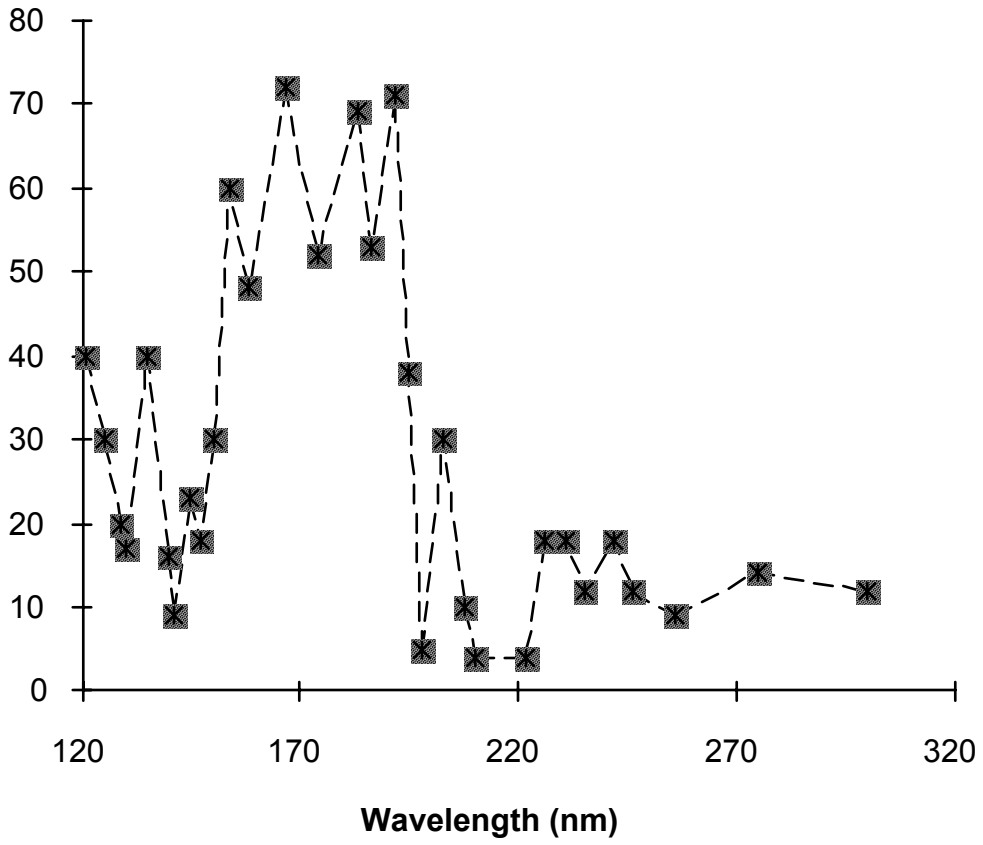


Figure 3. *Coating on the WIC mirrors.*

Originally we considered purchasing sealed image intensifiers from the same source used by Freja. Unfortunately, the past supplier of the tubes declined our order because they could no longer obtain the needed curved MCPs. Fortunately, we had the expertise to make detectors for the far UV spectral range at the University of California Berkeley (UCB). The detectors custom built at UCB were not sealed tubes and, therefore, needed to be connected to a vacuum system while in operation. The vacuum of space will evacuate them in orbit. In order to maximize cleanliness and to allow ground testing of the instrument (outside of a vacuum chamber) the detectors were made vacuum tight so that an attached ion pump could be operated to evacuate the detectors (Figure 2). This approach was used extensively during final testing and spacecraft integration.

The curved MCPs were produced by Photonis in France. The method of manufacture consisted of slicing a glass boule into wafers, and then grinding the flat surfaces of the wafers to the appropriate curvature. The pore fill was then dissolved and the resultant MCP was baked in a hydrogen atmosphere to create the semi-conducting film on the surface of the glass. This technique yielded a MCP with a constant bias angle with respect to the optic axis. Since the MCP was curved and the bias angle was constant, the pore length varied depending on the position on the MCP producing large gain non-uniformities. This was found to be a serious disadvantage because peak to peak variations of ≈30% were observable over the MCP surface and WIC would not have been acceptable as a staring imager without the TDI averaging process. Because of the serious schedule pressure of the short-duration IMAGE program, it was decided to orient the MCP in such a way that the non-uniformities were minimized in the direction perpendicular to the direction of TDI scanning. This way the TDI-ed net result will be a great deal more uniform than an individual WIC frame. The downside of this deficiency is that it resulted in a small region of extremely low gain MCP on the extreme right side of the CCD. This region will be suppressed by using the look up tables so that the CCD read out noise contribution from this area will also be excluded.

The Lockheed-Martin Palo Alto Research Laboratories built the CCD and the associated electronics. As mentioned previously, the WIC camera operated in a photon counting mode. In this mode the gain was sufficiently high (MCP voltage of >1050 V) that each photoelectron produced a detectable individual bright scintillation in a single frame CCD image. The output of the CCD is an 8 bit number representing the digitized value of the charge collected in a specific pixel during the previous 30 ms single frame integration. In a single test exposure, the A-D units contained by each spot were summed and the results were compiled in a histogram shown in Figure 4. It can be seen that the mean size of a photoelectron scintillation spot is of the order of 100 CCD A-D units at this MCP voltage. During WIC on orbit operation the exposure will be the result of the integration of about 300 frames. The frames are digitally added into a 16 bit TDI memory. The histogram produced in Figure 4 can be repeated on orbit and the high voltage adjusted to compensate for potential gain changes.

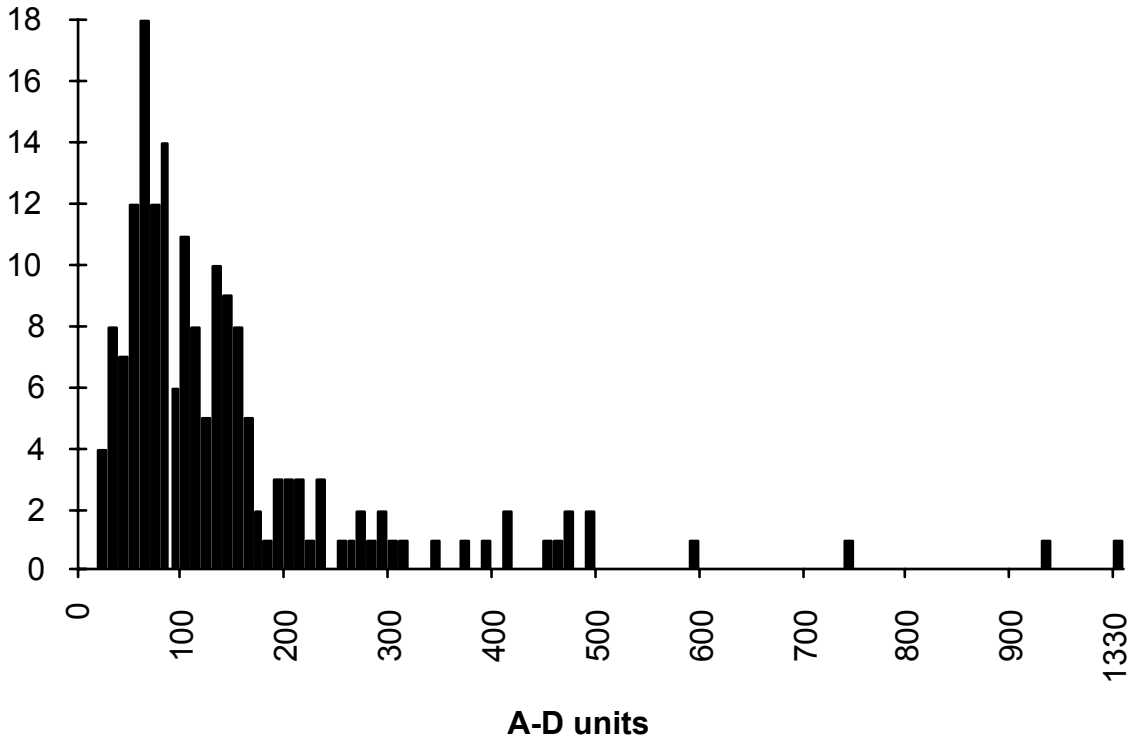


Figure 4. WIC pulse height distribution in CCD digitization units.

The measurement of the average size of the scintillation allows estimation of the overall quantum efficiency of the WIC detector system. During the calibration process, the signal output in CCD A-D units was measured as a function of photon flux incident on the primary optics. When this number was converted into the number of average size scintillations, it was possible to obtain the number of detected photons as a function of the input photon flux (photons cm^{-2}). This ratio provides the WIC effective aperture. This result is plotted as a function of wavelength in Figure 5. The overall response is a combination of the relatively smooth photocathode response and the undulating reflectivity of the mirrors shown in Figure 3. The instrument resources have been tabulated in Table 2.

Table 2
WIC resource utilization

Mass (kg)	Volume (cm^3)	Power Standby (W)	Power Acquire (W)
4.1	327 x 175 x 180	.84	3.90

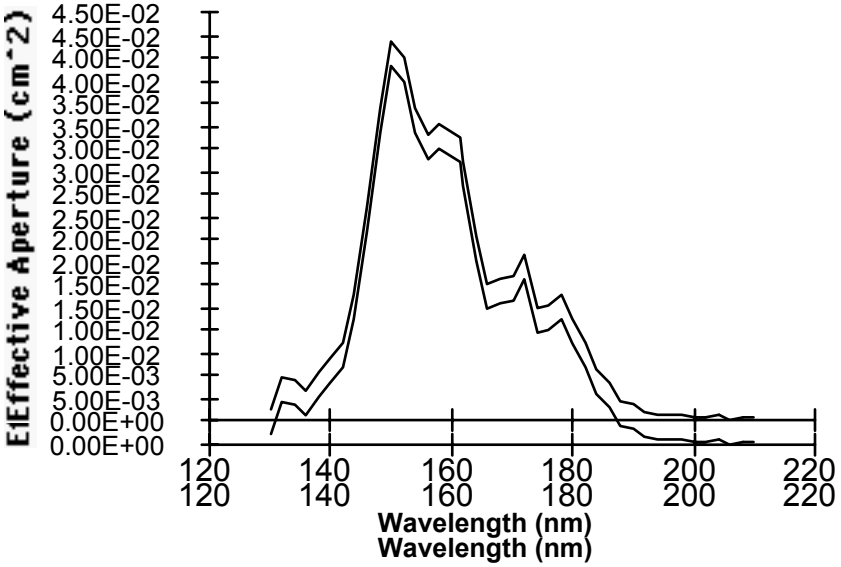


Figure 5. WIC effective aperture as a function of wavelength.

3. Instrument Calibrations

After the WIC camera was completed it underwent a thorough testing and evaluation program. The instrument, with its appropriate GSE, was moved to the Marshall Spaceflight Center in Huntsville, Alabama. There it was installed into a calibration tank that had the facility of producing monochromatic ultraviolet beams of selectable wavelength. It was important to have a uniform and parallel beam. This was accomplished by introducing a thin slab of sand blasted MgF_2 near the output of the monochromator near the focus of the collimator. The resultant beam profile was 60 mm in diameter and uniform within 30%. The pixel resolution measured as a function of MCP voltage is presented in Figure 6. The solid curve is FWHM in the x direction, and the dotted curve is resolution in the y direction. The third, steeply rising curve represents the total number of counts (CCD A-D units) in thousands within the resolution spot. As the voltage is increased, a slight increase in the spot size is accompanied by a large increase in overall gain. Note that a CCD pixel is 26 μm at the intensifier. Thus, the resolution spot size of the optics and image intensifier combination is about 2 pixels.

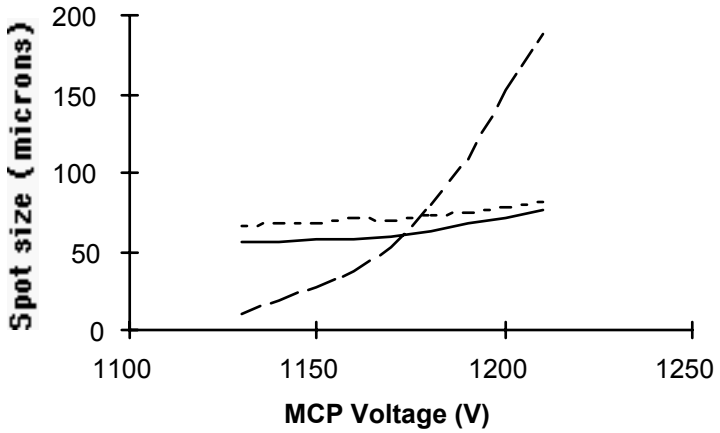


Figure 6. *WIC spot size in microns. Solid line in x direction, short dashed line in y direction. Spot size increases slightly with MCP gain. Dashed line with long dashes represents the total spot intensity in 1000 CCD A-D units.*

The instrument resolution was also calibrated as a function of temperature and it was found that the instrument focus was extremely temperature sensitive. The operating temperature range of the instrument was from -20^o C to +40^o C. The instrument was focused at 23^o C and the defocusing was particularly pronounced when the instrument was operated at the lower temperature range of -20^o C. Even at 0^o C the resolution spot developed three sub-spots corresponding to the three regions of the pupil as divided by the spider holding the primary mirror. At -20^o C the spots grew so large that their intensity diminished considerably and they were hardly perceptible. This deficiency was observed quite late in the WIC development and an extensive search for the cause was undertaken. It was proven that the problem was with the mounting of the optical system, and to minimize the problem a heater was added on the last baffle located near the back side of the secondary mirror. A thermistor was also bonded on the back of the secondary mirror. This heater and its thermistor were able to control the temperature of the optical mounting elements near the secondary mirror. It was shown that with the heater operating, the instrument remained in focus when subjected to -20^o C environment.

It was discussed in Paper 1 that the FUV system, the SI and the WIC, had to operate on a rotating platform in the so called TDI mode, and that to preserve the resolution, the imager distortions had to be corrected on orbit in real time. It was, therefore, important to obtain calibration data to determine appropriate input coefficients for the distortion correction look up tables. This data was obtained by turning the instrument through various angles around axes located near the entrance aperture while observing the spot corresponding to a collimated beam in the image. The angles and the corresponding x and y pixel locations were recorded to provide a matrix to find coefficients for least square fitting used in the distortion correction look up tables. The pixel responses for such a matrix were plotted in Figure 7. Figure 7 shows the degree of distortion in the WIC camera that has to be removed by the look up table.

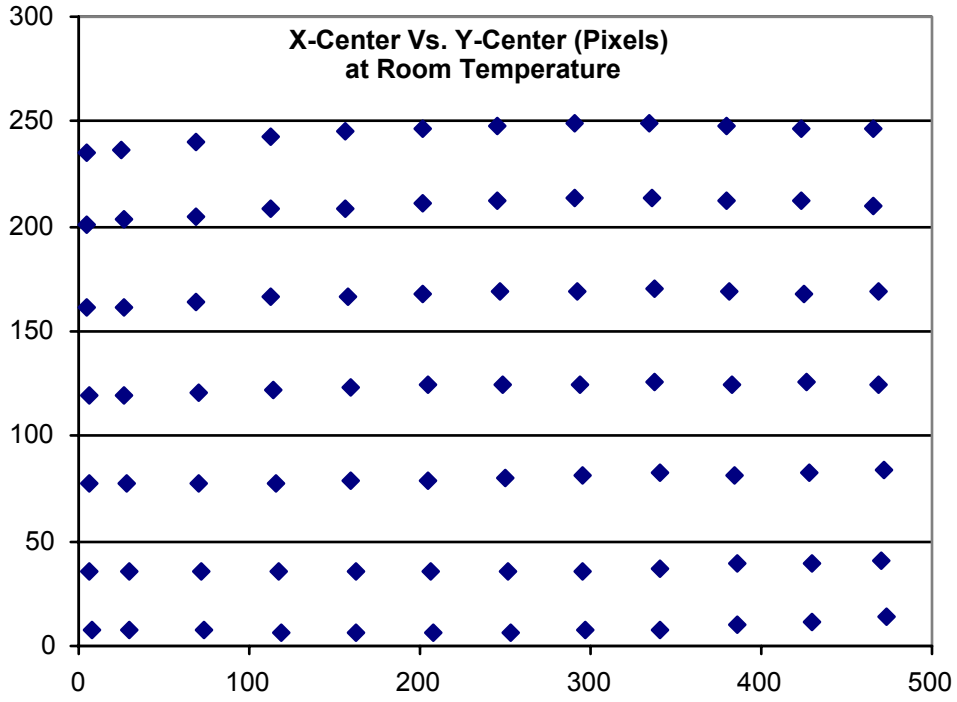


Figure 7. *Pixel values corresponding to the input angles of the collimated beam.*

From the data in Figure 5 it can be seen that the equivalent aperture at peak response is about 0.04 cm^2. The WIC resolution element field of view (resolution cell size) is approximately double the pixel size i.e. 0.18°. Using this as the angular size of a resolution cell, it provides a photon collection efficiency of 5.7 photons cm^{-2} R^{-1} $cell^{-1}$ for the exposure duration of about 10 s. Thus, a 100 Rayleigh UV aurora would produce a signal to noise ratio consistent with 23 equivalent photoelectrons per pixel at the peak of the instrument response. The spectral response match of the WIC compared with a model LBH auroral spectrum is shown in Figure 8.

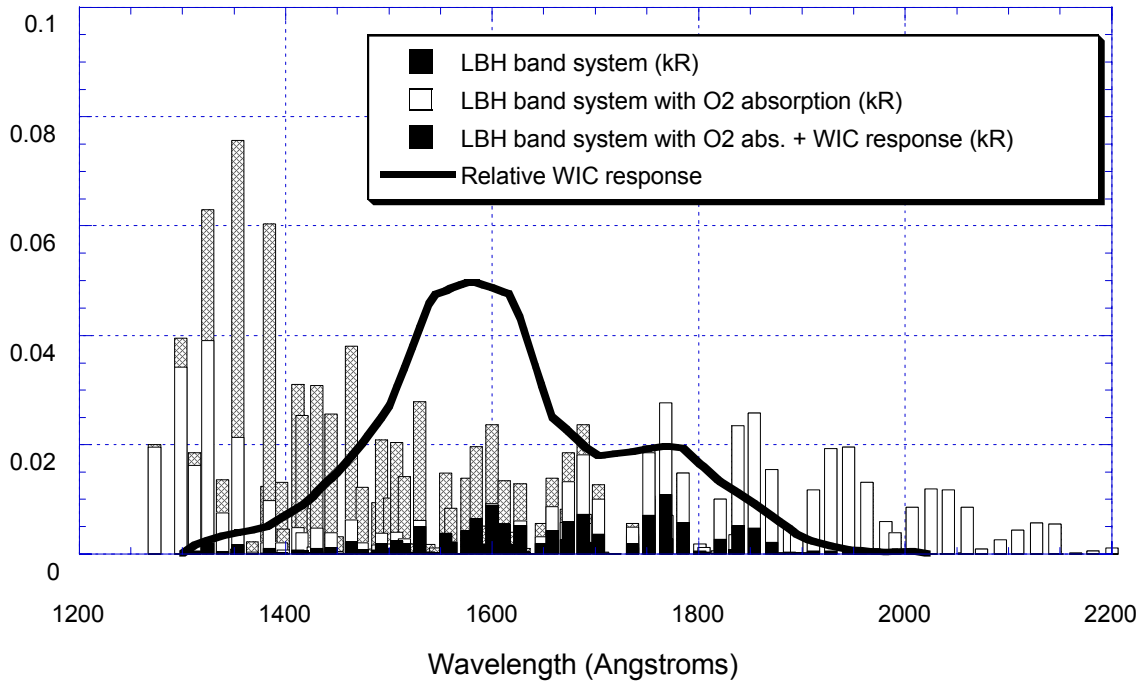


Figure 8. WIC response superimposed on a model of the LBH bands in the far UV wavelength range produced by 10 keV electrons.

Table 3
IMAGE WIC Instrument Performance Summary

Pixel Size (^{o})	Res. cell size (^{o})	Res. cell at apog. (km)	Res. cell at perig. (km)	Photon Collection cm^{-2} R^{-1} $cell^{-1}$	Meas. equiv. aperture A_e (cm^2)	Counts $cell^{-1}$ / 100 R/exposure
0.09	0.18	120	3.1	5.7	0.04	23

The instrument parameters are summarized in Table 3. The first column is the pixel size, the angular area associated with one memory element. The second column is the resolution cell size, which is the resolution full width at half maximum of the measured point spread function. On the WIC this quantity is approximately twice the pixel diameter. Column 3 and 4 represent the size of the resolution cell projected to the Earth from apogee and perigee, respectively. The resolution cell size defines the solid angle from which photons are collected and allows us the calculation of the photon collection efficiency per square cm during the exposure time. This is presented in column 5. Column 6 is the equivalent aperture A_e of each system as discussed earlier. This, combined with the photon collection efficiency, provides the number of significant quanta (column 7) per 100 Rayleigh source within the resolution cell of the instrument for a single spin of the spacecraft. Column 6, A_e, can be compared directly to the values in Table 1 expressing the instruments scientific requirements.

In summary, we have shown that WIC satisfies the IMAGE requirements. It has adequate resolution and sensitivity. There are, however, some lessons we have learned from developing the WIC instruments. The deeply curved photocathode was a source of many problems. One of these problems was the serious gain variation across the MCP. This defect was attributed to the MCP pore bias angle variation across the image. In general, it seems that the detectors are the most difficult parts of this type of imager. Therefore, it would be worthwhile to use systems that produce flat image planes at the expense of some optical complexity to allow the use of a simpler, flat detector.

References

Anger, C. D., S. K. Babey, A. L. Broadfoot, R. G. Brown, L. L. Cogger, R. Gattinger, J. W. Haslett, R. A. King, D. J. McEwen, J. S. Murphree, E. H. Richardson, B. R. Sandel, K. Smith and A. Vallance Jones, An ultraviolet auroral imager for the Viking spacecraft, *Geophys. Res. Lett.,* 14, 387-390, 1987.

Burch, C. R., Reflecting microscopes, *Proc. Phys. Soc.,* 59, 41, 1947.

Cogger, L. L., D. J. Hearn, J. S. Murphree, R. A. King, E. P. King, Y. I. Galperin, B. Gordon and J. Matsushita, Ultraviolet Auroral Imager (UVAI), in Interball Mission and Payload, edited by Y. Galperin, T. Muliarchik and J. P. Thouvenin, Russian Space Agency, Space Research Institute and French Space Agency, 382, 1995.

Frank, L. A., J. D. Craven, K. L. Ackerson, M. R. English, R. H. Eather and R. L. Crovillano, Global auroral imaging instrumentation for the Dynamics Explorer mission, *Space Sci. Instrum.,* 5, 369-393, 1981.

Murphree, J. S., R. A. King, T. Payne, K. Smith, D. Reid, J. Adema, B. Gordon and R. Wlochowicz, The Freja Ultraviolet Imager, *Space Science Reviews,* 70, 421-446, 1994.

Torr, M.R., D. G. Torr, M. Zukic, R.B. Johnson, J. Ajello, P. Banks, K. Clark, K. Cole, C.Keffer, G. Parks, B. Tsuratani, and J. Spann, A far ultraviolet imager for the International Solar-Terrestrial Physics mission., *Space Science Reviews*, 71, 329, 1995.

Auroral Imaging in Canada: Past, Present and Future

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Abstract

Over the past four decades, Canadian scientists and their industrial partners have made major contributions to both the technology of auroral imaging and to the advancement of knowledge through the analysis of auroral images obtained from both satellite-based and ground-based instruments. This paper provides a review of some of these achievements and an assessment of both the current status and the potential for future developments in this field.

Introduction

One of the earliest tools developed for the systematic observation of the aurora was the film-based all-sky camera. These were extensively used before and during the IGY (1957/58) at many high latitude locations, and as a consequence the concepts of the auroral oval and the auroral substorm were put on a firm observational basis. Canadian scientists contributed to these early explorations, notably researchers at the University of Saskatchewan under the leadership of Balfour Currie. Limitations of this technique were of course obvious: limited coverage, limited time resolution, and limited dynamic range, to name a few, but the scientific advances led to the development of new technology. Conversely, advances in relevant technology led to new opportunities to advance scientific knowledge. This close coupling of science and technology is clearly demonstrated in the history of auroral imaging. Research in Canada employing other optical instruments, especially spectrographs and spectrometers played a very important role in understanding auroral spectra, but with the advent of satellites, most of the sustained Canadian effort has been in the area of imaging rather than photometry or spectrometry. The other major optical space thrust in Canada has been the development of the wide-angle imaging Michelson Doppler interferometer by Gordon Shepherd and his colleagues at York University; however, their research emphasis has been the dynamics of the neutral atmosphere rather than the aurora.

What follows is a review of auroral imaging in Canada during the past 40 years, a period that coincides with the development of scientific satellites. Only a general overview will be attempted in order to highlight the significant developments. Details of instruments and scientific advances are available in various refereed journals.

1960-1980: Canada in Space

Auroral imaging from space began in Canada using rocket-born photometers designed by Cliff Anger at the University of Calgary and built by

SED Systems of Saskatoon. Imaging of the complete sphere was achieved with a monochromatic photometer by using a rotating prism to scan the field of view from nose to tail of the spinning rocket (Robertson et al., 1974). For his PhD project, Iain Robertson undertook the difficult task of generating the altitude emission profiles from the convolved data.

The ISIS-2 satellite gave Canadian scientists an opportunity to image the aurora from a spinning platform in a 1400 km polar orbit. Two optical experiments were included in the payload: the Red Line Photometer (G. Shepherd et al., 1973) and the Auroral Scanning Photometer (C. Anger et al., 1973). Images were produced once per orbit (110 min) by means of the combination of satellite travel and satellite spin. The groundstations at Ottawa and Resolute proved to be the most useful for auroral viewing, but other stations provided valuable views of the southern hemisphere aurora and the airglow at all latitudes. The 630 nm emissions of atomic oxygen observed by the Red Line Photometer were particularly suitable for studying the high-latitude emissions due to soft electron precipitation. The Auroral Scanning Photometer provided spectacular monochromatic images at 557.7nm and 391.4nm with a spatial resolution of about 7 km in the nadir at auroral altitudes. This resolution was achieved by means of an image dissector tube which provided 13 independent sequential samples every 25 ms. During the winter solstice period when the polar regions were not sunlit, this instrument could image the entire auroral oval during a pass of about 20 minutes. These images showed conclusively that the concept of a continuous auroral oval is not only true statistically as shown from ground-based cameras, but is also true on an instantaneous basis. Figure 1 shows an example from the ISIS-2 satellite. In addition, these experiments opened up new research opportunities in the polar cap regions, such as the study of what were then called sun-aligned arcs, and the study of the poorly understood cusp region of the dayside ionosphere. These two very successful experiments resulted in numerous publications on the auroral oval, the polar cap, and the cusp region, and brought considerable recognition to Canada for its pioneering science. Equally remarkable were the technical achievements. Thanks to the capability of the industrial partner, RCA Ltd. and its excellent group of experts, the instruments operated successfully until the project was terminated. Dave Boulding of the Communications Research Center managed the complex operations of the satellite.

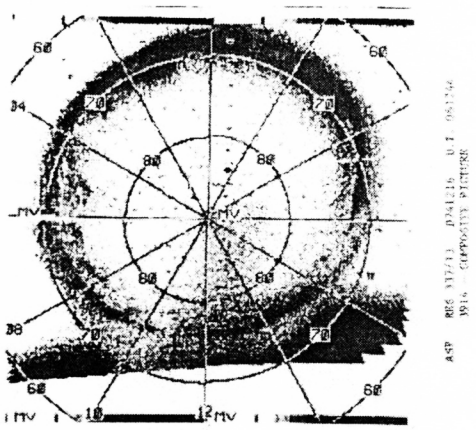


Figure 1: View of the northern auroral distribution from the ISIS-II satellite.

1980-1990: A New Approach to Imaging from Satellites

The ISIS-2 satellite was Canada's last scientific satellite. As priorities had shifted to the communication applications of satellites, the only recourse for the scientific community was to seek opportunities to participate in foreign space missions. Partly due to the ISIS-2 success, Cliff Anger was invited to place an auroral imager on Sweden's Viking satellite (Anger et al., 1987). The technical challenge was to achieve instantaneous two-dimensional imaging from a spinning platform and to observe the aurora on both the night side and the day side of the Earth. Dayside viewing demanded that observations be made in the Far UV part of the auroral spectrum. The passbands were designed to cover the atomic oxygen and molecular nitrogen emissions in the spectral regions 130nm to 180nm by using a combination of short-wavelength cut-off filters and appropriate photocathode materials. The needed sensitivity was realized by combining an inverse Cassegrain f/1 telescope developed by Harvey Richardson (NRC) with a detector con-

sisting of a curved photocathode, and an image intensifier coupled to a CCD array (Figure 2).

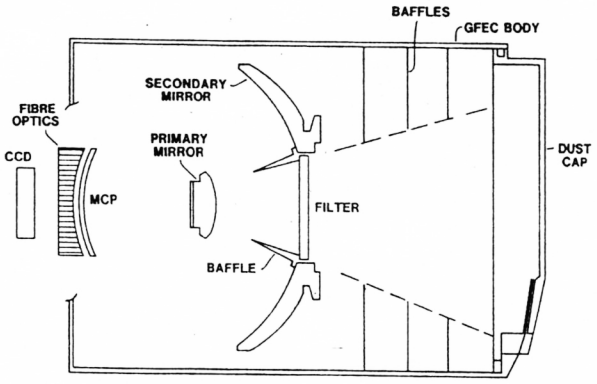


Figure 2: Schematic drawing of Viking camera

A field of view of 25 degrees permitted viewing of the entire auroral distribution from altitudes above about 10,000 km. The necessary 1-second time exposure was achieved by setting the scan plan perpendicular to the spin axis and clocking the charge along the columns of the CCD at the same rate as the spin of the satellite. Special fibre-optic couplers were designed to accompish the optical transformation from the spherical earth to the flat detector (King et al., 1988). This was a new approach to imaging repetitively from satellites that did not require the use of moving mirrors. CAL Corporation was the prime contractor for the instrument. With 1-sec exposures every 20 seconds, the imager became the means to investigate auroral phenomena in a new way, and subsequently over 100 papers were published on the spatial and temporal dynamics of the UV aurora. Instantaneous global auroral images were now available. Data were collected through most of 1986, and many members of the team participated in both the operations of the instrument and in the data analysis and interpretation. A lengthy review of the Viking-based contributions to the understanding of global auroral substorms was published by Elphinstone et al. (1996). Figure 3 is a sequence of images showing the development of a global auroral substorm. Another unique feature of the Viking project was the provision for real-time commanding of the instruments and real-time data acquisition. This allowed parameters to be changed during a satellite pass in response to what scientists were monitoring. All software for data acquisition, archiving and for analysis (instrument corrections, projections onto the earth, etc.) was developed at the University of Calgary.

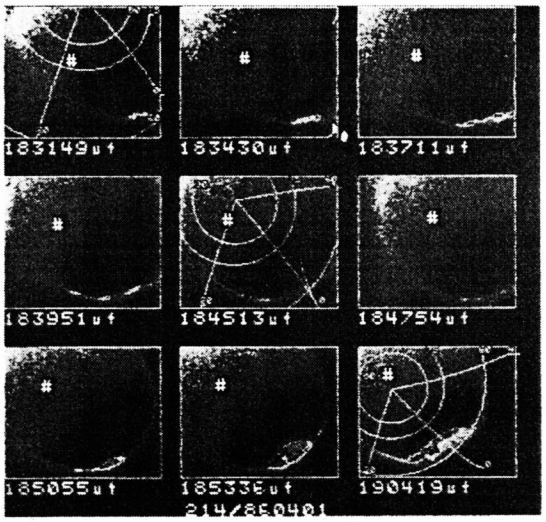


Figure 3: Development of a global substorm

1990-2000: Building on Success

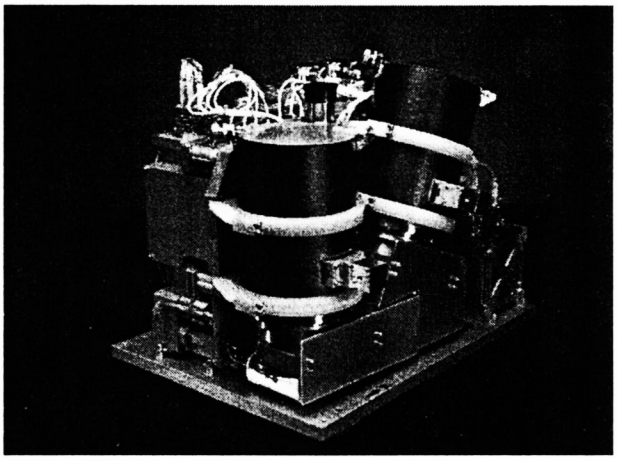
Following the success of the Swedish Viking satellite, Canada was invited to place similar instruments on a second Swedish satellite, Freja, and on the large Soviet satellite called Interball. These satellites created new technical challenges. A sealed intensifier unit was built by DEP Netherlands closely following the design advice of Bob King, University of Calgary. A sealed unit was essential to prevent contamination of the detector. The Freja instrument was updated from the Viking instrument in order to operate more efficiently and to function at a high spin rate of 10 rotations per minute. The Freja satellite was launched by China in 1992. With an elliptical orbit of perigee 600 km the special objective of this mission was to observe fine structure in UV aurora over small sections of the auroral oval, and to relate these observations to in situ plasma measurements. Figure 4 shows a sequence of high resolution images. Spirals and vortices became the topic of several studies, e.g. Murphree et al., [1994]. Routes Inc. was the prime contractor for this project.



Figure 4: High resolution Freja images taken 6 seconds apart

The Russian Interball-2 satellite was launched in 1996. The purpose of the UV imagers was to provide the auroral context for *in situ* measurements on two main satellites and two subsatellites. The Viking camera design was suitable for viewing the global auroral distribution from an apogee of 20,000 km over northern high latitudes. In order to increase the coverage at certain times of the year, it was decided to add an offset camera viewing at 67 degrees from the spin axis (Figure 5) giving a total field of view of about 50 degrees. The other technical innovation was to install the cameras on an adjustable gimbal plate so in-orbit corrections could be made for possible small differences between the design and actual spin axes. CAL Corporation was the industrial prime contractor in partnership with the University of Calgary.

Both cameras obtained about 3 months of auroral images, sufficient for several studies. The usefulness of the data was severely limited due to the unexpected wobble of the spacecraft. This wobble had two adverse effects: there was image smear due to motion of the spin axis during the 6.5 second exposures; and the changing attitude of the spin axis made it very difficult to determine where the cameras were pointing on the earth. Given the ten years of development of this satellite and the uncertain times in Russia, it is remarkable that even limited success was achieved.



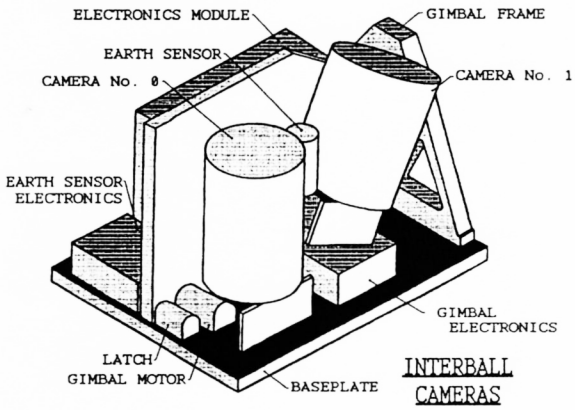


Figure 5. Interball cameras

Several Canadian scientists were members of the team that was successful in NASA's first MIDEX satellite competition. The IMAGE satellite instrument complement includes a UV imaging camera (WIC) that is based on the Canadian experience (Mende et al., 2000). The Freja telescope (flight spare) was mated to a detector designed at the University of California (Berkeley). Rather than using the TDI (time-delay-integration) mode as in the Canadian detectors, the new instrument has a fast readout scheme that permits the detection of the position of each photoevent on the CCD. Images are then constructed in onboard memory using the appropriate spin rate to effect a TDI scan in software. The IMAGE satellite was launched on March 25, 2000 and is now providing several types of images of the Earth's environment: neutral atom imaging, radio plasma imaging, as well as ultraviolet imaging (EUV and

FUV). This is the most comprehensive set of imaging instruments ever to be placed in orbit. The FUV images are free from the wobble effects of the Interball-2 satellite and therefore appear sharper; however, thermal correction is necessary to maintain the focus of the camera over the range of operating temperatures. Scientific operations are now underway, and the Canadian members of the Science Team have access to all IMAGE satellite data. This mission represents the culmination of imaging technology development during the past decades in both the U.S. and Canada.

The Future for Space-based Auroral Imaging in Canada

Canada has been a world leader in this field. Unfortunately, very little technical development has taken place in the past 10 years. In the U.S. imaging became a major thrust during the lavish SDI funding period, and now it is no longer possible for Canadian scientists to compete with the strong, well-funded groups in the U.S. Future space imaging experiments in Canada will have to be low-cost and will have to fill a niche that is being overlooked by U.S. scientists. One possibility is to construct reliable miniature imagers for Canadian and/or foreign microsatellites and to expand their applicability to other types of investigations.

One such appropriate mission is the Canadian Polar Outflow Probe (POP) that has been proposed by Yau et al., [2000].

Auroral Imaging from the Ground

There has also been on-going Canadian interest in ground-based auroral imaging. A CCD-based all-sky imager was developed at the University of Calgary for deployment at Gillam, Man. in 1986 as part of the CANOPUS network. The CANOPUS network is a ground-based network of magnetometers and optical instruments to provide support to space missions (Rostoker et al., 1995). Its operations are funded by the Canadian Space Agency. The imager has operated for 14 years and has provided a wealth of auroral data for analysis. Itres Research Ltd. of Calgary designed and built some of the key circuits. Figure 6 shows the imager in its environmental housing at Gillam. Data are transferred by satellite to Ottawa and are made available for public viewing on the World Wide Web.

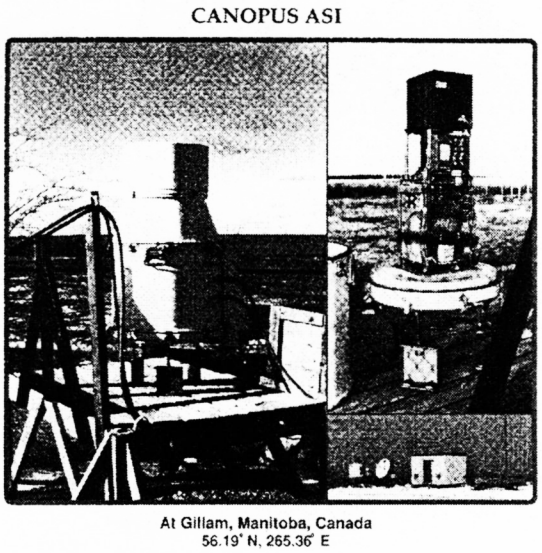


Figure 6: CANOPUS ASI at Gillam, Man.

Development of ground based imaging was greatly enhanced during the years of the Canadian Network for Space Research, 1990-1995. David Steele (U of Calgary) developed a two-camera system to simultaneously image weak aurora at two different wavelengths. This instrument was installed in the Eureka Observatory near the geomagnetic pole where it has operated for four winters (Steele and Cogger, 1996).

It was recognized by auroral scientists that an array of imagers on the ground could provide a great deal of information about the location and dynamics of the auroral oval on a continuing basis at a low cost compared to satellite instruments. Two science-quality imagers have been purchased with NSERC and Alberta Government grants for deployment in 2000 at Rankin Inlet and Resolute, and several more will be added as resources become available. Operations and data merging will be major challenges when greater coverage is realized, but the scientific potential of an array of imagers in Canada is very high, and ground-based projects create excellent training opportunities without the risks inherent in space-based projects.

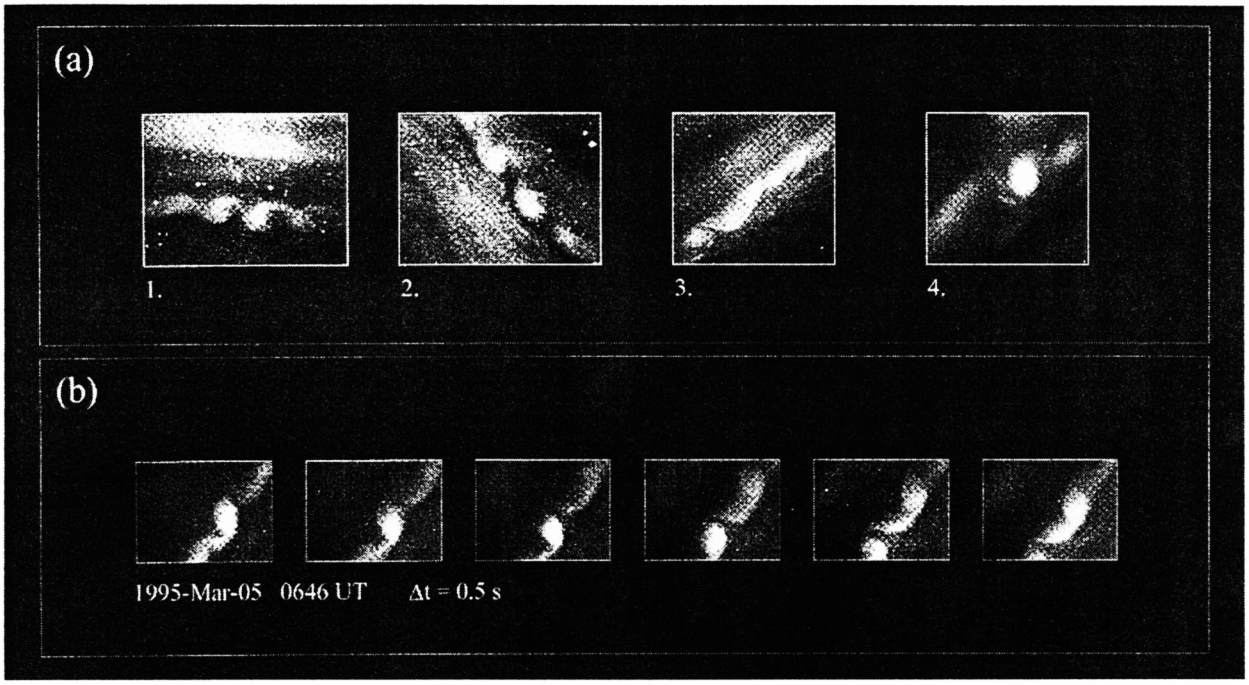


Figure 7: Fine structure in aurora observed by the Portable Auroral Imager

Finally, in response to a perceived need to improve the spatial and temporal resolution of auroral imagers, Trond Trondsen (U of Calgary) designed and assembled a TV-rate portable imager for his PhD project. This project has brought Trond and Canada international attention for advancing both the technology and the science (Trondsen and Cogger, 1998). An example of high-resolution auroral imaging is given in Figure 7.

Conclusion

Canadians have always had a fascination for aurora, partly because Canada is the most convenient place in the world to make observations. Auroral physics also enjoys a long tradition of accomplishments that Canadians can be proud to support. Although great strides have been made in the understanding of the physical and chemical processes responsible for the visible aurora, there are still many outstanding questions concerning the mechanisms of coupling solar wind dynamics through the magnetosphere and into the ionosphere. There will be a continuing need for improved instrumentation and better observations to keep pace with new theories and models.

References

Anger, C.D., T. Fancott, J. McNally and H.S. Kerr, ISIS-II Scanning Auroral Photometer, Applied Optics, ***12***, 1753-1766, 1973.

Anger, C.D., S.K. Babey, A.L. Broadfoot, R.G. Brown, L.L. Cogger, R.L. Gattinger, J.W. Haslett, R. A. King, D.J. McEwen, J.S. Murphree, E.H. Richardson, W.R. Sandel, K. Smith and A. Vallance Jones, An Ultraviolet Auroral Imager for the Viking Spacecraft, Geophysical Res. Letters, ***14***, 387-390, 1987.

Elphinstone, R.D., J.S. Murphree and L.L. Cogger, What is a Global Auroral Substorm?, Reviews of Geophysics, **34**, 169-232, 1996.

King, R.A., A.L. Broadfoot, Bill R. Sandel, and A. Vallance Jones, Correcting Image Distortion with Fiber-optic Tapers, Applied Optics, **27**, 2048-2054, 1988.

Mende, S.B., H. Heetderks, H.U. Frey, M. Lampton, S.P. Geller, R.Abiad, O.H.W. Siegmund, A.S. Tremain, J.Spann, H. Dougani, S. A.

Fuselier, A.L. Magoncelli, M.B. Bumala, S. Murphree and Trondsen, Far Ultraviolet Imaging from the IMAGE Spacecraft. 2. Wideband FUV Imaging, Space Science Reviews, **91**, 271-285, 2000.

Murphree, J.S., M.L. Johnson, L.L. Cogger and D.J. Hearn, Freja UV Imager Observations of Spatially Periodic Auroral Distortions, Geophysical Res. Letters, **21**, 1887-1890, 1994.

Robertson, I.W.H., D.D. Wallis, C.D. Anger and D.W. Johnson, A Rocket Instrument for Imaging the Aurora by Means of High Speed Photometric Scanning, Planet. Space Sci., **22**, 1003-1015, 1974.

Rostoker, G., J.C. Samson, F. Creutzberg, T.J. Hughes, D.R. McDiarmid, A.G. McNamara, A. Vallance Jones, D.D. Wallis and L.L. Cogger, CANOPUS-A Ground-based Instrument Array for Remote Sensing the High Latitude Ionosphere during the ISTP/GGS Program, Space Science Reviews, **71**, 743-760, 1995.

Shepherd, G.G., T. Fancott, J. McNally and H.S. Kerr, ISIS-II Atomic Red Line Photometer, Applied Optics, **12**, 1767, 1973.

Steele, D.P. and L.L. Cogger, Polar Patches and the 'Tongue of Ionization', Radio Science, **31**, 667-677, 1996.

Trondsen, T.S. and L.L. Cogger, A Survey of Small-scale Spatially Periodic Distortions of Auroral Forms, J. Geophysical Res., **103**, 9405-9415, 1998.

Yau, Andrew W. Leroy L. Cogger, David J. Knudsen, J. Sandy Murphree, Trond S. Trondsen, K. Tsuruda, H. Gordon James and Ian Walkty, The Polar Outflow Probe (POP): Science Objectives and Instrument Development, in Proceedings of ASTRO-2000 – 11th CASI Conference on Astronautics, Nov. 7-9, 2000, Ottawa.

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"RAVENS" – THE FAR ULTRA-VIOLET AURORAL MONITORING IMAGERS ON THE CHINESE 夸父-MISSION

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Abstract

For more than thirty years, auroral imaging from high altitude spacecraft has been our only true means of studying the global spatio-temporal evolution of the Earth's magnetosphere. It has provided us with invaluable insights into basic plasma physics and equipped us with tools to help better forecast magnetic storms and mitigate potential disruptions to infrastructure important to life and society on Earth. Kua-Fu (夸父) is a proposed three-satellite Chinese mission, to be launched in 2012, aimed in part at providing continuous imaging of the auroral distribution in the northern hemisphere. Two of the three satellites will be on identical polar orbits relatively phased so as to provide an unprecedented 24/7 imaging of the aurora. This part of the mission is based on the Canadian "Ravens" concept and is expected to significantly advance our understanding of magnetospheric dynamics and solar-terrestrial interactions. For example, for the first time ever, we will obtain continuous imaging of long-duration geospace processes like magnetic storms which represent the major large-scale manifestation of Space Weather events in our ionosphere. In this paper, we focus on the scientific objectives and technical design of the Ravens instrument, i.e., the FUV electron aurora imagers aboard Kua-Fu. While the heritage for the Ravens imagers is the past University of Calgary auroral imagers, the design of this new instrument – which is essentially a "next generation" Canadian FUV imager – has to make use of the very latest advances in far-ultraviolet imaging technology in order to meet the much more demanding science objectives of the Kua-Fu mission.

Introduction

The aurora represents one of the most dynamic products of the Earth's often violent electrodynamic relationship with the Sun. Auroral imaging from space has, for over thirty years, been our only true method for studying the spatio-temporal evolution of the Earth's magnetospheric system. In the very early days, global auroral images proved in one snapshot the existence of both the continuous auroral oval and the diffuse aurora. Global auroral images have since been used to map the evolution of the auroral substorm expansion and the effects of solar wind pressure pulses on the magnetosphere. Whenever they are available, global auroral images are used for essential context for other studies aimed at elucidating plasma physical processes of the Sun-Earth system. This is fundamental research which has not only given us invaluable insights into the field of basic plasma physics, but it has also equipped us with tools to help us better forecast magnetic storms and to mitigate potential disruptions to infrastructure important to life and society on Earth, such as electrical power grids and communications systems.

Canada has played a significant role in auroral imaging from space, beginning with the ISIS-II scanning photometer, continuing with UV imagers on Viking, Freja, and Interball, and presently through the use of a Canadian design for the IMAGE WIC. Together with missions like Polar, Akebono, DE, and DMSP, they have significantly advanced our understanding of the global auroral distribution, magnetospheric dynamics and the solar-terrestrial interaction. These were all single-spacecraft missions with a limited number of hours of good viewing of polar regions per orbit, just one consequence of which is that *no magnetospheric storm has ever been imaged from start to finish.*

The Chinese Kua-Fu mission is a planned multi-satellite mission aimed in part at providing continuous imaging of the global auroral oval in the northern hemisphere. One way to accomplish such continuous coverage is with two spacecraft relatively phased on coplanar elliptical orbits so that when one is at apogee, the other is at perigee. The relatively slow passage through apogee, and quick passage through perigee means that at all times at least one of the two spacecraft will be near apogee. This concept is illustrated in Figure 1. Of course, precession of the line of apsides causes the major axis of the orbital ellipse to precess, ultimately placing a time limit on how long such a satellite pair can maintain this continuous view of the auroral distribution. The three-satellite Kua-Fu mission will thus include two satellites carrying Canadian auroral imagers (*The Ravens*) on such identical polar elliptical orbits with an inclination of ~90 degrees and relatively phased so as to provide the first-ever 24/7 imaging of the aurora, essentially creating an unbroken movie of the global auroral distribution spanning not only individual storms, but tens of solar rotations. Such continuous global imaging will have a potentially enormous scientific impact as it will provide crucial information on the response of the auroral oval during magnetic storms, which tend to have time scales of days and represent the major large scale manifestation of Space Weather events in the ionosphere.

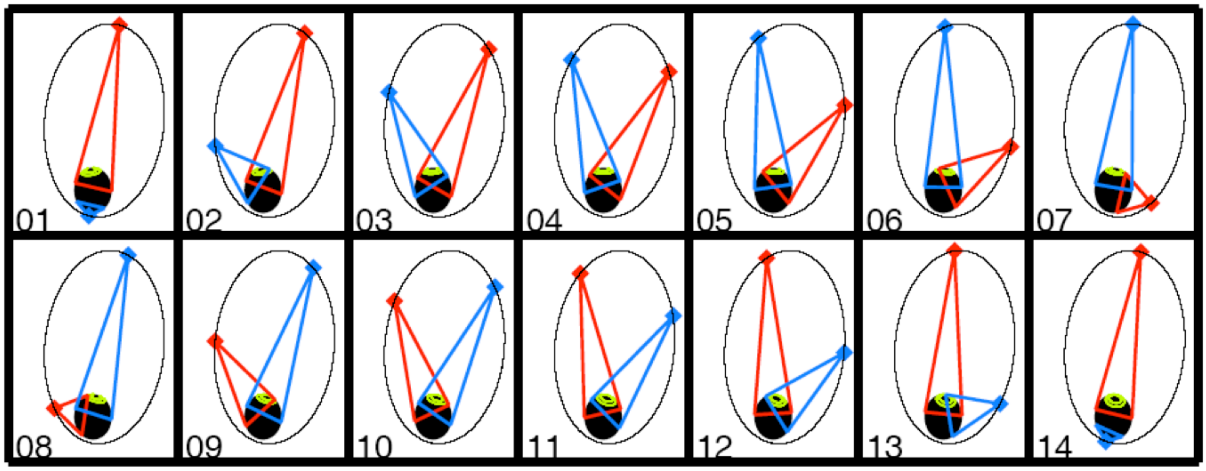


Figure 1: 14 snapshots of two satellites relatively phased on identical polar orbits so that when one is at apogee, the other is at perigee. At all times, the entire auroral oval (green) and polar cap are within good view of at least one of the two satellites.

In this paper, we focus on the scientific objectives and technical design of the *Ravens* instrument, i.e., the far-ultraviolet (FUV) electron aurora imagers aboard Kua-Fu. While the heritage for the *Ravens* imagers are the past Canadian auroral imagers, the design of this new instrument – essentially a "next generation" Canadian FUV imager – will make use of the very latest advances in far-ultraviolet optics (including state-of-the-art filter, coating, and detector technologies) in order to meet the much more demanding science objectives of the Kua-Fu mission. It is expected that *Ravens* will enter development Phase-A (funded by the Canadian Space Agency) some time mid-2006. It is only through improved technology that Canada can retain its prominent international position in the field of auroral imaging from space. It is also evident from history that advances in technology lead to advances in scientific knowledge.

Scientific Objectives and Measurement Requirements

The science requirements driving the design of the *Ravens* imagers are as follows:

1. The need for determination of characteristic energy and energy flux of precipitating electrons on a global scale.
2. The need for global images with on the order of 10 km spatial resolution to facilitate studies of multi-scale processes and natural complexity.
3. The need to image very weak auroral emissions, both on the nightside and sun-lit portions of the Earth (often simultaneously, requiring high intrascene dynamic range).

Deriving the spatial distribution of the average energy and total energy flux of precipitating particles on a global scale is critical to determining ionospheric conductivity and quantifying the impact of solar forcing and magnetic storms to the neutral atmosphere. To quantitatively do this on a global scale is a difficult task. Several instruments have imaged the high latitude regions on a large scale both on the day and night side including AI (DE-1), Viking, UVI/VIS/Pixie (Polar), FUV-WIC/SI (IMAGE). Each of these instruments is responsible for significant strides toward understanding the dynamic nature of the global aurora and the first quantitative assessments of large-scale auroral energetics.

Perhaps the most direct (model independent) way of deriving the auroral energetics is to compare large-scale images in two spectral regions of the far-ultraviolet Lyman-Birge-Hopfield (LBH) band system; 140 – 160 nm (LBH-short) where O_2 absorption at auroral altitudes is significant, and 160 – 180 (LBH-long) where the emissions are relatively free of absorption. The *Ravens* instrument (one instrument on each of the two polar-orbiting Kua-Fu satellites) would thus each be comprised of *two FUV imagers*: one for LBH-short and one for LBH-long measurements. These will provide quantitative intensities from two well-separated parts of the LBH band, with the objective of using relative and absolute intensities for determination of characteristic energy and energy flux of precipitating electrons, on a global scale.

Instrument performance requirements are closely dictated by the aforementioned scientific requirements. In the case of past and currently deployed FUV imaging missions, three primary obstacles to obtaining satisfactory quantitative results for the spatial distribution of auroral energetics can be identified:

- the lack of truly simultaneous observations of spectrally resolved LBH-long and -short bands.
- the lack of characterization of out-of-band contributions to the measurements.
- instrument performance that provides high spatial and temporal resolution images.

To quantify the spatial distribution of the average energy and total energy flux of precipitating particles on a global scale, and improve upon what is currently available, we set down the following measurement requirements for the proposed *Ravens* imagers aboard the two polar-orbiting Kua-Fu spacecrafts:

- 30 s temporal resolution
- 30 km nadir spatial resolution
- on the order of 10 counts/kR/s sensitivity
- greater than 10^{10} out-of-band spectral rejection

The requirement to maximize spatial and temporal resolution is derived from the need to determine the auroral energetics at the edges of the oval where the aurora is very dynamic. Such edges are particularly susceptible to effects of poor resolution as these regions are changing quickly from dark

(no emissions) to bright emission, and vice-versa, during the auroral substorm expansion phase. There is conjecture that at these edges, and also at substorm onset locations, emissions result from Alfvén driven processes (as opposed to the more static inverted-V acceleration process). In principle this can be verified by determining the auroral energetics using imaging. Current imagers on Polar and IMAGE are not capable of doing this. IMAGE has good image integration times (15 s every 120 s) but poor spatial resolution (100 km for WIC and worse for SI). Polar, even without the wobble problem, has no better than 50 km resolution and 37 seconds time integration, and appears to be suffering from significant leakage of a VIS-NIR contribution into its FUV bandpass.

The ~10 counts/kR/s sensitivity requirement is derived from the need to provide a significant advancement over what we have now. Currently, 50 R in 30 s is the best that is available in the FUV (Polar UVI). High sensitivity is needed to measure very weak polar cap emissions or dim remnants and precursor emissions of bright dynamic aurora that may help improve our understanding of the mapping to magnetospheric regions as well as auroral acceleration processes.

The requirement of more than 10^{10} out-of-band rejection is derived from the fact that the visible integrated dayglow (VIS-IR) is about 10^{11} R. Therefore, to measure a ~10 R signal on the daylit side of the Earth with an equal background, a rejection of at least 10^{10} is required.

Together, these requirements will push the envelope of current design, but not excessively so. That is, it is reasonable to expect that these requirements are achievable without revolutionary technological breakthroughs.

Consequently, there are at least three major instrumental issues that have to be resolved:

1. Acquiring a good solar blind photocathode. E.g., the purity of the CsI is critical.
2. Having the proper filter design/production. Recently developed multilayer dielectric filters can provide an average measured reflectance longward of 200 nm of 3.6%, with maximum reflectance of greater than 85% at 155nm.
3. Making sure that the imaging performance and sensitivity meet the requirement. Often, resolution has to be sacrificed for sensitivity or vice-versa. This is especially so in the case of all reflective systems, as they should not be over-designed by using too many optical components or they will be overly sensitive to component displacement. Spot size and throughput are critical to achieve the desired requirements. At least four filter reflections will be required in order to achieve the needed 10^{10} out-of-band rejection.

Instrument Concept

The design of the *Ravens* imagers for the Kua-Fu mission is motivated by a desire to record snapshots of auroral dynamics with high temporal resolution under night-time as well as fully sunlit conditions. An intensified FUV CCD-based imager with fast optics is proposed. Such a design allows each image pixel to be exposed simultaneously, giving true snapshot ability as well as high temporal resolution. Given a spacecraft spin rate of 2 rpm, which is the current baseline, a too long exposure time would result in smearing of the image across the CCD. In fact, given the various parameters of the proposed mission, the allowable exposure time would be no more than a fraction of a second before smear would become significant. Even with a fast optical design and an image intensifier, the allowable exposure time is far too short to be able to image faint auroral emissions. To overcome this problem, the CCD will be run in a fast frame-rate (snapshot) mode, with images being acquired at 30 frames per second and offset/summed in digital memory to simulate a longer effective exposure time. This mode is currently being successfully employed by the IMAGE WIC instrument. The advantages of this

approach are an almost unlimited dynamic range, and the fact that any corrections for misalignment of CCD columns with respect to the spin plane, and other motion-induced distortions, may be corrected for digitally, on the fly or in post-processing. The MCP gain would have to be set accordingly, so as to make insignificant the increased CCD read-noise contribution associated with such fast readout.

The instrument must have a field of view (FoV) wide enough to span the entire auroral zone and polar cap for a significant fraction of the orbit. A field of view of 25 degrees has therefore been chosen. This ensures continuous global coverage of the northern auroral oval from the combined measurements from the *Ravens* imagers on the two 180-degrees out-of-phase polar-orbiting Kua-Fu spacecraft, both on a 7 x 1.8 R_E (geocentric) orbit. A 1024×1024 pixels frame-transfer charge-coupled device (CCD) is baselined for this application. Images can be binned 2×2 to achieve a 512×512 format whenever spatial resolution can be sacrificed for sensitivity. The nadir apogee spatial resolution, employing 1×1 and 2×2 binning, is 16 km and 32 km, respectively, and therefore, to achieve the spatial resolution that we are aiming for from near apogee, the instrument must have at least 512×512 pixels. The 7 x 1.8 R_E orbit (geocentric distances) proposed for the *Ravens* segment of the Kua-Fu mission allows for continuous global imaging with excellent spatial resolution over much of the auroral and polar regions, and down to mid latitudes.

Temporal resolution is determined by the spin rate of the satellite. The proposed spin rate is 2 revolutions per minute, yielding a maximum image cadence of 30 seconds. Higher image cadence would require a faster-spinning satellite, but this would impact imager sensitivity. The effective image exposure time is determined by the imager's field of view and the satellite spin rate. For a 2 rpm spin rate (30 second spin period) and a 25 degrees field of view, the maximum available exposure time is 2.1 seconds. Such a short exposure time severely impacts imager sensitivity threshold, and places high demands upon the optical design.

The instrument shall provide simultaneous, wavelength-separated LBH electron auroral observations over the global auroral distribution. Proposed passbands are 140 – 160 nm (LBH-short) and 160 – 180 nm (LBH-long). The latter provides a measure of energy flux, and the ratio of the two provides information on characteristic electron energy. Sufficient suppression of unwanted continuum contribution from shortward of 140 nm and longward of 200 nm must be provided. Figure 2 shows the LBH spectrum with LBH-short and -long passbands indicated.

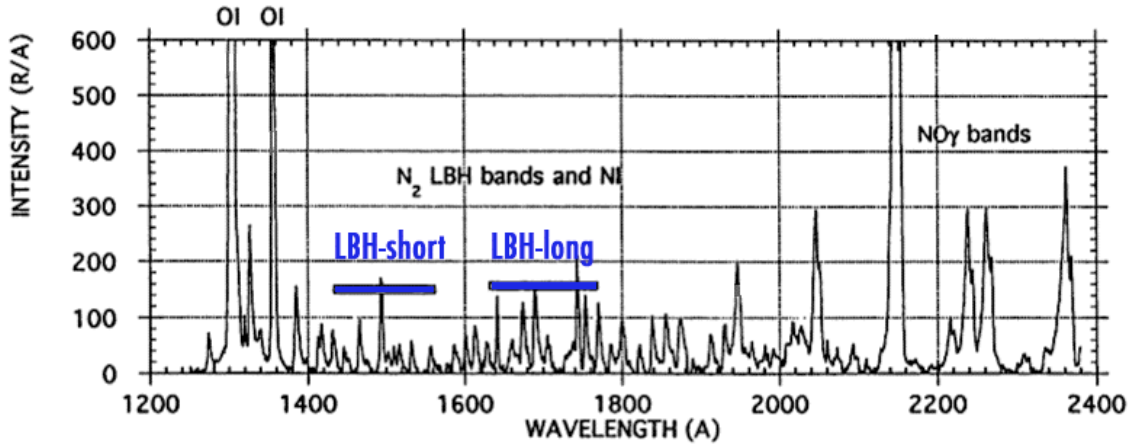


Figure 2: FUV spectrum, showing LBH bands and indicating the location of the desired "LBH-short" and "LBH-long" passbands.

The imager's optical aperture must be as large as practically possible, with instrument mass and size restrictions in mind, so as to admit enough light for reasonable signal to noise ratio in the case of dim auroral features (tens of rayleighs, as integrated across the appropriate part of the spectrum) during the relatively short 2.1 s integration time. As shown later (Table 2), a Noise Equivalent Signal (NES) of 30 R per exposure can be achieved with a 27.6 mm diameter aperture and careful selection of optical materials. The instrument must be capable of measuring very bright signals (on the order of 100 kR) in the auroral oval as well as very weak signals (tens of rayleighs) in the polar cap. It may be necessary to measure weak regions simultaneously with bright regions within the same field of view. An intrascene dynamic range of 1000, and an interscene dynamic range of 10^4 is desired. The interscene dynamic range can, as already indicated, be further extended by the use of image summation in memory during exposure. Some important required instrument characteristics are summarized in Table 1.

Table 1: Some required *Ravens* instrument characteristics.

Field of View	*25 degrees*
Number of Cameras (on each satellite)	*2*
Spectral Passband	*140 – 160 nm (camera 0)* *160 – 180 nm (camera 1)*
Image Format	*1024 x 1024 and 512x512 (selectable)*
Nadir Spatial Resolution	*16 km (1024x1024 pixels) and 32 km (512x512 pixels)*
Temporal resolution	*30 s (assuming 2rpm spin rate)*
Exposure Time	*2.1 s (assuming 2 rpm spin rate)*
Sensitivity	*30 R/exposure NES*
Dynamic Range	*10^4*
Rejection of VIS-NIR albedo	*~10^{10}*

Instrument Design

Optical Design

The image-forming section of the *Ravens* imagers will be comprised of fast, all-reflecting telescopes. In order to approach the selection of a suitable optical design, the required optical aperture and focal length were first examined. Modeling (see section on Instrument Sensitivity Performance) shows that in order to achieve the required sensitivity of 30 rayleighs per exposure, an aperture area of 6 cm^2 is required, translating into an unobscured diameter of 27.6 mm (D_A). The 25 degrees field-of-view projects onto the focal plane, where an image intensifier photocathode is located. The maximum active diameter photocathode currently suitable for space applications is 40 mm. In order to project a FoV of 25 degrees onto a 40 mm diameter focal plane (D_{FP}), a telescope effective focal length (fl) of 90.2 mm is required. The *f*-ratio (fl/D_A) of the system is therefore *f*/3.3 – a fast, but entirely realizable system. If the optical *f*-ratio is further increased in an attempt to make the optics even more feasible, the focal length will become larger, and hence the focal plane area will increase, increasing instrument physical size. Instrument size is driven by the resolution requirements, the required focal length, and field-of-view within which distortion must be minimized.

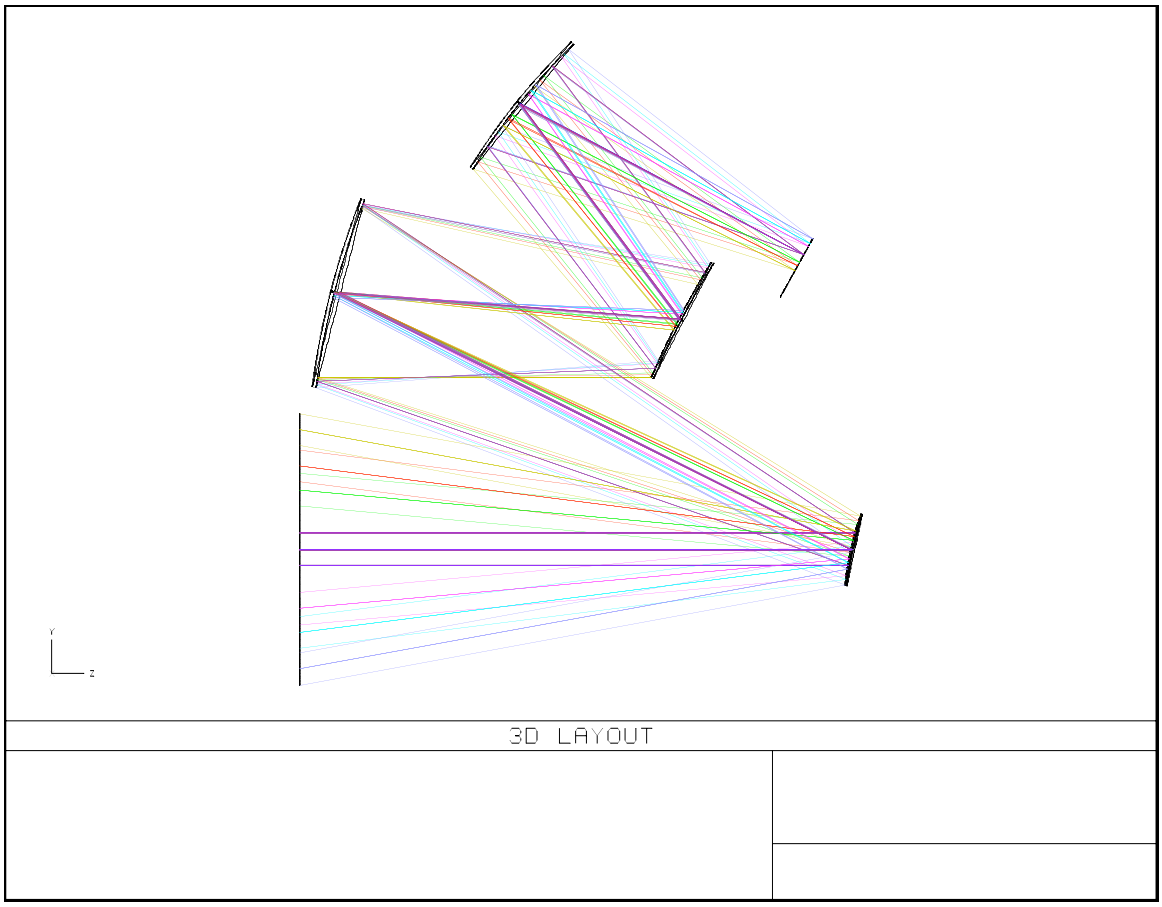


Figure 3: Wetherell-Womble Design

Thus, the *Ravens* far-ultraviolet imagers are required to operate over what is an extremely wide field of view for most reflective telescope designs , ±12.5 degrees, with a speed of at least *f*/3.3 and an effective focal length of 90 mm. An initial survey of possible design solutions found that the more compact the off-axis design, the greater the distortion. There is thus a limit as to how compact the design can be and still have reasonable distortion performance. Since sensitivity is a driving factor, an off-axis, all-reflective system with no obscurations was chosen. The chosen design for *Ravens* is a wide-angle Wetherell-Womble design, shown in Figure 3. In this telescope, all mirrors are spherical, with the stop at the secondary mirror. Distortion performance is very good (about 2%), considering the large field-of-view. The design is fully corrected for spherical aberration, coma, and astigmatism. Moreover, it has excellent resolution over most of the field of view and have a high throughput in the far ultraviolet part of the spectrum. Importantly, the image plane is not curved, thereby greatly reducing the complexity and cost of the micro-channel plate image intensifier. The design provides a 25 degrees circular field of view with an optical axis perpendicular to the spacecraft spin axis. Adequate baffling and a reusable aperture door will be implemented.

Selection of Optical Materials

The *Ravens* cameras will be operating in the "self filtering" mode [Zukic, 1990, 1995], in which the imaging mirrors themselves are coated with all-dielectric multilayer filters which only reflect the

desired wavelength. As such, the filtering and imaging properties are combined, helping reduce instrument size and mass while at the same time helping improve instrument performance. Detecting weak FUV emissions in the presence of bright visible light poses a significant design challenge. As mentioned earlier, and shown here in Figure 4, the integrated visible-to-infrared albedo is on the order of 10^{11} R.

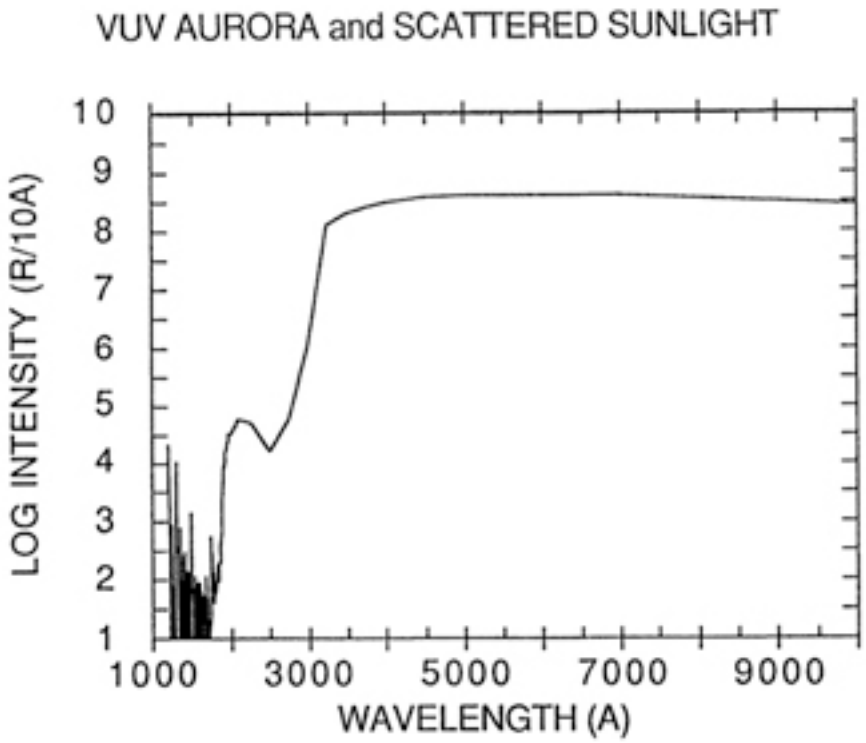


Figure 4: Brightness seen by nadir-viewing instrument looking at the sunlit Earth [Torr et. al, 1995].

To measure a signal on the order if 10 R, the long-wavelength continuum must be reduced by at least a factor of 10^{10}. Towards this end, *Ravens* will employ all-dielectric filters. Modern dielectric multilayer mirror coatings [Spann, 2005] will be used, having very low reflectivity in the Visible and Near-UV region and manufactured for high reflectivity in the LBH-short or LBH-long wavelength region, respectively. Most out-of-band wavelength photons impacting on the reflective surface of the mirrors (high quality fused silica or Zerodur) are either absorbed by the glass or pass through the mirror and are absorbed by absorptive coatings applied to the rear surface of the mirror. Using recent filter technology, only 4% of out-of-band wavelength photons are reflected and eventually imaged with in-band photons. The *reflectivity ratio* is the ratio of mirror reflectivity of out-of-band photons to in-band photons. Typical peak reflectivity of these filters are 0.85, as shown in Figure 5. The reflectivity ratio rapidly decreases with multiple reflections, as 0.05^{m}, where m is the number of reflective filters used. In the case of *Ravens*, m=4, yielding an out-of-band rejection of about 6×10^{-6}. Used in conjunction with a solar blind photocathode, a visible light rejection of 10^{10} can therefore be accomplished.

A CsI (solar blind) MCP photocathode provides an additional factor of more than 10^4 rejection longward of 200 nm. The CsI must be manufactured to the highest purity standards (~10^6 rejection has been shown to be achievable).

The short-wavelength cutoff will be achieved by proper selection of detector window material. For LBH-short, a BaF_2 window will be used. For LBH-long, a UV-grade silica (SiO_2) is considered a suitable material.

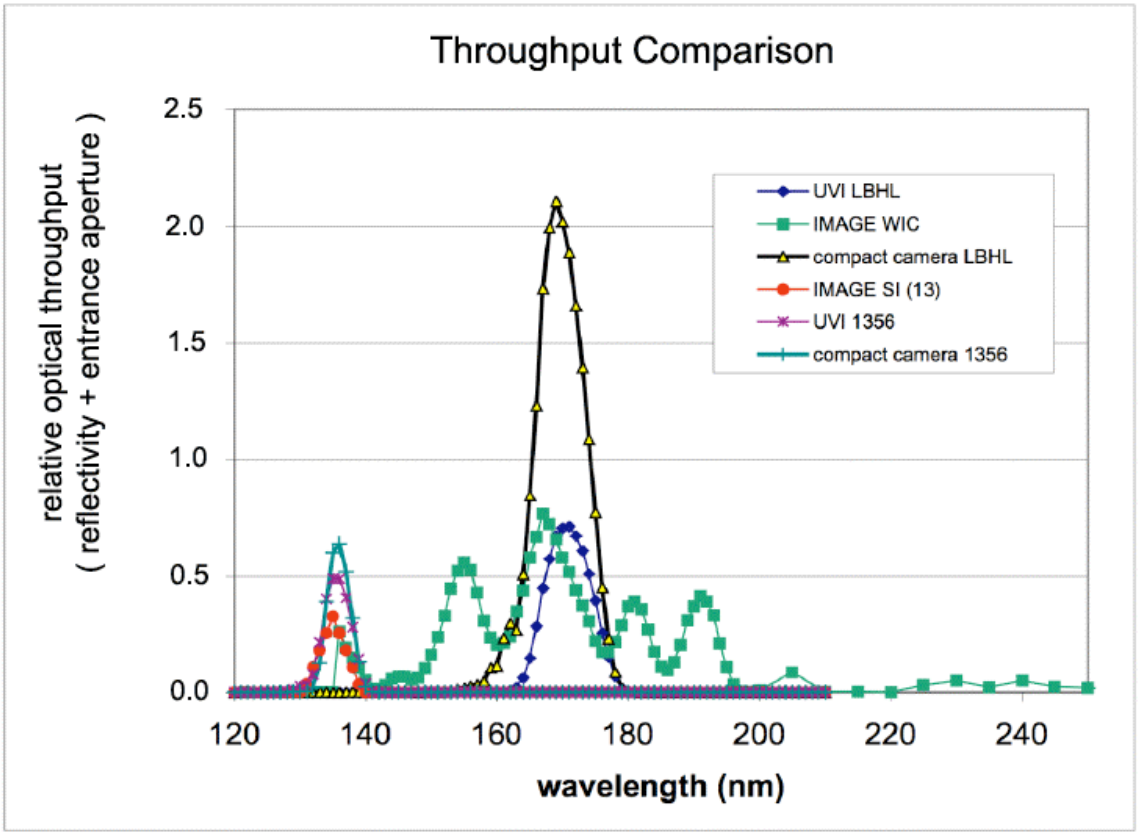


Figure 5: Traced in black is the passband of state-of-the-art LBH-long filter [Spann, 2005]. Average reflectance longward of 200 nm is 3.6%, reflectance at center of passband is greater than 80%. LBH-short filter has the same performance data. Similar technology will be employed for *Ravens*.

Sensor Selection

A 40 mm diameter micro-channel plate (MCP) image intensifier with a solar-blind (CsI) photocathode placed at the focal plane of the imagers is illuminated by the FUV image formed by the all-reflecting optics. Rather than an open intensifier as was used in the VIKING UV Imager, a sealed design is employed in order to avoid contamination of the photocathode and saturation due to ambient electron fluxes. The sealing is accomplished by placing a BaF_2 and SiO_2 window in front of the photocathode for the LBH-short and LBH-long imagers, respectively. Once a photon passes through the window, it impinges upon a photocathode material (CsI) designed to be photoemissive over a particular wavelength region. Once a photoelectron is confined to a MCP pore, it is accelerated by a potential of several kV to produce a cascade of electrons out from the rear of the MCP. This acceleration is necessary for the electrons to traverse an aluminum coating overlaid on a P43 phosphor. The purpose

of the coating is to shield the subsequent optical chain from light penetrating the MCP without photoconversion. A P43 anode screen is baselined in spite of its low efficiency (30% of P20) because of its particularly fast decay time (decay to 10% in 1.5 ms). This is required because of the relatively high spin rate of the spacecraft: since a pixel (a resolution element on the ground) sweeps through the field of view at a fairly high rate, it is required that the response of the phosphor due to one pixel must be sufficiently decayed before the next pixel arrives. P43 phosphor has a peak wavelength of 550 nm, which also happens to be the wavelength of maximum responsivity of the baselined CCD.

Once the electrons strike the phosphor, photons are produced. These photons are then fiber-optically coupled to the CCD. The proposed CCD is a 1024×1024 pixels scientific-grade frame transfer chip which can be binned down to 512×512, yielding a ~32 km spatial resolution from apogee with a 25 degree field of view. The CCD is operated in fast readout mode and will not require a mechanical shutter. The chosen CCD, manufactured by e2v, has 13-micron square pixels and therefore has an image dimension of 13.3 mm square. With a 40 mm diameter phosphor screen, a fibre optic taper ratio of 3:1 will be required to reduce the image size of the screen to the size of the CCD. The MCP and fiber taper is not expected to be the spatial resolution-limiting factor in this application.

In order to achieve a 1 electron rms noise for an exposure time of 2.1 seconds, a dark signal of 0.48 electrons/pixel/s is required, corresponding to a temperature of about –15 deg C for a typical AIMO (advanced inverted mode operation) back-illuminated CCD. This level of cooling can be readily achieved using passive cooling via a "cold-finger" and some supplemental (low-power) thermoelectric cooling when required. Temperature sensors will be mounted at strategic locations, and temperature will be continuously monitored.

Instrument Sensitivity Performance

Some modeled and calculated parameters pertaining to the proposed *Ravens* four-mirror optical design are tabulated in Table 2. The first vertical data column lists values relevant to the LBH-short imaging channel, while the second column is relevant to the LBH-long channel. The table is largely self-explanatory, but we will comment briefly on the "Optical Efficiency" and "Signal to Noise (SNR)" sections of the table.

Optical Efficiency.

As the *Ravens* optical design is based on the self-filtering principle, the center-of-passband mirror reflectivity used in this spreadsheet (0.85) is based on the properties of state-of-the-art multilayer dielectric filter coatings [Spann, 2005]. In the case of LBH-short, a SiO_2, intensifier window material is assumed, with a 0.82 transmission at 150 nm (BaF_2 has a transmission of only 0.59 at 150 nm, for the required window thickness). In the case of LBH-long, BaF_2 is assumed, with a transmission of 0.76 at 170 nm. A CsI photocathode quantum efficiency of 21% and 15% can reasonably be expected in the case of LBH-short and LBH-long, respectively. Using these data, the (effective) transmission and out-of-band-rejection is calculated and tabulated in the spreadsheet. Recall that an out-of-band rejection of better than 10^{10} is considered a requirement to meet science objectives. A solar blind photocathode (CsI) may provide a factor of 10^4, which means that the rest of the optical system must provide the remaining 10^6 of suppression. Clearly, the proposed four-mirror design appears to satisfy this requirement.

Table 2: Modeling of LBH sensitivity and calculation of some relevant parameters for a four-mirror all-reflective (self-filtering mode) optical design.

LBH SENSITIVITY CALCULATIONS (4 mirrors)		**LBH-short**	**LBH-long**
Exposure	CCD superpixels (2 x 2 binned)	512 x 512	512 x 512
	Field of View [degrees]	25	25
	Angular superpixel FoV [degrees]	0.049	0.049
	Spin Period (image cadence) [seconds]	30	30
	Spin Rate [degrees/second]	12.0	12.0
	Effective Exposure time [seconds]	**2.1**	**2.1**
Optical Efficiency	Mirror reflectivity	0.85	0.85
	Resulting reflectivity	0.52	0.52
	Intensifier window transmission	0.82 (SiO_2)	0.76 (BaF_2)
	Photocathode QE (CsI)	0.21	0.15
	MCP efficiency	0.60	0.60
	Throughput	**0.054**	**0.036**
	Out of band rejection	**6E-06**	**6E-06**
Optical Parameters	Aperture [cm^2]	6	6
	Diameter [mm]	27.6	27.6
	Assumed MCP diameter [mm]	40	40
	f/#	3.3	3.3
	Pixel Omega [square pixels]	7.26E-07	7.26E-07
Signal to Noise (SNR)	Radiance-kR conversion factor	7.96E+07	7.96E+07
	Calculated Sensitivity [counts/kR/s]	18.7	12.4
	Counts/R/pixel/exposure	0.039	0.026
	Noise Equivalent Signal [R/exp]	**25.7**	**38.8**
	Desired SNR	2.5	2.5
	Desired SNR requires brightness [R/exp]	160.0	240.0
Spatial Resolution	1 RE [m]	6.38E+06	6.38E+06
	Satellite Apogee [Re]	7	7
	Derived Altitude [km]	38280.0	38280.0
	Earth angle from above altitude [deg]	16.43	16.43
	Auroral Oval subtends from alt [km]	1048	1048
	Nadir resolution at apogee [km]	**32.6**	**32.6**
Data Rate	Bits per pixel	12	12
	Total bits/image	3.15E+16	3.15E+16
	Telemetry rate, no compression [Mbits/s]	0.10	0.10
	Telemetry rate, compressed [kbits/s]	30	30

Signal to Noise (SNR).

Calculated sensitivity in counts per kilorayleigh per exposure is listed in the SNR section of the table. The instrument's optical aperture is crucial to this calculation. Another important item here is the line tabulating Noise Equivalent Signal (NES), a figure often used for sensitivity comparison purposes. As can be seen, in the case of our four-mirror design the NES is in the neighborhood of 30 rayleighs per exposure, which is the original *Ravens* sensitivity target.

Application to Auroral Measurements

By clever selection of the orbit parameters of the two polar-orbiting Kua-Fu spacecraft, the *Ravens* imagers can meet the important scientific objectives of observing the auroral distribution on a continuous basis, a feat not previously achieved. Beyond monitoring the FUV auroral distribution the other primary objective is to provide quantitative images of precipitating electron energy flux and average electron energy. As mentioned previously, this can be done through measuring the auroral brightness in two separate spectral ranges of the N_2 LBH band, one between 140 and 160 nm (LBH-short) and the other between 160 and 180 nm (LBH-long). The LBH-long signal is directly related to the *electron energy flux* and the ratio of the LBH-short signal to the LBH-long signal is a function of the *average electron energy*. The ratio variation is based upon two effects: the more energetic electrons penetrate deeper into the atmosphere where the probability of absorption of the FUV photons by O_2 is larger; and the LBH emissions are preferentially absorbed at shorter wavelengths. Thus the ratio goes down with higher average electron energy.

In order to find out whether or not such quantitative measurements are feasible for *Ravens*, it was necessary to estimate the expected auroral brightness in the two spectral ranges. A detailed model analysis (not shown here) shows that the LBH-long brightness is in the range 100 to 250 R when the electron energy flux is 1 milliwatt per square meter (mW/m^2) and the average precipitating electron energy is in the range 1 to 10 keV. This energy flux gives rise to about 600 R of emission in the N_2^+1NG(0,0) band at 391.4 nm, which corresponds to a relatively weak aurora. The instrument, with sensitivity characteristics as described earlier, is more than capable of measuring 100 R in the LBH-long range. A 30 R/exposure noise contribution represents about 0.3 mW/m^2 uncertainty in the energy flux. For bright auroras (10 – 100 mW/m^2), the uncertainty due to the instrument noise becomes insignificant. Our preliminary analysis shows that the cameras will have the necessary sensitivity to allow the electron energy flux to be extracted from the data. However, it is known that proton precipitation, although weaker than electron precipitation also results in N_2 LBH photon emission; therefore, realistic models of global proton energy precipitation must be examined to ascertain the relative contribution of protons. Another source of uncertainty is the fact that the LBH-long emission rate is not completely independent of the average electron energy, i.e. the emission rate is somewhat higher for incoming electrons at higher energy. Preliminary analysis indicates that this effect can introduce a variation of about 10 to 20% for the electron energy range 1 keV to 10 keV at all energy flux levels. This lack of complete independence has been investigated by the Polar UVI team [Germany et al. 1998].

A second necessary component of our preliminary analysis was to verify the feasibility of obtaining the average electron energy from the ratio of the LBH-short to LBH-long. The validity of this technique relies on the fact that the O_2 molecules absorb many more photons in the LBH-short wavelength range than in the longer LBH-long range. The Polar UVI team have calculated the ratio for an electron energy range up to 10 keV based upon the UVI filter bandpasses [Germany et al. 1998]. Using modeled emission rates and brightnesses of auroral emissions.in the range 1 keV to 10 keV, we calculated the expected LBH-short to LBH-long brightness ratio for the incoming electron flux in the two spectral ranges. These are shown in Figure 6, for an electron energy flux of 1 mW/m^2.

Obviously, the expected uncertainty of this technique depends strongly on the auroral brightness. For a weak aurora (IBC I) that corresponds to an electron energy flux of around 1 mW/m^2 or less, the uncertainty is large for a single exposure with a noise equivalent signal of 30 R. However, for moderate auroras with energy flux near 10 mW/m^2, the uncertainty introduced by the measurements is relatively small and is likely dominated by other sources of uncertainty such as variability in the O_2 density in the 100 to 150 km altitude range. It will therefore be important to utilize the best available model atmospheres for the analysis and to make the best estimates of uncertainty that can be generated

by errors in the models. Fortunately, this analysis technique is independent of the N_2 density because the same species emits in both spectral ranges.

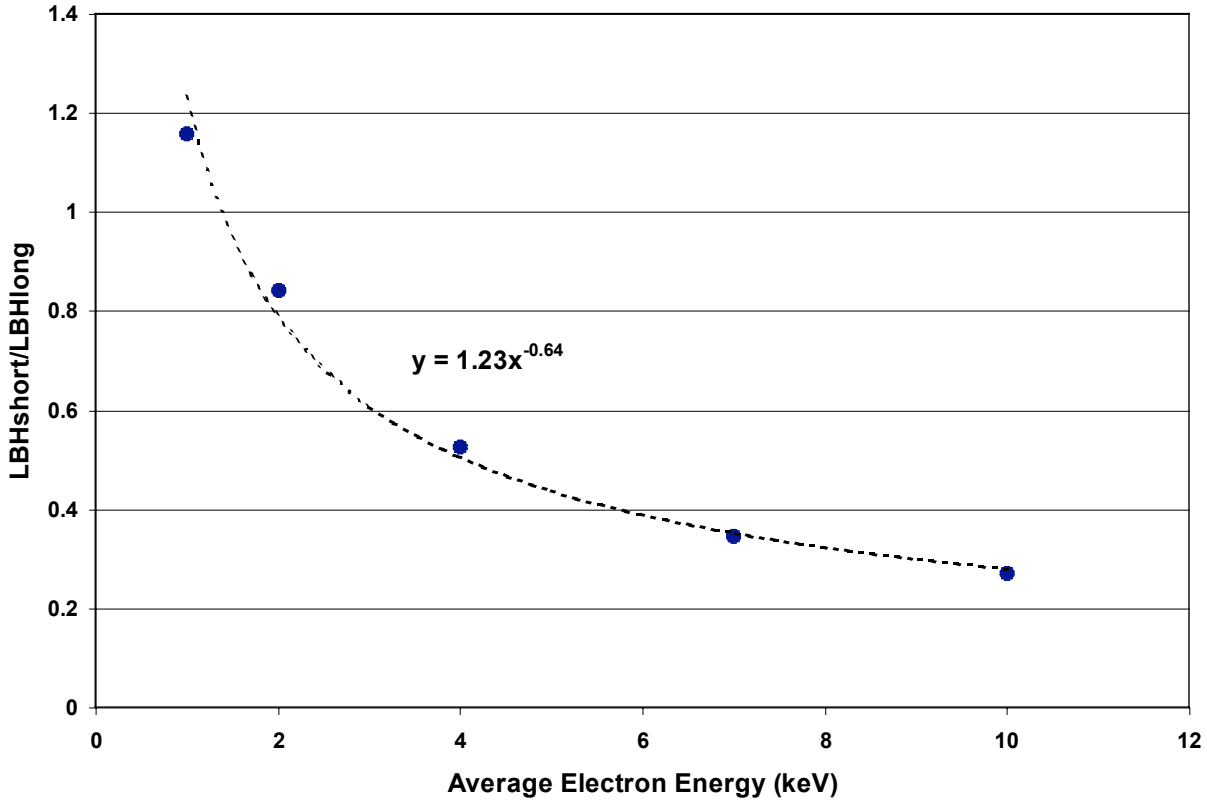


Figure 6: Expected LBH-short to LBH-long brightness ratios as a function of average electron energy, given an electron energy flux of 1 mW/m^2.

We conclude that the cameras will be capable of providing the necessary signals from which both the *electron energy flux* and the *average electron energy* can be derived. This conclusion appears to be valid for moderate and large electron energy fluxes, but more knowledge of the instrument will be required before a minimum usable electron energy flux can be estimated with confidence. It is clear from the above discussion of the auroral measurements that absolute calibration of the *Ravens* imagers is a requirement for the determination of the electron energy flux and the average electron energy. Once in orbit, long-term variations in sensitivity can be monitored by means of star images. Previous Canadian FUV imagers have been characterized in the laboratory but not calibrated, as they were developed for the purpose of providing morphological rather than quantitative measurements.

Spacecraft Resource Requirements

The following table shows the initial resource requirements budget for the *Ravens* imaging instrument. Each instrument will be partitioned into co-aligned LBH-long and LBH-short optical chains, with a separate "Electronics Box" handling control of both imaging channels. Two of these instruments are

required, one for each of the two polar orbiting Kua-Fu satellites. These are preliminary estimates which will be adjusted according to final design options selected during the upcoming Phase-A study.

Table 3: *Ravens* spacecraft resource requirements (preliminary)

	LBH-short channel	**LBH-long channel**	**Electronics Box**
Mass [kg]	9.0	9.0	3.0
Dimensions [cm^3]	25 x 24 x 15	25 x 24 x 15	20 x 20 x 10
Power [W]	4	4	3
Data Rate [Mbits/s]	0.1	0.1	N/A
Temperature Limits	-40 to +60 C (surv.) -25 to +20 C (ops.)	-40 to +60 C (surv.) -25 to +20 C (ops.)	-40 to +60 C (surv.) -25 to +40 C (ops.)

Acknowledgments

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References

Germany, G. A., J. F. Spann, G. K. Parks, M. J. Brittnacher, R. Elsen, L. Chen, D. Lummerzheim, and M. H. Rees. Auroral Observations from the POLAR Ultraviolet Imager (UVI). *AGU Monograph, "Encounter Between Global Observations and Models in the ISTP Era",* Jim Horwitz, Dennis Gallagher, and Bill Peterson, Eds, 1998.

Spann, J., Compact FUV camera concept for space weather applications. *Proc. SPIE*, Vol. 5901, 2005.

Torr, M. R., D. G. Torr, M. Zukic, R. B. Johnson, J. Ajello, P. Banks, K. Clark, K. Cole, C. Keffer, G. Parks, B. Tsurutani, and J. Spann, A far ultraviolet imager for the International Solar-Terrestrial physics mission. *Space Sci. Rev.*, 71, 329, 1995.

Zukic, M. and D. G. Torr, Extreme and Far ultraviolet narrowband and Broadband Filters. In *Thin Films for Optical Coatings,* edited by Rolf E. Hummel and Karl H. Gue, 1995.

Zukic, M., D. G. Torr, J. F. Spann, Jr., M. R. Torr, Vacuum Ultraviolet Dielectric Narrowband Filters. *Appl. Opt.,* **29**, 4293, 1990.

THE FAST AURORAL IMAGER EXPERIMENT TO INVESTIGATE THE DYNAMICS OF NIGHTTIME OPTICAL AURORA AS PART OF THE CASSIOPE/EPOP MISSION

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Abstract

The Fast Auroral Imager (FAI) consists of two CCD cameras: one to measure the 630 nm emission of atomic oxygen in aurora and enhanced night airglow; and the other to observe the prompt auroral emissions in the 650 to 1100 nm range. Good throughput will be realized through the combination of fast lens systems (f/0.8) with CCDs of high quantum efficiency. Both cameras have a common 27° field-of-view, to provide circular images of ~650 km diameter from apogee at 1500 km. In the nadir viewing mode, the near infrared camera will provide multiple images per second at a spatial resolution of a few kilometres, for studies of dynamic phenomena such as substorm onset, vortices and multiple narrow arcs, and for monitoring the auroral context for the complementary in situ measurements onboard. The 630-nm camera will produce images once per minute with an exposure time of 0.5 sec, which is compatible with the radiative lifetime of the $O(^1D)$ atom in the atmosphere. Not only will this camera image auroral forms such as discrete arcs that are produced by soft electrons, it will also measure the locations of the auroral oval and polar cap boundaries. With on-chip pixel binning it will be possible to investigate weak emission phenomena such as polar arcs and patches, midlatitude SAR arcs and detached arcs, and enhanced airglow from artificial ionospheric heating. Overall, the FAI instrument represents a major advance in the application of new technology to the study of nighttime auroral phenomena.

Introduction

The Fast Auroral Imager (FAI) is part of a set of instruments that have been selected for the Enhanced Polar Outflow Probe (e-POP) mission that is scheduled for launch in late 2007. The major scientific objectives of the mission are associated with the Earth's high latitude atmosphere and ionosphere. The first thrust is to investigate the outflow of plasma from the polar regions and the related processes of micro-scale ion acceleration and wave-particle interaction, and auroral excitation. The second thrust is the study of 3D ionospheric irregularities using both active and passive radio techniques. The third emphasis is on the escape of neutral particles from high latitudes caused by temperature enhancements as well as by non-thermal processes. The mission concept therefore naturally requires the highest possible in-situ measurements of electrons and ions, techniques for 3D radio wave propagation studies, and high temporal and spatial resolution images of meso-scale optical aurora from space. The Fast Auroral Imager was developed to meet the optical imaging objectives of the mission. Canadian scientists and their industrial partners have a long history of auroral imaging, beginning with the ISIS2 satellite that was launched in 1971 to investigate visible aurora during nighttime hours. For the next two decades, imagers were developed and flown for the purpose of studying the global distribution of FUV aurora under both sunlit and dark atmospheric conditions. These imagers used intensified CCD detectors to achieve the necessary sensitivity as part of the Swedish Viking and Freja missions and the Russian Interball mission. In this paper we describe the latest stage in Canadian imager development: the application of CCD technology to achieve a combination of high spatial and temporal resolution with high sensitivity using

optical (visible and near infrared) aurora as the target. These emissions are visible at night both from the ground and from space. The FAI is now in the final stages of assembly.

Auroral Imager for the e-POP Mission

Science Objectives and Measurement Requirements

In keeping with the overall scientific objectives for the ePOP mission, it was necessary to identify a complementary list of objectives for the auroral imager that would guide the measurement requirements and the instrument design. The general objective is to investigate the relationship between auroral emissions and ion bulk upflow, heating, acceleration, field-aligned currents, and plasma waves. In more specific terms, the FAI was designed to support the investigation of the following:

- The small-scale mechanisms for auroral excitation
- The phenomenon of black aurora and its relation to streaming electrons and ions
- The optical signatures of large-scale convection and their relation to radar measurements
- The connections between aurora and ion energization and bulk upflow

The above objectives are related to a wide range of auroral intensity and temporal/spatial scales. To accommodate this range, it is necessary to observe aurora in the visible and near-infrared portions of the spectrum rather than the FUV. The spatial resolution must be selectable, with a minimum pixel size corresponding to several km at auroral altitudes when observed from apogee. The temporal resolution and exposure time must also be selectable, with values as small as one second. A repetition rate of one second is achievable with a 3-axis stabilized platform and fast data transfer. Because the spatial and temporal characteristics of auroras generated by low and high energy electrons can be very different, it is desirable to incorporate the capability to measure both independently by the use of two cameras whose parameters are chosen for this purpose. Unlike many imaging missions, e-POP does not have a requirement for global imaging, because the target is meso-scale aurora that is of the order of a few hundred kilometres rather than thousands of kilometers.

Instrument Concept

The measurement requirements presented a challenge to design an auroral imaging instrument that would make advances in both temporal and spatial resolution as well as sensitivity and dynamic range. The spatial resolution capability for most auroral imagers over the past two decades has been of the order of 10s of km whereas the need in the e-POP mission was for an order of magnitude improvement. Likewise, a similar improvement in repetition rate was required. The challenge was met by carefully selecting the spectral elements to image and by taking advantage of the best available technology within the constraint of a very limited budget. It was decided to design two cameras that are to be co-aligned and identical in all respects except for the optical filters. One camera (SV) will image the emission from the atomic oxygen line at 630.0 nm. This emission is pervasive throughout the auroral region and polar cap, and it is excited efficiently by low-energy electrons. It is very useful for identifying features and boundaries in the atmosphere that correspond to different processes in the magnetosphere. However, because of the relatively long radiative lifetime, it is not a suitable emission to utilize for high temporal and spatial resolution, so the second camera (SI) was designed to image a range of auroral emissions in the 650 to 1100 nm part of the spectrum. The principal emission species in this range, N2, O2 and N2+, will respond preferentially to electrons with energies higher than those for the SV camera and will closely follow the dynamic variations of the precipitating particles.

The sensitivity of the cameras was maximized further through the choice of a CCD detector and optics module. We chose a thinned, backside-illuminated, high quantum efficiency and low noise CCD, the E2V CCD67 in a 256 by 256 pixel array. According to the manufacturer, the quantum efficiency is 0.8 at 630

nm, and effectively about 0.66 for the SI camera, and the read noise is less than 10 electrons. With thermal-electric cooling of the AIMO device, the dark current can be kept insignificant for normal instrument operating temperatures. As for the optics, we combined an f/4 telecentric lens system with a 5:1 fibre-optic taper to provide an effective f-number of 0.8. The price paid for the use of the taper is a reduction in optical transmission.

The electronic control system was designed to permit a selection of exposure times and on-chip summation in order to adjust to the various science modes during the mission. A large dynamic range was preserved through the use of 16-bit data words and a 16-bit analog-to-digital converter.

Instrument Design

The design and construction tasks have been distributed. The optics modules were designed and built by Coastal Optical Systems under the supervision of Keo Consultants. Greg Burley of Burley Scientific was responsible for the control and readout electronics as well as the flight software. Routes AstroEngineering undertook the mechanical design and construction of the camera bodies, the electronics housing, the baffles, the mounting of the CCDs and the thermoelectric cooling of the detectors. Routes have the overall responsibility for the assembly of the cameras.

Mechanical Overview

There are two mechanical structures. One structure contains both cameras and the other contains the electronics. A cut-away drawing of the camera unit is shown in Figure 1. The baffles are designed for a field of view of 27.5 degrees, which is slightly larger than the optical field of view to keep the vanes out of the camera field of view. Four knife-edge vanes are positioned to maximize the effectiveness of the baffles whose length is constrained by the spacecraft mounting requirements. The camera unit has a dust cover that will be removed prior to launch. The optics modules are rigidly attached to the camera unit, and the fibre optics block supporting each CCD is bonded to the small end of the fibre optic 5:1 taper. The electronics box is independently mounted to the deck plate of the satellite. The FAI instrument was allocated a mass of 7.7 kg.

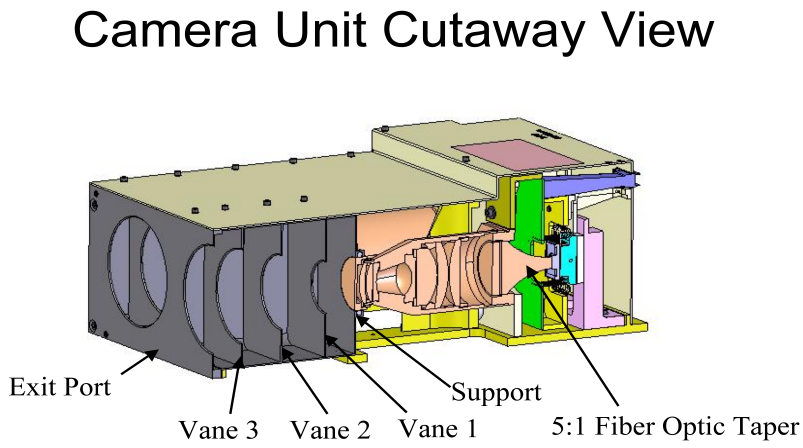


Figure 1. Cutaway drawing of the camera unit

Optical System Overview

A ray drawing of the optical system is shown in Figure 2. There are 7 AR coated lenses that produce an image diameter of 33 mm on the input end of the fibre optic taper. A circular image of diameter 6.6 mm is formed on the 6.6 mm by 6.6 mm CCD. The full-angle field of view of each f/4 camera is 27 degrees. The design is telecentric to ensure that the same cone angles are seen by all parts of the filters. The focal length of the system is 68.9 mm. The SV camera contains a metal oxide interference filter of half-width 2 nm and peak transmission of 0.8 manufactured by Barr Associates. The metal oxide design minimizes passband shifts from 630.3 nm due to temperature variations. The filter in the SI camera is a broadband filter, Schott RG645 that has a transmission of 0.9 over the range 650 to 1100 nm. Shorter wavelengths are blocked. The lenses are supported in a titanium housing.

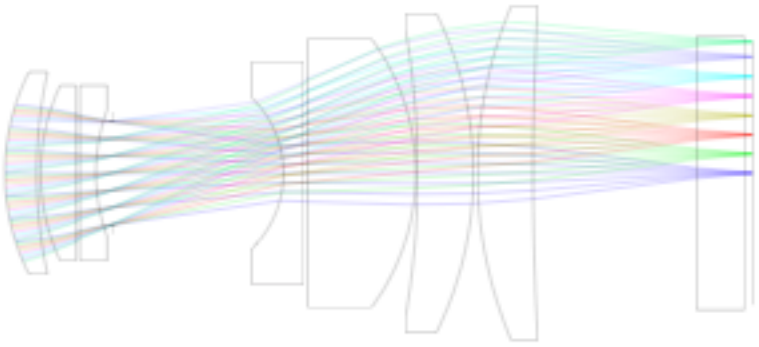


Figure 2. Ray drawing of the optical system

The CCDs are cooled by means of a two-stage thermal-electric cooler (TEC) that produces a delta T of about 25 degrees for baseplate temperatures above 15 degrees and that holds the CCD temperature at -10C for baseplate temperatures below 15C.

Electronic Overview

Figure 3 is a block diagram showing the various parts of the sensor system. The controller provides bias voltages, three phase clock signals to the CCD parallel and serial registers, signal processing to extract and digitize the CCD output signals, and a fast serial interface to a data handling unit (DHU).

The digital system processor (DSP) directly generates the sequences used to clock the serial and parallel charge transfers on each CCD. Extra clock lines are provided for frame transfer. The DSP also controls the dual-slope integrator, the A-to-D conversion, and the data transfer to the interface. The design of the dual-slope integrator and clock drivers are optimized for fast settling time.

The design is partitioned into three parts. Each CCD is packaged with a low-noise preamplifier and a temperature sensor. A cable connects each CCD to the main electronics unit, which contains all the support circuitry to operate the CCDs and communicate with the data handling unit.

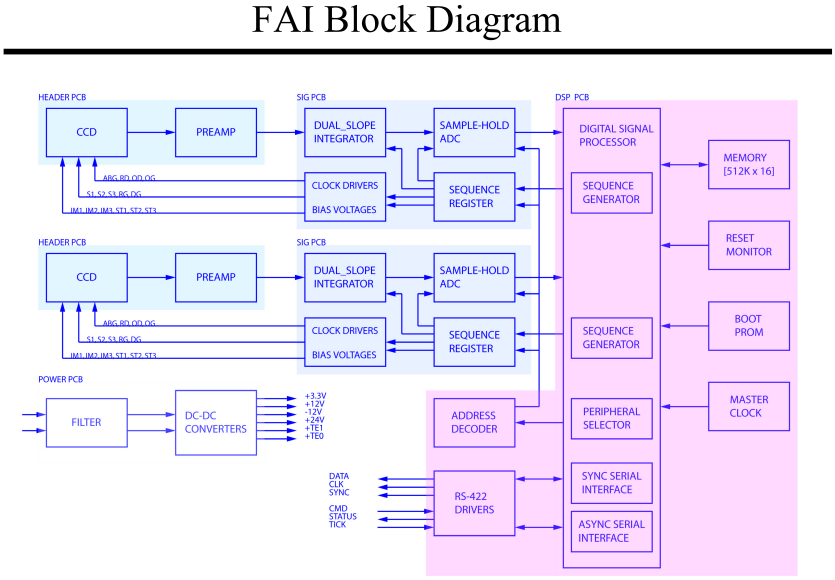


Figure 3. Block diagram of the FAI electronics

The preamplifier design is based on a low voltage-noise, fast-settling FET-input op-amp. The CCD output signal is ac-coupled to the preamp, which has a nominal gain of 20. To minimize the readout noise, the preamp is located as close to the CCD as possible. The CCD temperature is monitored with a sensor mounted to the ccd package, which connects to the header board.

The FAI main electronics unit is divided into four circuit boards to fit within the available volume: a power board, a digital logic DSP board, and two analog signal boards.

The DSP-based CCD controller is designed around a Motorola DSP56309 24-bit digital signal processor. On-chip resources permit the DSP to run code from an internal 20K program memory, and to use two internal 7K data memories for storage. The DSP runs at an internal clock frequency of 80 MHz, phase locked to an external 10 MHz oscillator.

To operate the CCD and signal processing, the DSP writes a sequence of data words to an external register, where each bit of the data word connects to one of the CCD control signals. The speed of the processor allows the CCD clocking sequences to be directly generated by the DSP under program control.

Program code and the CCD clock sequences are stored in the flash memory and loaded into the DSP on-chip memory during power up. There are two flash memories, each with two program images that are selectable by the DHU. A programmable logic device (EPLD) provides address decoding to memory map the sequence register, and analog-to-digital converter (ADC) peripherals, simplifying the software a great deal. Two external 256K x 16 SRAMs are available for storing the image data from the CCD. The external memory is not EDAC protected.

The control commands from the DHU to the DSP are sent over a bi-directional asynchronous serial link, using 8-bit words at 9600 bps. Commands are echoed back to the DHU. The image data is transferred on a synchronous serial link to the DHU. The transfer rate is up to 5 Mbps, with a word size of 16-bits. Image data is transferred to the DHU by DMA from the DSP memory.

On the signal board, clock drivers convert the logic level signals from the clock register to the voltage levels required by the CCD. The clock drivers use an analog switch with a complementary bipolar transistor buffer output stage to drive the capacitive loads presented by the CCD. The clock voltages and the CCD bias voltages are produced using a voltage reference, and resistive dividers followed by op-amp buffers.

Each signal processing channel features an input buffer for the signal from the CCD preamplifier (which arrives via shielded twisted pair), and a dual-slope integrator circuit to extract the CCD signal pixel by pixel. The A/D converter is a monolithic 16-bit chip, with a conversion time of 1.25 us, which is adequate for up to 500 kpixel/s readout rate (2us per pixel).

On the power board, external power is supplied from a 28 V DC power supply. On-board DC-DC converters provide +12V, -12V, +3.3V and +24V DC. Both the inputs and outputs of the DC--DC converters are filtered with LC networks and ferrite beads to suppress the switching noise and EMI as much as possible.

All analog circuits operate from the 12 volt supplies. The digital circuits operate in a mixed 5V/3.3V environment.

Housekeeping telemetry data from the CCD controller includes the CCD temperatures, and the power supply and reference voltages. These are collected by a low-power serial ADC serviced by the DSP.

Software Description

Development of the software uses the TASKING DSP C language cross-compiler and development tools (v3.0 or higher). The DSP code is written in a combination of C and assembly language to run on the DSP56309 processor in the FAI controller. The flight software for FAI has been adapted from existing software for the MOST science camera, and has a similar structure.

The code is built in three sections (1) a set of initialization routines, (2) an event loop that decodes the commands sent to the camera over the serial link, and (3) a set of subroutines to implement the decoded commands.

Instrument Operations

The default operating modes are given in Table 1 for each camera. Calculations of projected pixel size are shown for a satellite orbit apogee of 1500 km and perigee of 300 km. The assumed altitude of the aurora is 220 km for the 630 nm and 110 km for the near infrared emissions. A single pixel of size 26 by 26 microns limits the optical resolution of the camera and subtends an angle of about 0.1 degrees; this

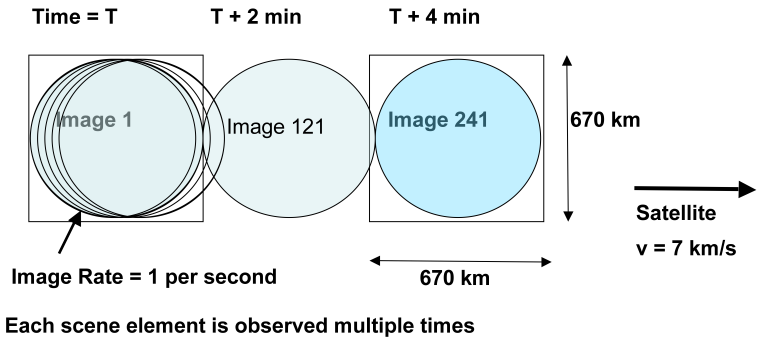


Figure 4. Spatial auroral coverage of SI camera

forms the basis for the given projected pixel size. Satellite motion during the exposure can of course degrade the spatial resolution. The effect is minimal when images are taken from apogee, even for a 0.5 second exposure in the case of the SV camera. For the occasional perigee viewing, the satellite can be made to slew at the appropriate rate to compensate for the satellite motion; otherwise significant smearing will occur. It is obvious from the table that the SI camera places the heaviest demand on the data handling operations because of the short exposure interval.

Observations with Default Operating Parameters

	SV(630 nm)	SI(NIR)
Pixel array	128 x 128	256 x 256
Projected pixel size	4.7 km	2.6 km (from apogee)
Projected pixel size	0.4 km	0.4 km (from perigee)
Exposure time	0.5 seconds	0.1 seconds
Exposure interval	30 seconds	1 second
Sensitivity (SNR>3)	200 rayleighs	100 rayleighs (557.7nm equiv.)

Table 1 Chosen default parameters for each camera to meet the science requirements

Shown in Figure 4 is the projected field of view from apogee of the SI camera. It is obvious that there is significant overlap between images that will allow the same location in the aurora to be observed many times (up to about 120 depending on the location) thus permitting a complete record of both spatial and temporal variations over a period of 2 minutes. This provides a promising new capability to investigate small-scale auroral dynamics.

The sensitivity of the cameras must be adequate to provide good images at sub-auroral, airglow intensity levels. Table 1 gives a calculated sensitivity for both cameras, based upon the default operating parameters and the instrument characteristics. The responsivity of a camera can be calculated from the irradiance per rayleigh:

$$Irradiance = \tau \times 10^{10} / (16 \times f - number^2) \text{ photons/(rayleigh•m}^2\text{•s)}$$

where τ is the overall optical transmission. The responsivity in units of electrons/rayleigh•second is then the irradiance multiplied by the quantum efficiency of the CCD and the pixel area. The responsivity is estimated to be 0.16 electrons/R.s for the SI camera and 0.13 electrons/R.s for the SV camera. Knowing this, the S/N can then be estimated for any exposure time and binning factor by including the expected dark current, read noise and background emission rate. The S/N for the SI camera as a function of auroral intensity is shown in Figure 5. The intensities are the actual values in the passband, but for reference to the 557.7 nm emission of atomic oxygen in aurora, these values should be divided by approximately 23 to give an equivalent 557.7 nm emission rate. The number 23 was derived for the SI camera by calculating the expected signal from the SI passband based on theoretical molecular band emissions and the quantum efficiency of the CCD as a function of wavelength. It is obvious from the figure that the noise component is dominated by the response to the near infrared airglow background.

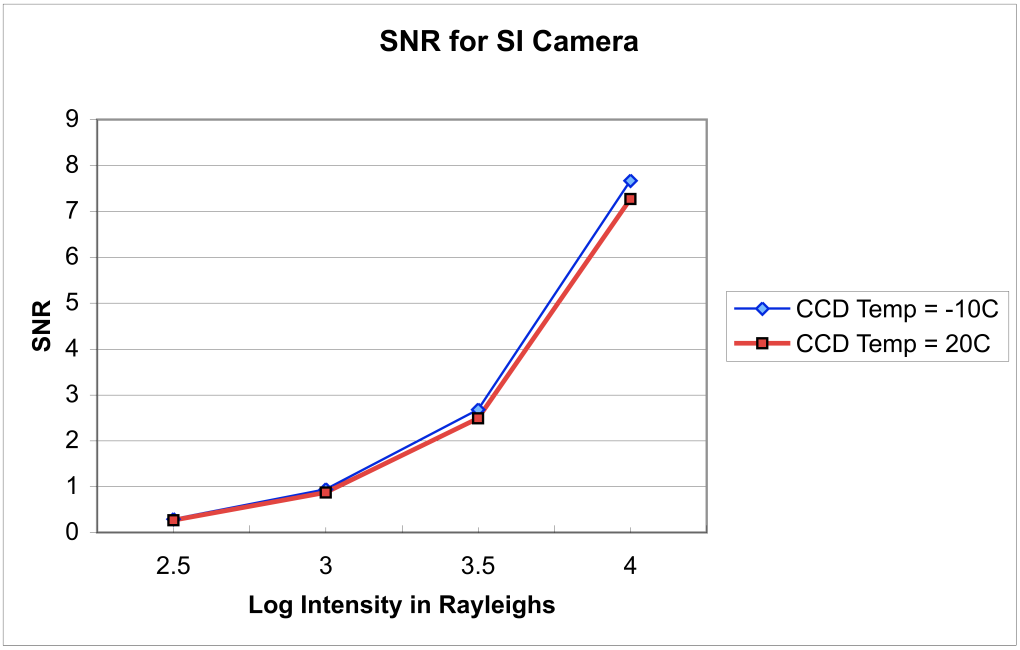


Figure 5 Signal-to-noise ratio for the default SI camera operating parameters

The S/N for the default operating parameters of the SV camera is shown as a function of the CCD temperature in Figure 6. It is clear that for this camera, the temperature of the CCD strongly affects the performance. These preliminary calculations will be replaced by values derived from the calibration and characterization of the cameras that will take place at the University of New Hampshire after the conclusion of the functional/performance tests at Routes AstroEngineering.

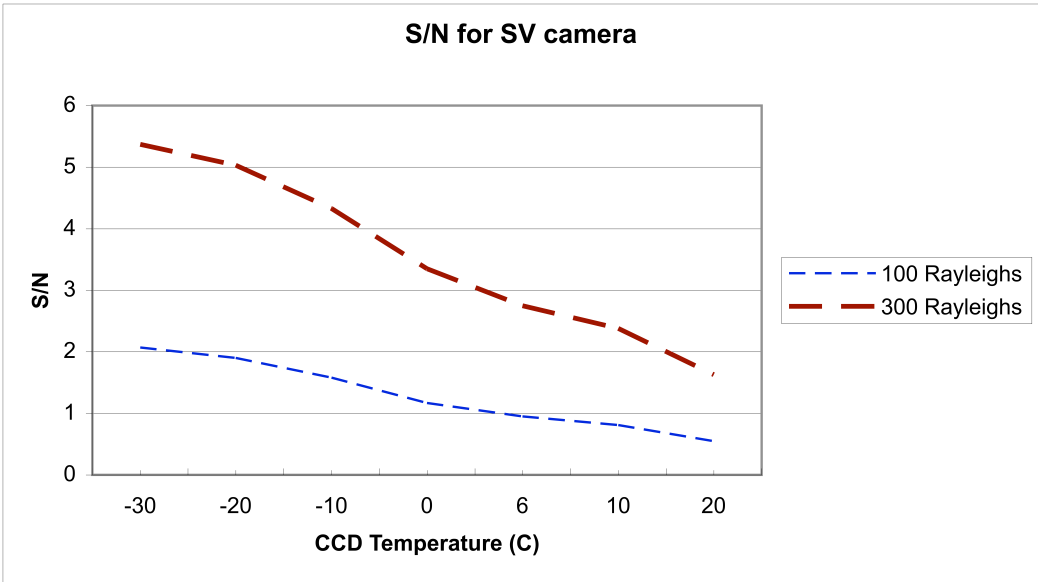


Figure 6 Signal-to-noise ratio for the SV camera as a function of CCD temperature

Science Planning

The satellite will have considerable ability to optimize the science return from the mission. An important feature is the attitude control system that has four modes that are of value to FAI. The default mode is nadir viewing in which images can be taken over a large latitude range during nighttime periods. At times there will be a need for the cameras to be pointed at a target fixed to the Earth such as an auroral observatory or rocket range, for example. The third mode is limb viewing when altitude profiles are of interest. The fourth mode is inertial pointing at a star field that will be used to check camera coalignment, field of view and focus. A summary of the science targets and the operational modes is given in Table 2. The FAI will have many applications to a variety of auroral and airglow phenomena. In the polar cap there will be transpolar arcs and enhanced airglow patches that drift from the dayside to the nightside over the polar region. The open/closed magnetic field boundary is identifiable by means of images at 630 nm. In the main auroral oval there will be multiple arcs and black aurora that are not understood. These are in addition to various dynamic substorm phenomena including the definition and observation of the onset. At lower latitudes there exist detached arcs that appear to be a signature of

FAI Science Targets

Viewing Mode	Polar Cap	Auroral Oval	Mid/Low Lat.
Nadir	Polar arcs Polar patches Polar airglow	Substorms Vortices Multiple arcs	Detached arcs SAR arcs
Limb	Emission Altitude Profile		
Earth Target	Aurora and airglow above stations		Airglow above stations
Inertial	Reference star field		

Table 2 FAI science targets and attitude modes

electrons enter the magnetosphere on the dayside and drift around the Earth towards the evening sector. In addition, there are stable red arcs that have been viewed mostly from ground stations but not from space. Finally, there exists the opportunity to observe and study 630 nm airglow in the equatorial region where it is enhanced due to the Appleton anomaly.

It is planned to produce public summary data at the science operations centre at the University of Calgary.

Summary

The FAI instrument will provide Canadian scientists with an opportunity to advance our understanding of auroral phenomena significantly because of the underlying advances in technology. In addition, it will provide essential context images for the other seven experiments on the e-POP satellite. What remains in the development of the instrument is assembly, testing and integration that are scheduled to take place during the next year. Launch is planned for late 2007 into an orbit of inclination 80 degrees, apogee of 1500 km and perigee of 325 km. With the initial apogee over Canada, observations during the first winter solstice period is a high priority.

Acknowledgments

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Global auroral imaging in the ILWS era

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Abstract

The overarching objective of the ILWS Geospace program is to facilitate system level science. This demands synoptic observations such as global auroral imaging. At present, there is no funded mission during ILWS that incorporates a global auroral imager. The imaging community needs to move now to address this important gap. While doing so, it is interesting to take stock of global auroral observations that have not been achieved, or that have been achieved only to a limited extent. These include simultaneous imaging across all relevant scales, spectral resolution of sufficient quality to allow for global maps of characteristic energy and energy flux of precipitating electrons, continuous global auroral imaging for time periods spanning long-duration geomagnetic events, systematic interhemispheric conjugate observations, auroral observations magnetically conjugate to *in situ* measurements, and automatic classification of auroral images. These observations can be achieved within the next decade. If they are, then they will facilitate exciting new science.
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Keywords: Global auroral imaging; Geospace; ILWS; System level science

1. Introduction

A planetary magnetic field carves a comet-shaped cavity out of the solar wind called a magnetosphere. The otherwise dipolar magnetic field is compressed on the dayside and stretched to great distances on the nightside. This topology is supported by large scale electric currents flowing on the surface of and throughout the system. The interaction of the solar wind and the magnetosphere provides the power for this current system, as well as the convection of magnetospheric plasma. These currents and the magnetospheric convection, like the solar wind that drives them, are constantly varying. Some of the electromagnetic and

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particle energy that has been fed into the magnetosphere finds its way to various sinks that include the radiation belts, plasmasphere, ionosphere, and thermosphere.

Numerous plasma processes mediate energy and mass transfer from the solar wind to the magnetosphere, and subsequent transport through the system and deposition in the sinks. These include magnetic reconnection, plasma waves, wave-particle interactions, magnetohydrodynamic (MHD) instabilities, and parallel electric fields. Understanding these geospace processes is important because they are of obvious significance: the Sun–Earth system is the only astrophysical object in which magnetic reconnection and its consequences can be directly observed. These consequences have societal and economic impact: magnetic storms and MHD waves, for example, enhance radiation belt fluxes of charged particles that pose a danger to satellites and astronauts, magnetic storms have knocked out power grids, and there are potential links between geospace phenomena and climate.

Previous satellite and ground-based missions have mapped out the overall magnetospheric topology, and identified interesting plasma physical processes. We are now moving into what can reasonably be called the quantitative era of geospace science. The objectives are to go beyond phenomenology, and now quantify effects of key geospace processes and develop predictive capabilities that both test our understanding against observation, and bring this developing knowledge to real world applications. The International Living With a Star (ILWS) satellite and ground-based observational programs will be designed to complement each other and facilitate quantitative global studies. Key players in ILWS must build on their historical strengths, and undertake bold new initiatives. The end result will represent a true leap forward in terms of physical understanding and benefit to society. One of the overarching themes of ILWS is to develop the capacity to study geospace as a complex coupled system (Table 1).

The schematic diagram in Fig. 1 illustrates our view of geospace as a complex coupled system. All the energy and much of the mass that populates geospace comes from the Sun, represented by the box on the left (i.e., sources). Ultimately, energy and mass end up in a number of sinks listed in the box on the right. Physical processes affect how energy and mass are transported from the source to the sinks. These operate in geospace, and are numerous (we have listed just a few at the center of the diagram). Many of these processes are understood only empirically, and some are understood only through simulation and theory. As well, we do not know right now which of these processes are dominant in terms of global mass and energy budget. In other words, while some of these processes occur in the system, it may be that if they were excised, there would not be any measurable effect on the global dynamic. For example, Kelvin–Helmholtz and other surface waves certainly exist on the magnetopause, but if the boundary was somehow changed so that it could not support their existence, would the ULF wave power distribution in the magnetosphere be measurably different?

Table 1
Brief summary of operating parameters of previous global auroral imaging experiments

Platform (Instrument)	Year of launch	Orbit	Wavelengths	Exp. time	Frame rate	Spatial resolution
ISIS 2	1971	1400 km	557.7 nm, 391.4 nm	15 min	2 h	10 km
ISIS 2 (redline)	1971	1400 km	630 nm	15 min	2 h	70 km
DMSP	1971	830 km	400–1100 nm	15 min	1.5 h	0.5,2.7 km
KYOKKO	1976	650–4000 km	120–140 nm	12 s	2 min	4–21 km
DE-1	1981	675–25,000 km	12 narrow bands from 130 to 630 nm	12 min	12 min	24–130 km
HILAT	1983	830 km	115–200 nm with 2 nm resolution	25 min	100 min	20×4 km
Viking	1986	800–13,500 km	125–160, 135–190 nm	1 s	20 s	14–20 km (1×1), 27–40 km (2×2)
Polar bear	1986	800 km	115–200 nm with 2 nm resolution	25 min	100 min	
AKEBONO	1989	300–8000 km	115–150 nm & 557.7	1 s	8 s	1 km
Freja	1992	650–1700 km	125–180 nm	0.4 s	6 s	5 km (2×2)
Interball	1996	475–20,000 km	125–160 nm	6.5 s	120 s	27 km (1×1), 55 km (2×2)
Polar (VIS)	1996	5100–51,000 km	732.0, 656.3, 630.0, 589.0, 557.7, 391.4, 308.5 nm	12 s	12 s	20×4 km
Polar (VIS Earth Camera)	1996	5100–51,000 km	125–150 nm	12 s	12 s	80 km
Polar (UVI)	1996	5100–51,000 km	128–133, 132–139, 140–158, and 166–174 nm	37 s	37 s	40 km
IMAGE (WIC)	2000	1000–44,500 km	140–190 nm	10 s	120 s	100 km
IMAGE (SI-12)	2000	1000–44,500 km	121.8 nm	5 s	120 s	100 km
IMAGE (SI-13)	2000	1000–44,500 km	121.6, 135.6 nm	5 s	120 s	100 km

Note that we have simplified the information in some cases for clarity. The table is ordered chronologically, from top to bottom. Polar and IMAGE are both still in orbit, and the imagers are still operating.

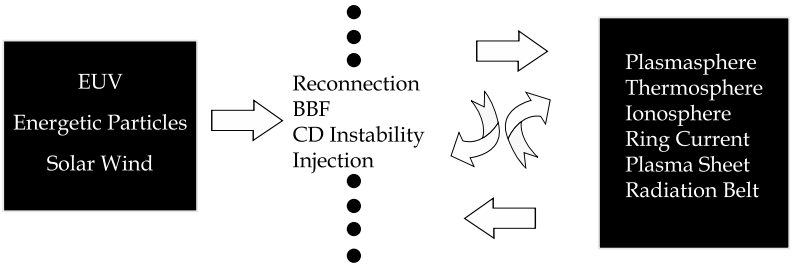


Fig. 1. Energy and mass enters geospace from the Sun and the solar wind. Various physical processes affect mass and energy transport through geospace, and how it is ultimately divided up and deposited in various sinks. Moreover, these geospace physical processes interact with each other, as do the sinks. The ILWS geospace program seeks to identify energy and mass pathways that are important, to quantify their effects, and understand the underlying physics at work.

Would the radiation belt evolution be different? Would the MI coupling be different? Moreover, these processes interact, and there is interaction between the sinks. So it is not as simple as source, process, and sink. Geospace is a complex coupled system that is a more than a passive recipient of solar energy – it is an active participant and source of much of the dynamics that are observed.

This "systems level approach" to geospace science is the natural next step in the evolution of our field. Key missions under the ILWS banner will target physical process such as reconnection (i.e., Magnetospheric Multiscale), wave-particle interactions (i.e., the LWS Radiation Belt Storm Probes and ORBITALS), ionospheric–thermospheric variability (LWS Ionosphere Thermosphere Storm Probes), or Alfvénic acceleration (i.e., Geospace Electrodynamic Connections and Swarm), with the objective of physics-based understanding. At the same time, greatly enhanced and ever more integrated global networks of ground-based instruments, and contemporaneous global imaging of the ring current, plasmasphere, aurora, and even the CPS (see e.g., Ergun et al., 2000) will provide the quantitative observations of the source and sinks necessary for complete specification of the geospace system.

The upcoming NASA Time History of Events and Macroscale Interactions During Substorms (THEMIS) mission is a microcosm of this systems level approach. THEMIS will involve five satellites in a constellation on the nightside magnetosphere, arranged to provide observations of current disruption, mid-tail reconnection, and communication between those two processes via bursty bulk flows and rarefaction waves. THEMIS also includes a ground-based network of all-sky imagers and fluxgate magnetometers which will specify the azimuthal evolution of the substorm disturbance via its effect on the aurora and ionosphere (Frey et al., 2004; Donovan et al., 2006). This combination of targeted *in situ* and coordinated ground-based observations is necessary to close the question of what causes substorm expansive phase onset.

Although it has not always been so strategically targeted as it is in the case of THEMIS, the idea of monitoring the global spatio-temporal evolution of geospace via its impact on the above-mentioned sinks has been the driver behind SuperDARN (Greenwald et al., 1995, MIRACLE Syrjäsuo et al., 1998), Canadian Geospace Monitoring (see cgsm.ca), and global imaging of the aurora, ring current, and plasmasphere (Williams et al., 1992). It is the motivation for current activities designed to create virtual observatory networks of magnetometers, riometers, and all-sky imagers that span the globe. This includes the planned United States Distributed Arrays of Small Instruments (DASI) initiative, which if it goes forward will involve the deployment of a worldwide array of ground-based geospace instrumentation, with the stated objective being to facilitate system level science (Foster, 2004). It was certainly the motivation for the Geospace component of the proposed Chinese KuaFu satellite program (Tu et al., 2005).

ILWS must promote space missions and ground-based observations that target the solar energy and mass sources, that explore the physics of and interrelationship between geospace processes that affect energy and mass transfer, and finally that provide quantitative synoptic observations of every mass and energy sink in the Geospace system. This is a grand challenge, by any means. It is also, however, the logical next step in the over forty year exploration of geospace. Furthermore, it is fitting of an international effort that draws on the collective experiences of the last 40 years and more.

Our objective is to present a high-level view of what we might do, as an international community, in future global auroral imaging projects, particularly within the framework of ILWS. In order to do this, we start with a brief review of the technical accomplishments of the imaging community, woven together with a very brief review of how those technical accomplishments have facilitated ground-breaking science. We then review observations that have either not been carried out, or have been carried out to only a limited extent. Examples include long-term continuous (i.e., "24X7") global auroral imaging, simultaneous imaging across all relevant spatial scales, and systematic interhemispheric imaging. If we were to carry out these new observations, then we would facilitate exciting new science. Within the constraints of our space limitations, we outline the new science that these new observations would facilitate.

2. A brief history of global auroral imaging

Global auroral imaging began in the early 1970s with the Auroral Scanning Photometer (ASP) on ISIS2 satellite (launched April 1, 1971). ASP used the satellite spin and its orbital motion to provide the very first global auroral images (obtained in both 557.7 and 391.4 nm once per orbit). The ISIS2 system was operated for almost 10 years and yielded a number of discoveries, including the diffuse auroral oval (Lui et al., 1975).

Since ISIS2, global auroral imaging has evolved significantly. Imagers on Kyokko, Dynamics Explorer (DE), HILAT, and Polar Bear operated in the UV, allowing for the first time imaging of the aurora on the dayside. Global imagers on DE and Viking allowed more than one image per pass, with the Viking UV instrument providing an impressive cadence of one image every 20 s. In fact, the Viking UV imager utilized a novel combination of filters, reflective coatings, and UV-sensitive photocathodes to obtain short-exposure (1.2 s) simultaneous global UV images on two 256 by 256 pixel CCDs in two passbands: 135–190 nm, responding mainly to Lyman–Birge–Hopfield (LBH) N2, and 125–160 nm, responding mainly to the 130.4 nm OI line. The Viking imager was the first instrument that simultaneously exposed the entire image, hence obtaining the first-ever true global images of auroral activity. Viking provided an exciting new picture of the global time-evolving auroral distribution and new insights into the substorm dynamic (Henderson et al., 1998). Images from the two filters could be used to estimate energy deposition and the mean electron energy, although resonant scattering and a requirement of knowing the O/N2 ratio seriously limited the accuracy of these derived quantities.

The next significant leap forward in global imaging came with the ISTP Polar satellite, which carried three imaging packages: the Visible Imaging System (VIS), the Ultraviolet Imager (UVI) and the Polar Ionospheric X-ray Imaging Experiment (PIXIE). The VIS was designed to achieve high time and spatial resolution images of the nighttime polar and auroral emissions at visible wavelengths (Frank et al., 1995). The package consisted of three low-light-level cameras: two auroral cameras which viewed the aurora at visible wavelengths in narrow passbands as selected by a filter wheel, and one ancillary camera equipped with broad-band filters for FUV wavelengths in the range 124–149 nm. The two visible-light cameras had a spatial resolution of 10 and 20 km, respectively, from a spacecraft altitude of 8 RE. The FUV camera included in the VIS package was used as an Earth-monitoring camera used for verifying the proper pointing of the two-axis targeting mirror of the two primary visible-wavelength auroral cameras. The VIS FUV imager provided full images of the Earth from radial distances of 6 RE and had a spatial resolution of no more than 100 km.

The Polar UVI provides sequential spectrally resolved images in the far ultraviolet of the entire auroral oval for roughly half of the 18 h Polar orbit (Torr et al., 1995). Polar UVI has been widely used in studies of global magnetospheric dynamics (Sergeev et al., 1999). The innovative all-dielectric UV filters developed for UVI enabled the first qualitative estimates of large scale auroral energetics (Lummerzheim et al., 1997). The nominal UVI spatial resolution is 50 km at apogee, with an integration time of 30 s and sensitivity of 50 R. This sensitivity is still the best ever achieved with a global imager. From 1996 to 2002 the X-ray imager on Polar (PIXIE) provided global X-ray images of the auroral region, the first to do so (Imhof et al., 1995). PIXIE is a multiple-pinhole X-ray 'camera' designed to obtain images in 128 X-ray energy intervals in the range between 2 and 60 keV. The spatial resolution of the images is about 50–1100 km at apogee and 50–250 km at perigee. Integration times for an image depend on the source brightness but typically range from 1 to 30 min.

In 2000, NASA launched the IMAGE satellite. This was the first space science satellite with an instrument complement entirely devoted to remote sensing via optical and radio means. IMAGE carried with it a global imaging Far Ultraviolet (FUV) package consisting of three instruments. One of the FUV instruments onboard IMAGE is the Spectrographic Imager, one channel of which (the SI-12 channel) provides global proton auroral images every 2 min, which is the satellite spin period (Mende et al., 2000). IMAGE thus provides the first global picture of the proton aurora and thus certainly the first simultaneous

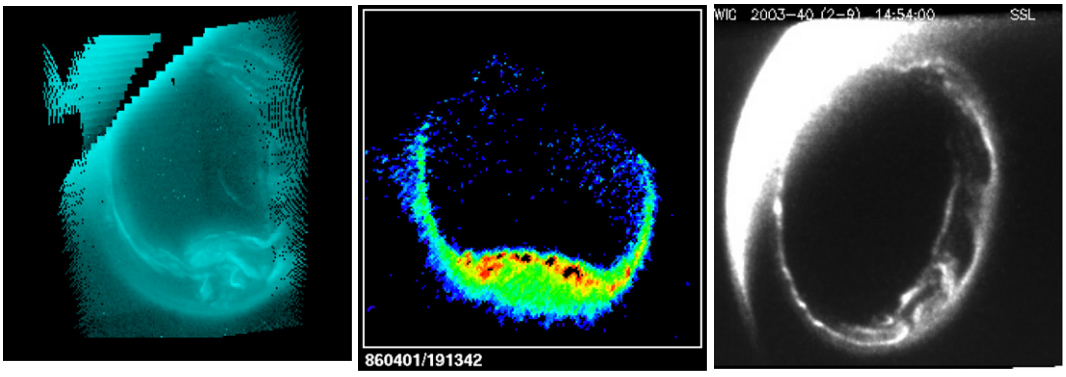


Fig. 2. Images from three satellite-borne imagers. From left to right: ISIS 2; Viking; IMAGE-WIC.

global images of the electron and proton aurora. Global auroral images from three generations of imagers are shown in Fig. 2.

3. Technical objectives for global auroral imaging in ILWS

By the time IMAGE was flown, there had been great advances, and great achievements, in global auroral imaging. Still, after 35 years of global imaging from space, there is a surprising list of technical challenges that have either not been met, or have been done to a degree that could be improved upon. Surpassing previous accomplishments, or striking out in new ways would facilitate new science. This must be the primary motivation in developing future missions. Within the context of ILWS, this should be *system level science*, as discussed above. Before we discuss the science that global imaging missions would attack during ILWS, we first outline significant measurements that have either not been achieved, or have been achieved only in part. In each case we also point out, in broad-brush terms, what will be necessary to achieve these objectives.

Simultaneous imaging across all relevant spatial scales: Spatial resolution of global images has to date been limited to no better than 50 km. As well, it is only in recent years that ground-based arrays of all-sky imagers (ASIs) are capable of providing continent-scale images with ~km resolution. Imagers with resolution significantly better than 1 km (Trondsen and Cogger, 1997; Trondsen et al., 26) have not been operated with larger-scale imagers (i.e., with spatial coverage larger than that of one ASI). Consequently, there has never been a systematic program for simultaneous auroral imaging across all important spatial scales (i.e., from global down to tens of meters). All relevant spatial scales can be observed with existing technologies (see

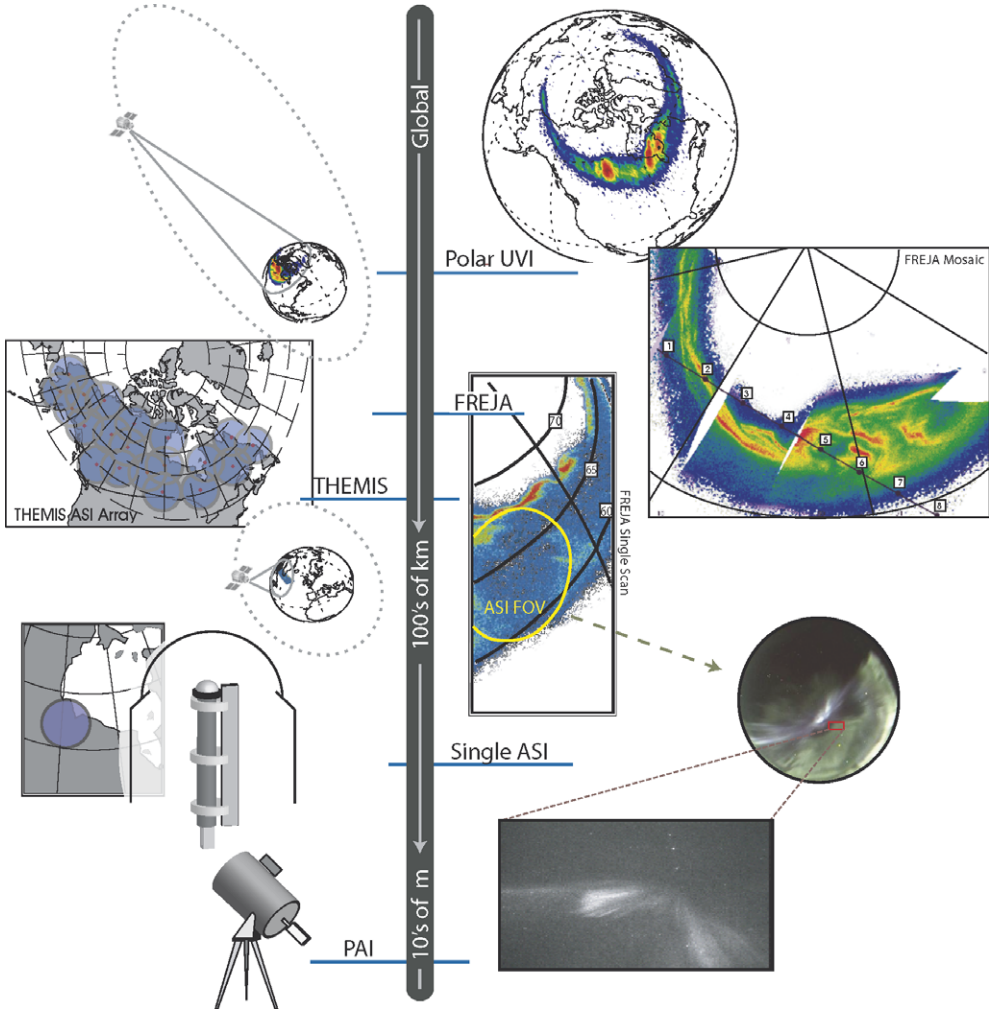


Fig. 3. The scales across which auroral observations are necessary range from tens of meters up to global. Different optical instruments provide observations in different and overlapping parts of the auroral scale size spectrum. Imagers on high altitude satellites such as Polar provide global observations. Imagers on lower altitude satellites such as Freja and ground-based networks such as MIRACLE, the THEMIS ASI-array, and NORSTAR provide mesoscale (continent-scale) observations. Individual ASIs operate with fields of view that span hundreds of km and auroral features such as vortices. Telescopes, such as the Portable Auroral Imager Trondsen and Cogger, 1997; Trondsen et al., 26 provide us with a view down to tens of meters. Simultaneous imaging across these scales has not been achieved. Due to enhancements in the capabilities of ground-based instruments and arrays, and provided that global images are available in the future, simultaneous imaging across these scales will be achieved.

Fig. 3). Provided that global observations are available in the future, simultaneous imaging across all relevant scales will be a reality. There is an important caveat, however, in that kilometer scale resolution images will be available for only a part of the global auroral distribution, and even higher resolution images for even smaller regions. This scenario will provide a complete picture of the cross-scale distribution only if fine scale structure is not globally organized. While this is a logical assumption, it has not been proven.

Spectral resolution of sufficient quality to allow for global maps of characteristic energy and total energy flux of incoming electrons: The most direct way of deriving the auroral energetics is to compare large scale images in two spectral regions of the far-ultraviolet LBH band-system; 140–160 nm (''LBH short'' or ''LBH 1'') where O2 absorption at auroral altitudes is significant and 160–190 (''LBH long'' or ''LBH 2'') where the emissions are relatively free of absorption (Strickland et al., 1983; Germany et al., 1994a; Germany et al., 1994b; Germany et al., 1990). While there are difficulties with this approach due to factors such as O2 upwelling and other factors that obfuscate atmospheric composition, it is the best technique available. Previous global auroral imaging experiments have obtained nearly simultaneous images from different parts of the electron auroral spectrum (i.e., see Polar UVI above and studies utilizing Polar-PIXIE data (Imhof et al., 1995; Anderson et al., 2000)). The UV data, however, has not yet met the technical requirements necessary to quantify the spatial dynamics of the average energy and total energy flux of precipitating particles on a global scale (these are 5 km/10 s spatial/temporal resolution, 10 counts/kR/s sensitivity, and 10^{10} out-of-band spectral rejection), and as such, time evolving maps of the global distribution of both characteristic energy and total energy flux have not been obtained. Instrument development programs are currently underway in several institutions to achieve the technical requirements stated here. Strategies that are being explored include the use of newly developed materials for reflective coatings and filters for better out of bandpass rejection.

Long-duration continuous global auroral imaging: Previous global imaging experiments have been flown on single satellite missions, and hence have provided continuous imaging (at whatever cadence the imager is working at) for only a fraction of the satellite orbit. The UV imagers on Polar, for example, provide continuous complete hemispheric auroral coverage for less than half of Polar's 18 h orbit. As a consequence, there are no unbroken sequences of images that span the relatively long time-scale geospace processes such as magnetic storms. Continuous global auroral imaging of one hemisphere can be obtained with two satellites on elliptical polar orbits, relatively phased on those orbits so that when one satellite is at apogee the other is at perigee (see the discussion of ''KuaFu-B'' in Tu et al., 2005). As is pointed out in Tu et al. (2005), it is straightforward to generate several years or more of continuous imaging with such an orbital configuration (i.e., this is subject to precession of the line of apsides).

Simultaneous global imaging of both hemispheres: The northern and southern hemisphere auroral ovals have been simultaneously imaged during serendipitous events when two UV imaging satellites had a clear view of the two hemispheres (see, eg., Craven et al., 2001; Østgaard et al., 2004; Stubbs et al., 2005), or when one satellite had an oblique view of the two hemispheres (see e.g., NASA EPO material on Polar and DE-1 observations of conjugate aurora, http://www.gsfc.nasa.gov/topstory/20011025aurora.html). To date, there has never been a systematic program for interhemispheric conjugate auroral observation on the global scale. As in the case of continuous global auroral observations, interhemispheric conjugate observations can be achieved with well-planned orbital configurations in multi-satellite missions. In a KuaFu-B type scenario, in which two satellites are used to provide continuous global observations in one hemisphere, a ''perigee-imager'' on the satellites would provide some conjugate observations during every orbit of both satellites. As the continuous imaging can only be achieved with two satellites if they are on highly elliptical orbits (see Tu et al., 2005), the perigee imager would have to have a wide field of view. A design for an imager with a wide field of view (based on microchannel plate properties) which could be flown on a low earth orbiting spacecraft has recently been developed (Hamilton et al., 2005), utilizing a proposal for an all sky X-ray camera (Fraser et al., 2002).

Simultaneous in situ particle and field and conjugate auroral observations: Serendipitous topside ionospheric satellite overflights of aurora observed by ground and/or satellite borne imagers, as well as targeted campaigns (Germany et al., 1997; Stenbaek-Nielsen et al., 1998; Frey et al., 2001) have provided some excellent data sets for studying the precipitation and fields that are the direct cause of auroral features. As in the case of interhemispheric conjugacy, there has not been a systematic program designed to build up a large data set of *in situ* and magnetically conjugate high time and space resolution observations. This could be achieved systematically with a specialized imager, operated on a Fast Auroral SnapshoT (FAST) type satellite, and dedicated to observing the auroral distribution at the magnetic footpoint of the satellite. The imager would have to provide multispectral observations of small dynamic phenomena with high spatial and temporal resolution over 10 s of seconds. For practical reasons, at least two spacecraft would be required in order to separate time and space dimensions of the *in situ* measurements. This is difficult and resource intensive. Fast spinning spacecraft, ideal for *in situ* measurements, will not accommodate the observational time for imaging unless a fast despun component is developed. Three-axis stabilized spacecraft, ideal for remote sensing, will not meet the *in situ* field requirements unless several duplicate plasma instruments are used.

Machine vision: Automatic processing of auroral images is in its infancy. At present, global auroral images can be

analyzed with automated tools to identify boundaries, integrated brightness and other straightforward geophysical parameters. More complicated analysis, such as determining the stage of substorm and the kind of auroral features in various parts of the image are done manually. Recent work has demonstrated that machine vision techniques are capable of automatic classification of auroral type in All-Sky Images (Syrjäsuo and Donovan, 2004), but success to date has been limited to classifying an entire image as "arc", or "patch", or other clear auroral form. Classifying more complicated images in which there are multiple types of aurora has yet to be accomplished. This would be a necessary step towards classifying the global distribution of *type* in global auroral images. The ultimate goal is to quantify auroral type, such as discrete, diffuse, omega bands, etc., in a way that can be automated.

It is not at all unreasonable that all of the above technical objectives could be met within the next decade. Over and above meeting these one by one, there will be synergy between missions that are carried out at the same time. There are in general several geospace missions and the world-wide array of ground instrumentation operating simultaneously. This was the essence of ISTP, and will be an objective in ILWS. With synergy between missions and ground-based observations it is possible to carry out new science with instruments that have been flown before, but not previously in a given combination. Synergy is not a new tool in space physics, but it can and will be improved upon.

4. Science objectives

Of late, Universal Processes have entered the lexicon of our science. Indeed, space plasma physics inquiries have both fundamental significance to science and a unique vantage to probe the universal processes embedded in the Sun–Earth System. Nonlinearity is a universal process that permeats, to wit, the Universe. Aurora is nearly as universal, observed in all magnetized planets in the solar system that have an atmosphere. Global imaging is that crucial link which connects the fundamental science we want to understand (nonlinearity) and Nature's gift to us to achieve this understanding – the multiscale dynamics of aurora; no other naturally occurring phenomenon is so within our experimental reach, yet so strenuously challenges our theoretical thinking. When we say geospace science has entered into the quantitative era, in the context of auroral physics, we mean a change of our mentality and approach.

To date, much of auroral imaging is an auxiliary to the substorm study, particularly that of the expansive phase. While there is great scientific value in this emphasis, there are additional pay-offs, if we allow ourselves to ask the question: "what else?" In other words, the evolution of aurora, and other global signatures of magnetospheric dynamics, contain a rich store of information on nonlinear physics which has not been fully exploited. In order to make progress, we need to make sustained (in time) and multiscale (in space) measurements of aurora, rest assured that the auroral process has an intrinsic, if very complicated, order and pattern that points to new knowledge to be gained. The ideal would be "hyperspectral", time-continuous, high time resolution, high space resolution, global imaging. While we are presently far from that ideal, it is within our grasp in the next decade to carry out fundamentally new observations that would achieve the technical firsts discussed in the previous section. So rather than hypespectral, we should start with better spectral information. Rather than high spatial resolution on a global scale, we can start with global imagers operating in consort with continent-scale ASI arrays and local very high resolution observations, and so on. In other words, we should embark on a program that achieves the observational objectives laid out in the previous section.

Perhaps the most fundamental science would be achieved by simultaneous imaging across all relevant scales. The fact that complex systems give rise to repeatable structures in space and time is becoming increasingly clear. Understanding how energy cascades across scales, and the mechanisms that give rise to these structures is a goal that certainly transcends space physics, or even physics.

Spectral resolution of the LBH short and long wavelength bands will allow for time evolving maps of the energy deposition and characteristic energy. There are two main sources of the electron aurora, the first being the magnetospheric plasma sheet. The electric fields generated by the large-scale convection of magnetospheric plasma create currents that close through field aligned currents. These currents cannot be supported by the conductivity of the plasma at the ionosphere/magnetosphere boundary and electric potentials develop that accelerate the particles and can divert portions of the plasmasheet population into the loss cone producing the so called inverted-V electron energy distribution that is often observed in satellite transits of the auroral oval. The second source is due to the interaction of the cold electrons in the outer ionosphere, within several Re of the earth, with Alfvén waves propagating along Earth's magnetic field. This interaction leads to downward acceleration and precipitation of very high fluxes of low energy beam-like electrons. The Alfvén waves are indicative of reconfigurations of magnetic lines of force in the magnetotail that occur during all types of reconnection events including substorms.

Plasmasheet electrons accelerated into the loss cone by inverted-V potential patterns are almost all above 1 keV of energy, while the mean energy in Alfvén wave driven aurorae is often no more than 1 keV. Multi-spectral space-based auroral imaging offers the capability of determining the mean energy of precipitating electrons. Imagers that can discriminate simultaneously between these two energy ranges and types of aurorae can do much to identify the magnetospheric source of the precipitation. Though several imaging missions to date have had some capability for these types of analyses, none have been launched that have all of the requirements: 10 km or better spatial resolution,

simultaneous imaging of spectrally separable emission, such as the N2 LBH emissions at long and short wavelengths (a nomenclature adopted by POLAR-UVI), and global imaging field of view. A properly instrumented platform could remotely identify the source regions of aurora and effectively track reconfigurations events of the magnetic field that occur during reconnection events as they occurs in the magnetotail or on the dayside magnetospause.

From the spectrally resolved FUV emissions, we can obtain a good approximation of the ion and electron energy deposition, and hence the effects of precipitation on ionospheric conductivity. By using forward modeling, we can estimate the ionization rates from the ion and electron particle precipitation, and estimate the 3D ionospheric density and composition. Because of the complexity of the feedback between the composition and the energy deposition, this is a difficult process, and requires modeling of the coupled thermosphere and ionosphere. Even with the difficulties involved, imaging with appropriate spectral resolution is the best hope for determining the large-scale particle input into the atmosphere.

The SuperDARN radars measure the doppler shift of electromagnetic waves scattering from ionospheric irregularities. This is the best technique for inferring the global distribution of ionospheric electric field, although it is at times limited by absorption or lack of irregularities. Ground-based magnetometer measurements can be used to estimate the distribution of ionospheric current. Combining the current with the conductance pattern determined in part from global auroral observations as described in the previous paragraph, an electric field can be estimated, thus providing an important complement to SuperDARN convection observations.

By determining the state of the ionospheric electric field and particle precipitation, one can start modeling the thermospheric and ionospheric dynamics with much more accuracy. The electric field and particle precipitation are of primary importance when considering the temperature structure, composition, winds, and energy balance in the thermosphere. In addition, the magnetosphere is in part controlled by the ionosphere, so specifying the conditions in this region would allow a more accurate representation of the global magnetosphere.

Sofko et al. (1995) showed that the upward field-aligned current (FAC) in the ionosphere can be written as:

$$J_{\parallel} = \sum_{\mathrm{P}} \vec{B} \cdot \left(\nabla \times \vec{V}\right) - \vec{E} \cdot \nabla \sum_{\mathrm{P}} - \left(\hat{b} \times \vec{E}\right) \cdot \nabla \sum\nolimits_{\mathrm{H}}$$

where $\sum_{\mathrm{P}}$ and $\sum_{\mathrm{H}}$ are the height integrated Pederson and Hall conductivities, respectively. Based on the above equation, it is obvious that, if the conductivities and the conductivity gradients can be determined, then the complete solution to the FAC distribution can be computed. The complementarity of the SuperDARN radars and optical instruments is obvious – provided there are adequate irregularities for obtaining good radar echoes, and that global images with adequate spectral resolution in the FUV spectral band are available, the combined radar and global auroral images will provide us with the ability to specify the global distribution of upward FAC.

FUV electron auroral observations, in combination with global proton auroral images from an auroral imaging spectrograph such as the one carried on the IMAGE satellite (see above), allow us to determine the ionospheric projection of the earthward edge of the ion and electron plasma sheets. Particularly at the inner edge of the plasma sheet, there is an interesting and not fully understood relationship between convection, flux tube energy content, precipitation, and the cross-tail, ring and Region II field-aligned currents. This is particularly interesting during extreme geomagnetic events such as storms, which have durations of several days or more. During these events, auroral activity moves equatorwards to even mid-latitudes, and the CPS moves inwards across the outer radiation belts, providing a seed population for the ring current, while at the same time plasmaspheric material is drawn outwards into the trough and inner CPS. With continuous global auroral imaging we will be able to image such long-duration geomagnetic events for the first time. We will be able to explore how the CPS acts as a seed population for the inner magnetosphere, and in particular the ring current, quantify the impact of solar forcing and magnetic storms to the neutral atmosphere, and address the storm–substorm relationship.

Aside from the simple fact that the northern and southern auroral ovals are ever-present features of the terrestrial environment, and that discrete auroral forms are sometimes conjugate and sometimes not, surprisingly little is known in relation to auroral conjugacy. We certainly expect the proton aurora and diffuse electron aurora to be essentially magnetically conjugate phenomena, although a systematic demonstration that this is in fact true would certainly be helpful. It would be more interesting, however, to explore how differences in the discrete aurora might reflect significant and temporally varying field-aligned electric potentials. Along the same lines, there is some evidence that substorms are more prevalent around equinox than around solstice, a possible indication that the substorm onset can be affected by the difference between the conductivity in the two hemispheres. A systematic program to build up a data base of conjugate auroral observations would obviously be of tremendous scientific value. It would also be a powerful complement to high time and space resolution auroral observations at the magnetic footpoint of a FAST-type satellite. The *in situ* auroral conjugate observations would allow us to explore the auroral electrodynamics on a fundamentally new level. They would facilitate exploration of how spatial structure of electromagnetic fields in the topside ionosphere is related to structure in the aurora, and the mechanism(s) by which auroral electrons are accelerated.

The auroral observations described in this paper would provide an excellent basis for testing global magnetospheric models, and in particular their ability to quantitatively

reproduce longer duration geomagnetic events such as storms, given adequate specification of the solar wind conditions. This in turn would allow us to critique our understanding of the physics of geospace, at least the physics that is represented in the models. It is commonly held that methods for automatic classification of images (i.e., machine vision) are being developed to facilitate automatic processing of large image data bases. In fact, the primary motivation is to *quantify auroral type* in a way that can be compared with model outputs or used as an input to models. This would allow another important quality of the aurora – namely its type which is in general different in different regions – to be used quantitatively rather than qualitatively. It is only a matter of time before such algorithms are capable of providing this information on a routine basis.

Finally, global auroral imaging is a powerful complement to all other geospace missions that may be mounted during ILWS. The ESA Swarm mission is just one example. Swarm will consist of three satellites in low altitude orbits, carrying out high precision electric and magnetic field observations. The primary mission objective is to explore the internal field of the Earth, which requires the higher quality observations of the external electric and magnetic fields than have been obtained to date (*their noise is our signal*!). Swarm electric and magnetic field observations will provide us with detailed field-aligned current, transverse ionospheric current, and Poynting flux measurements obtained to date, and builds on the successful heritage of the Ørsted and CHAMP satellite missions (see e.g., Neubert and Christiansen, 2003; Moretto et al., 2002). Global auroral observations, in conjunction with Swarm electric and magnetic field measurements, would advance our understanding of the relationship between the global FAC distribution and the aurora (testing, for example, FACs derived from SuperDARN inferred convection and auroral observation inferred conductivity as discussed above), and the role of Poynting flux in the overall deposition of energy in the ionosphere and thermosphere (see eg., Wygant et al., 2000). The LWS Ionosphere Thermosphere Storm Probes (ITSP) is another mission that will greatly benefit from continuous global imaging. The imaging requirements put forth in this paper will enable the determination of the dynamics and scale of the O/N2 ratio for high and mid latitudes. These large scale observations over long periods of time are needed for the ITSP mission to extend the in situ measurements to global models of ionospheric–thermospheric variability.

5. Summary

There are important classes of global auroral observations that have not been done or have been done only to a limited extent. These are simultaneous imaging across all relevant scales, spectral resolution of sufficient quality to allow for global maps of characteristic energy and energy flux of precipitating electrons, continuous global auroral imaging for time periods spanning long-duration geomagnetic events, interhemispheric conjugate observations, auroral observations magnetically conjugate to *in situ* measurements, and automatic classification of auroral images. As well, we can reasonably expect that, if the effort is made, each of these technical objectives can be achieved within the next decade. That is, within the ILWS era.

ILWS seeks to understand geospace as a complex coupled system. This ambitious goal demands synoptic observations such as global auroral imaging. Given that global auroral imaging would play an essential role in meeting the overarching objectives of ILWS, and given that there is at present no funded mission during the ILWS time frame that incororates a global auroral imager, it is urgent that the international imaging community act now, rather than later, to make imaging a part of ILWS, rather than the unfortunately missing essential piece.

Colloquially speaking, if we are going to do something, then we should do something new. It would be exciting to attempt to address most, if not all of the technical objectives outlined in Section 3. Certainly KuaFu-B (see Tu et al., 2005) would address continuous imaging and the separation of LBH long and short, if that mission goes forward. Any global auroral imaging mission, in conjunction with ground-based arrays of ASIs such as MIRACLE, and a well-placed narrow field of view imager (see Fig. 3), will allow us to achieve simultaneous imaging across all scales. Continuous imaging is an excellent first-step towards comprehensive interhemispheric auroral imaging. These are readily achievable goals.

While we have only briefly touched on the science that these new observations would facilitate, we hope it is clear that an imaging program that meets some or all of the objectives set out in Section 3 would lead to fundamentally new science on many levels. As it is already doing in the wake of the great successes of the Polar and IMAGE programs, auroral imaging would provide far more than simply context.

References

Anderson, P.C., McKenzie, D.L., Lyons, L.R., Hairston, M. Global X-ray observations of magnetospheric convection-driven auroral disturbances. Geophys. Res. Lett. 27, 3233–3236, 2000.

Craven, J., and J. Murphree. Simultaneous DE-1 and Viking observations of magnetically conjugate auroral phenomena and the evolution with increasing latitudes, EOS TRansactions AGU, 82(42), Fall Meeting Supplement, Abstract SM31C-03. (2001).

Donovan, Mende, S., Jackel, B., et al. The THEMIS all-sky imaging array – system design and initial results from the prototype imagerJ. Atmos. Terr. Phys. 68, 1472–1487, 2006.

Ergun, R.E., Larson, D.E., Phan, T., et al. Feasibility of a multisatellite investigation of the Earth s magnetosphere with radio tomography. J. Geophys. Res. 105, 361–373, 2000.

Foster, J.C., DASI: Distributed Arrays of Small Instruments for Space Weather Research. Space Weather Symposium, American Meteorological Meeting:Book of Extended Abstracts (2004).

Frank, L.A., Sigwarth, J.B., Craven, J.D., et al. The visible imaging system (vis) for the polar spacecraft. Space Sci. Rev. 71, 297–328, 1995.

Fraser, G.W., Brunton, A.N., Bannister, N.P., et al. Lobster-ISS: An imaging all-sky monitor for the International Space Station, in: Flanagan, K., Siegmund, O. (Eds.), Proc. SPIE: X-Ray and Gamma-Ray Instrumentation for Astronomy XII, 4497, pp. 115–126, 2002.

Frey, H.U., Mende, S.B., Angelopoulos, V., Donovan, E.F. Substorm observations by image-fuv. J. Geophys. Res. 109, doi:10.1029/2004JA010607, 2004.

Frey, H.U., Mende, S.B., Carlson, C.W., et al. The electron and proton aurora as seen by IMAGE-FUV and FAST. Geophys. Res. Lett. 28, 1135–1138, 2001.

Germany, G.A., Torr, M.R., Torr, D.G., Richards, P.G. Use of FUV auroral emissions as diagnostic indicators. J. Geophys. Res. 99, 383–388, 1994a.

Germany, G.A., Torr, D.G., Richards, P.G., Torr, M.R., John, S. Determination of ionospheric conductivities from FUV auroral emissions. J. Geophys. Res. 99, 23297–23306, 1994b.

Germany, G.A., Torr, M.R., Richards, P.G., Torr, D.G. The dependence of modeled OI 1356 and N2 LBH auroral emissions on the neutral atmosphere. J. Geophys. Res. 95, 7725–7733, 1990.

Germany, G.A., Parks, G.K., Brittnacher, M., et al. Remote determination of auroral energy characteristics during substorm activity on march 27, 1996. Geophys. Res. Lett. 24, 995–998, 1997.

Greenwald, R., Baker, K., Dudeney, J., Pinnock, M., Jones, T., Thomas, E., Villain, J.-P., Cerisier, J.-C., Senior, C., Hanuise, C., Hunsucker, R., Sofko, G., Koehler, J., Nielsen, E., Pellinen, R., Walker, A., Sato, N., Yamagishi, H. DARN/SuperDARN: a global view of the dynamics of high-latitude convection. Space Sci. Rev. 71, 761–796, 1995.

Hamilton, F., Bannister, N.P., Fraser, G.W., Price, G.J., Milan, S.E., Willingale, R., Fairbend, R., Cowley, S., Lapington, J.S. A wide field FUV auroral imager for low Earth orbit missions, to be submitted, 2005.

Henderson, M.G., Reeves, G.D., Murphree, J.S. Are north-south structures an ionospheric signature of bursty bulk flows? Geophys. Res. Lett. 25, 3737–3740, 1998.

Imhof, W.L., Spear, K.A., Hamilton, J.W., et al. The polar ionospheric X-ray imaging experiment (PIXIE). Space Sci. Rev. 71, 385–408, 1995.

Lui, A.T.Y., Anger, C.D., Venkatesan, D., Sawchuck, W., Akasofu, S.-I. The topology of the auroral oval as seen by the ISIS 2 scanning auroral photometer. J. Geophys. Res. 80, 1795–1804, 1975.

Lummerzheim, D., Brittnacher, M., Evans, D. High time resolution study of the hemispheric power carried by energetic electrons into the ionosphere during the May 19/20, 1996 auroral activity. Geophys. Res. Lett. 24, 987–990, 1997.

Mende, S.B., Heetderks, H., Frey, H.U., et al. Far ultraviolet imaging from the IMAGE spacecraft. Space Sci. Rev. 91, 287–318, 2000.

Moretto, T., Olsen, N., Ritter, P., Lu, G. Investigating the auroral electrojets with low altitude polar orbiting satellites. Ann. Geophys. 20, 1049–1061, 2002.

Neubert, T., Christiansen, F. Small-scale field-aligned currents at the top-side ionosphere. Geophys. Res. Lett. 20, doi:10.1029/2003GL017808, 2003.

Østgaard, N., Mende, S.B., Frey, H.U., Immel, T.J., Frank, L.A., Sigwarth, J.B., Stubbs, T.J. Interplanetary magnetic field control of the location of substorm onset and auroral features in the conjugate hemispheres. J. Geophys. Res. 109 (A7), A07204, doi:10.1029/2003JA010370, 2004.

Sergeev, V.A., Liou, K., Meng, C.-I., Newell, P.T., Brittnacher, M., Parks, G., Reeves, G.D. Development of auroral stramers in association with localized impulsive injections to the inner magnetotail. Geophys. Res. Lett. 26, 417–420, 1999.

Sofko, G.J., Greenwald, R.A., Bristow, W.A. Direct determination of large-scale magnetospheric field-aligned currents with SuperDARN. Geophys. Res. Lett. 22, 2041–2044, 1995.

Stenbaek-Nielsen, H.C., Hallinan, T.J., Osborne, D.L., Kimball, J., Chaston, C., McFadden, J., Delory, G., Temerin, M., Carlson, C.W. Aircraft observations conjugate to FAST: Auroral arc thicknesses. Geophys. Res. Lett. 25, 2073–2076, 1998.

Strickland, D.J., Jasperse, J.R., Whalen, J.A. Dependence of auroral FUV emission on the incident electron spectrum and neutral atmosphere. J. Geophys. Res. 88, 8051–8062, 1983.

Stubbs, T.J., Vondrak, R.R., stgaard, N., Sigwarth, J.B., Frank, L.A. Simultaneous observations of the auroral ovals in both hemispheres under varying conditions. Geophys. Res. Lett. 32, doi:10.1029/2004GL021199, 2005.

Syrjäsuo, M.T., Donovan, E.F. Diurnal auroral occurrence statistics obtained via machine vision. Ann. Geophys. 22, 1103–1113, 2004.

Syrjäsuo, M.T., Pulkkinen, T.I., Pellinen, R.J., Janhunen, P., Kauristie, K., Viljanen, A., Opgenoorth, H.J., Karlsson, P., Wallman, S., Eglitis, P., Amm, O., Nielsen, E., Thomas, C. Observations of substorm electrodynamics using the MIRACLE network, in: Kokubun, S., Kamide, Y. (Eds.), Proceedings of the International Conference on Substorms-4, vol. 238. Astrophysics and Space Science Library, pp. 111–114, 1998.

Torr, M.R., Torr, D.G., Zukic, M., et al. A far ultraviolet imager for the international solar-terrestrial physics mission. Space Sci. Rev. 71, 329–383, 1995.

Trondsen, T.S., Cogger, L.L. High-resolution television observations of black aurora. J. Geophys. Res. 102, 363–378, 1997.

Trondsen, T.S., Cogger, L.L. Fine-Scale Optical Observations of Aurora (Invited), in: Proceedings of the 2nd EGS Alfv n Conference (Auroral Particle Acceleration), EGS Physics and Chemistry of the Earth, 26, 179–188, 2001.

Tu, R.S.E.D. e.a., C.-Y. Space Weather Explorer – The KuaFu Mission. Adv. Space Res., 2005, submitted for publication.

Wygant, J., Keiling, A., Cattell, C.A., et al. Polar spacecraft based comparisons of intense electric fields and poynting flux near and within the plasma sheet-tail lobe boundary to uvi images: an energy source for the aurora. J. Geophys. Res. 105, 18675–18692, 2000.

Williams, D.J., Roelof, E.C., Mitchell, D.G. Global magnetospheric imaging. Rev. Geophys. 30, 183–208, 1992.

Data-derived spatio-temporal resolution constraints for global auroral imagers

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Abstract.

We report data-derived constraints on spatio-temporal resolution of global auroral imagers. This analysis is based on an extensive set of images from two previously flown instruments, POLAR UVI and IMAGE WIC. Our results show the existence of a nontrivial scaling relation $T \approx 0.4\,L^{1.3}$ between the relaxation time T and the spatial dimension L of auroral emission events. We use this relation as a proxi to the *resolution scaling function* providing non-redundant combinations of spatial and temporal resolution of an optimized auroral imager consistent with the dynamics of multiscale auroral precipitation.

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1. Introduction

Discrete auroral activity involves wide ranges of temporal, spatial, and energy scales, starting from the smallest auroral forms defined by kinetic processes up to the largest auroral phenomena associated with the behavior of the entire auroral oval (*Paschmann et al.* [2003]; *Donovan et al.* [2006]). Each scale brings relevant physical information, whereas the interaction between the scales provides insight into the mechanisms of cross-scale coupling in the dynamically connected magnetosphere – ionosphere system.

Since spatial and temporal resolutions of any realistic global auroral imager are limited, their optimization is one of the central problems in mission design. Higher spatial resolution means larger and more complicated optical system; shorter exposure time and higher image cadence require better sensitivity and may increase power consumption. Yet, covering the broadest possible range of scales remains the key to scientific success of any auroral imaging mission.

Physically, spatial and temporal scales of the auroral precipitation are intrinsically connected. Short precipitation events tend to occupy smaller spatial regions compared to long-living events, and they usually exhibit faster small-scale displacements. Our analysis is the first attempt to quantify this tendency on a rigorous empirical basis using extended image databases from previous auroral imaging missions. We show the existence of a nontrivial scaling relation between the relaxation time and the size of auroral emission events, and use this scaling relation to derive the resolution scaling function ensuring non-redundant combinations of spatial and temporal resolution of an optimal auroral imager.

2. The space-time coupling

Our approach to the optimization of spatiotemporal resolution parameters recognizes the fact that the auroral activity is a distributed dynamic physical process. The distribution of luminosity inside a seemingly stable auroral oval is far from homogeneous, and it may become quite complex during geomagnetic disturbances. Auroral emission regions of interest can appear and disappear at different locations, change their size and shape, move around, split into smaller fragments, and interact. Each of these changes takes a certain time, involves a specific spatial domain, and is associated with a finite speed of motion. Spatial and temporal domains of this complex dynamical behavior are closely interconnected, and it seems obvious that spatial and time resolution of a global auroral imager should be chosen in a way that is consistent with this physical constraint. Small auroral features tend to be very dynamic. If these dynamics are not adequately resolved in time, the amount of physically relevant information contained in high-resolution images will be limited due to the distorted time history of small scale auroral structures.

Fig. 1 illustrates this idea by showing "good" and "bad" resolution choices for two basic observational constraints associated with the finite life cycle and the spatial displacement of a dynamic auroral form. The first constraint requires that the image sampling time Δt does not exceed the lifetime T of the observed auroral structure. In general, T decreases with the linear size L of the emission region (smaller regions have shorter relaxation times). For this reason, observing the time history of fine auroral structures residing in the smallest resolved spatial scale Δl requires higher time resolution compared to the history of large precipitation regions. The second constraint takes into account the fact that some auroral forms can travel distances exceeding their spatial dimensions. If the time scale of such a

motion is shorter than Δt (in other words, if the velocity v of the motion exceeds $L/\Delta t$), the imager will see the moving feature in a stroboscopic (undersampled) fashion as a series of disconnected spatial regions. The gaps between the regions will make it impossible to reconstruct the space-time history of the emission event. The solution to this problem is, again, a high enough sampling rate (*i.e.*, short exposure times combined with a high frame-rate) enabling smooth tracking of fast auroral forms.

3. The optimization problem

In order to make small-scale observations informative in the physical sense, the sampling time of the image cadence should be consistent with the spatial resolution of the imager. However, it is important to avoid excessively high accuracy of temporal sampling. If the image cadence is much faster than the dynamics of the smallest auroral features observed at a chosen spatial resolution, the consecutive images will be nearly identical at all scales, and the observation may become heavily redundant while consuming large spacecraft resources (such as, power and telemetry).

Our goal is to avoid such redundancy by exploring the relationships between the T, L and v parameters describing the auroral dynamics in the context of the two observational constraints presented in Fig. 1. This task will be accomplished by using the data from two previously flown auroral imaging missions, POLAR and IMAGE. The data-derived scaling laws between the chosen emission parameters allow us compute the optimal sampling time defined as

$$\Delta t(\Delta l) = min \left\{ T(L), \frac{L}{v(L)} \right\}_{L=\Delta l} \quad (1)$$

The first term in the r.h.s of this equation represents the characteristic lifetime of the emission events observed at the spatial scale L; the second term is the typical traverse time associated with this scale. As we show below, both terms decrease monotonously as L decreases. The term that takes the smallest value in the limit $L \rightarrow \Delta l$, with Δl being the required spatial resolution, places a stronger resolution restriction and is used to as an estimate for Δt. The time resolution satisfying this term should be sufficient to resolve most of the dynamics observed at the scale Δl according to either of the two resolution constraints. This resolution is non-redundant since the obtained Δt is, by definition, the longest sampling time providing correct measurements of the shortest time scales associated with dynamic auroral forms at spatial scale Δl.

In the following text, we refer to the $\Delta t(\Delta l)$ dependence as the resolution scaling function (RSF). This function is derived based on general scaling assumptions and empirical data. The results are discussed in the context of previously flown auroral imaging missions.

4. Data and methods

4.1. Auroral images

For the purpose of this study, we constructed an extensive database containing a total of 41,700 auroral images obtained by the Ultraviolet Imager (UVI) onboard the POLAR spacecraft (*Torr et al.* [1995]) as well as by the Wideband Imaging Camera (WIC) onboard the IMAGE spacecraft (*Mende et al.* [2000]). We used POLAR UVI images taken in the 160 to 180 nm portion of the Lyman-Birge-Hopfield spectral band (LBH-L filter). IMAGE WIC observations were in the adjacent portion of the ultraviolet part of the optical spectral (140 nd 160 nm). The images represented the night time portion of

the auroral oval between 2000 and 0400 MLT and 55 to 80 MLat. Table 1 summarizes information on the studied data sets.

4.2. Spatiotemporal feature tracking

Our analysis is based on automatic spatiotemporal tracking of dynamic auroral features. In this approach, each auroral emission event is represented by a subvolume of the three-dimensional space-time (x, y, t) composed of spatial positions of image pixels (magnetic longitude x and magnetic latitude y) and the observation time t. The event is defined as a connected set of image pixels with the emission flux above a specified value (tracking threshold). The description of the tracking algorithm can be found in our previous publications (*Uritsky et al.* [2002, 2003, 2006]). In this study, we used the most recent realization of this algorithm developed in aid of planning global auroral imaging missions (see *Donovan et al.* [2007]; *Tu et al.* [2008]). The algorithm applies hierarchical labeling of clusters of pixels using the "breadth-first search" principle avoiding backtracking of search trees representing individual emission events.

The spatiotemporal domain of analysis made it easy to estimate for the lifetime T of the emission events as well as for their average linear dimensions in the longitudinal (L_x) and latitudinal (L_y) directions as shown in Fig. 2 (top panel). We also computed the x- and y components of the average velocity of motion (denoted respectively v_x and v_y) of each emission region. The number of events extracted by tracking algorithm from each of the image data sets listed in Table 1 was sufficient to obtain statistically stable estimates of both terms entering the RSF equation 1.

4.3. Scaling assumptions

Preceding studies of spatiotemporal auroral emission dynamics (*Uritsky et al.* [2002, 2003, 2006, 2008]) have revealed its scale-invariant properties indicative of dissipative nonlinear system operating at the edge of global instability. It has been found that probability distribution functions of many emission parameters, including the emission lifetime T, the emission linear size L, and the emission area A, have a stable power-law form.

The scale-free nature of auroral activity is clearly seen in the convergence of distribution functions of emission events obtained from ground-based TV auroral observations and from satellite-based global auroral imagers (*Kozelov et al.* [2004]) as illustrated in Fig. 2 (lower panel). The values of power-law exponents describing these data sets are nearly identical across virtually all scales associated with high-latitude magnetospheric activity, ranging from small localized precipitation regions observed under quiet geomagnetic conditions to large-scale auroral forms accompanying fully developed magnetospheric substorms.

Power-law probability distributions of different measures of the same statistical set imply the existence of pair-wise scaling relations between these measures, which is a fundamental property of scale-free dynamical systems exhibiting finite-size scaling (*BenHur and Biham* [1996]; *Sethna et al.* [2001]; *Uritsky et al.* [2006]). In accordance with this property, we start our analysis by postulating $T = \beta L^{\alpha}$, with β and α being the scaling factor and the scaling exponent of the $T(L)$ relation, correspondingly. Our strategy is to calculate α using the broad-band scaling of $p(T)$ and $p(A)$ distributions reported by *Kozelov et al.* [2004], and then to derive β from POLAR and IMAGE data. The results will be extrapolated to

small spatial and temporal scales based on the convergence of ground-based and satellite-based statistics (*Kozelov et al.* [2004]). We will also use image data to evaluate the average velocity of auroral features at all relevant scales.

5. Lifetime constraint

5.1. The scaling exponent α

Direct empirical evaluation of α exponent requires knowledge of the two-dimensional joint probability distribution function $p(T, L)$. This approach usually suffers from poor statistical convergence even though the scaling behavior of the one-dimensional distributions of $p(T)$ and $p(L)$ is well defined. Here we invoke a more accurate method exploiting the fact that the three distributions are not independent, which provides an opportunity to evaluate α indirectly from already established scaling laws for $p(T)$ and $p(A)$.

Our approach is straightforward. It has been shown (*Uritsky et al.* [2002]; *Kozelov et al.* [2004]) that $p(T) \sim T^{-\lambda}$ and $p(A) \sim A^{-\mu}$. The conservation of probability requires that $p(T)dT \sim p(A)dA$, which yields $d(\mu - 1) = \alpha(\lambda - 1)$, where d is the dimension of the emission regions ($A \sim L^d$) and α is the scaling exponents to be obtained ($T \sim L^\alpha$). Since the auroral emission regions are compact, to the first approximation $L \sim A^{1/2}$ and therefore $d = 2$, which yields $\alpha = 2(\mu - 1)/(\lambda - 1)$. Substituting values of λ and μ exponents from ground- and satellite-based auroral observations (see Table 1 in *Kozelov et al.* [2004]), we find that $\alpha = 1.29 \pm 0.05$.

The obtained α estimate is valid for the entire range of scales of the power-law behavior of $p(T)$ and $p(A)$ distributions reported by *Kozelov et al.* [2004]. In particular, it is expected to correctly describe the emission dynamics at the scales $L = 10 - 100$km and $T = 10 - 100$s which present the major interest for global imaging resolution analysis.

5.2. The scaling factor β

We derived the parameter β based on statistical analysis of spatiotemporal emission events identified in the studied data sets of auroral images (Table 1). We considered two pairs of correlated variables, $\{L_x, T\}$ and $\{L_y, T\}$, and assumed that α takes the same value ($\alpha \approx 1.3$) in the longitudinal and latitudinal directions. The latter assumption implies that auroral emission regions are self-similar rather than self-affine, which is correct within the accuracy of our analysis. The value of β for each pair of variables has been found from the condition

$$\int_{T=0}^{\beta L^{\alpha}} \int_{L=0}^{\infty} p(T, L)\, dLdT = \int_{T=\beta L^{\alpha}}^{\infty} \int_{L=0}^{\infty} p(T, L)\, dLdT \equiv \frac{1}{2} \tag{2}$$

where $L \in \{L_x, L_y\}$. The equation (2) means that the line $T = \beta L^{\alpha}$ is a median cut of the $p(T, L)$ distribution at a given value of α. Since this method operates with crude cumulative statistics (we simply sum up all the probabilities below and above $T = \beta L^{\alpha}$ and vary β until the two sums become equal), it is much more accurate than any analysis relying on a particular functional form of $p(T, L)$.

Before applying the median criterion given by (2), we excluded the subpopulation of small emission events contributing to the truncated portion of the regression cloud due to limited spatial and temporal resolution of studied data as shown in Fig. 3 (top panel). The upper boundary of the discarded regression region was chosen orthogonal (in the double logarithmic coordinates) to the direction $T \sim L^{\alpha}$, which ensured unbiased evaluation of β in the remaining data.

Fig. 3 (bottom panel) shows an example of evaluation of the scaling factor for one of the data sets. Each curve corresponds to a different probability $p(\beta)$ of finding auroral emission events above the line $T = \beta L_x^{\alpha}$, including the probability p =0.5 (blue curve)

defining the median value of β. The plots are extrapolated to smaller spatial and temporal scales based on the scale invariance of the auroral dynamics manifested in $p(A)$ and $p(T)$ distributions discussed above.

Since the lifetime constraint is typically more restrictive than the velocity constraint (see below), the optimal pairs of Δt and Δl resolution lie on the blue (median) curve, which plays the role of the RSF for this data set.

The analysis yields consistent results for all four sets of images (Fig. 4) despite substantial variability of the resolution parameters and observation conditions across our database, with the average value $\beta_x = 0.36 \pm 0.04$ in the longitudinal direction and $\beta_y = 0.52 \pm 0.17$ in the latitudinal direction. The longitudinal β predicts smaller emission lifetimes compared to its latitudinal counterpart (because $\beta_x < \beta_y$ and $\alpha > 0$) and should therefore be used as a proxi to β for computing the first term in the RSF (1).

6. Velocity Constraint

Spatial displacement of emission regions is the second factor requiring sufficiently high temporal resolution for a given Δl. Surprisingly, we have found that this constraint is less significant than the sampling requirement due to the short life cycle of small-scale emission events manifested in the scaling relation $T(L)$.

Fig. 5 shows that the time needed to travel a one-pixel distance Δl=20km (used as an example) reduces with the time resolution of an auroral imager. The extrapolated behavior (red dashed lines) suggests that the first of these time scales is greater than or equal to the second. The bottom panel shows the dependence of the full displacement time $L/v(L)$ on the lifetime T of the emission event. $L/v(L)$ is the time which is needed for an emission region to travel a distance equal to its overall average linear size $L = (L_x + L_y)/2$

with the speed $v = \sqrt{v_x^2 + v_y^2}$. It can be seen that the majority of the data points fall above the line $L/v(L) = T$ (shown in red), with no obvious accumulation of outliers below this line for small T. The latter tendency allows us to expect a similar behavior for a higher resolution data. Therefore, resolving the life cycle of emission events according to the scaling law derived in the previous section would also be sufficient to observe the motion of the auroral forms at the smallest visible spatial scale.

The same conclusion can be drawn from a theoretical perspective. If the spatial displacement of traveling auroral forms is associated with a wave process in the magnetosphere-ionosphere system, which is often the case (*Paschmann et al.* [2003]), the upper limit of the phase velocity of wave fronts observed at the scale Δl is roughly $\Delta l/\Delta t$. If the time resolution is optimized to observe the life cycle of short-living auroral forms as explained above, this limit is a decreasing power-law function of the spatial resolution (since $\alpha < 2$). This is more than enough because most of the plasma waves exhibit the opposite tendency (their phase speed increases with wavelength), and no new fast-traveling features are expected to be found at smaller spatial scales for a given wave mode.

7. Discussion and Conclusions

Our results show that the resolution scaling function $\Delta t(\Delta l)$ of an optimized auroral imager is governed by the first of the two observational constraints included n (1), namely by the power-law scaling of the lifetime of emission events with their linear scale. Consequently, the RSF takes the form

$$\Delta t(\Delta l) = \beta(\Delta l)^{\alpha}, \;\; \beta \approx 0.4, \, \alpha \approx 1.3 \tag{3}$$

where we use the longitudinal β as explained in section 5.2. The consistency of α and β estimates obtained from different instruments makes us believe that these parameters represent fundamental constants of the auroral dynamics.

Table 2 provides several examples of combinations of Δt and Δl satisfying the derived RSF. The values of Δt are calculated according to (3) and are shown with 95% confedence intervals. Since α is greater than unity, the recommended sampling time reduces faster than Δl, which has be taken into account when developing high-resolution auroral imagers.

Fig. 6 places resolution parameters of several previously flown auroral imagers in the context of our results. The error bars show the range of nominal Δl values corresponding to the ionospheric spatial resolution achieved from the apogee of each spacecraft and from the distance 4Re to the center of the Earth which is usually considered as the closest distance enabling observations of the whole auroral oval.

As one can see from the figure, POLAR UVI observations with the basic time cadence Δt = 184 s could not correctly represent the auroral dynamics due to a significant discrepancy between Δt and Δl. From any point in the orbit, the sampling frequency was considerably lower than optimal, and so the time history of the majority of small-scale auroral features was not resolved. The situation was considerably better when POLAR UVI was operated in the single-filter mode with Δt=37s. However, even in this regime POLAR UVI images were somewhat undersampled. IMAGE WIC data were collected with a clearly insufficient time resolution. The sampling frequency of IMAGE WIC was at least a factor of three lower than it should be according to the RSF. The resolution parameters of IMAGE spectrographic imager (SI) were technically close to an optimized Δt – Δl combination,

but the low resolution values prevented this instrument from capturing most of the small-scale auroral dynamics.

Fig. 6 also shows resolution parameters of the currently designed Ultraviolet Auroral Imager (UVI) proposed for the upcoming Polar Communication and Weather (PCW) mission (*Canadian Space Agency* [2010]). PCW–UVI will significantly extend the capabilities of previous auroral imaging missions by pushing the limits of correctly observed emission events towards smaller and larger scales. The smaller scales will be accessed through the improved and properly optimized resolution parameters (angular resolution 0.06 degrees ensuring to $\Delta l = 45$ and the apogee and $\Delta l = 30$ km at the altitude 4Re, with $\Delta t = 20$ s). The largest scales will become available due to the multi-spacecraft configuration of the mission allowing a unique continuous imaging of long-term auroral phenomena.

In general, reaching small Δt and Δl is easier on a 3-axis stabilized platform than with a spin-stabilized platform. Spin-axis nutation of previous auroral imaging missions has in some cases significantly deteriorated the quality of the obtained data. Our spatiotemporal analysis has shown that this effect was particularly detrimental for IMAGE observations by disrupting time history of small-scaled auroral events. This problem will be minimized in the non-spinning PCW satellites which will provide an opportunity to overcome limitations resulting spin axis wobble in previous global auroral imaging mission.

Formulating physically justified resolution constraints for planning auroral imaging missions is an important and challenging task, and our results are only one step in this direction. There are many problems that remain open for future consideration. In particular, the assumption of the two-dimensional geometry of bright emission regions ($d = 2$, section 5.1) can be inaccurate for small-scale auroral events with $L < 100$ km (*Kozelov and Ryp-*

dal [2007]) and will need to be verified. The isotropic α is another ad hoc simplification requiring additional data validation and adjustment. The unaccounted contribution of image sensitivity and instrumental noise to the interplay between Δl and Δt should be carefully addressed in the future, along with other relevant factors.

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References

BenHur, A., and O. Biham (1996), Universality in sandpile models, *Phys. Rev. E*, *53*(2), R1317–R1320.

Canadian Space Agency (2010), Polar communication and weather mission (PCW), http://www.asc-csa.gc.ca/eng/satellites/pcw/.

Donovan, E., et al. (2006), The THEMIS all-sky imaging array - system design and initial results from the prototype imager, *J. Atmospheric Solar - Terrestrial Phys.*, *68*(13), 1472–1487.

Donovan, E., et al. (2007), Global auroral imaging in the ILWS era, *Adv. In Space Research*, *40*(3), 409–418.

Kozelov, B. V., and K. Rypdal (2007), Spatial scaling of optical fluctuations during substorm-time aurora, *ANNALES GEOPHYSICAE*, *25*(4), 915–927.

Kozelov, B. V., V. M. Uritsky, and A. J. Klimas (2004), Power law probability distributions of multiscale auroral dynamics from ground-based TV observations, *Geophysical*

Research Lett., *31*(20), doi:10.1029/2004GL020962.

Mende, S. B., et al. (2000), Far ultraviolet imaging from the IMAGE spacecraft. 1. System design, *Space Science Rev.*, *91*(1-2), 243–270.

Paschmann, G., S. Haaland, and R. Treumann (Eds.) (2003), *Auroral plasma physics*, Kluwer Academic Publishers, Dordrecht, Netherlands.

Sethna, J. P., K. A. Dahmen, and C. R. Myers (2001), Crackling noise, *Nature*, *410*(6825), 242–250.

Torr, M. R., et al. (1995), A far-ultraviolet imager for the international solar-terrestrial physics mission, *Space Science Rev.*, *71*(1-4), 329–383.

Tu, C. Y., R. Schwenn, E. Donovan, E. Marsch, J. S. Wang, L. D. Xia, Y. W. Zhang, and K. W. Team (2008), Space weather explorer - The KuaFu mission, *Adv. In Space Research*, *41*(1), 190–209.

Uritsky, V. M., A. J. Klimas, D. Vassiliadis, D. Chua, and G. Parks (2002), Scale-free statistics of spatiotemporal auroral emissions as depicted by POLAR UVI images: Dynamic magnetosphere is an avalanching system, *J. Geophys. Res.*, *107*(A12), doi: 10.1029/2001JA000281.

Uritsky, V. M., A. J. Klimas, and D. Vassiliadis (2003), Evaluation of spreading critical exponents from the spatiotemporal evolution of emission regions in the nighttime aurora, *Geophys. Res. Lett.*, *30*(15), doi:10.1029/2002GL016556.

Uritsky, V. M., A. J. Klimas, and D. Vassiliadis (2006), Critical finite-size scaling of energy and lifetime probability distributions of auroral emissions, *Geophys. Res. Lett.*, *33*(8), doi:10.1029/2005GL025330.

290 Uritsky, V. M., E. Donovan, A. J. Klimas, and E. Spanswick (2008), Scale-free and scale-
291 dependent modes of energy release dynamics in the nighttime magnetosphere, *Geophys.*
292 *Res. Lett.*, *35*(21), doi:10.1029/2008GL035625.

Table 1. Parameters of studied sets of auroral images: Δt - imager sampling time, n - number of images, m - number of spatiotemporal emission events extracted from each data set.

	Instrument	Observation interval	Δt, s	n	m
1	POLAR UVI	1997/01/01 - 1997/02/28	184	14937	8456
2	POLAR UVI	1998 /01/01 - 1998/02/28	184	7476	4715
3	POLAR UVI	1998/01/19 - 1998/02/12	37	7994	5072
4	IMAGE WIC	2001/10/16 - 2002/03/23	120	11382	12368

Table 2. Examples of optimal pairs of temporal and spatial resolution satisfying the RSF (3).

Δl, km	10	15	20	25	30	40	50
Δt, s	8 ± 2	14 ± 4	20 ± 6	26 ± 7	33 ± 9	48 ± 14	58 ± 18

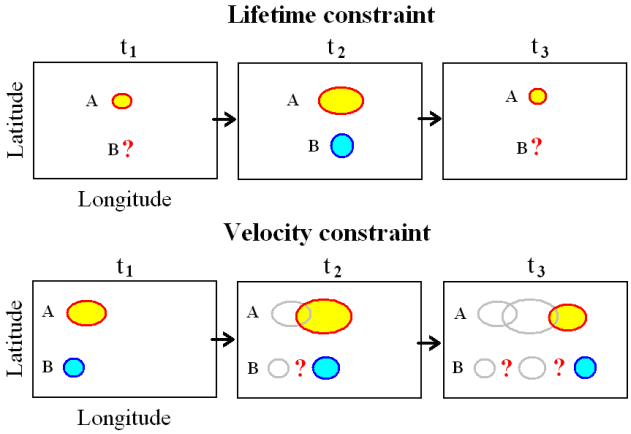


Figure 1. Two basic observational constraints imposed by the dynamics of auroral emission regions and requiring a coordinated choice of space and time resolution of an auroral imager. Each constraint is illustrated by a set of consecutive image frames containing a pair of emission events. In both cases, the event A is observed correctly while the event B is not.

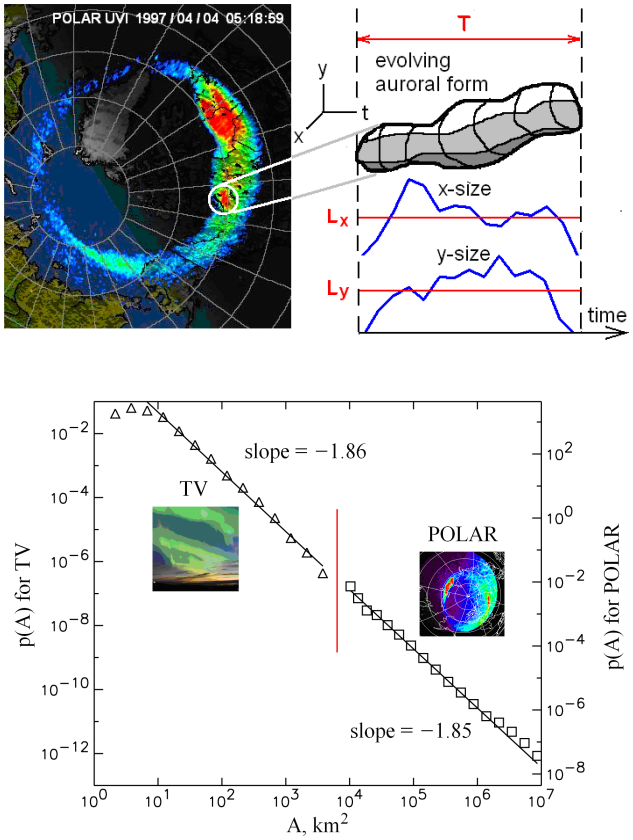


Figure 2. Upper panel: illustration of a spatiotemporal emission event and its measured parameters. Lower panel: convergence of small- and large-scale probability distributions of auroral emission area (adapted from Kozelov et al., GRL 2004).

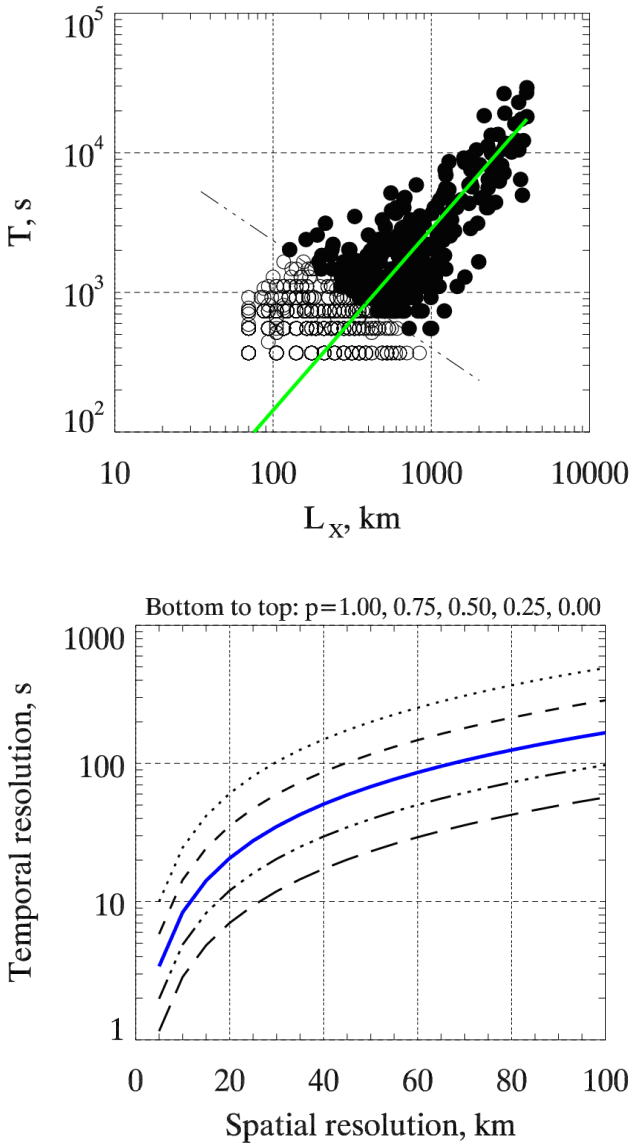


Figure 3. Example of the RSF analysis of auroral emission events. Upper panel: scatterplot of T versus L_x showing longitudinal $T(L)$ scaling in 1997 POLAR UVI observations (Δt=184s, Δl=70km). Empty circles below the dash-dotted line are the events excluded from the statistics due to systematic regression errors introduced by finite spatial and temporal resolution of the auroral imager; solid green line is the scaling law $T = \beta L^{\alpha}$ computed for the remaining set of events. Lower panel: data-derived resolution scaling functions for five different levels of the cumulative probability p below the scaling curve, giving an estimated fraction of successfully observed events. The blue curve is the median with $p = 0.5$ and $\beta = 0.36$.

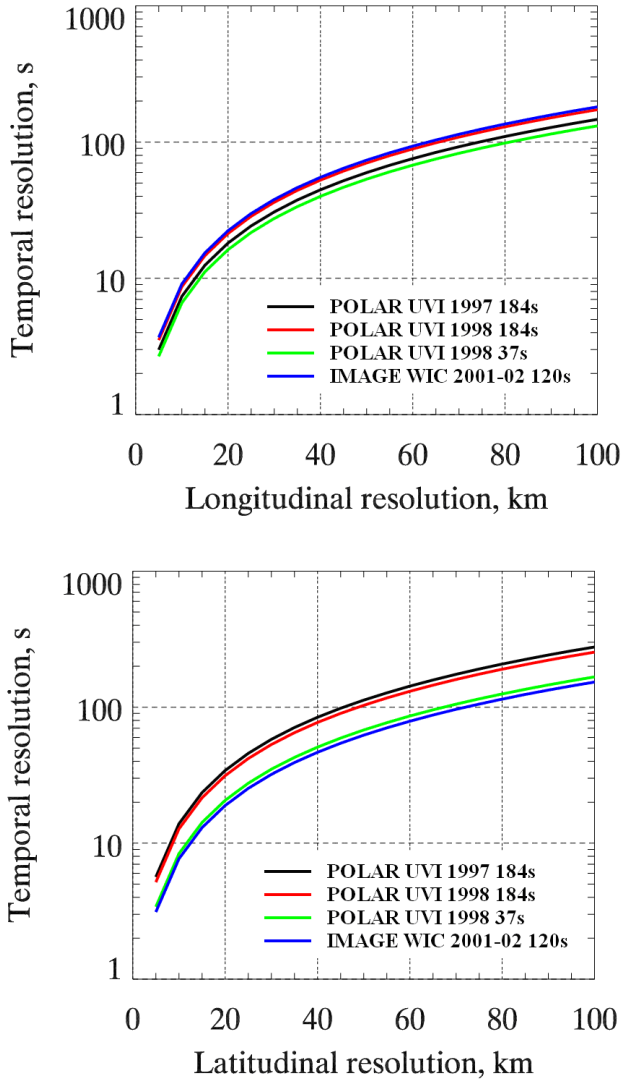


Figure 4. Longitudinal and latitudinal scaling functions (respectively $T(L_x)$ and $T(L_y)$) for the four studied sets of images.

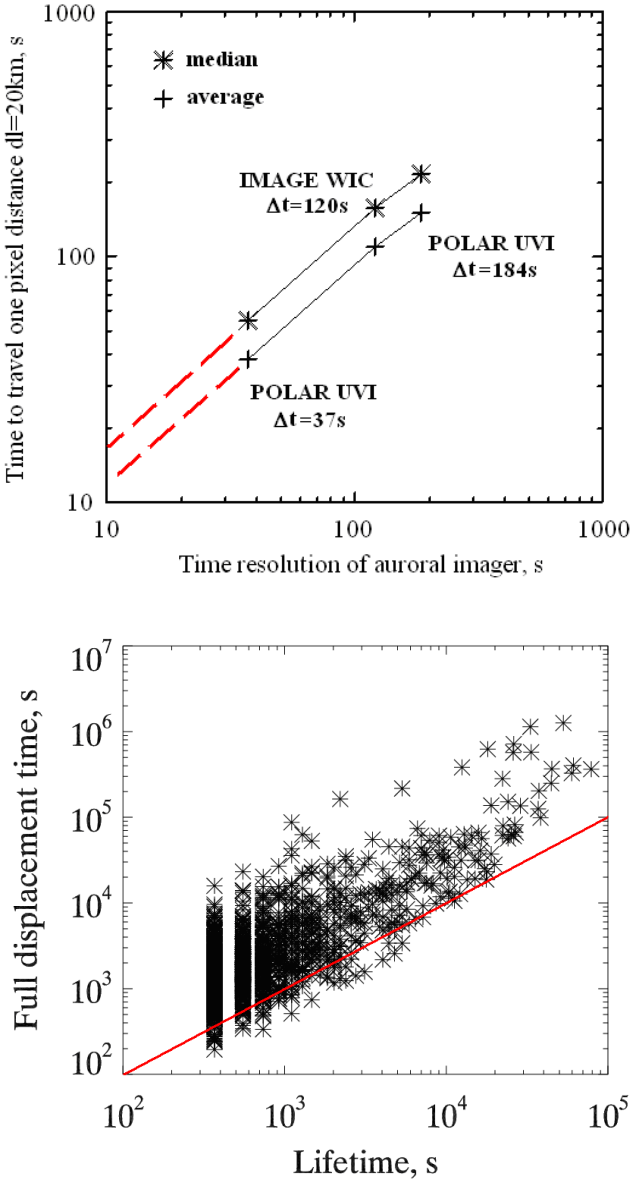


Figure 5. Upper panel: time needed to travel a linear pixel size of 20km versus data base time resolution. Lower panel: dependence of the full displacement time of auroral emission events on their lifetime (POLAR UVI 1997, Δt=184s).

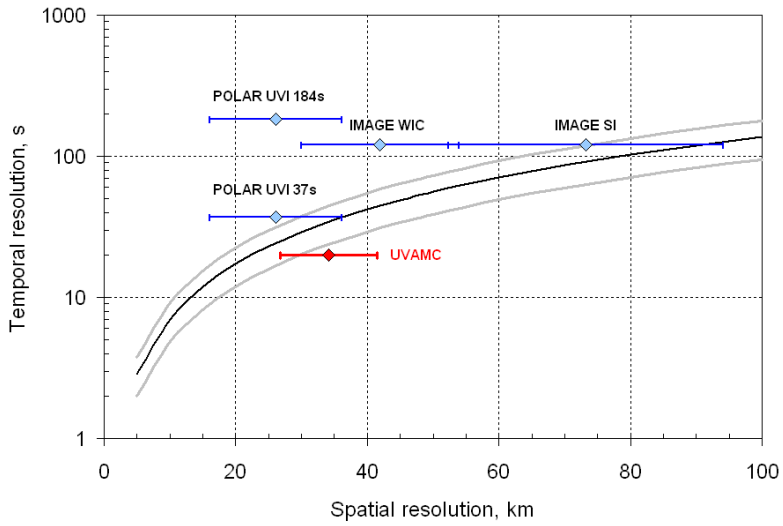


Figure 6. Data-derived resolution scaling function (black curve) with 95% error margines (grey curves) superposed with resolution parameters of previously flown auroral imagers (POLAR UVI at ΔT=37 and 184s, IMAGE WIC, and IMAGE SI, shown in blue), as well as the proposed PCW–UVI imagers (red). The left and the right ends of each horizontal bar show nominal values of the ionospheric spatial resolution Δl achieved from the altitude 4Re and from the apogee of each satellite, correspondingly.

Appendix V – List of Contacts

Role	Name	Position	Address	Phone	Fax	Email
Project Manager	Michael Greffen	Program Manager, Auroral Imaging Group	SB-605 2500 University Dr. NW, Calgary, AB T2N 1N4	403-554-5729	403-210-8974	mgreffen@ucalgary.ca
Principal Investigator	Dr. Eric Donovan	Associate Proffesor	SB-605 2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-6337	403-210-8974	edonovan@ucalgary.ca
Deputy Principal Investigator	Dr. Emma Spanswick	Research Associate???	SB-605 2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-6339	403-210-8974	elspansw@ucalgary.ca
Technical Lead	Dr. Trond Trondsen	Research Associate???	SB-605 2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-7913	403-210-8974	trond.trondsen@ucalgary.ca
Contracting Authority	Glen McMurray	Senior Executive Director, Research Services and Research Accounting	Research Services, 2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-6354	403-289-0693	glenn.mcmurray@ucalgary.ca
Claims Officer	Chantel Watt	Senior Project Administrator	Research Services, 2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-7126	403-210-6996	clwatt@ucalgary.ca
Communications	Leanne Yohemas	External Relations, Faculty of Science	2500 University Dr. NW, Calgary, AB T2N 1N4	403-220-5144	403-282-9154	leanne.yohemas@ucalgary.ca
Major Subcontractor	Blair Gordon	President and Director of Business Development	303 Legget Dr., Kanata, Ontario K2K 2B1	613-592-0748 ,112		b_gordon@routes.com

Appendix VI – Letters of Agreement with Subcontractors

Subcontractor Letters of Support/Agreement

Leroy Cogger
Donna-Lee Desaulniers
Blair Gordon
Gregory Fahlman
Martin Ingle (Photek Ltd.)
Mark Cropper (MSSL)
Francois Chateauneuf (INO)

382 Point McKay Gdns N.W.
Calgary, Alberta T3B 4V8
February 15, 2010

Eric Donovan,
Department of Physics and Astronomy
University of Calgary

Dear Eric,

As a potential subcontractor in your proposed imager project I am writing this letter to indicate my support for your project. In my judgment this is an excellent proposal that will build on Canada's past experience in UV auroral imaging and will result in major scientific advances as well as international recognition for Canada's program in space science.

I look forward to working with the imager team in the design and development of this novel instrument.

Yours truly,

Leroy Cogger

Leroy Cogger

ROUTES ASTROENGINEERING
space instruments | spacecraft subsystems | systems engineering

303 Legget Drive
Ottawa, Ontario
K2K 2B1, Canada

February 3, 2010

Ms. Donna-Lee Desaulniers
23 Belleview Drive
Ottawa, ON
K2L 3Y1

As a contractor working with Routes AstroEngineering on the response to Solicitation 9F007-090217/A, PHEMOS, as per Part 5, Certifications, Sub-section 1.1.4 Status and Availability of Resources "If the Bidder has proposed any individual who is not an employee of the Bidder, the Bidder certifies that it has the permission from that individual to propose his/her services in relation to the Work to be performed and to submit his/her résumé to Canada. The Bidder must, upon request from the Contracting Authority, provide a written confirmation, signed by the individual, of the permission given to the Bidder and of his/her availability. Failure to comply with the request may result in the bid being non-responsive".

Please sign this letter to acknowledge permission for Routes AstroEngineering to propose your services in relation to the proposed work in the solicitation response and to submit your résumé to Canada. Furthermore, acknowledging you're available to perform the work should Routes be successful and be contracted to complete the work as per the solicitation response.

Proposed work in the solicitation response includes Optical Systems Design under the following:

- Instrument concept design and trade offs
- Optical technology review and assessments

I have read this Agreement and fully understand the nature and effect of it and that the terms of this Agreement are fair and reasonable and correctly set out my intentions.

IN WITNESS OF WHICH the parties have signed and delivered this Agreement

BY: _____
Ms. Donna-Lee Desaulniers

BY: _____
(name of witness)

ROUTES ASTROENGINEERING LTD.

BY: _____
Laurie Ouellette
Director Finance & Operations

ROUTES ASTROENGINEERING
space instruments | spacecraft subsystems | systems engineering

303 Legget Drive
Kanata, Ontario
K2K 2B1, Canada

Eric Donovan
Associate Professor
Department of Physics and Astronomy
University of Calgary
2500 University Drive NW
Calgary, AB
T2N 1N4

February 15, 2010

Subject: **Letter of Support - Routes AstroEngineering Limited**

Reference: **Polar Highly Elliptical / Molniya Orbit Science» (PHEMOS) Mission - Phase 0/A Studies**
Category B Instruments – Geospace Imaging
RFP Response to PWSGSC Reference: 9F007-090217/A

Dr. Donovan,

Routes AstroEngineering is pleased and excited to support you as your industry partner in this ambitious opportunity to continue Canada's leadership in auroral imaging from space. We recognize that the orbit chosen for the PCW mission is ideal for providing 24x7 imaging of the aurora, and that this capability has excellent alignment with the PCW primary mission goals related to weather in Canada's far-north.

Routes AstroEngineering has extensive heritage in the development of scientific instruments for space, and in particular the development of auroral imaging instruments. Many of our staff have direct hands-on experience with the nuances and challenges posed by these instruments, as they held key technical and leadership roles in the development of the previous Canadian auroral imagers: VIKING, UVAI, FREJA, and IMAGE. Our people have a corporate memory and knowledge that spans almost 30 years.

As your industry partner, Routes AstroEngineering will provide technical engineering support in the review of the PCW mission/orbit parameters, and assist in the development of the instrument specification as well as defining the physical interfaces and resource requirements on the PCW satellite. Routes will also lead the instrument concept design activities, the technology assessment/roadmapping activities, and the instrument concept trade-off studies. Given the budgetary constraints of Phase 0 & A, Routes will be making a significant financial contribution in the form of in-kind labour for both of the Phase 0 & A workplans. This contribution is estimated to be in excess of 20% of the value of the Phase 0 and Phase A subcontracts.

We look forward to partnering with University of Calgary on this exciting opportunity.

Sincerely,



Blair Gordon
President
Routes AstroEngineering

National Research Council Canada
Conseil national de recherches Canada

Herzberg Institute of Astrophysics
Institut Herzberg d'astrophysique

Office of the Director General
Bureau du Directeur général

NRC-CNRC

02 February 2010

Dr. A. R. Taylor
Institute for Space and Imaging Science
Department of Physics & Astronomy
Science Building, Room 605
University of Calgary
2500 University Drive
Calgary, AB T2N 1N4

Dear Russ

RE: Support for PHEMOS Mission Payload Phases 0/A Work

We are pleased to support your work on the PHEMOS Mission Payload Phases 0/A of the proposal being prepared for submission to the CSA for the construction of a polar communications and weather satellite through the PWGSC Solicitation No. 9F007-0090217/A (PHEMOS). As subcontractor to the University of Calgary Department of Physics & Astronomy we are prepared to support your estimate of up to 20 days (150 hours) of optical design consulting effort from our staff.

The NRC fee-for-service charge-out rate for these efforts is currently $180 per hour.

NRC-HIA has extensive experience and ongoing interest in supporting ultraviolet observation capabilities from space. We are well-suited to work on this project, and look forward to doing so.

Yours sincerely,

Gregory G. Fahlman
Director General

Cc: Mr. Glenn McMurray
Senior Executive Director Research Services and Research Accounting, U. of Calgary

5071 W. Saanich Road
Victoria, B.C. V9E 2E7

5071, chemin Saanich, O.
Victoria (C.-B.) V9E 2E7

(250) 363-0040
Fax (250) 363-8483
Greg.Fahlman@nrc-cnrc.gc.ca

Canada

Mr. Blair Gordon, President
Routes AstroEngineering
303 Legget Dr.
Ottawa, Ontario
K2K 2B1

18 January 2010

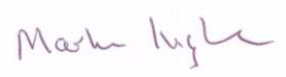
Dear Blair

I have just had a telephone conversation with Don Asquin and he has indicated that Routes AstroEngineering are bidding on project for imaging the aurora borealis. As you know Photek have been involved in providing detectors for space applications for many years. We have recently provided the detectors for the UVIT project, a joint collaboration with India, CSA, MSSL and Routes AstroEngineering and would welcome the opportunity to develop detector technology further.

This letter is to express Photek's interest in joining this project. Should you wish to discuss this further please do not hesitate to contact me.

Yours Sincerely,

Martin Ingle



Technical Director
Photek Ltd

Photek Limited
26 Castleham Road, St Leonards on Sea, East Sussex, TN38 9NS, United Kingdom
Tel: +44 (0) 1424 850555 Fax: +44 (0) 1424 850051 E-mail: sales@photek.co.uk Web: www.photek.co.uk

Registration Number: 2641768 England
Registered Office: Priory House, St John's Lane, London, EC1M 4HD

UCL DEPARTMENT OF SPACE & CLIMATE PHYSICS
MULLARD SPACE SCIENCE LABORATORY

20-Jan-2010

Blair Gordon, President
Routes AstroEngineering
303 Legget Drive
Ottawa, Ontario
K2K 2B1

Dear Blair,

I am sure you are aware that we have worked successfully with your team on the ultra violet imaging telescopes (UVIT) instrument for the Indian Astrosat mission. This followed on from our heritage with instruments like the Optical Monitor for the European Space Agency's XMM-Newton observatory (which has just completed 10 years in service) and the UV and Optical Telescope on the NASA SWIFT gamma ray burst mission.
It was a pleasure to work with Routes on the UVIT instrument. Without the contribution from Routes, that was professional yet pragmatic, we would not have been able to progress with our work.
As far back as November 1998, MSSL staff teamed with Routes staff to present intensified CCD detector systems to the Canadian Space Agency, so our links are well established.
In the UK, the partnership between MSSL and Photek Ltd, to produce high voltage generators and image intensifiers respectively, means that we can deliver complete detector systems already tested.
We hear that a proposal is being developed for a Canadian FUV auroral imaging instrument. We would be delighted to be included in the potential team and will gladly support Routes with any contribution to the proposal that may be helpful.

Yours sincerely

MARK CROPPER, Deputy Director

pp Professor Alan Smith

MSSL Director and Head of the UCL department of Space and Climate Physics

University College London • Department of Space & Climate Physics
Mullard Space Science Laboratory • Holmbury St. Mary • Dorking • Surrey • RH5 6NT • UK
Tel: +44 (0)1483 204100 • Fax: +44 (0)1483 278312 • www.mssl.ucl.ac.uk

January 21, 2010

INO
CHALLENGING LIGHT
FOR OUR PARTNERS

2740 Einstein Street, Sainte-Foy
Quebec, Canada G1P 4S4
T 418 657.7006 F 418 657.7009
Canada/USA 1 866 657.7406
www.ino.ca

Mr. Blair Gordon, President
Routes AstroEngineering
303 Legget Dr.
Ottawa, Ontario
K2K 2B1

Mr. Gordon,

We are writing to express our strong interest and support for your proposed Far UV Auroral Imager as a science instrument of the Polar Communication and Weather mission.

INO has over 20 years of experience in optical thin film development. The optical thin film deposition processes available at INO involve two technologies. The first of these, ion plating, uses a plasma to densify the optical thin films, enhancing their optical and mechanical properties. Dense layers are resistant to scratching, delamination, and hostile environments and can also withstand very high optical powers. The second technique, ion-beam assisted deposition, is a physical vapor evaporation technique assisted with an ion gun to densify the optical thin films and generate the same benefits as mentioned above.

INO has two ion guns that use oxygen or argon as the ionization gas. Neither ion plating nor ion-beam assisted deposition raises the substrate temperature during the deposition process, a definite advantage for keeping stress levels to a minimum.

The deposited materials currently available cover a spectral range from the UV (0.23 µm) to the far-IR (14 µm) and include oxide-based dielectrics, metals (Au, Ag, Al), and amorphous silicon. Dielectric materials deposited by ion plating have demonstrated excellent stability at cryogenic temperatures of 77°K, a crucial property for filtering applications in astronomy. Indeed, the development of thin film stacks of amorphous silicon and silicon dioxide allowed a uniform reflector exhibiting 90% reflectance without phase jumps to be achieved. The use of these reflectors in a Fabry-Perot cavity enabled the creation of a filter capable of operating at cryogenic temperatures and tunable over a wide spectral range. This type of filters has been developed for the James Webb Space Telescope.

To address wavelength ranges close to 150 nm, different materials must be used to manufacture the multilayer coating. Alternating layers of Molybdenum and Silicon or layers of MgF2 and LaF3 are two possible options.

INO has conducted several technology development projects with the Canadian Space Agency and has delivered flight qualified hardware for future Earth Observation missions. INO is also the largest pool of expertise in optical design in Canada and our optical designers have worked on optical layouts for wavelengths in the Extreme Ultraviolet as short 57 nm.

We believe that the study that you are proposing will be a significant benefit to the development of future auroral imagers and we look forward to participating in this project.

Sincerely yours,

François Châteauneuf
Program Manager,
Technologies for Space and Astronomy

Appendix VII – Letters of Agreement/Support

Mission PIs, Chairs of Programs, Modelers, Program Scientists, Rocket PIs

Vassilis Angelopoulos	THEMIS PI
Thomas Bogdan	SWPC Director
James Burch	MMS (and formerly IMAGE) PI
Eigil Friis-Christensen	Swarm Lead Scientist
M. Fujimoto	Scope Projetc Scientist
Larry Kepko	ADEx PI
Marc Lessard (support letter)	Rocket PI
Mike Liehmon	GEM Steering Committee Chair
Kristina Lynch	Rocket PI
Joachim Raeder	Modeler
Aaron Ridley	Modeler
Michael Ruohoniemi	SuperDARN US PI
Jeffrey Thayer	CEDAR Science Steering Committee Chair
David Sibeck	NASA THEMIS & RBSP Program Scientist
Jing-Song Wang	National Center for Space Weather, China

Public Outreach

James Pugsley	CEO Astronomy North
Karen Matthews	CBC Meteorology

Science Team

Pontus C. Brandt
Martin Connors
Thayill Jayachandran
Konstantin Kabin
David Knudsen
Jack McConnell
Mark Lester
Tuija Pulkkinen
Suiyan Fu
Kathryn McWilliams
Robret Rankin
Susan Skone
James Spann
Nikolai Østgaard
Chi Wang

UNIVERSITY OF CALIFORNIA, BERKELEY

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SANTA BARBARA • SANTA CRUZ

(510) 643-1871
(510) 643-8302 fax
vassilis@ssl.berkeley.edu

SPACE SCIENCES LABORATORY
7 GAUSS WAY
BERKELEY, CA 94720-7450 USA

January 26, 2010

Prof. Eric Donovan
University of Calgary
Department Physics & Astronomy
Location SB 636
Canada

Re: THEMIS letter of support for PCW

Dear Eric:

I understand you are pursuing funding from the CSA for a UVI imager on the upcoming Polar Communications and Weather dual satellite system to be launched in 2016. This is a letter of support for this endeavor in my capacity as the Principal Investigator of the NASA THEMIS MIDEX mission.

As you know, THEMIS, and its offspring mission ARTEMIS, involve five satellites that are operated in Earth's equatorial plane at distances at 6-60R_E, achieving monthly radial alignments over central Canada. One of the primary objectives of the mission has been to understand the macroscale evolution of substorms, a fundamental space weather process. The upcoming solar maximum and its declining phase, in 2015-2020, are the most relevant for space radiation effects because it is in such conditions that space hazards maximize. In that period, THEMIS and ARTEMIS will be able to make significant observations of radiation belt sources and losses, and will contribute to a fleet of other NASA satellites (RBSP and SDO) that are now being prepared for launch. The aurora is a primary loss region of radiation belt fluxes, and understanding the loss rates and processes is critical to understanding the energy circulation in Earth's space environment. This is especially true with the data that will be afforded by the next solar cycle.

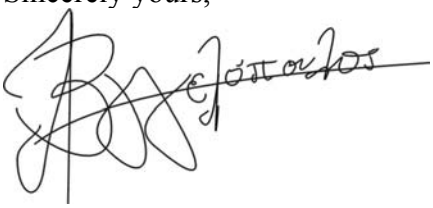
Despite the significant investment by NASA in space assets, a properly designed auroral monitor to address space weather phenomena is sorely missing. PCW, with its proposed UVI instrument, will be filling this crucial observational gap by providing wavelength-resolved, 25km spatial resolution images to determine total energy loss and precipitating electron energy. In fact, PCW-UVI, a highly capable instrument on a 3-axis stabilized platform, will provide the best space-based imaging ever achieved, and with two spacecraft it will achieve continuous (24/7) auroral observations. Both items are crucial to obtaining optimal correlations with in-situ measurements to understand space weather processes. The instrument will enable studies of diffuse auroral precipitation (which are responsible for draining the radiation belts), the ionospheric signatures of magnetotail dynamics (which are responsible for driving space weather processes at the Van

Allen belts), and cusp energization (which is responsible for the largest amount of ionospheric outflow into the magnetosphere, affecting storm strength, evolution and decay times).

I would therefore like to express the THEMIS team's enthusiastic support for the PCW/UVI project, as the proposed imager will bring about a new era in our understanding of ground-space correlations during the upcoming solar max. With ideal space weather conditions and ideal instrumentation from PCW, THEMIS, RBSP and SDO, the cascade of energy from the Sun to the aurora and the radiation belts will be observed in all its forms through the near-Earth space environment. PCW-UVI observations will be a crucial link in an international concerted effort to understand space weather processes. I am certain that the UVI imager data will be widely used, and will represent an important database that will be analyzed for years to come. I also anticipate that development of predictive space weather models will be a natural product from this period, enabling better protection of national and international assets from space weather hazards.

Good luck with your proposal and I look forward to even stronger collaboration between THEMIS and the PCW-UVI team as the project comes to fruition.

Sincerely yours,



Vassilis Angelopoulos
THEMIS Principal Investigator

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
National Centers for Environmental Prediction
Space Weather Prediction Center
325 Broadway W/NP9
Boulder, CO 80305
Telephone: (303) 497-3311 Fax: (303) 497-4006
Mobile: (720) 384-7659 Tom.Bogdan@noaa.gov

Dr. Thomas J. Bogdan
Director

FEB 1 0 2010

Professor Eric Donovan
Department of Physics & Astronomy
University of Calgary
2500 University Drive
Calgary, Alberta T2N 1N4
Canada

Dear Professor Donovan:

NOAA's Space Weather Prediction Center (SWPC) is our Nation's official source for space weather alerts, watches and warnings and is one of only four National Critical Systems in the US National Weather Service. We are also the flagship World Warning Center of the International Space Environment Service (ISES). ISES is an international consortium of 13 Regional Space Weather Warning Centers around the globe, including Canada. Under these mandates, we utilize data from a number of assets operated by NOAA and the US Air Force, as well as NASA and other international organizations to provide our clients with real-time assessments of space weather and forecasts based on models and data. In doing so, we benefit from the free exchange of data, and our data providers gain significant international exposure for their efforts and for their funding agencies.

Our clients include US and international agencies and companies that operate space assets and communications and other technological systems that are affected by space weather, as well as the public. To meet our mandate, we use data from all relevant sources that can access in order to provide the best possible information. Information about the auroral distribution is important for space weather, and to date we have only been able to use proxies for the location and intensity of the aurora. An example proxy is a data constrained model auroral oval produced using in situ particle data from LEO satellites such as NOAA POES. This oval, which can be accessed from http://www.spaceweather.gov , is not particularly reliable away from the meridian of the satellite pass, and is updated on a timescale of tens of minutes. In general, we find that users of space weather data often have somewhat higher standards in terms of the temporal and spatial quality of the data they would like to use.

I understand that you are proposing to the CSA to place UV auroral imagers on the Canadian Polar Communications and Weather (PCW) satellites. The Canadian Government plan is for PCW to consist of two satellites on Molniya orbits. The satellites would be phased on those orbits so that when one is at perigee the other is at apogee. Apogee for both would be above the northern hemisphere. Consequently, an auroral imager on each satellite would provide 24 hour per day 7 day per week continuous viewing of the entire auroral oval. Moreover, the Molniya orbits maintain the latitude of apogee so that the viewing of the northern hemisphere would be sustained for the six year duration of the mission. As well, your plan is for images

with a cadence of tens of seconds and spatial resolution of tens of kilometers (nominally 40 seconds and 40 kilometers), and to collect and make the data available in real-time.

The proposed quality of the PCW-UVI images, the continuity of imaging, rapid imaging, real-time data collection and dissemination, and the planned six year mission duration makes PCW-UVI ideal as a resource for space weather service providers around the globe, and it fills a critical gap in our current capabilities. I expect that space weather services all over the world offering services of the type offered by SWPC will clamor for access to the real-time data from PCW-UVI.

While obviously I cannot promise anything at this time, I genuinely expect that we at SWPC would want to have the real-time global auroral images displayed prominently on our web page, and integrated into our forecast office operations. As well, I anticipate that you and others will develop real-time space weather products that could be derived from the PCW-UVI data. One idea of yours that interests me already is to develop a real-time service based on the PCW-UVI images that would specify the uncertainties in GNSS (e.g., GPS) positioning that result from ionospheric scintillation at high latitudes. I anticipate that there would be a wide market for such information.

What you are proposing would be a significant step forward in real-time Space Situational Awareness. The information from PCW-UVI would be valuable to space weather services, and would form the fundamental basis for a variety of important derived space weather products. In my personal opinion, this would be an important contribution by Canada to the international geospace effort.

Sincerely,



Thomas J. Bogdan

Cc: Dr. David Boteler, Natural Resources Canada
Mr. Graham Gibbs, Canadian Space Agency
Mr. Dale Eisler, Consulate General of Canada

SOUTHWEST RESEARCH INSTITUTE

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SPACE SCIENCE AND ENGINEERING DIVISION • FAX: (210) 647-4325

January 22, 2010

Dr. Eric Donovan
Dept. of Physics and Astronomy
University of Calgary
Calgary, Alberta
Canada

Dear Eric,

As you know, I was the PI of the NASA IMAGE mission, which was operational from 2000 through 2005, and am the PI of the NASA Magnetospheric Multiscale (MMS) mission, which is scheduled to be launched in August 2014. MMS will be a four-satellite cluster-type mission with an equatorial orbit designed to explore fundamental processes in geospace such as magnetic reconnection, wave-particle interactions, and boundary layer processes.

IMAGE was a significant mission in that it was designed for remote sensing large parts of the geospace system. The objective was to observe, for example, the global plasmasphere (EUV imaging), ring current and inner central plasma sheet (CPS) with ENA imaging, and auroral distributions (FUV imaging in part by WIC, an instrument of Calgary design), and explore how large geospace systems interact. Global auroral observations on IMAGE provided a key element of the overall program along with, in some sense, our best global images of the CPS as projected along magnetic field lines into the upper atmosphere.

MMS has a different, but related theme. MMS will measure plasmas, waves, fields, and gradients in regions where specific small-scale processes are thought to play an important role in overall geospace dynamics. Other missions that might be flying at the time include Scope and CrossScale, as well as THEMIS, all of which will provide observations of small-scale and MHD-scale processes that contribute to geospace dynamics. These missions are the "microscope" to complement IMAGE's "telescope." The fact is, while these targeted missions will provide excitng insights into how the smaller-scale processes work, we will not have the comtemporaneous larger-scale auroral observations such as those provided by IMAGE unless a project like PCW-UVI materializes. This element is critically important to the overall objectives of the international geospace research community, for without those global-scale observations we will be disadvantaged in terms of understanding how the smaller-scale processes accomplish coupling between larger-scale systems.

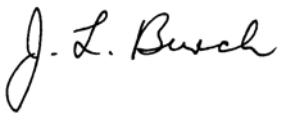
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From the vantage point of my experience with IMAGE, it is clear that the UV auroral imaging you are proposing will be significantly better than anything accomplished to date. Significant new aspects of your program are better space and time resolution, and 24/7 imaging of the northern hemisphere aurora (it is a nice touch that the images will be available to the world in real time). Based on the fact that there is no other global auroral imaging project currently planned, and on the importance of the information global auroral imaging would provide within the context of the in situ geospace missions that will be flying in the PCW era, it is obvious that PCW-UVI would be a tremendously high-impact and highly visible project for Canada. I anticipate that its data would be widely used by members of not only the MMS team, but researchers who are working with Scope/CrossScale, THEMIS, and other missions as well. I expect that PCW-UVI would have a significant impact on the international space science effort.

I wish you success with your proposal.

With best regards



James L. Burch
Vice-President

DTU Space

Professor E. Donovan, Associate Professor
University of Calgary
Dept. of Physics and Astronomy
Calgary, T2N 1N4
Canada

26 January 2010
efc

Letter of support regarding PCW Proposal

Dear Professor Donovan,

As you are aware, I am the lead investigator of the ESA selected Swarm satellite mission. Swarm is a constellation mission designed to carry out detailed observations of the terrestrial magnetic field with the prime objective to advancing our understanding of the Earth's internal field. In order to accomplish our objectives, we must be able to separate internal contributions from external ones, and hence to be able to specify that part of the field due to ionospheric and field-aligned currents. The mission requirements, in the end, are that we specify dE and dB to better accuracy at the satellites than has previously been obtained. The consequence is that, in trying to remove the auroral noise, we will create the best set of observations of the in situ auroral fields ever collected.

The Swarm dE and dB will allow us to specify Poynting flux associated with the aurora, and the auroral field-aligned currents. The result is that Swarm data will be useful in state-of-the-art studies of MI coupling via currents and momentum transfer, auroral electrodynamics, and certainly much more. Obviously, the usefulness of the Swarm data in terms of auroral studies will be greatly enhanced by any complementary auroral imaging that will be available. Ground-based programs such as NORSTAR and MIRACLE are going to be in full operation during Swarm, and so overflights of those arrays will be of great value during Swarm. To my knowledge, there is at present no approved global auroral imaging mission for the Swarm epoch.

I understand that you are submitting a proposal to the CSA for a Phase 0/A study for UV auroral imaging to be included in the planned Polar Communications and Weather (PCW) satellite program. PCW will consist of two satellites on Molniya orbits, and will provide an excellent vantage for global auroral imaging. UV imagers on PCW would be able to provide real-time, 24/7 (e.g., continuous), high-time and space resolution images for the duration of the mission (2016 onwards). This would be the best global auroral imaging ever delivered by any program in our field's history, and the only such imaging during the next decade.

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PCW would overlap with later years of the nominal Swarm operational phase. The data would obviously be an excellent scientific and operational complement to Swarm. Swarm in situ observations of dE and dB will provide high-quality information about auroral fields. PCW-UVI would provide complementary (magnetically conjugate) auroral imaging during every Swarm northern hemisphere transit. This would be extremely valuable for researchers interested in auroral electrodynamics, and I would expect to see dozens, if not hundreds, of studies that would utilize the data together. For example, the in situ observations of currents and Poynting flux could be related not only to the optical auroral structures, but assessed in terms of their importance in energy deposition and (together with SuperDARN & magnetometers) Joule heating. Furthermore, the global auroral images would provide us with the ability to better understand the orientation of and stationarity of auroral structures that Swarm will be flying through. As well, the auroral images would provide a powerful basis for separating spatial from temporal variations in the Swarm data, thus increasing the usability of the Swarm data.

In my opinion, the 24/7 global electron auroral imaging would be a powerful scientific complement to Swarm. Certainly we will be able to carry out innovative science using data from the two missions. Furthermore, PCW-UVI would be filling a disturbing gap in the future line up of missions – there are no global auroral imaging missions approved for the Swarm timeframe. Thus, the kind of contextual information we have grown accustomed to in geospace science will not be available. I expect that this will be very sorely felt by the scientific community. So, if Canada is able to provide these imagers on PCW, there will be an enormous payoff in terms of new science and also in terms of the goodwill that the contextual information would earn. This is an excellent means to contribute in a high-profile way to ILWS.

I want to take this opportunity to express my strongest support for your proposal, and I wish you every success.

With my best regards



Eigil Friis-Christensen
Director

Masaki Fujimoto
Professor
Director, Space Plasma Research Group
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24 January, 2010

Professor Eric Donovan
Department of Physics and Astronomy and Institute for Space Imaging Science
University of Calgary
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Re: A letter in support of PCW-UVI

Dear Eric,

Here I would like to support your proposal for a Phase 0/A study to develop a technology roadmap and initial design for UltraViolet Imagers (UVIs) to be flown on both PCW satellites (PCW-UVI).

As I understand it, the primary objectives of the PCW mission are the long-term "24/7" imaging and communications with everywhere above 45º geographic latitude. This will be achieved by two three-axis stabilized satellites that are relatively phased so that when one is at apogee, the other is at perigee. Any space plasma physicists can tell that this is also ideally suited for auroral imaging and I first fully support your proposal from this very general point of view.

Aurora is the projection of what is happening in the space around our planet under the influence of the Sun. Aurora is highly variable, dynamic and of multi-scale nature. Furthermore we do not know when it starts to explode. It should be clear from these issues that it is desirable (almost necessary) to have continuous, high-cadence and high-resolution imaging. Because these requirements are *all* met by PCW-UVI, it will enable better space-based global auroral imaging than ever. It will provide information essential for studies of auroral and magnetospheric dynamics, along with space weather

research and our understanding of how space technological systems are affected by disturbances in the near-Earth space.

I also enthusiastically support your proposal as the Study Scientist of SCOPE. SCOPE is a future spacecraft mission under joint study by the Japanese space agency JAXA and the Canadian Space Agency CSA. SCOPE is a multi-spacecraft, formation flying mission to perform simultaneous multi-scale in-situ observations of magnetospheric dynamics. While space plasma processes like “magnetic reconnection” have large-scale consequences, their engines are quite often driven by plasma physics at smaller scales. Smaller yet multi-scale processes are operative in key regions embedded in the whole system and they couple among themselves in a rather complicated manner to drive the large scale phenomena as a whole. SCOPE will zoom-in to the key regions where these engines are situated and will perform unprecedented high-quality measurements and elucidate the ultimate mechanisms that drive attractive phenomena such as “aurora explosion”. The mission concept of SCOPE is highly acknowledged in the international space plasma physics community. It, at the same time, faces the fact that the global consequences cannot be observed by SCOPE itself. The best partner to SCOPE is continuous, high-cadence and high-resolution global auroral imaging that is available when SCOPE in the orbit, namely, several years after ~2018 (launch year): PCW-UVI just matches *all* of these requirements.

In summary, PCW-UVI will just do it. In addition to its high stand-alone capability, it, together with SCOPE and other magnetospheric missions operative at the time, will make the late 2010’s and early 2020’s to be the “Golden Age” of space plasma physics and space weather research.

Sincerely,



M. Fujimoto

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771



Reply to Attn of: 674

January 29, 2010

Dear Eric,

I am currently a Research Astrophysicist at NASA Goddard Space Flight Center (GSFC). The primary focus of my research is on magnetospheric dynamics, and I am heavily involved in, for example, the GEM efforts to investigate modes of transport in the magnetotail. I am also lead convener of IAGA Division III.2, "Magnetospheric substorms and tail physics." A central theme in my research, and that of much of our community, is the necessity of developing better protocols for magnetic mapping between the magnetosphere and ionosphere. This is motivated by a number of reasons, not the least being allowing us to take better advantage of ionospheric observations to investigate magnetospheric processes. Just one example of a problem that relies heavily on such mapping capabilities is "*What is/are the magnetospheric driver/drivers of auroral arcs*."

I am the PI of a possible Explorer class mission called Auroral Dynamo Explorer (ADEx). The science objective for ADEx is to identify the magnetospheric drivers of auroral arcs. ADEx would be a constellation of nine satellites in equatorial orbits (apogee at 9 Re), each of which would carry a fluxgate magnetometer and electrostatic analyzer for CPS electron and ion distributions. As in the case of THEMIS, and increasingly for Geospace in situ missions, closure on the science objectives cannot be achieved without complementary observations of the aurora. The ADEx satellites would identify spatial gradients in the magnetosphere that correspond to the drivers of auroral arcs, and simultaneous auroral observations would characterize the related auroral structures. ADEx is currently undergoing a mission design study.

ADEx would obviously benefit significantly if your plan for UV auroral imaging on PCW becomes reality. PCW-UVI would be an important step forward in global auroral imaging, with significant operational "firsts" such as 24/7 observations with 10s of km spatial and 10s of second temporal resolution. PCW-UVI would provide auroral observations that would always be conjugate to ADEx in situ measurements, creating a very large number of events where we would have the possibility of identifying the magnetospheric counterparts of specific auroral features. This would contribute to closure of the ADEx primary question, and contribute to our understanding of diffuse aurora, modes of geospace transport, and magnetic mapping between the magnetosphere and ionosphere.

There is no other global auroral imaging mission planned during the next decade. This would be a great opportunity for Canada to contribute a remarkably high impact mission to the international Geospace program – in fact this is without question a critically

important opportunity for our community. I believe that PCW-UVI would greatly strengthen the science case for ADEx, and thus increase the chances that ADEx will be competitively selected. Even without ADEx, PCW-UVI data would be very widely used by myself and other researchers studying magnetospheric dynamics, the aurora, and MI coupling.

I strongly support your proposal to have UV auroral imaging included in the Canadian PCW mission.

Good luck,

Larry Kepko

Larry Kepko
NASA Goddard Space Flight Center
Code 674.0 / Space Weather Laboratory

UNIVERSITY *of* NEW HAMPSHIRE

Prof Eric Donovan
University of Calgary
Calgary, AB

January 28, 2010

Dear Eric,

This is a letter of support for your proposed Phase A study to provide auroral imagers for the Canadian Polar Communications and Weather (PCW) satellites. In the field of space science, hundreds of research papers have been published that use global auroral observations. Such observations are essential because of the fundamental information they provide about the state of solar wind coupling to Earth's magnetosphere. While the majority of these studies have used data from NASA's Polar and IMAGE satellites, these data are no longer available because the Polar satellite (launched in 1996) has been decommissioned and the IMAGE satellite had a major failure in late 2005. The current situation is that a major void exists in the availability these data, which are desperately needed for space weather studies.

The imaging described in your proposal, though, goes well beyond "replacing" a platform for global auroral observations. Indeed, I have always found it frustrating that observations from Polar and IMAGE had such poor temporal and spatial resolution. This limitation resulted in their data being useful primarily for contextual purposes and only a limited number of papers have been published that use these images as a standalone data source.

The proposed instrumentation resolves both of these issues: the need for global imaging for contextual purposes *and* the need to obtain high enough spatial and temporal resolution to support standalone studies. In addition, however, the availability of these data in real-time provides the most exciting possibilities. Worldwide, many researchers are working towards providing real-time (i.e., useful) space weather products, including the magnetometer/riometer group at NRCAN.

In addition to space weather products, real-time data are essential for supporting other research efforts, such as the work that I am involved with, using auroral sounding rockets. Our group routinely uses sounding rockets to study "micro-physical" aspects of various types of aurora, including pulsating aurora, wave-driven aurora, etc. Of course, these rockets are typically launched precisely when we believe we have the right auroral conditions. In order to make this determination, we currently use data from various ground-based sites, which are often clouded over, or are limited in their real-time data capabilities, etc. The availability of global real-time aurora data would certainly open up important new possibilities in auroral research for this reason and would be very welcome by the sounding rocket community, as well as any other groups in field campaigns, etc.

I wish all the very best and sincerely hope that your proposal succeeds.

Sincerely,

Marc R. Lessard
Associate Research Professor

SPACE SCIENCE CENTER
Institute for the Study of Earth, Oceans, and Space (EOS) • Morse Hall • 8 College Road • Durham, New Hampshire 03824-2600

DR. MICHAEL W. LIEMOHN

ASSOCIATE PROFESSOR
ATMOSPERHIC, OCEANIC, AND SPACE SCIENCES

UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

February 12, 2010

Dear Eric,

I am writing this letter in my capacity as the Chair of the Geospace Environment Modeling (GEM) Steering Committee, on behalf of this group, to express our enthusiastic support of your proposal for UV auroral imagers on the Canadian Polar Communications and Weather (PCW) satellites. Auroral imaging is a critical dataset for the geospace science community, and with the recent losses of the Polar and IMAGE spacecraft, this capability is greatly reduced to an unacceptably low level. PCW-UVI would fill this essential role.

I understand that the PCW plan is for two satellites on Molniya orbits, and that PCW-UVI would provide continuous (e.g., "24/7") auroral images in the way envisioned in your earlier Ravens mission concept. There are significant advantages in the PCW mission scenario for global auroral imaging over anything previously flown. The advantages include the fact that the satellites will not be spinning, which means that you will be able to collect higher resolution images in less time, meaning better spatial resolution at a higher cadence than any previous global auroral imaging mission. Furthermore, you plan to obtain images in two FUV bands, which will allow both dayside auroral imaging (greatly increasing coverage of the cusp region), and some knowledge of the characteristic energy and energy flux of precipitating electrons. Finally, there are no other global auroral imaging missions that are approved for this timeframe, so it is virtually certain that PCW-UVI would be the only such data set from the 2016-2022 timeframe. Taken as a whole, if your plan for PCW-UVI comes to fruition, this will represent a major step forward in global auroral imaging, and a timely and internationally high impact data set for Geospace studies.

As you know, GEM is an NSF sponsored program that involves hundreds of researchers from the US and around the world. Research under the GEM umbrella aims to improve the evolving Geospace General Circulation Model (GGCM), and is carried out within a number of time-limited "focus groups". At the present time, there are 10 active focus groups and 3 more selected to begin soon. These focus groups run in parallel but with staggered start and end dates, each of which typically lasts five years. These focus groups include activities that will directly benefit from the continuous auroral imaging to be provided by PCW-UVI, including the following: "GGCM Metrics and Validation", "Plasma Entry and Transport into and within the Magnetotail", "Cusp Physics", "Diffuse Auroral Precipitation", "Substorm Expansion Onset: The First 10 Minutes", and "Modes of Solar Wind-Magnetosphere Energy Transfer."

The global auroral distribution is our most effective way of observing geospace as a whole because auroral emissions represent a two-dimensional projection of the global system. Global images of the quality you describe would provide fundamentally important information about large-scale coupling in geospace, auroral energy deposition

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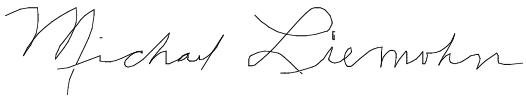
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and its effects on ionospheric conductivity, loss of magnetospheric particles, and the relationship between aurora and magnetospheric dynamics. The images would provide important information about the system-level consequences of small-scale processes and characterize the global state of the system. This would be valuable in studies of specific dynamic processes. The fact that the data would be available 24/7 means that it would provide an excellent basis for data assimilation and for constraining and testing global simulations and models. In addition, the 24/7 imaging would allow for unprecedented imaging of processes like geomagnetic storms which typically unfold over several days.

For the reasons I outlined in the above paragraph and more, the PCW-UVI data would be highly relevant to most, if not all, of the current focus GEM focus groups. Of course GEM evolves over time, and the specific focus groups will all have made way for new ones before PCW-UVI is on the scene. However, GEM is "Geospace Environment Modeling," so the focus will not be different in an overarching sense from what it is now. I can say with the utmost confidence that if Canada can deliver the auroral imaging program that you are proposing for PCW, this would be a remarkably important contribution to our field and would synergize with virtually every aspect of the GEM program.

On behalf of the GEM Steering Committee, I wish you success with this proposal and ultimately this project.

Best wishes,



Michael W. Liemohn, Chair
GEM Steering Committee

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January 27, 2010

Eric Donovan
Physics and Astronomy Department
University of Calgary

Re: PCW-UVI proposal

Dear Eric,

I am writing this letter to endorse your proposal to provide UV auroral imagers for each of the planned Canadian PCW satellites. The proposed result of 24/7 high quality auroral imaging from 2016 onward, for six years or more, would be widely used in our community. Applications would include the provision of context for event studies during that period, all the way through to fundamental science derived from the PCW-UVI data alone. The proposed effort clearly builds on Canadian heritage (e.g., Viking, Freja, InterBall, and IMAGE-WIC), and has significant synergies with Canada's ground and space-based programs including CGSM, THEMIS-ASI, RISR, Swarm, and ePOP.

There are a number of ways in which PCW-UVI would be valuable for my own research, which is based upon rocket-borne in-situ observations of small-scale processes in the auroral ionosphere. In particular we rely heavily on ground-based imaging to decide on our "launch call", that is, when to launch the rocket in order to pass through a particular type of auroral event. Presently existing ground-based optical support provides a picture of tens of kilometer scales over most of the rocket trajectory, and is limited by cloud cover. If PCW-UVI data were available, we would have a completely reliable global picture of the aurora from global scales all the way down to tens of kilometers.

As a PI and Co-I of multiple auroral sounding rockets from the Poker Flat Research Range, I can attest to the many nights spent waiting for the ideal conditions into launch our experiments. We know that we miss many opportunities for launches because of cloudiness or moon-up conditions, and having PCW-UVI images available in real time would significantly improve the situation. This would translate both into significant cost savings (perhaps cutting four or five days off typical waiting periods), and probably better events (by providing a more comprehensive view of the overall dynamics at the time of launch), and thus ultimately better science. Of course for most rocket missions these cost savings would not be realized directly for the CSA. However, the community of researchers that would be affected by this improved situation, and NASA and other agencies that fund the rocket flights, would view this as a significant and obviously high-profile contribution by an international partner. I wish you success in your proposed effort.

Kristina A Lynch
Associate Professor of Physics and Astronomy
Dartmouth College
646 9311 kristina.lynch@dartmouth.edu

January 15, 2010

Joachim Raeder
Professor of Physics
Space Science Center
245G Morse Hall
39 College Road, Durham, NH 03824
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J.Raeder@unh.edu

Prof. Eric Donovan
University of Calgary

Dear Eric,

Thank you very much for making me aware of your proposal to provide novel auroral imagers for the upcoming Canadian PCW mission. The prospect of having 24/7 auroral imaging with the parameters of your proposed imagers, i.e., 40km spatial resolution, 20 sec cadence, and several UV bands, is truly exciting. This would not only enable unprecedented studies of the aurora and how it relates to magnetosphere processes, but also enable new developments in global modeling of geospace, and ultimately in space weather forecasting. Since no model is perfect they need to be constrained by data. In practice various data assimilation approaches are used to ingest data into a model. Multispectral images play a unique role in this approach, because they allow us to calculate parameters like electron precipitation mean energy and flux. These parameters are a predictive output of geospace models, and thus the data can be used for assimilation. Furthermore, there are only few routine measurements available measurements in space that provide a global view of the geospace domain. Because the aurora acts like a projection screen for magnetospheric processes auroral images provide some of the strongest constraints on the forecast models. My own group, as well as several other global modeling groups, are currently incorporating data assimilation algorithms into our codes. The lack of reliable routine measurement is the main impediment for making substantial progress in this area. *Your proposed imagers would go a long way to making a quantum leap in our modeling and space weather forecasting capabilities, similar to the improvements made in terrestrial weather forecasting when satellite imagery was first used in assimilative prediction models.*

With my best wishes for your success,

sincerely,



Joachim Raeder
Professor of Physics
Department of Physics & Space Science Center

Aaron J. Ridley, Associate Professor
University of Michigan
Department of Atmospheric, Oceanic and Space Sciences
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(743) 764-5727; ridley@umich.edu

January 30, 2010

Dear Dr. Donovan,

The thermosphere and its overlapping electrical counterpart, the ionosphere are an important boundary between the atmosphere and space. This is the region of space in which low Earth orbiting satellites traverse through. It is also where our astronauts live. Further, we utilize the ionosphere to bounce radio signals over the horizon so airplanes and troops can stay in contact. The ionosphere also bends GPS radio waves so errors in positioning result.

The upper and lower atmosphere are similar in some ways, but are fundementally different in many ways. The first major difference is the fact that the troposphere is driven in an extremely systematic and predictable way - the Earth spins on its axis such that the sun is overhead once every 24 hours. The energy from the sun is either reflected off the clouds or is absorbed by the ground and water. This drives the weather. The largest regulator of the solar energy for climate and weather is cloud cover. Luckily, we have satellites that sit in geosynchronous orbit that take pictures of the cloud cover, allowing modelers to determine how much energy is begin input into the system.

The upper atmosphere is a strongly driven system. It expands and contracts on a global scale in a very short amount of time (hours), causing satellites to deorbit and other peices of space debris to become “lost”, which makes it difficult to determine when and where collisions between objects may take place.

There are three major sources of energy into the upper atmosphere that can radically change the thermospheric and ionospheric properties in a matter of a few hours: (1) the solar extreme ultraviolet light from the sun; (2) auroral particles that stream along magnetic field-lines from the magnetosphere; and (3) electric fields that drive strong currents in the ionosphere at latitudes above about 60 degrees latitudes. At this time, there is an expanding network of radars called SuperDARN that measure the electric fields at high latitudes. In February, the Solar Dynamics Observatory will be launching. This satellite will measure the flux of extreme ultraviolet light on a minute-by-minute basis. The largest hole in our observation of the energy input into the upper atmosphere is the auroral preciptation.

The lack of auroral specification has quite a few ramifications:

1. We can not accurately specify the ionization of the upper atmosphere, therefore the ionosphere is ill defined.

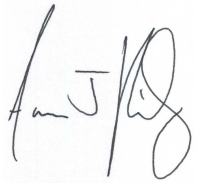
2. The ionosphere has strong currents that can cause massive heating in the upper atmosphere. If the ionosphere is not well definined, then this current-driven heating can't be specified accurately, leading to extremely poor predictions of satellite orbits.

3. The aurora not only allows currents to flow, it add heat to the upper atmosphere also. Therefore, without accurate specification, the heating is not well defined.

4. There is a large number of scientists that are trying to understand both the cause of the aurora and the ramifications of the aurora on the upper atmosphere. Without the specification of the aurora, this research can not happen.

For these reasons, it is important to have imagers in space that measure the auroral distribution. A satellite in Molniya orbit is a perfect platform for taking pictures of the aurora, since it "hovers" over the pole for hours at a time. The Polar Communications and Weather satellite is such a vehicle, and therefore would be an extremely advantageous opportunity for improving the science in the field of auroral physics and specification of the near-Earth space environment, which is important for the health and safety of both satellites and astronauts.

Sincerely,



Aaron J. Ridley

VirginiaTech
College of Engineering

Center for Space Science and Engineering Research
356 Whittemore Hall (0111)
Blacksburg, Virginia 24061
540/231-6211 Fax: 540/231-3362

February 12, 2010

Professor Eric Donovan
University of Calgary

Re: Proposal for a UVI payload for the Canadian Polar Communications and Weather satellites

Dear Eric,

I understand that you are proposing to include UltraViolet Imagers (UVIs) as a secondary payload on the PCW satellite program. As you know, auroral imagers have been incredibly productive in space research and there is a critical need for the deployment of a new generation of instruments into orbit. The PCW program presents a wonderful opportunity for Canada to play the leading role in meeting this need.

Many of the major scientific and technical challenges today require a large-scale, synoptic observational capability, and indeed this concept is embedded in the PCW satellite program. My research group at Virginia Tech is part of the international Super Dual Auroral Radar Network (SuperDARN) collaboration, which seeks to provide comprehensive and continuous measurements of ionospheric electric fields over the auroral regions. The data are synthesized into global-scale maps of the large-scale circulation of ionospheric plasma, which reveals important aspects of the coupling of energy from the solar wind into the magnetosphere and ionosphere and finally into the neutral atmosphere. SuperDARN now counts 25 radars and partners in a dozen countries, including Canada. I am also lead-PI for a major NSF-funded project to construct a chain of 8 mid-latitude radars extending across North America; in combination with the established auroral radars and newer efforts in the polar cap centered on Resolute Bay the result will be dense coverage of ionospheric electric fields and related effects from the northern U.S. states through Canada to the high polar cap. Completion of the mid-latitude chain is scheduled for 2012.

The auroral imagers you are proposing will reveal the dynamics of energetic particle precipitation which is the most fundamental aspect of the coupling of matter and energy in the space environment. The coverage, everywhere poleward of 45º and 24/7, is truly remarkable and dovetails nicely with our planned SuperDARN coverage. We also are implementing techniques to achieve resolutions of seconds and tens of kilometers, as these are the scales required to fundamentally understand auroral processes. There is no doubt that the U.S. and overseas research communities will clamor for access to the PCW-UVI dataset set and collaborations with Canadian scientists. I count myself and my SuperDARN partners in this number as we will obviously want to integrate our two sets of observations to depict the flows of energy in the upper atmosphere, the relationships between ionospheric electric fields and plasma density, and the onset and progress of major geomagnetic disturbances that present risks to technological systems operating in the near-space environment. The PCW-UVI data are certain to be incorporated in the development of comprehensive models that seek to predict space weather and its impacts.

You are proposing a paradigm shift in auroral imaging capabilities that will position the PCW mission to be a major source of scientific discoveries. I wish you well in this effort and I look forward eagerly to the possibility of collaboration with you and the PCW team.

Best wishes,

J. Michael Ruohoniemi

Dr. J. Michael Ruohoniemi
Associate Professor
Bradley Department of Electrical and Computer Engineering
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U.S. CEDAR Program – Coupling, Energetics and Dynamics of Atmospheric Regions

Chair of the CEDAR Science Steering Committee
Dr. Jeffrey P. Thayer
Aerospace Engineering Sciences Department
Colorado Center for Astrodynamics Research (CCAR)
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January 28, 2010

Dear Eric:

The members of the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) science steering committee express our enthusiastic support for the proposed addition of UltraViolet Imagers (UVI) on both of the planned Canadian Polar Communications and Weather (PCW) satellites. As will be demonstrated, the PCW-UVI expected science goals complement those of the CEDAR program, adding unique value to resolving grand challenges within earth's geospace system.

The CEDAR program, funded by United States National Science Foundation (NSF), is an element of the U.S. Global Change Program which started in 1986 to undertake coordinated collaborative studies of the Earth's upper atmosphere and geospace system. Its primary objective is to understand the energetic and dynamic processes that determine the composition and structure of the atmosphere above 60 km, particularly how energy, momentum, and chemical processes from the magnetosphere, and those originating in the lower atmosphere, couple to and affect the mesosphere, thermosphere and ionosphere. CEDAR scientific efforts involve researchers, students and technicians, studying aspects of the upper atmosphere and ionosphere through modeling, data analysis and ground based observations.

The CEDAR program has reached the level of icon status and is recognized around the world as the leading forum for upper atmosphere research. In this role, the CEDAR community is preparing its future research plan. The community recognizes the scientific advancements made and the rapidly changing research landscape. This has led the CEDAR community to take on a more holistic view of upper atmosphere processes. It is the vision of the CEDAR community that the physics and chemistry of the upper

atmosphere be fully integrated with the response and evolution of the whole sun-earth system. Grand challenges within CEDAR are to address questions such as: What makes a planet habitable, variable and sustainable? and How does the sun-earth system influence our space-reliant society?

Resources on the ground and in space will be required to meet these challenges.
I understand that the PCW mission is planned for launch in 2016, that its primary objectives relate to tropospheric imaging and to communications in the North, and that the CSA is inviting proposals for Phase 0/A for instruments for a "secondary payload". I am writing this letter, as Chair of the CEDAR Science Steering Committee (CSSC), to express the strong support of the CSSC and myself personally, for your proposal for a Phase 0/A study for UV auroral imaging on PCW.

The PCW UV imagers, with its 24/7 multi-spectral viewing of the northern hemisphere aurora, would provide a continuous estimate of particle energetics entering our earth's upper atmosphere. The energetics of these particles are so influential on the response and structure of the geospace system that the proposed measurements will be in great demand by the international science community. The capabilities of the UVI instruments with a spatial resolution of ~30 km and 15 second temporal resolution would be a significant step forward for global auroral imaging, better than anything ever achieved previously by any project, and the only global auroral imaging project planned for the near future. The PCW-UVI measurements will strongly complement the measurement suite of the ground-based CEDAR community and provide a new data set to constrain modeling efforts. It would provide quantitative estimates of the distribution of energy deposition into the upper atmosphere by the aurora, complementing global information about plasma convection, total electron content, and currents provided by the SuperDARN, GPS, and SuperMAG instruments, respectively. The data would be equally useful for studies of a more localized nature. Just one example would be studies of polar electrodynamics that would be enabled by simultaneous PCW-UVI observations and the new NSF ionospheric radar systems located in Poker Flat, Alaska and in Resolute Bay, NWT.

The recent Canadian partnership of installing another ionospheric radar system in Resolute Bay, solidified this past year, demonstrates the existing strong collaborations among US and Canadian geospace scientists. The CEDAR program is an integral part of the US National Space Weather Program (NSWP) and the unique vantage point afforded by the PCW- UVI over North America will enable continuous unprecedented study of geomagnetic storms and solar effects on the upper atmosphere. This mission will thus provide critical information on storm-induced particle energetics. PCW-UVI will be the premier satellite mission for advancing our understanding of the fundamental drivers of the thermosphere and ionosphere by auroral particles and to advancing models of the space environment.

The CEDAR Science Steering Committee requests that the benefits of adding a multi-spectral UV imager to the PCW mission be given substantial weight as decisions are made concerning the phase 0/A part of the mission. I am confident that PCW-UVI would be important and utilized by the US CEDAR community. Concurring members of the

CEDAR science steering committee were unanimously supportive of this proposal and are listed below, with the exception of Dr. Susan Skone, University of Calgary, given her assumed proximity to the proposal.

Sincerely,



Jeffrey P. Thayer, Ph.D., Assoc. Professor, Aerospace Engineering Sciences Department
CEDAR Science Steering Committee Chair
Colorado Center for Astrodynamics Research
431 UCB
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Concurring Committee Members:
Dr. Mark Conde, Geophysical Institute, Alaska; **Dr. John Foster,** MIT, Haystack Observatory, **Dr. Tim Fuller-Rowell**, University of Colorado; **Dr. Larisa Goncharenko** MIT, Haystack Observatory; **Dr. Joseph Huba**, Naval Research Laboratory; **Dr. John Noto**, Scientific Solutions Incorporated; **Dr. Meers Oppenheim,** Boston University; **Dr. Mike Ruohoniemi,** Virginia Tech; **Dr. Tony van Eyken**, SRI International; **Dr. Lara Waldrop,** Univ. of Illinois Urbana-Champaign

National Aeronautics and
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Reply to Attn of: 674

January 23, 2010

Professor Eric Donovan
Department of Physics and Astronomy
University of Calgary
Calgary, Alberta
Canada T2N 1N4

Dear Eric

I was delighted to learn that you are proposing to instrument both of the planned Canadian Polar Communications and Weather (PCW) satellites with UltraViolet Imagers (UVI). No forthcoming mission will have a greater impact on our understanding of the solar wind-magnetosphere interaction, none will more readily place forthcoming ground- and space-based observations in context, and none will contribute more readily to our ability to nowcast and forecast space weather.

Global auroral images have the potential to revolutionize our understanding of the solar wind-magnetosphere interaction. While magnetic field lines with footprints in the auroral oval map to the outermost boundaries of the magnetosphere and to the region(s) where substorms are initiated, the oval itself expands equatorward and contracts poleward in response to geomagnetic storms. Continual observations of the auroral oval will therefore enable us to track the entry of solar wind particles and energy into the magnetosphere, to pinpoint when and where geomagnetic substorms begin and track their subsequent development, and to understand the evolution of multi-day geomagnetic storms that encompass the entire magnetosphere. Global images offer a unique opportunity to establish the complex and as yet poorly understood macroscale relationships connecting these phenomena. However, images with high temporal and spatial resolution will also pinpoint when and where disturbances occur, thereby providing crucial information needed to understand the microphysical processes governing these dramatic phenomena.

Because it can be difficult to place isolated in situ observations in context or determine their generality, the proposed auroral imagers will be ideal partners for a host of existing and forthcoming missions, enhancing Canada's visibility and participation in the international space physics research community. With respect to geomagnetic storms, the imagers will determine the location and extent of the storm-time disturbances to be observed by the planned RBSP (NASA), ERG (Japanese), Swarm (ESA), and ORBITALS (Canadian) missions, providing important clues to the global current systems that govern disturbances in the Earth's radiation belts. They will provide the context needed to interpret substorm observations by the existing THEMIS (NASA) and forthcoming MMS (NASA) and SCOPE (Japanese) missions.

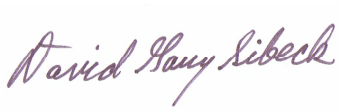
However, as a scientist whose research focuses upon the processes that occur at the magnetopause, I am particularly excited by your plans to provide observations of the dayside auroral oval with enhanced sunlight suppression. I look forward to employing these UVI observations in conjunction with in situ THEMIS and MMS NASA-spacecraft and ground-based NSF-sponsored AMISR and SuperDARN radar observations to define the characteristics and occurrence patterns of both steady and transient phenomena at the dayside magnetopause, including steady-state and bursty reconnection, diffusion, waves driven by the Kelvin-Helmholtz instability, and the response to variations in the solar wind dynamic pressure. UVI observations will prove invaluable in determining the spatial extent of these phenomena and tracking their motion, key aspects in determining their contributions to the overall solar wind-magnetosphere interaction.

Space weather models for the solar wind-magnetosphere interaction require observations of the auroral oval for both data assimilation and validation because the size of the auroral oval and the flux of magnetospheric particles precipitating into it as determined from auroral intensities represent two key metrics defining the intensity of the solar wind-magnetosphere interaction. The same observations have additional operational applications. Auroral blobs and polar-cap patches are associated with ionospheric scintillations that can disrupt communications and can be a source of clutter in ground-based radar observations. Energetic solar particle events gain ready access to the polar cap at latitudes above those of the auroral oval, where they pose a hazard to communications and high-altitude aircraft.

Given the above considerations, there is no doubt in my mind that UVI observations on the PCW mission will provide an immense scientific return both as a stand-alone mission and in conjunction with forthcoming in situ measurements.

Observations from the mission are likely to lead to dramatic improvements in our ability to forecast space weather and have important operational applications. For all these reasons, I wish you every success on your proposal.

Sincerely,



David G. Sibeck

Astrophysicist, NASA/GSFC

Mission Scientist, LWS/RBSP

Project Scientist, THEMIS

National Center for Space Weather

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Feb. 10, 2010

Dear Dr. Eric Donovan,

The dynamical structure and progress of the aurora phenomena requires the coordinated observations of spacecraft from all nations, and these observations provide fundamental information for studies of auroral electrodynamics and storm-substorm relationship for understanding how space weather affects Earth's environment and technological systems. As Director-General of National Center for Space Weather, I have responsibility of ensuring the cooperation between CMA and PCW-UVI with the maximum scientific benefit from Canadian and CMA missions.

Coordinated efforts from PCW and FENGYUN mission will provide a unique opportunity for scientists from all nations to study the research questions related to the aurora phenomena. The PCW mission would provide the first ever 24/7 view of the entire auroral oval and polar cap, as well as the first ever real time global auroral images with the highest spatial and temporal resolution, starting from the planned launch in 2016. In the time frame of PCW mission, CMA will launch the FENGYUN-3C&3D) satellites with a Wide-angle Auroral Imager (WAI) and in situ instruments on board. WAI will image the FUV emission in the 140-180 nm range, with high spatial and temporal resolution for global ionospheric (auroral) observations. Combined with other geospace missions (such as, THEMIS, LWS RBSP, and CEDAR), remote observations and in situ measurements from PCW and FENGYUN missions will prove tremendously useful for space weather.

Since PCW and FENGYUN-2 missions will be highly complementary, I and my colleagues will positively participate the PCW mission and also look forward to working with you on the PCW mission. I am sure that the PCW mission will greatly benefit international scientists to explore the forefront questions of space weather and also contribute to understanding how space weather impacts the geospace and technological systems.

Sincerely yours,



J.-S. Wang

Astronomy North

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January 25, 2010

Eric Donovan
Department of Physics and Astronomy
University of Calgary
2500 University Drive
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To Whom It May Concern,

The Astronomy North Society strongly supports the University of Calgary's proposal to introduce a Geospace Imaging payload as part of the Polar Communications and Weather (PCW) satellite program.

The potential for real-time geospace imaging to enhance northern and national participation in space science education is very real. As data flows to northern educators, tourism stakeholders, the scientific community and the public, it will offer a full spectrum of education and outreach opportunities that will contribute to curriculum enhancement in the North and foster new North-South partnerships using an iconic "made-in-Canada" view of the aurora above Yukon, Northwest Territories and Nunavut.

From a northern perspective, data of this nature would also attract a new generation of Canadian youth to the northern sky, and would present all levels of government with new opportunities to enhance territorial, pan-territorial and national resources to include experiential learning (aurora viewing) through programs that promote polar sky awareness and space science advancement in classrooms and living rooms in the North and across Canada.

Nationally, this initiative represents an exciting opportunity for Canada to lead a specialized field using flagship technology. It is also an enormous opportunity to capitalize on Canada's geographical advantage. As the country with more land mass located beneath the auroral oval than any other nation, we are extremely well positioned to take advantage of our geographical and geomagnetic assets by investing in projects that have linkages to Arctic sovereignty, environmental awareness, innovation, connectivity and tourism. The proposed project has all of necessary ingredients to become an international centrepiece that will positively contribute to Canada's northern and national interests while bolstering our international reputation in a post-Shuttle era.

From a purely Astronomy North perspective, this initiative would offer a cutting-edge platform that would build upon the foundation of knowledge created by The AuroraMAX Project and The Legendary Sky Project, which are both now underway. Our public outreach program also includes ground-based observation, a library of time-lapse aurora photography, public presentations, and a daily aurora forecast on www.astronomynorth.com, each of which would align very well with real-time aurora data from above.

Moving forward, Astronomy North is prepared to assist in any capacity to ensure northern youth are connected to this initiative, and believe through partnership development and a commitment to education and outreach, this opportunity will lead to lasting benefits and a lifetime of learning for skywatchers of all ages from coast to coast to coast.

Clear Skies



James Pugsley
President
Astronomy North

Karen Matthews
Meteorologist
CBC News: Weather Centre
Toronto, Ontario
Karen.matthews@cbc.ca

Attn: Eric Donovan
edonovan@ucalgary.ca
University of Calgary
Calgary, Alberta

January 18, 2010

I am a meteorologist at the CBC News: Weather Centre in Toronto. We received an email from a colleague of yours, Leanne Yohemas, in regards to the auroral project you are working on that is of interest to us, and we would like to offer you our support.

The sample aurora image we received looked spectacular. The idea that this project will help scientists learn more about space weather is a benefit Canadians cannot ignore. The fact that there is then the potential for the general public to have access to these images and increase their knowledge is also a great benefit. Being a Canadian news network, we would be in a position to provide access of the imagery to a wider population than may be generally available to the scientific community.

At this point in time, we are not able to provide you with any guarantee that we would be able to use this technology on a day-to-day basis; however, we would definitely use it occasionally. With stations spread throughout the country, there may be some locales that would be able to use it on more of a daily basis, especially those further North whose viewers are directly affected by auroral storms, as it would be more relevant and informative for them. Being able to forecast in advance auroral flare-ups could provide potential life-saving warning to people who rely on satellite relays and wireless communications. For viewers in the south, which happens to be most of the CBC's main audience, these images wouldn't have any practical application to their daily lives, but would definitely be increasing their knowledge base and appreciation for such a unique phenomenon.

From a technical aspect, we wouldn't be able to guarantee in what shape or form we would be able to retrieve and use the imagery. This however, does not subtract from our support of your project in any way. Further research would be needed to see how we would be able to incorporate your images into our weather broadcasts, both on-air and online. The possibility for either real-time or delayed images of the aurora would be a potential asset to our presentations. If you were also able to provide briefings on the images, this too could enhance our interest in using the images more on a daily basis. At this point, none of our presenters on-air are experienced enough to properly interpret the images and thus present an accurate forecast; however, we could still show them and provide basic information on the aurora.

Thank you for thinking of the CBC. Again, we strongly support you and wish you the best of luck with your proposal.

Karen Matthews

JOHNS HOPKINS
UNIVERSITY

Applied Physics Laboratory

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240-228-5000 / Washington
443-778-5000 / Baltimore

13 February 2010

Dr. Eric Donovan
Dept. of Physics and Astronomy
University of Calgary
Calgary, Alberta, Canada

Dear Dr. Donovan,

I very much look forward to collaborate with you on your proposal for Ultra Violet Imagers (UVI) as secondary payloads on the Canadian Polar Communications and Weather (PCW) Satellites. I would like to emphasize that the orbits and payload mass resources provided, would be game-changing in that it would meet the requirements of continuous, global, high-resolution imaging of the auroral oval, which reflects the dramatic space weather events that take place in the magnetosphere. Such a strong space weather component you are proposing on the platform PCW provides would surely propel PCW internationally to a high-quality, long-term space weather monitoring system that the science community is in critical need of.

I intend to work with you to develop science scenarios on how the global auroral imaging can be used in understanding and predicting space weather. In particular, it would be of high importance to investigate how we can coordinate your auroral imaging and Energetic Neutral Atom (ENA) imaging of the plasma surrounding the Earth that I intend to propose under the name of EAGLES to fly on separate satellites for the upcoming NASA Explorer Mission of Opportunity. UV auroral imaging and ENA magnetospheric imaging are *the recognized top two techniques to image space weather* and their combined strength has already been demonstrated in past missions such as the NASA/IMAGE mission (2000-2005). However, such missions have lacked the observational continuity and multi-vantage point imaging capabilities that the combination of PCW and EAGLES would provide. These features together with the global, high-quality imaging proposed for PCW and EAGLES would make a critical leap towards a first 3D Space Weather imaging system.

I wish you the best of luck on the proposal.



Dr. Pontus C. Brandt
The Johns Hopkins University
Applied Research Laboratory
Laurel, MD, USA

Athabasca University

Dr. Eric Donovan
Department of Physics and Astronomy
University of Calgary
Calgary AB T2N 2N1
Canada

12 February 2010

Re: Polar Communications and Weather (PCW) UV Imager

Dear Eric

Thank you for your invitation to join the initial team working on PCW-UVI. I would be pleased to be a science collaborator on the Phase A/0 project, and further to support technical development as much as possible. We are already collaborating on the Athabasca University Geophysical Observatory (AUGO) where we, along with other collaborators, have done innovative studies favored by its latitude. AUGO has received major funding (AUGOURI) that will allow its continuance into the era of PCW. It will be very exciting to participate in planning the science that will come from having the outstanding new developments in space-based imaging that you propose coupled not only with AUGO, but also with an unprecedented number of ground magnetic observatories. My AUTUMN network contributes a substantial fraction of the magnetic observations made in Canada, and by the PCW era we should have a Canadian national research magnetometer network of which AUTUMN and the STEP network (which we support) are the prototypes. Possibly by then, my magnetic inversion techniques will be in wide use; if not, some other technique will have matured so that optical data can be compared with ground magnetic data as never before. Recent developments using the THEMIS ground network have shown the potential for high-cadence imaging with high sensitivity, yet there are many disadvantages to operating from the ground. What you propose will overcome the disadvantages while still providing a high cadence and sensitivity. Comprehensive and continuous imaging coverage will be unprecedented, and valuable to those like myself who study substorms and need data available at any given time, usually for fairly short intervals. It will also for the first time allow entire storm periods to be studied with uninterrupted imaging. I will make a high priority of participating in studies that will lead to this optimal scientific return.

At this time, we do not have a space imaging capability that covers large regions of the auroral zone at all. Obviously, Canada can spring to the forefront again in this area, if the use of PCW as a platform for this most logical scientific instrument is possible. The idea goes naturally with the PCW concept for communication and weather coverage over exactly the same regions as are of interest for auroral oval and related solar-terrestrial relations studies.

As you know, my initial interactions with the University of Calgary were in the 1980s at the time when the Viking imagers were the foremost such instruments in the world, and led to immense progress in our field. I have maintained a good relationship ever since, mostly collaborating on ground-based projects (although involved in e-POP, but mostly from a perspective of ground-based complementarity). The demonstrated capabilities of the University of Calgary in space instrumentation make it the natural place from which to expect ground-breaking proposals. The track record of success at University of Calgary makes it clear that a science plan developed under a Phase A/0 will actually be able to be carried out. The insight to use PCW as a platform will allow a huge advantage in cost/benefit ratio as opposed to that of any mission that would require its own spacecraft. This is without even mentioning the reliability and lifetime that will come along with being on an operations platform.

In short, I am excited about this project as I am about no other. I strongly wish to see the Phase A/0 succeed as a first step to returning to the Canadian space science community the excitement and spirit of collaboration that the University of Calgary was a leader in providing in the 1980s and 1990s.

Best regards,



Martin Connors, Ph.D.
Professor and Canada Research Chair
Space Science, Instrumentation and Networking
Centre for Science, Athabasca University
Visiting Professor, Department of Earth and Space Science, UCLA, Los Angeles, USA

CC: Rory McGreal, Associate Vice-President Research, AU

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Dr. Eric Donovan,
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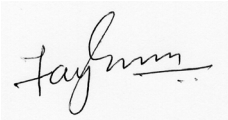
January 27, 2010

Dear Eric,

I am pleased to be named as a science collaborator on your PCW-UVI phase 0/A proposal and I agree to work with the rest of the team in identifying science and space weather synergy between Canadian High Arctic Ionospheric Network (CHAIN) and PCW-UVI. I will commit the small amount of time and effort towards achieving the goal of the phase 0/A, specifically by contributing to the science planning as it pertains to future coordinated use of CHAIN and PCW-UVI data.

Since there are no other auroral imaging missions planned by the international community, and new features of 24/7 imaging and unprecedented spatial and temporal resolution, PCW-UVI would be important within the international space physics effort. Moreover, by combining with the array ground based instruments, the mission can provide crucial "space weather" information for user community. I strongly support this proposal and wish you all the best. If you need further information please contact me.

Yours sincerely



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UNIVERSITY OF ALBERTA

Feb 14, 2010

Dr. Eric Donovan
Department of Physics and Astronomy
The University of Calgary

Dear Eric:

Thank you very much for inviting me to participate in your PCW-UVI proposal as a science collaborator. I am very happy to accept the invitation and I look forward to working with your excellent scientific team.

I confirm that I will actively participate in all the tasks identified for me in your proposal and that I will be able to commit an adequate amount of time to this project. Specifically, I will contribute to the development of the data assimilation and modelling plans concerning global UV imaging as well as magnetospheric dynamics. As you know, magnetosphere-ionosphere coupling is one of the main focuses of my research interests and the PCW-UVI mission will be a major stepping stone in improving our understanding of its physics. A continuous 24/7 high-quality imaging of the auroral oval is essential for monitoring the energy storage and release processes in the terrestrial magnetosphere, and for understanding the complicated dynamics of the Earth's space environment. PCW-UVI is an excellent and very timely space science initiative which builds on the outstanding heritage of Canada in auroral studies and will help to keep our country as one of the leaders of International Space Research.

Sincerely,

Konstantin Kabin

Department of Physics
Faculty of Science

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Eric Donovan, Principal Investigator
PCW-UVI Phase 0/A

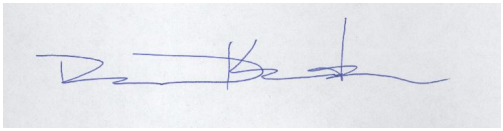
February 16, 2010

Dear Eric,

I hereby agree to be named as a science collaborator in your PCW-UVI phase 0/A proposal, and I agree to carry out the work identified for me. Specifically, I will support you and your team in the development of a science plan that includes i) quantifying the relation between ionospheric electrodynamics and auroral forms through comparison of the UVI and ionospheric probes such as Swarm, and ii) using UVI's unprecedented combination of coverage and resolution in both space and time as a basis of critical tests of auroral theories.

Overall, I support the PCW-UVI concept enthusiastically. This pair of instruments and the 24/7 auroral observations they will enable will fill a critical niche in the international space science endeavor over the next ten years. Nearly every conceivable study of the magnetosphere-ionosphere system stands to benefit from either the detailed or contextual views that PCW will provide. PCW-UVI is exceptionally well-aligned with Canada's historical strengths in auroral and magnetospheric science, its current focus on polar science, and the future ambitions of our field as laid out in our recent space environment "roadmap". I appreciate the opportunity to help make it a reality.

Sincerely,



David Knudsen, Principal Investigator
Swarm Canadian Electric Field Instrument Science Team

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13th February, 2010

Dear Eric

As you know we are interested in the interaction between auroral energy deposition and NOx formation in the MLT and its impact on the stratosphere via descent of MLT air in the winter night and also via stratospheric warmings. The group at York has done some calculations using the CMAM mode revealing a significant impact on the ozone layer. We would certainly like to be considered as "Science Collaborators" (perhaps interdisciplinary scientist would be a more appropriate term) with the UV Auroral Imager UVI) - UVI phase 0/A proposal. We would anticipate using the energy fluxes inferred from the UVI to generate energy deposition and NOx formation in the MLT region and would model its impact on the stratosphere and compare with measurements. In the time frame of 2016 these would involve PCW/Phemos imaging FTS/UV-Vis-NIR instruments for northern latitudes since perforce they must look through the stratosphere they can measure ozone column as well as columns of other species. Also instruments such as IASI on Metop will measure ozone column and perhaps PREMIER, an ESA possible Explorer Mission instrument which focuses on the UTLS will be launched.

Yours sincerely

John McConnell,
416-736-2100 ex 77709



Prof. Eric Donovan,
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University of Leicester

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February 16, 2010

Dear Eric

I would like to express my support for your proposal for PCW-UVI and am delighted to confirm that I agree to be named a "science collaborator" on PCW-UVI. In addition I will work with Professor George Fraser, the Director of the Space Research Centre (SRC), University of Leicester, to explore hardware contributions to the project, focusing most likely on high-voltage power supply. The SRC has a long history of working on Space projects going back to the 1960s and current missions in which Leicester has PI responsibility for hardware involvement include XMM-Newton, Bepi-Colombo, and ExoMars. There are also a number of future missions which the SRC are working on including IXO, EJSM, and SVOM.

As the Chair of the Executive Council of the Super Dual Auroral Radar Network (SuperDARN), I also note that this exciting proposal to develop an auroral imager for PCW fits well with the current and planned programme of science exploitation within the international partnership. SuperDARN consists of 22 operational radars of which 7 are currently in the southerm hemisphere and 15 in the northen hemisphere with complete coverage over Canada. The implementation of this PCW-UVI will provide exciting new opportunities for joint science between the Imager and the radar network.

Finally, as you know, we are developing new tools for looking at the magnetosphere, ionosphere and atmosphere at the system-level. This is an entirely new approach to the way in which we investigate this system. The capability that PCW-UVI offers for new scientific developments in system level science is considerable and will, I believe, lead to major new discoveries in the next decade.

I wish you luck with your proposal.

Best wishes,



Professor Mark Lester
Professor of Solar Terrestrial Physics

FINNISH METEOROLOGICAL INSTITUTE

Eric Donovan
Department of Physics and Astronomy
University of Calgary
2500 University Drive
Calgary, Alberta
Canada T2N 1N4

Dear Eric,

Thank you for your invitation to join the Polar Communications and Weather (PCW) satellite program. I am pleased to accept the invitation to join the Ultraviolet imager (PCW-UVI) team in the phase 0/A proposal as a science collaborator. I am happy to work with your team to define the science plan for the mission and the instrument requirements following from the science plan. My present budget includes sufficient resources to cover this activity.

As we have discussed earlier, I am also interested in exploring possibilities of my group providing some hardware contributions. However, those can be agreed on at a later stage, as the hardware contributions are also dependent on the level of funding we are able to obtain for this project from our national sources.

I have over 20 years of experience utilizing auroral observations to resolve basic questions in magnetospheric physics, which was already a topic of my thesis. Thus, I'm obviously highly excited about the possibility to get 24/7 coverage of global auroras at high time cadence and high spatial resolution. These data would bring the magnetospheric physics to quite a new level! It is to me very surprising that yours seems to be the only international effort in this front, given that global auroral imaging is the only possibility we have today to monitor the solar wind energy input into the magnetosphere - ionosphere system in a quantitative way!

With best regards,

Tuija Pulkkinen

Tuija Pulkkinen
Head, Earth Observation
Finnish Meteorological Institute
POBox 503, FI-00101 Helsinki
Finland

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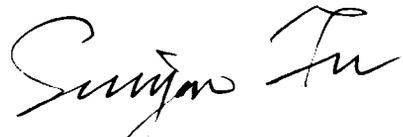
4 Feb, 2010

Dear Dr. Eric Donovan,

It is my great pleasure to know that you are planning to submit the proposal of PCW-UVI to CSA , and I am very happy to join the PCW-UVI Phase 0/A study as a team member.

I think PCW will be an excellent partner mission to our Kuafu project, which is one of the very prospective candidate missions now being considered in China. The main scientific objective of Kuafu is to studying the energy coupling process between the Sun and the Earth, therefore, aurora imagining is one of the most important observation items. As I understand, PCW could provide a better time and space resolution imaging of the aurora, and it would accomplish KuaFu auroral imaging objectives in a simpler way. It would be helpful for both missions if we could work out how to integrate the two programs for space weather and space science purposes. During the Phase 0/A study, we could work together on developing a partnership between KuaFu and PCW-UVI, including data sharing, observing strategies, and science, etc.

Sincerely,



Suiyan Fu
Institute of Space Physics and Applied Technology
School of Earth and Space Sciences
Peking University
Beijing, 100871
China

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Eric Donovan
Dept. of Physics and Astronomy
University of Calgary
2500 University Drive
Calgary, Alberta
Canada T2N 1N4

12 February 2010

Dear Eric,

Re: Ultraviolet Imagers for PCW (Category B), PCW-UVI

Thank you very much for your invitation to participate in Ultraviolet Auroral Imagers (UVIs) proposal, in response to the PCW Geospace Imaging (Category B) Announcement of Opportunity. I am writing to confirm that agree to be a member of the PCW-UVI science team.

I look forward with great anticipation to a possible return of global auroral images to space science. These have been sorely missing for the better part of a decade. As part of the international SuperDARN community and a member of the Canadian SuperDARN team, I am particularly interested in global convection modes, fundamental state(s) of dynamic equilibrium in magnetosphere, hemispheric symmetries and connections, magnetosphere-ionosphere-thermosphere coupling, cusp science, polar cap size, flux and energy deposition, and field-aligned currents. All of these topics benefit immensely from the global auroral images, and the non-spinning platform for the PCW-UVI imagers would be superb.

I look forward to the excellent scientific opportunities that will be made possible by the PCW-UVI imagers. This mission will fill a large gap in the current suite of scientific instruments deployed by the space science community as a whole to study geospace. I wish you good luck with your proposal, and I look forward to working with the team on this project.

Sincerely,



Dr. Kathryn McWilliams

UNIVERSITY OF ALBERTA

February 1st, 2010

Dear Eric

I confirm that I am named as a science collaborator on your PCW-UVI phase 0/A proposal to the Canadian Space Agency, and agree to work to the best of my ability on the tasks you have identified for me in the proposal. In particular, I will work with the team you have assembled in identifying science and space weather synergy between PCW-UVI imager capabilities and data assimilation and modeling capabilities developed within my research program in the department of physics at the University of Alberta. I understand that this requires a time commitment on my part during phase 0/A, and enthusiastically agree to make this commitment.

The proposal to deploy UVI imagers on a pair of polar orbiting satellites such as PCW is very timely. In particular continuous high quality global coverage of the auroral and polar regions is critical to answering many long-standing science questions related to geomagnetic storms that can be imaged by UVI cameras on-board the pair of PCW satellites. It seems fitting that the University of Calgary should lead this effort as a result of their long and successful history in designing UVI imagers that flew on the Swedish Viking and Freja spacecraft.

I strongly support your application and am very excited at the scientific possibilities that will result from placing state-of-the art instrumentation on orbiting platforms.

Yours Sincerely

Robert Rankin

Robert Rankin
Professor
Department of Physics
University of Alberta

Dr. Robert Rankin
Department of Physics
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February 16, 2010

Dr. E. Donovan
Department of Physics and Astronomy
University of Calgary
2500 University Dr. N.W.
Calgary, AB T2N 1N4

I am writing to express my enthusiastic support for your proposed auroral imaging payload for the Polar Communications and Weather satellite program. I am pleased to join you as a collaborator. I look forward to working with your team to develop real-time space weather products for Global Navigation Satellite System (GNSS) users.

GNSS signals experience adverse effects while propagating through the auroral region. The resulting degradation in positioning accuracy and navigation capabilities is a challenge for high-latitude GNSS applications. This is a significant area of research in the GNSS community; for example the European Space Agency has recently committed several million Euros to developing an Arctic GNSS Testbed to study such effects, among others, in anticipation of the next solar maximum. Continuous monitoring of the auroral oval and associated ionospheric disturbances will allow unprecedented advances in international geospace programs and in particular the practical applications in space weather monitoring for GNSS.

We are willing to share GPS data from our Canadian GPS Network for Ionospheric Monitoring (CANGIM). Data from our ground-based sites at auroral latitudes will be used to quantify the level of ionospheric scintillation and impact on GNSS users. Simultaneously observing high-resolution auroral images will allow us to gain insight into the physical drivers and processes – ultimately allowing development of better space weather prediction capabilities.

Sincerely

Susan Skone
Associate Professor

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

February 16, 2010

Reply to Attn of: VP60

Dr. Eric Donovan
Dept. of Physics and Astronomy
University of Calgary
Calgary, Alberta T2N 1N4
Canada

Dear Dr. ~~Donovan~~ Eric,

I agree to be identified on your PCW-UVI Phase 0/A proposal as a "science collaborator". During the study, I will work with the University of Calgary and Routes Astroengineering Teams, providing consultation on technical problems related to using thin films on optical surfaces for UV out of band filtering. This consultation will be provided at no cost to your contract. My involvement will be subject to technology transfer restrictions for NASA.

The planned Canadian Polar Communications and Weather (PCW) satellite program to carry out imaging of polar tropospheric weather, including a secondary payload to image geospace, offers an opportunity for significant progress in understanding the how mass and energy flows in magnetospheric-ionospheric systems determine and control their coupled behavior. It is in the magnetosphere-ionosphere system where the basic physical processes of particle acceleration and transport have the most direct impact on human activity. These impacts include space weather effects on satellite operations, disruption of electromagnetic signals passing through the ionosphere, and dramatic reconfigurations of the electrodynamic currents that connect the Earth to the heliosphere through the ionosphere and magnetosphere. Imaging the high latitude ionosphere for extended periods with significantly improved spatial, temporal and spectral resolution will provide the data required to make advances in understanding the ionopshere-magnetosphere coupling and to increase our knowledge in order to address and mitigate impacts of space weather upon human activity.

I look forward to collaborating in this effort to realize the opportunity offers.

Kind Regards,

James F Spann
Manager, Science and Exploration Research Office
NASA/Marshal Space Flight Center

UNIVERSITETET I BERGEN
Institutt for fysikk og teknologi
Department of Physics and Technology

Bergen, February 15, 2010

Prof. Eric Donovan
Dept. of Physics and Aeronomy
University of Calgary
25000 University Drive
Calgary, Alberta,
Canada T2N 1N4

Dear Eric Donovan:

This is to express my interest in the (planned) Canadian Polar Communication and Weather (PCW) satellite program and confirm that I am listed as a Science Collaborator in the proposal for a Phase 0/A study for 'PCW-UVI' submitted by Prof. Eric Donovan, for a secondary payload for PCW under 'Category B: Geospace Imaging'. I confirm that I will take part in the science definition for the 'PCW-UVI'. I will also express my interest in contributing to the hardware development for the PCW-UVI instrument. In case of any hardware contribution from Norway to 'PCW-UVI', I am aware that I will need to find funding in Norway.
A secondary payload for the PCW satellite like the 'PCW-UVI' will provide unprecedented high quality imaging data continuously (24/7) of the entire northern hemisphere's aurora. Such data will be of great scientific interest for the entire space science community and will further strengthen the role of Canadian space scientists as being in the forefront of auroral imaging from space.



Nikolai Østgaard
Professor
Department of Physics and Technology
Universitety of Bergen, Norway

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Center for Space Science and Applied Research,
Chinese Academy of Sciences

January 28, 2010

Dear Prof. Eric Donovan,

I am writing this letter to strongly support the PCW UVI proposal and be willing to join the PCW-UVI Phase 0/A study as scientific collaborators. The solar wind-magnetosphere-ionosphere coupling is vital to understanding the influence of the solar activity on the geo-space, and the frontier of space weather. Having 24/7 global auroral imaging will give us the key observations to understand this coupling process.

China is developing space science program for next 20 years. In the field of space physics and space environment, the program includes both space-born and ground-based projects. As for the ground-based projects, we will finish the Meridian Project by the end of this year; the second phase of Meridian Project is under discussion as well. The space-born missions will include KuaFu and Magnetosphere-Ionosphere-Thermosphere coupling project (MIT). PCW-UVI focuses on the global auroral imaging, which complements the overall space science program well.

I look forward to the success of PCW-UVI.

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Chinese Academy of Sciences



Chi Wang

Professor/Deputy Director

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Appendix VIII – Statements of Work for Subcontractors

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PHEMOS Mission Payload Phase 0

Statement of Work

to be done by

Routes AstroEngineering ("The SubContractor")

for

The U of Calgary ("The Prime Contractor")

during Phase 0

The following Work Packages, as detailed in the Prime Contractor's response to PWGSC Solicitation No. 9F007-090217/A(PHEMOS), are to be completed by The SubContractor within budget and the time allotted:

1) **WP 3.1.1-0 (PCW Mission Analysis):** Based on a close study of all available PCW Mission documentation, the SubContractor shall achieve a full understanding of the operational environment of the proposed Science Payload.
2) **WP 3.2.1-0 (PHEMOS/PCW Interface Requirements):** Based on an analysis of the PCW Mission, the SubContractor shall generate a list of requirements to be placed upon the PCW satellite by the proposed instrument concept design. The list of requirements shall include power, mass, volume, EMC, thermal, and the pointing & stability requirements of payload for the S/C to provide.
3) **WP 4.1.1-0 (Payload Design Concept):** The SubContractor shall develop a viable payload conceptual design. Towards this end, The SubContractor shall perform a conceptual design, including baffles, optics/coatings, detectors, electronics, controls, data storage and handling. The SubContractor shall define interfaces and any common resources, perform analysis of the concept and confirm compliance to the defined science requirements (WP 3.x), as well as develop a preliminary Concept of Operations.
4) **WP 4.2.1-0 (Payload Engineering Budgets):** The SubContractor shall perform a first-order technical budgeting of mass, volume, power, and dataflow. The SubContractor will perform a first-order orbit radiation analysis and calculate the expected Total Integrated Dose (TID) resulting from the PCW Mission orbit. The SubContractor shall iterate the design (as and if required) to meet the science requirements and available PCW spacecraft resources.
5) **WP 4.3.1-0 (Payload Interfaces and Compatibility):** The SubContractor shall produce a preliminary interface design. This includes determining power, command/control, data output, mechanical (mass, mounting, structural, volume), and thermal requirements and characteristics.

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PHEMOS Mission Payload Phase A

Statement of Work

to be done by

Routes AstroEngineering ("The SubContractor")

for

The U of Calgary ("The Prime Contractor")

during Phase A

The following Work Packages, as detailed in the Prime Contractor's response to PWGSC Solicitation No. 9F007-090217/A(PHEMOS), are to be completed by The SubContractor within budget and the time allotted:

1) **WP 3.1.1-A (Mission Requirements):** The SubContractor shall, based on Phase 0 reports and updated PCW documentation, detail the mission-level requirements that will address the science objectives and measurement needs of the mission. The SubContractor shall refine and produce mission requirements (power, mass, volume, EMC, thermal, pointing) for the S/C to provide.
2) **WP 3.2.1-A (Instrument Requirements):** The SubContractor shall produce an Instrument Technical Specification document that will address the science objectives and the measurement needs of the mission. This shall include documenting the instrument performance requirements including: spatial resolution, coverage, pointing accuracy, precision, dynamic range, noise floor, external and internal scattered light rejection, maximum optical contamination, geometric distortion, passband separation, visible light rejection, and Lyman-Alpha rejection, command, control, & data/telemetry requirements, operational modes, physical (mass, power, volume) requirements, physical interface requirements, environmental requirements, storage/transportation/handling requirements, test requirements, parts & materials requirements, and related.
3) **WP 3.3.1-A (PHEMOS/PCW Interface Requirements):** The SubContractor shall produce list of interface requirements for mission-level work in subsequent phases. This includes requirements as to sun angles, FoV, exclusion angles, cooling (radiator), command, telemetry, data and venting. The SubContractor shall provide an updated list of power, mass, volume, EMC, thermal, pointing & pointing stability requirements that the payload requires the S/C to provide.

4) **WP 4.1.1-A (Design Concept and Trade-offs):** The SubContractor shall perform trade-off analysis to be used as input to later study phases. The SubContractor shall make an effort to optimize and simplify the design in order to minimize instrument complexity and reduce technical/technological risk.
5) **WP 4.2.1-A (Engineering Budgets):** The SubContractor shall update and refine mass, volume, power, dataflow, and thermal budgets and available resources since Phase 0 and shall iterate the design as required and confirm that instrument respects spacecraft resource constraints.
6) **WP 4.3.1-0 (Payload Interfaces and Compatibility):** The SubContractor shall generate instrument failure modes and mitigation strategies, and an updated interface design. Towards this end, the SubContractor shall perform a more detailed analysis of potential and credible failure modes so as to determine and document effect on instrument and satellite operation & performance and to aid in designing the instrument and interfaces in a way that minimizes the effects of such failures. The SubContractor shall identify mitigation strategies to minimize failure modes on the satellite. The SubContractor shall develop an Opto-Mechanical Interface Control Drawing to capture the physical interface requirements of the instrument, including defining a proposed satellite mounting interface.

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PHEMOS Mission Payload Phase 0

Statement of Work

to be done by

NRC Herzberg Institute of Astrophysics ("The SubContractor")

for

The University of Calgary ("The Prime Contractor")

during Phase 0

The following work, which refers to Work Package 4.1.1-0 of the Prime Contractor's response to PWGSC Solicitation No. 9F007-090217/A (PHEMOS), are to be completed by The SubContractor within budget and within the time allotted.

WP 4.1.1-0 (Payload Design Concept)

The SubContractor shall report to the Prime Contractor throughout all activities listed herein.

The SubContractor shall assist the Prime Contractor and Routes AstroEngineering in developing several candidate concept optical systems designs, which are to be based on optical design requirements as derived from Prime Contractor's measurement needs and PCW mission characteristics (such as, but not necessarily limited to, orbit, stabilization, and viewing angle).

The SubContractor shall provide expert review and comment on the concept optical designs, and to make optical performance improvements/optimizations as and if required. The SubContractor shall provide the Prime Contractor and Routes AstroEngineering with Zemax versions of their improved and optimized designs.

The SubContractor shall provide an independent assessment in order to confirm that concept designs will meet set down instrument requirements.

The SubContractor shall assist Routes AstroEngineering in identifying and assessing optical systems technical and/or technology risks, and will also identify potential sources for manufacture.

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PHEMOS Mission Payload Phase A

Statement of Work

to be done by

NRC Herzberg Institute of Astrophysics ("The SubContractor")

for

The University of Calgary ("The Prime Contractor")

during Phase A

The following work, which refers to Work Package 4.1.1-A of the Prime Contractor's response to PWGSC Solicitation No. 9F007-090217/A (PHEMOS), are to be completed by The SubContractor within budget and within the time allotted.

WP 4.1.1-A (Design Concept and Trade-offs)

The SubContractor shall report to the Prime Contractor throughout all activities listed herein.

The SubContractor shall support Routes AstroEngineering in performing trade studies where various elements of the design are traded-off with an overall goal of simplifying manufacturing, alignment, and reducing cost, while maintaining adequate margins at EOL on technical performance.

The SubContractor shall work with Routes AstroEngineering in re-assessing technical and technology risks, and to identify potential sources/facilities for manufacture both inside and outside Canada. They shall also work together to assess the cost of developing key new capability within Canada.

The SubContractor shall work with Routes AstroEngineering and the Prime Contractor to develop Technology Roadmaps for those FUV optics and FUV optical materials related technology items whose TRL maturity is too low for the mission requirement and requires further development in order to achieve the required TRL maturity level.

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PHEMOS Mission Payload Phase A

Statement of Work

to be done by

Dr. Leroy L. Cogger ("The SubContractor")

for

The University of Calgary ("The Prime Contractor")

during Phase A

The following work, which refers to Work Packages of the Prime Contractor's response to PWGSC Solicitation No. 9F007-090217/A (PHEMOS), are to be completed by The SubContractor within budget and within the time allotted.

The SubContractor shall report to the Prime Contractor throughout all activities listed herein.

WP 3.1.1-A (Mission Requirements)
The SubContractor shall review mission-level science and measurement requirements to help ensure that they adequately address the overarching science objectives of the mission. The SubContractor shall assist in finalizing the science and measurement requirements, as input to CDRL EN3.

WP 3.2.1-A (Instrument Requirements)
The SubContractor shall assist in reviewing and revising instrument requirements, as to resolution, coverage, pointing accuracy, measurement precision, etc., in order to ensure that they meet measurement needs of the mission. This shall provide input to CDRL EN4.

WP 4.1.1-A (Design Concept and Trade-offs)
The SubContractor shall assist with reviewing the conceptual rdsign and perform a Compliance Matrix check and verify that science and mission objectives are met. The SubContractor shall comment on potential risks and advise on mitigation strategies, as well as help perform concept design trades to improve design for lower cost/technical. This shall provide input to CDRL EN5.

Appendix IX – CDRL SC1 (Preliminary)

Document No. PCW-UVI.CDRL.SC1.0001. Preliminary
Rev 0001
February 17th 2010

Science Objectives and User Needs Definition Document

PCW-UVI
CDRL SC1

Contract No. XXXXXXXX
Prepared for:
Canadian Space Agency
Prepared by:
University of Calgary (Eric Donovan, PI)
2500 University Drive N.W
Calgary, AB T2N 1N4
(403)-220-6337
CAGE CODE: 1C344

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1. Scope

This document has been written to formally define the science objectives and user needs for the PCW-UVI mission. This is a preliminary draft that will be finalized by the mid term-report milestone in the Phase 0 contract. This document is referred to as:

PCW-UVI.CDRL.SC1.0001. (Preliminary)

2. Applicable and Reference Documents

A complete list of scientific and technical references are attached at the back of this document in appendix A and appendix B.

3. Introduction

Geospace processes are important for expanding our fundamental knowledge of the cosmos and for applications. For a "fundamental knowledge" example, the Sun-Earth system is the only astrophysical object in which magnetic reconnection and its consequences can be directly observed [see e.g., *Biskamp* [2000]). Real-world applications with societal and economic effects include degradation of the ability of GPS systems to provide position by ionospheric scintillations that owe their origins to magnetosphere-ionosphere coupling, and possible links between space weather and climate.

Early on, it was discovered that geospace sub-systems interact with each other, and that larger-scale processes are powered by radiation and the solar wind. *Dungey* [1961] and *Axford and Hines* [1961] led the way, proposing theories of global convection powered by magnetic reconnection and viscous interactions. The objectives of the International Solar Terrestrial Physics[1] (ISTP) program were to identify energy and mass pathways through geospace, quantify their effects, and to understand the underlying physics (*Acuña et al.,* [1995]). Figure 4.1 represents this overarching concept of smaller-scale plasma processes mediating energy and mass transport from the solar wind and through geospace.

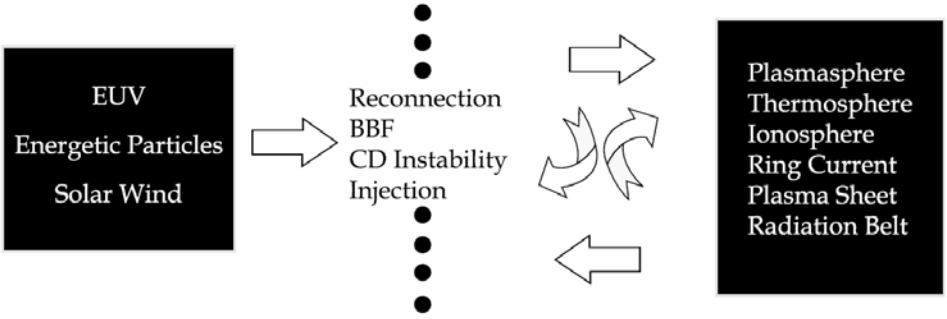


Figure 4.1: Energy and mass enters geospace from the Sun and solar wind. Physical processes affect mass and energy transport through geospace, and how it is divided and deposited in sinks (right box). These sinks interact with each other through physical processes. In this way, geospace is active, and much of the observed dynamics are intrinsic to the system rather than impressed upon it. Figure from *Donovan et al.* [2007].

[1] This applies also to the subsequent International Living With a Star (ILWS) program.

Geospace energy and mass transport requires simultaneous solar input, geospace system level[2] information, as well as *in situ* observations. *In situ* contributions target the processes and gradients such as reconnection or boundaries, while system level measures are used to quantify effects on elements like the ionosphere and the Central Plasma Sheet (CPS). This "telescope-microscope" approach [*Baker et al.* 2002] motivated the choice of instruments and orbits in the ISTP constellation. Cluster, Geotail, and Polar provided direct observations of small-scale processes, and the system level view came from imagers on Polar and extensive networks of ground-based instruments (see e.g., the ISTP special issue, *Space Science Reviews,* 71:1-877). Presently increasing focus is being paid to the system level geospace approach, where different tools simultaneously probe processes on different scales. This figures highly, for example, in the Executive Summary (page v) of the NASA 2009 Heliophysics Roadmap[3] (herein NASA2009). It is interesting to contemplate the geospace missions planned for the 2012-2016 Canadian Polar Communications and Weather (PCW) satellites era. Figure 4.2 shows the anticipated geospace mission lineup based on information from various sources including NASA2009.

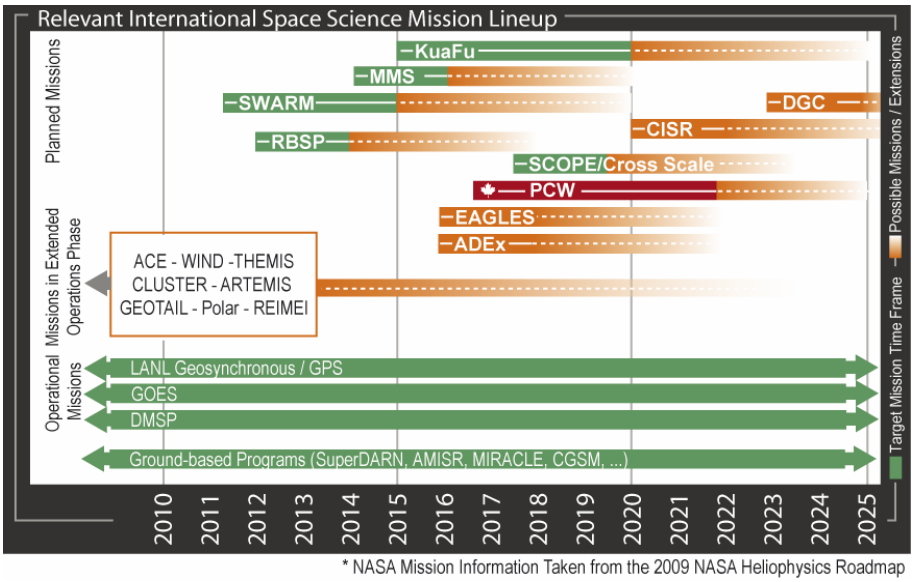


Figure 4.2: Geospace mission lineup. Green and orange indicate approved and proposed (or extended) missions.

We only point out four missions specifically, as most acronyms/scenarios are part of the lexicon of our field. ADEx (Auroral Dynamo Explorer) is a proposed NASA mission of 9 near-equatorial satellites with the objective of identifying the magnetospheric driver of auroral arcs (see Kepko letter). CISR (Climate Impacts of Space Radiation) is LWS science target #7 in the NASA Roadmap with a yet to be identified mission. DGC (Dynamic Geospace Coupling) is another Roadmap science target (LWS #8), aimed at imaging multiple geospace systems (e.g., the inner CPS and the aurora) simultaneously. EAGLES is a proposed Mission of Opportunity that would carry out Energetic Neutral Atom (ENA) imaging from two geosynchronous satellites (see Brandt letter).

Between GOES, LANL, MMS, THEMIS, RBSP, and possibly Scope/CrossScale and ADEx, the PCW era promises the most comprehensive probing of the near-equatorial magnetosphere in history. There will be at least 15 and as many as 30 satellites giving us an unprecedented opportunity to investigate the smaller scale processes important in geospace. Surprisingly, no system level observations (except the EAGLES ENA imaging) are planned for this timeframe. There is a risk that in spite of this remarkable armada, we will not know how these processes act across scales, how they fit into the larger

[2] This can be thought of as synoptic and/or large (even global) scale.
[3] See http://sec.gsfc.nasa.gov/sec_roadmap.htm

dynamics, nor address fundamental long-standing questions related to magnetosphere-ionosphere coupling and the aurora. **PCW-UVI will address this.**

4. High-level Science Objectives

While the potential uses of the PCW-UVI data are almost endless for the field of space science, the PCW-UVI mission has targeted four scientific objectives that are critically enabled by the PCW-UVI global auroral imaging program. They are:

Science Objective 1: Magnetospheric Drivers of Auroral Type, Structure, and Dynamics [**Obj.S1**]
Science Objective 2: Geospace Dynamic Coupling [Obj.S2]
Science Objective 3: Space Weather Effects on Climate [Obj.S3]
Science Objective 4: Space Weather Effects on Global Navigation Satellite Systems (GNSS)[Obj.S4]

Complete descriptions of these science objectives given below. The descriptions of these multifaceted objectives have been broken down into sub-themes that identify the set of "key questions" that each objective is meant to answer.

Scientific Objective Descriptions

Cross-scale coupling is critical to Geospace dynamics. Mid-tail magnetic reconnection involves spatial scales ranging from kinetic (diffusion region), to large-scale plasma transport and redistribution, such as during the expansion phase. Bursty plasma jets and new plasma intrusions in the magnetotail provide another example of an intense cross-scale coupling associated with interplay between the size of the plasma bubble (typically 1-2 Re), the traveled distance (many Re), and the small-scale eddy turbulence at the boundaries of the plasma channel (fractions of Re). Near-Earth plasma sheet instabilities associated with current disruption are thought to begin at kinetic scales and propagate up to the global MHD scales in an inverse-cascade.

The future of geospace science will be defined by how well we understand primary mechanisms and basic phenomenology of cross-scale plasma coupling. Auroral observations will be crucial as they remain the only consistent source of instantaneous information on spatially separated but physically connected parts of the magnetosphere-ionosphere system. Most of the scientific results from THEMIS would not be possible without the spatiotemporal picture of moving, evolving, and interacting auroral forms provided by the All-Sky Imagers (ASIs) [see e.g., *Angelopoulos et al.,* 2008; *Kepko te al.,* 2009]. An innovative global auroral imaging mission, taking maximum advantage of the PCW mission design would be able to do this job incomparably better.

Science Objective 1: Magnetospheric Drivers of Auroral Type, Structure, and Dynamics [**Obj.S1**]

In spite of the successes of the coordinated THEMIS *in situ* and auroral observations, there are significant limitations in our knowledge of connections between aurora and their magnetospheric drivers. Addressing this topic motivates our first science objective, work on which will enable more effective use of auroral observations to remote sense the magnetosphere, and answer fundamental questions about the physics of the aurora. There are two subthemes, the first of which is the establishment of one-one connections between specific aurora and magnetospheric counterparts, and involves questions exemplified by "**what is the magnetospheric counterpart of an auroral arc**?", "**is there an ionospheric signature of mid-tail reconnection?**", and "**what physical processes give rise to diffuse aurora?**"

These long-standing questions need to be resolved in order to establish a complete picture of auroral physics. There has been some headway on each. Comparisons of *in situ* plasma and magnetically conjugate ASI observations have hinted at a connection between sharp steps in CPS electron temperature and auroral arcs [*Borovsky, Cully, separate private communications*], and Field Line Resonance fields (thought to be associated with arcs) that have been observed *in situ* [*Sarris, et al.,* 2009]. Previous studies have ascribed the formation of arcs, auroral brightenings, and X-ray enhancements to mid-tail reconnection [e.g., *Ieda et al.*, 2001; *Sergeev et al.*, 2005; *Borg et al.*, 2007]. Recent theoretical work and *in situ* observations are making connections between plasma wave modes and pitch angle scattering that is ostensibly the cause of diffuse auroral precipitation [e.g., *Ni et al.,* 2008; *Liang et al.,* 2010]. The reality is, however, the connections that have been made between these aurora and their magnetospheric counterparts are tenuous. Difficulties include the subtlety of the magnetospheric effects and lack of simultaneous auroral arc observations, inadequate global scale observations and *in situ* measurements from single satellites that cannot adequately isolate magnetospheric effects like reconnection, and lack of simultaneous auroral and *in situ* measurements and the fact that there are a number of different types of diffuse aurora.

During the PCW timeframe, the Cluster-type geospace missions (e.g., MMS and Scope) will directly observe the gradients and reconnection. All geospace satellites will obtain point measurements of wave modes and reconnection effects, and the plasma conditions around sharp boundaries. The overall effect could approach that envisaged for Magnetospheric Constellation[4], with a fleet of satellites providing *in situ* observations of the plasma properties and dynamics related to aurora, with the required density (from the clusters) and extended coverage and quality of measurement (from all) to separate space and time effects and appropriately sample the magnetospheric counterparts to the sub-auroral, and auroral regions. One significant opportunity, for example, will be the first extensive probing of the transition region between stretched and dipolar field lines, a region which has been the focus of Canadian efforts to understand auroral physics [e.g., *Samson et al.,* 1992; *Knudsen,* 1996; *Rankin et al.,*2005]. PCW-UVI will make appropriate images of aurora magnetically conjugate to the *in situ* observations *always available*. We expect, with PCW-UVI in conjunction with contemporaneous *in situ* geospace observations, to bring closure to the three questions listed above, and usher in a new era of understanding **the relationship between aurora and their magnetospheric drivers.**

The connection between aurora and the magnetosphere complements our second subtheme**,** multi-scale processes in the magnetosphere-ionosphere system. There is growing interest in multi-scale analysis of auroral and other geospace data from which various scaling laws and inferences about the physics that underlies geospace dynamics have been made. One example is recent work showing the power law for the auroral spatial distribution depends on latitudinal position with the auroral oval, ostensibly pointing to different dynamical drivers in the inner and outer CPS [*Uritsky et al.,* 2009]. This type of "Natural Complexity" work is founded on the principles of statistical physics, and brings the concepts like Self Organized Criticality (SOC) to geospace science [e.g., *Watkins et al.,* 2001]. The auroral distribution offers us our best view across all relevant scales, but there are difficulties. There is a lack of simultaneous observations across all relevant scales, a lack of time series of such observations, limited understanding of the connections between aurora and their magnetospheric drivers (e.g., how much of the auroral structure is reflective of structure in the CPS?), and difficulties with bridging the gulf between complexity research and the more traditional "reductionist" geospace style.

Research under the first subtheme will better enable us to assess how well auroral structure reflects structure in the CPS. High quality auroral imaging during the PCW timeframe when the magnetospheric fleet discussed above is operating, will provide our community with an unprecedented opportunity to foster stronger ties between the traditional geospace community and the natural complexity community. We will take advantage of the PCW mission characteristics and design PCW-UVI to specifically address

[4] See http://stp.gsfc.nasa.gov/missions/mc/mc.htm

the lack of simultaneous auroral observations across all scales, and the lack of time series of those observations (see data subsection). These new auroral observations will allow us to use PCW-UVI to address and close exciting new questions related to multi-scale dynamics. Two examples of such questions are "**what are the dominating particle acceleration mechanisms operating at different spatial auroral scales?"** and "**how do the scaling parameters of the auroral oval (probabilistic scaling laws, structure function exponents, spatial power spectra) change with large-scale reconfigurations in the magnetosphere-ionosphere system as reflected by global geomagnetic indices (AU/AL/AE, Pc, Kp, Dst, etc.)?**"

Science Objective 2: Geospace Dynamic Coupling [Obj.S2]

We borrowed the name of this objective from the NASA2009. This objective will be realized with an innovative imaging strategy on PCW, carried out at the same time as *in situ* observations. We will address questions in three subthemes, the first being "solar wind driving of geospace dynamics". Dayside physical processes have a direct impact on magnetospheric and ionospheric dynamics through reconnection, surface waves, and other processes. Some of our best insights into these processes and their geospace effects have come from *in situ* observations near the magnetopause combined with radar and optical observations in the vicinity of the cusp [see e.g., *Amm et al.,* 2005, and references therein].

During PCW, the THEMIS, MMS, and possibly Scope/CrossScale missions will provide unprecedented multi-scale dayside magnetopause observations. The new PolarDARN and RISR radars will provide unprecedented, multi-scale observations of the convection response to the dayside processes. Finally, PCW-UVI will provide unprecedented multi-scale dayside auroral observations. The combined radar and optical observations would always be available complementary to *in situ* dayside observations, and would provide quantitative evidence of electric currents, dayside reconnection, and convection changes in response to dayside phenomena [see eg. *McWilliams et al.,* 2001; *Mozer et. Al.,* 2003; *Moen et al.,* 2008; *Hosakawa et al.,* 2010] Using this combination of observations, we will address specific questions including "**how do dayside conditions determine if magnetic reconnection is steady or bursty?**", "**how do dayside processes affect the formation of polar cap patches?**", "**how are poleward moving auroral forms produced?**" and "**what is the impact of solar wind turbulence on the polar cap plasma?**". Answers to these and related questions will provide insights into how dayside processes form structure in geospace plasmas, and drive magnetospheric dynamics.

The second subtheme is long duration geomagnetic events. This subtheme was the original motivation for the Ravens mission as outlined in the Ravens Mission Concept and *Donovan et al.* [2007]. Every global imaging mission flown to date has utilized only a single satellite platform, which means that the longest duration global imaging achievable to date is around ten hours. However, many geospace events such as steady magnetospheric convection (SMS) events, sawtooth events, and geomagnetic storms last for many hours or even days (see e.g., *Yahnin et al.,* [1994], *Belian et al.,* [1995], and *Chapman and Bartels*, [1967], respectively). Consequently the system level view that would be provided by PCW-UVI was not available for the durations of these events, limiting our ability to quantify, for example, energy deposition and magnetospheric state during those events.

PCW-UVI images will be continuously available for the duration of the mission. The auroral observations, in combination with radial cuts of the CPS/ring current (see e.g., Figures 2 and 3 of *Runov et al,* [2008]) by magnetospheric satellites including THEMIS, RBSP, and possibly ADEx, will allow us to determine the ionospheric projection of the earthward edge of the electron plasma sheet. Particularly at the inner edge of the plasma sheet, there is an interesting and not fully understood relationship between convection, flux tube energy content, precipitation, and the cross-tail, ring and Region II field-aligned currents. This is particularly interesting during extreme long-duration events such as storms, which have durations of several days or more. During these events, auroral activity moves equatorwards to even mid-latitudes, and the CPS moves inwards across the outer radiation belts, providing a seed population for the ring current, while at the same time plasmaspheric material is drawn outwards into the trough and inner

CPS [see e.g., *Goldstein et al*., 2005; *Henderson et al*., 2010]. With continuous global auroral imaging we will be able to image such long-duration geomagnetic events end-end for the first time. We will be able to address questions including "**how does the CPS act as a seed population for the inner magnetosphere?**"

The possibilities for exploring the inner magnetospheric dynamics using PCW-UVI are dramatic, especially when one considers the possibility of simultaneous multi-point ENA observations from EAGLES, should that Mission of Opportunity be selected. ENA imaging is the only method we have at our disposal for imaging the 3D magnetospheric plasma pressure [see e.g., *Roelof et al.,* 1985; *Burch,* 2005]. The particle pressure distorts the geomagnetic field magnetic field and drives a 3D electrical current system that connects the magnetosphere with the ionosphere which can be inferred from the ENA images [see e.g., *Brandt, et al.*, 2008]. Note that while such combined imaging has been available before, the combination of PCW-UVI and EAGLES ENA would be the first time that such geospace imaging was available 24/7 and in 3D (for the ENA images from two geosynchronous satellites).

PCW UVI, together with EAGLES ENA imaging, will allow us to simultaneously image the auroral distribution and 3D magnetosphere. This capability, illustrated by ENA and UV images from IMAGE, is illustrated in Figure 4.3. If EAGLES and PCW-UVI are funded, we will be able to track the time-evolving auroral distribution and 3D inner magnetospheric plasma distribution through long-duration geomagnetic events. With this capability, we could address questions such as "**what is the role of the substorm in the storm?"** and "**how does O^+ of ionospheric origin affect geospace dynamics during long-duration geomagnteic events?"**

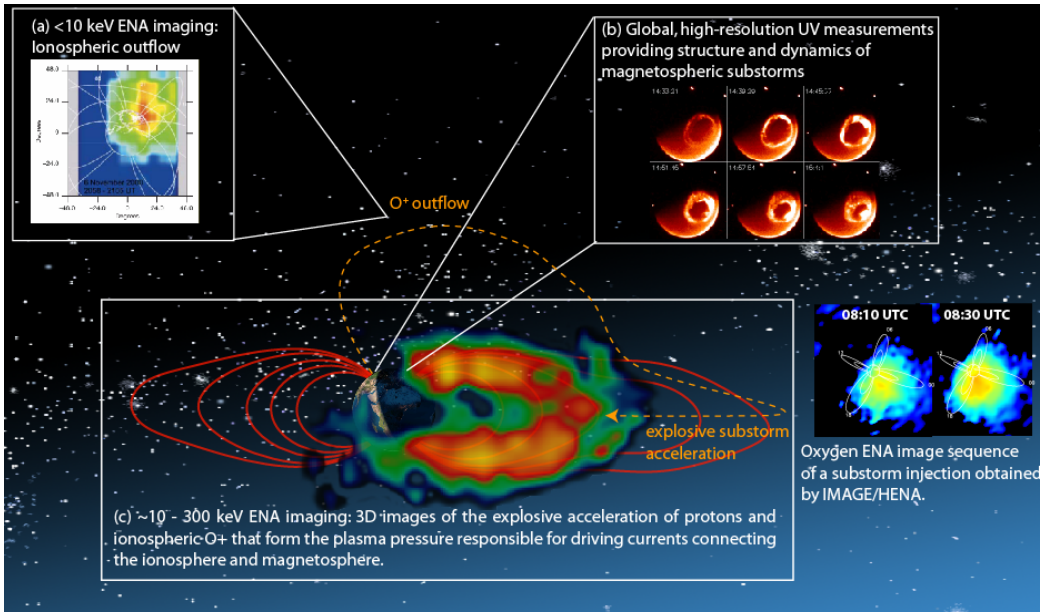


Figure 4.3: Combining UV auroral imaging with global and simultaneous ENA imaging enables PCW to address the critical question in space weather at the system level for the first time.

Science Objective 3: Space Weather Effects on Climate [Obj.S3]

Our third science objective, which relates to the important environmental issue of ozone depletion in Earth's stratosphere, is our riskiest but potentially has the most societal impact. Nitrogen oxides (odd nitrogen) $NO_x = NO + NO_2$ are the dominant ozone-depleting substance [*Ravishankara et al*., 2009]. A significant source of NO_x comes from energetic (including auroral) particle precipitation [*Funke et al*., 2005; *Randall et al*., 2007], which causes excitation, dissociation, and ionization of neutrals, generating odd nitrogen at high altitudes which is transported downward during the polar winter to the stratospheric ozone layer initiating its catalytic destruction. There have been no continuous global optical observations

for tracing auroral zone NO_x generation over the extended periods relevant to the atmospheric response [*Lopez-Puertas et al*., 2005]. NOAA POES is used for this, but infers the auroral power based on *in situ* measurements from polar passes separated by 100-minute time gaps. Without consistent quantitative global auroral data, evaluation of middle atmosphere chemistry climate models and isolating environmental NO_x effects is difficult.

We propose to use PCW-UVI for exploring linkage of solar variability, magnetospheric dynamics, and the chemical and climatological state of the middle atmosphere. PCW-UVI would give a total auroral power time series as well as the spatial distribution of precipitating auroral particles. Using estimates of mean energy and energy flux precipitation models would be used to generate NOx profiles in the MLT which would be used in CMAM to estimate impacts in the middle atmosphere [*Semeniuk et al*., 2008]. Enhancement of NOx in the middle atmosphere may be apparent in enhanced HNO3 measured by PHEMOS-FTS in nadir viewing. There may be other limb viewing satellites such as PREMIER for vertical profiles. We will utilize data from PCW spectroradiometer LWIR channel (total ozone), national ozone monitoring programs around the world[5] and instruments on potential NASA[6], ESA[7], or CSA missions, and/or the potential PCW/PHEMOS FTS/UV-vis-NIR instrument to track the ozone response.

We will have time series of auroral input and ozone. We will use these measurements to study direct and indirect (delayed) response of odd nitrogen species in lower thermosphere and upper mesosphere to auroral precipitation events. Our objective will be to answer questions such as "**What is the typical time sequence, and what are the characteristic time scales, of the ozone depletion initiated by auroral precipitation events**?" and "**How does the position of a precipitation event affect the production of NO_x in a local and global sense, and which auroral regions provide the largest concentration of NO_x?"** Finally, using the data from solar wind and geosynchronous satellites, we will study the role of the solar wind driver, as well as relative contribution of ionization due to solar proton events, energetic electron precipitation, and low-energy electron precipitation to this process, to address the question **"Under what physical conditions does the auroral precipitation become the dominant factor for NO_x production?"**

This research would be a partnership between auroral researchers and atmospheric scientists, and could form the basis for a PHEMOS Science Payload incorporating elements from Category A and Category B. The results of proposed studies will be useful for evaluating and constraining global ozone depletion models including the odd nitrogen contribution, for exploring any influence it might have on climate and environment. They will also provide a better understanding of the relative importance of space weather factors and human activities in NO_x emissions, which could impact future political decisions involving protection of our planet`s ozone shield.

Science Objective 4: Space Weather Effects on Global Navigation Satellite Systems (GNSS) [Obj.S4]

Our fourth science objective is our most applied. Ionospheric range delays are the largest GNSS error source[8] [*Klobuchar,* 1996]. They are proportional to the free electron density along the signal path. These effects are reduced by applying an external model or differential processing. Such methods are not generally effective, however, during enhanced ionospheric activity [*Skone and Yousuf,* 2007].

Canadian efforts have focused on reducing the impact of auroral phenomena on GNSS. Auroral zone meters- to kilometers-scale irregularities cause rapid GNSSS signal phase and amplitude variations which can cause the loss of GNSS capabilities [*Smith et al.*, 2008]. During the past solar maximum such

[5] This includes Canada's Ozone and Ultraviolet Research and Monitoring (http://woudc.ec.gc.ca/e/ozone/ozone.htm)
[6] E.g., NASA's Earth Science Mission Profile plans for two Ozone Mapping and Profiler Suites during the next decade.
[7] E.g., ESA EOP MetOp series.
[8] This includes the best known GNSS, the Global Positioning System (GPS).

scintillation effects correlated with auroral events [*Skone,* 2001]. Lacking any real-time space weather warning service, surveyors in northern Canada used their own magnetometers in the field to measure auroral activity. Decisions regarding probability of a successful survey and whether to commit cost-intensive resources (e.g. helicopters and manpower) were based on the magnetic fluctuations observed. Other northern GNSS applications adversely affected by enhanced auroral activity include marine navigation – in support of Arctic mapping and hydrographic surveying initiatives – and wide area GNSS augmentation systems for commercial aviation.

The U. Calgary CANGIM[9] tracks GNSS effects of ionospheric auroral scintillations, but only at CANGIM stations [*Skone and Hoyle,* 2005]. We will compare PCW-UVI images and CANGIM assessment of ionospheric effects on GNSS to answer "**how does auroral type relate to the effect of auroral precipitation on GNSS accuracy?"** Our objective is to establish a basis for using auroral characteristics[10] as a proxy for GNSS risk due to ionospheric scintillations. This will form a basis for using PCW-UVI images to create a real-time space weather product. By entering their approximate location a GNSS user would be provided with a map of their GNSS satellite links (PRNs) affected and statistics for expected loss of signal lock, positioning error, etc., based on level of local ionospheric activity as inferred from the PCW-UVI images in real-time. Ultimately, our intention is to work with a Canadian GNSS manufacturer such as NovAtel Inc. to incorporate such a warning into a GNSS augmentation system capability.

The four science objectives and corresponding subthemes listed here represent investigations at the forefront of geospace science and are well aligned with national and international research community interests as espoused in various planning documents. The first science objective encompasses the primary ADEx science objective of establishing the magnetospheric driver of auroral arcs. The auroral and geospace dynamics themes that comprise objectives 1 and 2 are relevant to essentially every geospace theme in SEW2009. The theme of Dynamic Geospace Coupling is NASA2009 science target LWS #8, which specifically identifies global auroral and ENA imaging as enabling observations. In the NASA 2010 Heliophysics Roadmap, "Climate Impacts of Space Radiation" is a priority science target (see LWS #7 on pgs 72-73 of that document). The NASA roadmap committee has "penciled in" a mission under this theme for 2018 (Figure 2). They identify NO production by aurora, vertical transport, and ozone depletion as a critically important problem under this theme, and auroral inputs to the upper atmosphere as one of the measurements necessary for attacking this theme.

5. Mission/Science Objectives

5.1 Links to Canadian Science Objectives

5.2 Science Concept

PCW-UVI is about world class global auroral imaging. Development of this concept has been made a priority by the Canadian Space Agency as evidenced by contracts 9F007-033080 (Ravens Concept Study) and 9F007-080324 (UVAMC Pre-PhaseA Study) held by the Bidder. The Ravens concept study was completed in December 2006 and the UVAMC Pre-PhaseA study is scheduled for completion in October 2010. Expanding on results from these contracts, we present an innovative global auroral imaging

[9] CAnadian GPS Network for Ionospheric Monitoring
[10] Here, we mean spatio-temporal characteristics including intensity, temporal variation, spatial scale, etc.

payload specifically targeted for the PCW mission. The PCW-UVI mission concept involves placing auroral imaging payloads on each PCW satellite to obtain the world's first continuous, real time, global auroral imaging facility. Recent improvements in Far Ultra-Violet (FUV) optics combined with the PCW three-axis stabilized platform dramatically improve detection capabilities in this spectral emission region. As a result, the science objectives described in Section 4.1 are, for the first time ever, achievable via satellite based auroral imaging.

A similar auroral imaging mission concept was proposed for, and subsequently developed with the Ravens Concept Study[11]. Ravens was envisaged as a two-satellite imaging mission providing 24/7 multi-channel FUV observations. The orbits were to be 90^o inclination, with geocentric apogee and perigee at 8 and 1.8 Re, respectively. The satellites were to be spinning. This mission concept was exactly that of KuaFu-B, which was based on Ravens. PCW provides a *slightly lower* quality of view averaged over the auroral and polar cap regions than Ravens[12] but is arguably the best imaging platform to date for the purpose of imaging the North. The Molniya orbits maintain apogee at the highest latitude part of the orbit for the mission duration, so precession of the line of apsides does not limit the duration of effective high-latitude imaging. The satellites are not spinning so that PCW payloads can image at a higher cadence with longer integration times, meaning higher frame rate and better SNR. The pointing requirements for the primary meteorological payload are significantly better than would have been possible on the spinning satellites, so as a matter of course, knowledge of position of auroral features will be optimized and negative effects of wobble will be minimized. The longer integation time and stable pointing of the nadir pointing imagers will also allow for better spatial resolution than would otherwise be possible. PCW-UVI will produce, without a doubt, the most spectacular and scientifically useful global auroral imagery to date.

WAVELENGTH SEPARATION (ENERGY RESOLUTION)

Isolation of parts of the auroral spectrum is an absolute necessity for the ultimate quantification of the flux and characteristic energy of auroral electrons, which are in turn essential to our ability to truly understand magnetosphere-ionosphere coupling, and magnetospheric dynamics. The instrument-specific objectives for UVI are to achieve appropriate spatial resolution and suppression of out of band contributions to two isolated parts of the LBH band.

Deriving the spatial distribution of the average energy and total energy flux of precipitating particles on a global scale is critical to determining ionospheric conductivity and quantifying the impact of solar forcing and magnetic storms to the neutral atmosphere. To quantitatively do this on a global scale is a difficult task. Several instruments have imaged the high latitude regions on a large scale both on the day and night side including AI (DE-1), Viking, UVI/VIS/Pixie (Polar), FUV-WIC/SI (IMAGE). Each of these instruments is responsible for significant strides toward understanding the dynamic nature of the global aurora and the first quantitative assessments of large scale auroral energetics.

The most direct way of deriving the auroral energetics is to compare large scale images in two spectral regions of the far-ultraviolet Lyman-Birge-Hopfield (LBH) band-system, for example 140-160 nm (LBH

[11] and the ongoing UVAMC study
[12] when Ravens has apogee at 90 degrees latitude

short) where O2 absorption at auroral altitudes is significant and 160-190 (LBH long) where the emissions are relatively free of absorption and the brightness in rayleighs is linearly related to incident energy flux (Strickland et. al., 1983; Germany et. al., 1994 a, b, 1990). Other approaches have been employed that are more model dependent. These use auroral observations that include 135.6, 130.4 nm OI lines, broadband LBH observations, 121.6 nm Doppler shifted hydrogen Lyman-α and auroral X-rays (Lummerzheim et. al., 1991, Hubert et. al., 2002, Østgaard et. al., 2002). There is evidence that the contribution of proton precipitation is not significant for magnetically disturbed events but should be taken into account for quiescent periods (Hubert et. al, 2002 and see previous section).

Dr. Dirk Lummerzheim of the Geophysical Institute in Fairbanks, Alaska calculated the expected brightness of the N2 LBH bands for a given electron energy flux and a range of average electron energies [*Ravens Concept Study*, Contract 9F007-033080, Final Report]. His calculations correct for attenuation in the atmosphere and therefore provide the auroral surface brightness as viewed from above the atmosphere. In order to study the feasibility of using LBH-short and LBH-long specifically, we summed the brightness values within each of the two spectral ranges. The numbers presented here therefore refer to the photons incident on the instrument without taking into account the instrumental characteristics such as the actual shape of the filter passbands. A more thorough analysis will be undertaken when the instrument characteristics are known.

The numbers show that LBH-long brightness is in the range 100 to 250 R when the **electron energy flux** is 1 milliwatt per square meter (mW/m2) and the average precipitating electron energy is in the range 1 to 10 keV. This energy flux gives rise to about 600 R of emission in the N2+1NG(0,0) band at 391.4 nm which corresponds to a relatively weak aurora. The instrument should therefore be capable of measuring at least 100 R in the LBH-long range. A 30 R/exposure noise contribution represents about 0.3 mW/m2 uncertainty in the energy flux. For bright auroras (10 to 100 mW/m2), the uncertainty due to the instrument noise becomes insignificant. This simple analysis shows that a camera with a 50 R sensitivity will have the necessary sensitivity to allow the electron energy flux to be extracted from the data.

However, further analysis is required. For example, it is known that proton precipitation, although weaker than electron precipitation also results in N2 LBH photon emission; therefore, realistic models of global proton energy precipitation must be examined to ascertain the relative contribution of protons. The combination of a reliable precipitation model should help reduce this source of error. Another source of uncertainty is the fact that the LBH-long emission rate is not completely independent of the average electron energy, i.e. the emission rate is somewhat higher for incoming electrons at higher energy. Preliminary analysis indicates that this effect can introduce a variation of about 10 to 20% for the electron energy range 1 keV to 10 keV at all energy flux levels. This lack of complete independence was investigated by the Polar UVI team [Germany et al. 1998].

A second necessary component of this preliminary analysis is to verify the feasibility of obtaining the **average electron energy** from the ratio of the LBH-short to LBH-long. The validity of this technique relies on the fact that the O2 molecules absorb many more photons in the LBH-short wavelength range than in the longer LBH-long range. The Polar UVI team calculated the ratio for an electron energy range up to 10 keV based upon the UVI filter bandpasses. Using Lummerzheim's tables for the range 1 keV to 10 keV, we have calculated the expected LBH-short to LBH-long brightness ratio for the incoming electron flux in the two spectral ranges. These are shown in the figure below for an electron energy flux of 1 mW/m2.

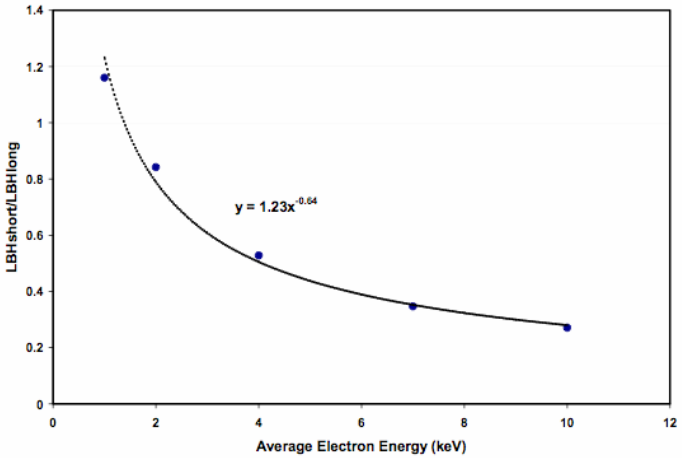


Figure 1 Expected LBH-short to LBH-long brightness ratios as a funtion of average electron energy, given an electron energy flux of 1 mW/m^2

It is obvious that the expected uncertainty of this technique depends strongly on the auroral brightness. For a weak aurora (IBC I) that corresponds to an electron energy flux of around 1 mW/m2 or less, the uncertainty is large for a single exposure with a noise equivalent signal of 30 R. However, for moderate auroras with energy flux near10 mW/m2, the uncertainty introduced by the measurements is relatively small and is likely dominated by other sources of uncertainty such as variability in the O2 density in the 100 to 150 km altitude range. It will therefore be important to utilize the best available model atmospheres for the analysis and to make the best estimates of uncertainty that can be generated by errors in the models. This topic will require considerable study during the pre-launch period. The good news is that this analysis technique is independent of the N2 density because the same species emits in both spectral ranges.

In order to utilize these (or other) FUV intensity ratios and absolute values to infer characteristic energy and energy flux, the following technical requirements must be met.

First, and most obviously, we must have simultaneous spectrally resolved images of the two regions of the FUV band.

Second, we must either characterize the out-of band contributions to these signals, or we need to sufficiently suppress them. The total signal due to scattered visible and IR sunlight is approximately 1E+11 R [Torr et al., 1995]. If we wish to measure auroral signal on the order of 100 R the daylit side, the long-wavelength continuum Earth albedo contribution must be reduced by a factor on the order of 1E+9. Although this is getting ahead of this stage of the development, this would be achieved by using a *very* pure CsI photocathode (1E+6 rejection) and radiation-hard FUV dielectric filters (1E+3 rejection). *It is important to note that driving down out-of-band contributions will be expensive, complicated, and risky. This needs to be investigated – the cost implications are a risk from this particular point.* Separating the LBH into two spectrally resolved parts, and driving down the out-of-band contributions to the signals requires more light, and in turn a larger aperture, and ultimately a heavier, more complicated, and more expensive instrument. Dealing with those issues (or establishing whether we can back off on these stringent requirements and still meet our scientific objectives) will be dealt with in Phase 0 (provided we are selected for Phase 0), and likely the single biggest factor in determining the cost of the instruments to Canada. Among other viable options being considered is to image the strong OI 130.4 nm line, or the OI

135.6 nm line which behaves very similarly to LBH-long, along with the *entire* LBH band, for increased photon flux, and use the LBH band and OI/LBH ratio (instead if LBH-L/LBH-S) to derive the desired quantities, as was done on Viking and Freja. The costs and benefits of these various options are illustrated in Table 1.

Third, we must also characterize the contributions to both spectral regions due to secondary electrons created by primary auroral proton precipitation, as mentioned above.

Additional uncertainties that must be propagated are:

- Effect of O2 absorption uncertainty
- Airglow
- Scattered sunlight
- S/N considerations for estimated LBH signal
- Calibration uncertainty

		LBH-L / LBH-S	OI1356 / LBH	OI1304 / LBH
SCIENCE	BENEFIT	Can determine column integrated Hall and Pederson conductances (*)	Potentially more signal, better SNR	Strongest line in the FUV electron aurora, implies better SNR
		Most accurate determination of energy flux and energetic electrons (E>3 keV)	Very sensitive to characteristic electron energy across all energies	
		Less Atmospheric model-dependent	Good spatial resolution	
	COST	Not a sensitive indicator of characteristic electron energy <3 keV	No column integrated Hall and Pederson conductances	Resonantly scattered severely lowering spatial resolution of emitting source
		LBH contains weak lines, potentially low SNR	OI1356 depends on the highly variable (time/space) altitude distribution of O	The ratio depends heavily on O/N2 density ratio
		Determination of conductances require an atmospheric model		
ENGINEERING	BENEFIT	Suitable optical materials conveniently available	Potentially more signal, simplifying optical design	Potentially more signal, simplifying optical design
		Can draw upon polar UVI heritage for Filter and Window materials	Less stringent requirements as to VIS-IR albedo rejection?	Viking/Freja heritage
		Same optical design can be used for both imagers (similar expected signal)		Less stringent requirements as to VIS-IR albedo rejection?
	COST	Need fast optical system due to limited signal in LBH-l and LBH-s	Narrow-band OI filter potentially difficult to design, may have to compromise	Narrow-band OI filter potentially difficult to design, may have to compromise
			Potentially need for heating of intensifier window to avoid OI 130.4 nm line.	Potentially need for heating of intensifier window to avoid Lyman-alpha

Table 1: Costs and Benefits of three different choices of wavelengths for FUV ratio measurements.

RAYLEIGH SENSITIVITY

To assess the intensity requirements we should be going after, we decided to focus on the evening sector aurora, and more specifically taking data from 280 periods during January to April 2001 when IMAGE had a good view of the evening sector auroral oval. We wanted to make sure that this data reflected the typical range of magnetic activity. To do this, we compared SYM-H for the periods of interest with SYM-H for an entire solar cycle. (The SYM-H index is a one-minute estimate of the average deviation of the northward equatorial magnetic field, and with caveats discussed in [Wanliss and Showalter, 2006] can be treated as a high time version of DsT. Large negative SYM-H corresponds to storm-time conditions.) The results of that comparison indicate that we have an excellent cross-section of magnetic activity, according to SYM-H (which is the most appropriate index in terms of magnetic storms at least). We took that data, and focused our attention on typical auroral latitudes in the 2300 MLT sector. This in turn was used to create the histogram in Figure 2. Note the noise floor which we assert is due to a combination of readout noise and the exponential noise from the intensifier. Note also that the peak of intensity occurrence is roughly 200 Rayleighs above the noise floor. We limited our latitudes to just encompassing the typical auroral oval, and so we believe (though we cannot prove) that the decrease in frequency of occurrence left of the peak represents a true decrease of occurrence (ie., in the oval there is a peak in occurrence that is away from 0). Further, the decrease if it is real as we suggest is a convolution of the true occurrence statistics and the instrument response. In any event, we see that the peak intensity is ~200 Rayleighs above the noise floor, and most intensities are above that (in the evening sector auroral zone). Taking the rule of thumb discussed above, we assert that we will be able to do as well as IMAGE WIC in terms of intensities if we target a sensitivity of 100 Rayleighs (i.e., as well in each of the two spectrally resolved channels). If we target lower intensities (which we intend to), we will do better.] At the present time we believe we can get to 50 Rayleighs in each channel, which in each channel will be significantly better than IMAGE.

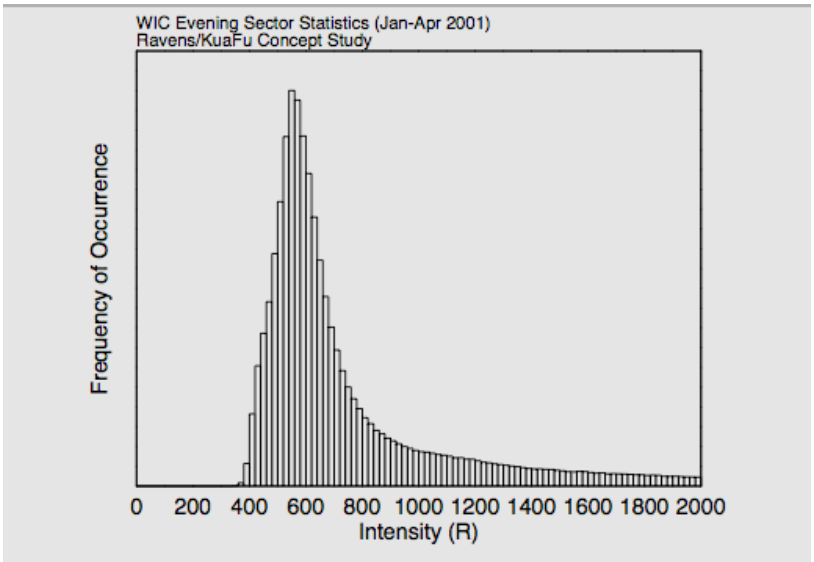


Figure 2 Histogram of WIC intensities for the 280 periods studied (see text). Original image contained in the Raven Concept Design Report

As might be expected, considering differences is more challenging in terms of interpretation. The histograms shown in Figures 2 and 3 show differences in space (between adjacent pixels separated north-

south) and time (same pixel adjacent frames), broken down according to brightness. We are most likely most interested in accurate tracking of changes in bright features . As well, subject to the caveats above, those differences are probably comparable in IMAGE WIC and PCW-UVI (each channel), at least within a factor of 2. Looking at the top two panels of each stack plot of histograms, again the number 100 Rayleighs could be viewed as a reasonable target. We will target 50 Rayleigh sensitivity, and based on this cursory discussion we believe that we will be able to track bright quickly changing small features better than has ever been done before.

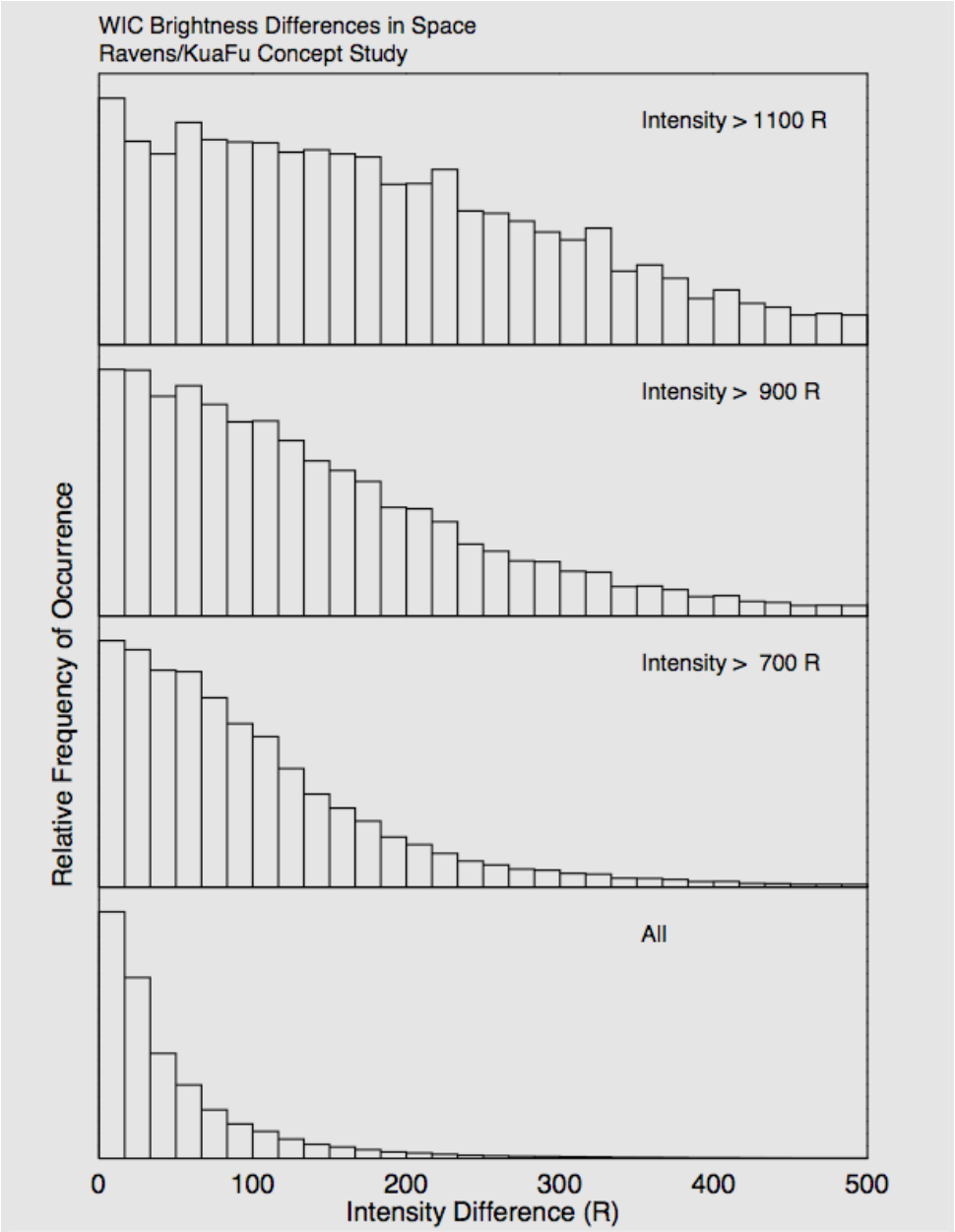


Figure 3 Histograms of differences in intensity between adjacent pixels in WIC that are roughly aligned north-south (in separation), broken down in terms of brightness of those pixels. Original image contained in the Ravens Concept Design Report.

SPATIAL RESOLUTION

Straightforward consideration of orbital parameters of satellites that have carried previous imagers, and their optics and sensors, shows that the achievable spatial resolution provided by global imagers, at nadir, has been at best ~70 km, and usually larger (i.e., less well resolved). While these imagers have produced data that has clearly moved our understanding forward, it is equally clear that better resolution would be a welcome improvement. Resolution is limited by a number of factors, ranging from the point spread function, the pixel count of the CCD, the field of view, the distance from the emitting region, and the thickness of the emitting layer. We are confident that we can bring down PCW-UVI data produced by a 1024X1024 CCD, binned down using 2 x 2 or 3 x 3 binning, at a frame rate of 1 image every 20 seconds. With the given PCW Molniya orbit, we have to determine what the best possible spatial resolution would be.

To do this, we assumed an emitting layer with a thickness of 40 km. In reality, the layer is likely somewhat thinner (see Figure 8 in Gérard et al. [2001]), however there is variation in the height of the emission layer, and this is a reasonable compromise to get a first-look idea of achievable spatial resolution. We used the programs developed for the *Ravens Concept Study* to use quality of view to explore the optimal orbital parameters. In this simulation, which was specifically for the proposed Chinese Kua-Fu mission, we placed two satellites on orbits very similar to those of PCW, each with a 512X512 25 degree field of view (this simulation will be modified and refined for Molniya orbits and 20 deg field of view in Phase 0). We restricted our attention to points above 40° geomagnetic (PACE 2000 epoch) latitude. We broke that region down into cells. Each cell is viewed by one, the other, or both PCW-UVI satellites, depending on where the satellites are on the orbit. The spatial resolution at the location of the cell depends on where the satellite is. So each cell, at any time, can be seen better by one satellite than the other (or occasionally the viewing quality is roughly equal but that does not matter). For each cell, we determine which satellite can see aurora at that location with better spatial resolution. The resolution provided by that satellite is the resolution we assign to that cell.

We did this for evenly spaced times during the orbital period of one of the satellites. The results are shown in the figure below. We found that, in general, nadir resolution is sometimes better than 30 km, and falls away with increasing distance from nadir. At first, that fall off is due to the increasing spatial footprint of the pixel width with increasing angle away from nadir. Inevitably, unless the thickness of the emitting layer is set to zero, *the limiting factor becomes the fact that the line of sight from the pixel starts to look across too much of the thick emitting region.* In other words, near nadir, spatial resolution is limited by pixel size. Well away from nadir, it is limited by thickness of the emitting region.

By carrying out this analysis for a number of different thicknesses and CCD density (i.e., angular size of CCD pixels), we came to the conclusion that given the reality of a finite thickness of the emitting layer, which must be in reality exacerbated by variation in the height of the emitting layer within the field of view, a reasonable target resolution can be achieved by a 512X512 pixel CCD. As can be seen from the figure below, this translates to ~30 km resolution at nadir, falling away to more than 60 km resolution well away from nadir. With this, we will have most of the region over 40° magnetic latitude observed with ~40 km resolution, and the overall effect will be global images with much better spatial resolution than has previously been achieved. PCW-UVI will be designed for a 40 km spatial resolution, with this spatial resolution being achieved continuously for more than 5 years.

We must point out that in Phase A and Phase B, we will need to take instrument designs and attempt to assess the point spread function, taking into account both optical effects and potential uncertainties in

pointing. At present we believe that with these additional factors, the spatial resolution will still be roughly what we are showing here.

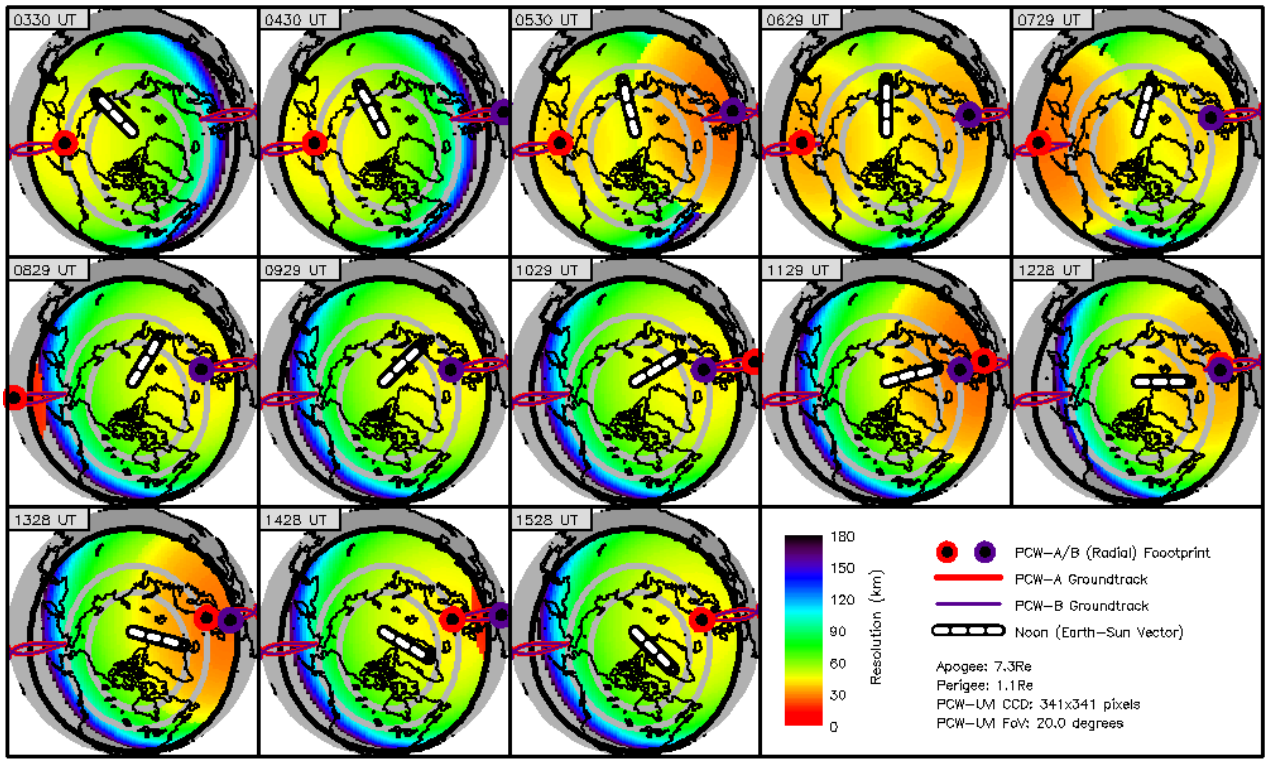


Figure: Quality of viewing analysis for an orbital period of the proposed PCW-UVI imagers. Resolution calculations are based on a 342x342 image size and a 20 degree imager field of view from the PCW orbit. Imager operational time is assumed to be ±3.5 hours from apogee. The combined spatial resolution of both imagers is colour coded as a function of geographic location, the resolution at a given point is defined as the best resolution between the two imagers. We have used the (rough) apogee longitudes as indicated in MDA-PCO. Any other choice of apogee longitudes (e.g., alignment with the Churchill meridian) would improve auroral viewing over central Canada, but not change the average time integrated quality of view.

TEMPORAL RESOLUTION

Discrete auroral activity involves wide ranges of temporal, spatial, and energy scales, starting from the smallest auroral forms defined by kinetic processes in the ionosphere up to the largest auroral phenomena associated with the behavior of the entire auroral oval. Each scale brings relevant physical information, whereas the interaction between the scales provides insight into the mechanisms of cross-scale coupling in the dynamically connected magnetosphere – ionosphere system. Since spatial and temporal resolutions of any realistic global auroral imager are limited, their optimization is one of the central problems in imager mission design. Higher spatial resolution means larger and more complicated optical system; shorter exposure time and higher image cadence require better sensitivity and may increase power consumption. Yet, covering the broadest possible range of scales remains the key to scientific success of any auroral imaging mission.

Physically, spatial and temporal scales of the auroral precipitation are intrinsically connected. Short precipitation events tend to occupy smaller spatial regions compared to long-living events, and they usually exhibit faster small-scale displacements. Uritsky et al. [2010] have quantified this tendency on a

rigorous empirical basis using extended image databases from previous auroral imaging missions. They show the existence of a non-trivial scaling relation between the relaxation time and the size of auroral emission events, *and use this scaling relation to derive the resolution scaling function ensuring non-redundant combinations of spatial and temporal resolution of an optimal auroral imager.*

Starting with a set-down spatial resolution requirement of 40 km, applying the analysis of Uritsky et al. [2010] yields an optimal temporal resolution of **20 seconds**. That is, for the given spatial resolution, there is nothing to gain scientifically by aiming for a faster than 20 second cadence.

5.3 Closure

5.4 Links to PCW Primary Objectives

The PCW URD[13] spells out the mission objectives. The meteorological objectives are to be met by the primary meteorological instrument, the spectroradiometer [URD section 3.5]. PCW-UVI will carry out continuous imaging of an important *upper* atmospheric phenomenon, the aurora. One of the PCW-UVI science objectives [Obj.S3] targets space weather effects on climate, and will utilize data from at least one channel of the spectroradiometer. PCW-UVI space weather work, will be aimed at developing space weather data products, based on PCW-UVI real-time auroral images, that will provide geographic maps of risk to RF communications at high latitudes, beginning with the GNSS application outlined in [Obj.S4]. This complements the PCW communications objectives outlined in URD section 4, will serve the needs of PCW communications users as outlined in URD section 4, and augments space weather operations (described in URD section 6) aimed at providing warnings to users of RF communications in the North of space weather effects (URD section 6.3 and 6.4). Overall, PCW-UVI has significant science compatibility with PCW, complementing and utilizing PCW imaging, providing valuable space weather information to PCW communications clients, and augmenting PCW space weather operations.

PCW will provide continuous, near-real time, high spatial resolution Earth observations of the high arctic for the purposes of weather prediction and monitoring climate change. It will also facilitate two-way, high bandwidth communications with the Canadian north. Together, these two objectives have driven the design of the PCW platform and orbital configuration, meaning two three-axis stabilized satellites (with excellent pointing accuracy) in elliptical Molniya orbits, phased so when one is at apogee the other is at perigee, affording 24/7 viewing above 50º geographic latitude, and continuous communications with the North. As stated in section 4, taken as a whole this makes PCW a dream platform for global auroral imaging. As a consequence of almost identical *technical* objectives, the technical compatibility of PCW-UVI and PCW is excellent.

[13] *PCW Mission User Requirements Document, V4.0 October 2008*

6. User Needs

6.1 Measurement Needs

Preliminary Mission/Science Definition (Summary of CDRL SC1 – Appendix IX)		**Preliminary Measurement Requirements**
Science Objectives	**Measurement Needs**	
Obj. S1 **The Magnetospheric Drivers of Auroral Type, Structure, and Dynamics** *Image global auroral dynamics with sufficient temporal and spatial resolution to identify auroral type and structures at apogee. . Imaging during timeframes of appropriate magnetospheric measurements (for example, plasma sheet dynamics, LEO boundary measurements, etc.)*	Global images of auroral luminosity	**Req. S1-M1** Instantaneous coverage of entire northern auroral oval (>55^{o} geomagnetic latitude)
	Observe full range of aurora luminosity	**Req. S1-M2** Sufficient intrascene and interscene dynamic range to record full range of expected auroral luminosity
	Average image resolution of 40km or better across the FoV	**Req. S1-M3** Apogee ground mapped pixel to pixel distance of 40km **Associated Interface Requirement, Req. I1** Knowledge of S/C pointing to within one pixel (0.06^{o}) ***Enabled by PCW Mission***
	Image Cadence 20 seconds	**Req. I2** S/C pointing stability less than half a pixel (0.03^{o}) over a 20 sec period ***Enabled by PCW Mission***
		Req. S1-M4 Sufficient imager sensitivity at apogee to achieve acceptable SNR in 20 sec exposure
Obj. S2 **Geospace Dynamic Coupling** *Specify the energy input in the auroral region under different geospace coupling conditions. For long duration events (such as geomagnetic storms) provide continuous measurements of precipitating electron flux and energy.*	Dual band auroral images (sufficient to derive precipitating e^{-} energy flux and characteristic energy) Auroral N2 (LBH long and LBH short) bands *-Or-* Images of the auroral LBH and OI bands	**Req. S2-M5** To sufficiently (so as to enable meaningful quantitative work) separate LBH-l and LBH-s while rejecting the strong adjacent OI lines and maintaining adequate signal *- Or -* To sufficiently (so as to enable meaningful quantitative work) separate the LBH band from the intense OI line.
	Image entire auroral oval (including dayside)	**Req. S2-M6** Sufficient rejection of VIS-IR Earth albedo.
	24/7 viewing of northern auroral oval	**Req. S2-M7** Continuous imaging operations
Obj. S3 **The Effects of Space Weather on Climate**	Enabled by measurement needs above	No additional Measurement Requirements

Obj. S4 **Space Weather Effects on Global Navigation Satellite Systems (GNSS)**	Enabled by measurement needs above	No additional Measurement Requirements

6.1.1. Science Requirement 1 (Req. S1)

> ***Determine magnetospheric drivers of auroral type, structure and dynamics.*** *Image global auroral dynamics with sufficient temporal and spatial resolution to identify auroral type and structures at apogee. Imaging during timeframes of appropriate magnetospheric measurements (for example, plasma sheet dynamics, LEO boundary measurements, etc.)*

Field of view. The instrument shall have a field of view (FoV) wide enough to span the entire nighside auroral zone and polar cap as seen from apogee.

Spatial Resolution. The apogee spatial resolution (ground-mapped pixel-to-pixel distance) shall be 40 km or better across the FoV. The Monlniya orbit proposed for the PCW mission allows for continuous global imaging with excellent spatial resolution over much of the auroral and polar regions, and down to mid latitudes.

Temporal Resolution. The maximum temporal resolution (image cadence) shall be 20 seconds. I.e., one complete image will be presented to the S/C every 20 seconds.

Sensitivity. A maximum 20-s image cadence and a 3-axis stabilized platform yield a minimum image exposure time of 20-s. In-band sensitivity and out-of-band rejection shall be sufficient to detect a 50 rayleighs emitting source within the imager's pass-band with an SNR of better than unity, during each 20-second exposure.

Dynamic Range. The instrument must be capable of measuring very bright signals (on the order of 100 kR) in the auroral oval as well as very weak signals (several tens of rayleighs) in the polar cap. It may be necessary to measure weak regions simultaneously with bright regions within the same field of view. An intrascene dynamic range of 1000, and an interscene dynamic range of 104 is desired. The interscene dynamic range can be further extended by the use of image summation in memory during exposure, and by varying image intensifier gain and image exposure times.

6.1.2. Science Requirement 2 (Req. S2)

> ***Determine the relative contribution and importance of loss mechanisms during varying dynamic geospace couplings.*** *Specify the energy input in the auroral region under different geospace coupling conditions. For long duration events (such as geomagnetic storms) provide continuous measurements of precipitating electron flux and energy.*

Measurements Needs stated above apply, with the following overrides:

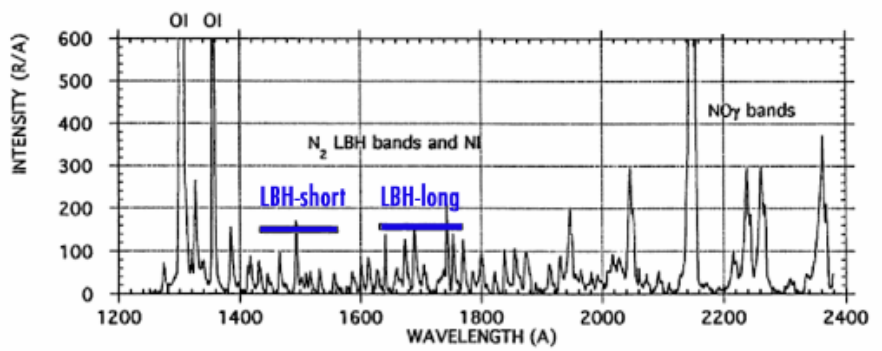
Field of view. There shall be two instruments on each of two S/C on 180 deg phased orbits. Each instrument shall have a field of view (FoV) wide enough to span the entire auroral zone (dayside and nightside) and polar cap for a significant fraction of the orbit. This ensures continuous 24/7 global

coverage of the northern auroral oval from the combined measurements from the two PCW spacecraft on their Molniya orbits.

Wavelength Separation. The energy flux and characteristic energy of precipitating particles at all local times shall be determined by remote sensing. This is most efficiently achieved by measuring the absolute intensities, and ratio of intensities, of auroral emissions within the FUV band. The two instruments on each S/C shall therefore provide simultaneous, wavelength separated LBH electron auroral observations over the global (nightside and dayside) FUV auroral distribution. Sufficient suppression of unwanted continuum contribution from out-of-band shall be provided so as to achieve the required Sensitivity. As outlined in Sect 5.2, candidate emission pairs are:

- **LBH-short** with **LBH-long**
- **OI** with **LBH-short + LBH-long**

See Figure XXX below.



- **Energy Flux**. Using LBH-long to determine the energy flux is doable, if the O2 absorption is low enough [Germany et al., 1998]. An absolute calibration of the instrument is required.

- **Characteristic Electron Energy I**. There are suggestions in literature that LBH-long to LBH-short may actually be a rather poor indicator of characteristic electron energy regardless of how good the filtering is. The emission ratio remains constant up to about 3 keV and then starts to decrease [Torr et al., 1995]. The ratio of LBH to OI 1356 appears much more sensitive to characteristic energy. If we design for "energetic electrons" (E>3 keV) the LBH-long to LBH-s scheme is useful, but in that case there should be some statement of this restriction. Using OI 1356 has the disadvantage in that this emission rate depends on the altitude distribution of O which varies considerably with space and time. Using the strong OI 1356 with LBH wideband (say 140-180 nm, using all the available FUV auroral signal) should yield good integrated signal levels, which again impacts the choice of optical design.

- **Characteristic Electron Energy II**. A second way of determining characteristic electron energy is to use the OI 1304 line with the LBH band. The ratio 1304/LBH is indicative of characteristic energy with higher ratios indicating softer fluxes [Rees et al., 1988, Steele et al.,1992] . The ratio depends on O/N2 density ratio and on the mean energy of precipitating electrons. The O/N2 ratio must be determines by different means (from dayglow measurements?). The OI 1304 is resonantly scattered as it comes out of the atmosphere, which will degrade spatial resolution.

- **Column integrated Hall and Pederson conductances**. What we *can* do with the LBH-l to LBH-s ratio (uniquely) is to determine the column integrated Hall and Pederson conductances [Torr et al., 1995]. This requires an atmospheric model.

6.2 Data Needs

We must establish our global auroral imaging measurement needs[14], which are spatial/temporal resolution, and the desired spectral bands. Naively, one wants arbitrarily good spatial resolution, however, given a finite height of the emission region, there is a fundamental limit on spatial resolution averaged over the entire auroral region. In the Ravens Concept Study Report, we showed that this limit is most likely around 30 km, and so there is no need to aim for better (see pg 108 of that report). We have settled on 40 km as our target nadir resolution from apogee[15]. From the Ravens Concept Study Report, and *Uritsky et al.* [2010], we know that larger-sized features tend to change more slowly than smaller features, so that for a given spatial resolution, there is actually an optimum cadence[16]. Based on the *Uritsky et al.* [2010] study, we have selected 20 seconds as our target cadence.

This combination 40 km/20 seconds is significantly better than the real resolutions of any previous global auroral imager to date (see *Donovan et al.* [2007]). Furthermore, this spatial resolution should allow us to identify auroral features for Science Objective 1 Theme 1 (magnetospheric drivers of aurora), as well as for Science objective 4 (GNSS). This will not allow us to simultaneously capture the full spectrum of auroral spatial scales (Science Objective 1, Theme 2), however PCW-UVI, together with contemporaneous ground-based ASI imagers, will be able to. Science Objectives 2 and 3 have lower requirements for spatio-temporal resolution.

Science Objectives 1, 2, and 3 require precipitating electron characteristic energies. We want to (1) investigate the relationship between structure and both energy deposition and acceleration mechanism, to (2) quantify energy input into the ionosphere, and to (3) model NOx production due to auroral preciiptation. We can exploit LBH and OI emissions to obtain such information [e.g., *Strickland et al*., 1983; *Germany et al*., 1990]. Specifically, the intensity of LBH "long" emissions is proportional to the energy flux of precipitating electrons. The intensity of the LBH in the "short" part of the band, which is partially absorbed by atmospheric O2, can be compared to the LBH-long emissions to estimate the characteristic electron energy [Germany et al., 1997;1998]. Alternately, one can exploit other FUV ratios, such as LBH to OI 1356, to get characteristic energy. There are advantages and disadvantages to each scheme that we will investigate during the Phase 0/A, but for now we state that we will be needing intensities in two FUV bands to get electron energy.

Finally, daylight suppression, needed for Science Objective 2, will be accomplished as an ancillary benefit of adequately isolating the FUV spectral bands, and "long-duration events" requires continuous viewing, enabled by the PCW satellite pair. Table 1 is a tentative list of PCW-UVI data products.

Data Product [Format]	Description
Level 0 [PGM]	**Single Imager Product.** Reconstructed, unprocessed imager data at full resolution, with any and all communication artifacts (e.g. CCSDS packet headers, synchronization frames, etc.) removed.
Level 1-B [PGM, CDF]	**Single Imager Product.** Radiometrically corrected brightness, time referenced and annotated with ancillary information (e.g. spacecraft location, calibration version, etc.).

[14] We assume measurements from other programs will be available, but will revisit that issue in Phase 0/A.
[15] Meaning significantly better resolution near nadir when the satellite is at lower altitude.
[16] This means that for a given spatial resolution, there is a time resolution that there is little or on reason to do better than.

Level 3-1 [CDF, JPG*]	**Combined Imager Product.** Radiometrically corrected brightness mapped onto a geographic grid using pixels with the highest spatial resolution at each location, time referenced (at full temporal resolution) and annotated (in the case of CDF) with ancillary satellite information.
Level3-2 [CDF,JPG*]	**Combined Imager Product.** Same as Level3-1 but in geomagnetic coordinates.
Level3-3 [CDF, JPG*]	**Combined Imager Product.** Derived auroral energy flux and average energy mapped onto a geographic grid using pixels with the highest spatial resolution at each location, time referenced (at full temporal resolution) and annotated (in the case of CDF) with ancillary satellite information.
Level3-EPO [JPG*]	**Combined Imager Product.** Radiometrically corrected brightness (at full temporal resolution) mapped onto geographic grids using pixels from the satellite with the highest spatial resolution at each location. EPO data products will be made available in a variety of map projections (highlighting different locations on the Earth) and in a variety of image sizes (to allow for web-streaming content). The EPO set of data products will likely evolve as the EPO needs become more clearly defined.

Table 1: Anticipated PCW-UVI standard data products (SDPs). Processing level designations are based on the Earth Observing Science Data Information System (EOSDIS) data definitions (see NASA's Earth Observing Science Data Resource document). [*or equivalent raster image format (e.g. PNG)].

To support our assertion that PCW-UVI data will be extensively used, we include letters from leaders of most major programs approved or planned for the PCW-UVI timeframe. The authors of the letters are

Angelopoulos	THEMIS PI	Lynch	Sounding Rocket PI
Burch	MMS & IMAGE PI	Raeder	Representative Modeler
Friis-Christensen	Swarm Scientific Leader	Ridley	Representative Modeler
Fujimoto	Scope Mission Scientist	Ruohoniemi	SuperDARN PI
Kepko	APEx PI	Sibeck	THEMIS & RBSPProject Scientist
Lessard	Sounding Rocket PI	Thayer	CEDAR SteeringCommittee Chair
Liemohn	GEM Steering Committee Chair		

Thayer and Liemohn describe synergies between PCW-UVI and essentially all aspects of CEDAR and GEM, representing >500 researchers. Sibeck communicates the relevance of PCW-UVI to the NASA mission lineup, while Angelopoulos, Burch, Fujimoto, Kepko, and Brandt[17] (EAGLES) write as mission PIs. For each mission complementary to PCW-UVI, the synergies would enable new science and lead to use of the PCW-UVI data by their respective teams representing again a large number of researchers worldwide. Ridley and Raeder are modelers who communicate the value of global imaging for geospace studies. More than 100 researchers worldwide are carrying out global simulation work that would directly benefit from PCW-UVI. Ruohoniemi writes as PI of several SuperDARN radars, also anticipating extensive use of the PCW-UVI data. It is easy to imagine that the international communities who utilize magnetometers, GPS networks, riometer networks, and incoherent scatter radars would find similar value in PCW-UVI. Lessard[18] and Lynch are PIs of sounding rockets who describe benefits PCW-UVI would provide by decreasing their reliance on ground-based imagers for calling launches, and for the contextual information PCW-UVI would make available in real time. They both state PCW-UVI data would decrease the number of days spent waiting for ideal launch conditions.

PCW-UVI would be the only global auroral imaging mission at a time when the international fleet of *in situ* satellites would be comprised of an unprecedented constellation. For the uniqueness of the data, and the list of technical firsts that would be achieved, we assert that PCW-UVI would produce one of the most highly visible, highly relevant, and most widely utilized geospace data sets. **Overall, we assert that PCW-UVI, as a secondary science payload on PCW, would have the science impact of a NASA Explorer class mission.**

[17] Brandt is a collaborator on this proposal.
[18] Lessard is a science collaborator on this project, so his letter is not *independent* in that sense.

Appendix A: Science References

- Acuña, M. H., K. W. Ogilvie, D. N. Baker, S. A. Curtis, D. H. Fairfield and W. H. Mish, The Global Geospace Science Program and its Investigations, Space Science Rev., 71, 5, 1995.

- Amm, O., E.F. Donovan, H. Frey, M. Lester, R. Nakamura, J.A. Wild, A. Aikio, M. Dunlop, K. Kauristie, A. Marchaudon, I.W. McCrea, H.J. Opgenoorth, and A. Strømme, Coordinated studies of the Geospace environment using Cluster, satellite and ground-based data: An interim review, Ann. Geophys., 23, 2129, 2005.

- Angelopoulos, V., McFadden, J. P., Larson, D., Carlson, C. W., Mende, S. B., Frey, H., Phan, T., Sibeck, D. G., Glassmeier, K.-H., Auster, U., Donovan, E., Mann, I. R., Rae, I. J., Russell, C. T., Runov, A., Zhou, X.-Z., and Kepko, L.: Tail Reconnection Triggering Substorm Onset, Science, 321, 931–935, doi:10.1126/science.1160495, 2008.

- Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433, 1961.

- Baker, D. N., R. E. Ergun, J. L. Burch, J.-M. Jahn, P. W. Daly, R. Friedel, G. D. Reeves, T. A. Fritz, and D. G. Mitchell, A telescopic and microscopic view of a magnetospheric substorm on 31 March 2001, Geophys. Res. Lett., 29(18), 1862, doi:10.1029/2001GL014491, 2002.

- Basu, S., E. MacKenzie, and S. Basu (1988), Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum periods, Radio Sci., 23(3), 363–378.

- Belian, R. D., T. E. Cayton, and G. D. Reeves, Quasi-periodic global substorm-generated variations observed at geosynchronous orbit, in Space Plasmas: Coupling Between Small and Medium Scale Processes, Geophysics Monograph Series, volume 86, 143–148, 1995.

- Biskamp, D., Magnetic reconnection in plasmas, Cambridge University Press, ISBN 0 520 58288 1, 2000.

- Borg, A. L., et al., Simultaneous observations of magnetotail reconnection and bright X-ray aurora on 2. October 2002., J. Geophys. Res., 112(A6), A06215, doi: 10.1029/2006JA011913, 2007.

- Brandt, P. C., R. DeMajistre, E. C. Roelof, D. G. Mitchell, and S. Mende, IMAGE/HENA: Global ENA imaging of the plasmasheet and ring current during substorms, J. Geophys. Res., 107, 1454, 2002.

- Brandt, P. C., Y. Zheng, T. S. Sotirelis, K. Oksavik, and F. J. Rich, The Linkage Between the Ring Current and the Ionosphere System, Geophysics Monograph. Series, volume 181, 135-143, 2008.

- Burch, J. L., Magnetospheric imaging: Promise to reality, Rev. Geophys., 43, doi: 10.1029/ 2004RG000160., 2005.

- Chapman, S., and J. Bartels, Geomagnetism, Clarendon Press, Oxford, UK, 1967.

- Donovan, E., Trondsen, T., Spann, J., Liu, W., Spanswick, E., Lester, M., Tu, C.-Y., Ridley, A., Henderson, M., Immel, T., Mende, S., Bonnell, J., Syrjäsuo, M., Sofko, G., Cogger, L., Murphree, J., Jayachandran, P. T., Pulkkinen, T., Rankin, R., Sigwarth, J., Global auroral imaging, system level science, and ILWS, Adv. Space Res., 40, pp 409-418, 2007.

- Dungey, J. W., Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., 6, 47, 1961.

- Funke, B., M. Lopez-Puertas, S. Gil-Lopez, T. von Clarmann, G. P. Stiller, H. Fischer, and S. Kellmann, Downward transport of upper atmospheric NOx into the polar stratosphere and lower mesosphere during

the Antarctic 2003 and Arctic 2002/2003 winters, J. Geophys. Res. – Atmospheres, 110 (D24), D24308, doi:10.1029/2005JD006463, 2005.

- Funke, B., M. Garcia-Comas, M. Lopez-Puertas, N. Glatthor, G. P. Stiller, T. Von Clarmann, K. Semeniuk, and J. C. McConnell, Atmos. Chem. Phys., 8, 3805–3815, 2008.
- Germany, G., M. Torr, , P. Richards, and D. Torr, The dependence of modeled OI 1356 and N2 LBH auroral emissions on the neutral atmosphere, J. Geophys., Res., 95, 7725, 1990.
- Germany, G., G. Parks, M. Brittnacher, J. Cumnock, D. Lummerzheim, J. F. Spann, L. Chen, P. Richards, and F. Rich, Remote determination of auroral energy characteristics during substorm activity, Geophys. Res, Lett., 24, 995, 1997
- Germany, G., G. Parks, M. Brittnacher, J. Spann, J. Cumnock, D. Lummerzheim, F. Rich, and P. Richards, Energy characterization of a dynamic auroral event using GGS UVI images, AGU Monograph 104, page 143, 1998.
- Goldstein, J., J. Burch, B. Sandel, S. Mende, P. Brandt, and M. Hairston, Coupled response of the inner magnetosphere and ionosphere on 17 April 2002, J. Geophys. Res., 110, doi:10.1029/ 2004JA010712, 2005.
- Henderson, M., E. Donovan, J. Foster, I. Mann, T. Immel, S. Mende, and J. Sigwarth, Start-to-end global imaging of a sunward propagating, SAPS-associated giant undulation event, J. Geophys. Res., doi:10.1029/ 2009JA014106, in press, 2010.
- Hosokawa, K., J.-P. St-Maurice, G. Sofko, K. Shiokawa, Y. Otsuka, and T. Ogawa, Reorganization of polar cap patches through shears in the background plasma convection, J. Geophys. Res., 115, doi:10.1029/ 2009JA014599, 2010.
- Ieda, A., et al., Plasmoid ejection and auroral brightenings, J. Geophys. Res., 106, 3845, 2001
- Kepko, L., E. Spanswick, V. Angelopoulos, E. Donovan, J. McFadden, K. H. Glassmeier, J. Raeder, and H. J. Singer, Equatorward moving auroral signatures of a flow burst observed prior to auroral onset, Geophys. Res. Lett., 36, doi:10.1029/2009GL041476, 2009.
- Klobuchar, J.A., Ionospheric Effects, in Global Positioning System: Theory and Applications, Vol. I, American Institute of Aeronautics and Astronautics, Washington, D.C., 1996.
- Knudsen, D. J. (1996), Spatial modulation of electron energy and density by nonlinear stationary inertial Alfvén waves, J. Geophys. Res., 101(A5), 10,761–10,772
- Liang, J., Vadim Uritsky, Eric Donovan, Binbin Ni, Emma Spanswick, Trond Steinar Trondsen, John Bonnell, Alain Roux, Ulrich Auster, Davin Larson, THEMIS observations of electron cyclotron harmonic emissions, ULF waves, and pulsating auroras, Submitted to Journal of Geophysical Research – Space Physics.
- Lopez-Puertas, M, B. Funke, S. Gil-Lopez, T. von Clarmann, G. P. Stiller, M. Hopfner, S. Kellmann, H. Fischer, and C. H. Jackman, Observation of NOx enhancement and ozone depletion in the Northern and Southern Hemispheres after the October-November 2003 solar proton events, J. Geophys. Res. – Space Physics, 110 (A9), A09S43, doi:10.1029/2005JA011050, 2005.
- McWilliams et al., Annales Geophysicae, volume 19, pages 707-721, 2001

- Moen, J., Y. Rinne, H. C. Carlson, K. Oksavik, R. Fujii, and H. Opgenoorth, On the relationship between thin Birkeland current arcs and reversed flow channels in the winter cusp/cleft ionosphere, J. Geophys. Res., 113, A09220, doi:10.1029/2008JA013061, 2008.

- Mozer, F., T.D. Phan, S.D. Bale, The complex structure of the reconnecting magnetopause, Phys. Plasmas, 10, 2480, 2003.

- Ni et al., 2008 B. Ni, R.M. Thorne, Y.Y. Shprits and J. Bortnik, Resonant scattering of plasma sheet electrons by whistler-mode chorus: contribution to diffuse auroral precipitation, Geophys. Res. Lett. 35 (2008), p. L11106.

- Østgaard, N., R. R. Vondrak, J. W. Gjerloev, and G. Germany, A relation between the energy deposition by electron precipitation and geomagnetic indices during substorms, J. Geophys. Res., 107(A9), 1246, doi:10.1029/2001JA002003, 2002.

- Randall, C.E., V. L. Harvey, C. S. Singleton, S. M. Bailey, P. F. Bernath, M. Codrescu, H. Nakajima, and J. M. Russell,. Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992-2005. J. Geophys. Res. – Atmospheres, 112 (D8), D08308, doi:10.1029/2006JD007696, 2007.

- Rankin, R., K. Kabin, J. Y. Lu, I. R. Mann, R. Marchand, I. J. Rae, V. T. Tikhonchuk, and E. F. Donovan, Magnetospheric field-line resonances: Ground-based observations and modeling, JGR, 110, doi:10.1029/2004JA010919, 2005.

- Ravishankara, A. R., J. S. Daniel, and R. W. Portmann, Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century, Science, 326(5949), 123, doi:10.1126/science.1176985, 2009.

- Roelof, E., D. Mitchell, and D. Williams, Energetic Neutral Atoms (E 50 keV) from the Ring Current: IMP 7/8 and ISEE 1, J. Geophys. Res., 90(A11), 10991-11008, 1985.

- Runov, A., V. Angelopoulos, N. Ganushkina, R. Nakamura, J. McFadden, D. Larson, I. Dandouras, K.-H. Glassmeier, and C. Carr, Multi-point observations of the inner boundary of the plasma sheet during geomagnetic disturbances, Geophys. Res. Lett., 35, doi:10.1029/2008GL033982, 2008.

- Samson, J. C., L. R. Lyons, P. T. Newell, F. Creutzberg, and B. Xu Proton aurora and substorm intensifications, Geophys. Res. Lett.,19(21), 2167–2170., 1992.

- Sarris, T. E., et al. (2009), Characterization of ULF pulsations by THEMIS, Geophys. Res. Lett., 36, L04104, doi:10.1029/2008GL036732.

- Semeniuk, K., J. C. McConnell, J. J. Jin, J R. Jarosz, C. D. Boone, and P. F. Bernath, N_2O production by high energy auroral electron precipitation, J. Geophys. Res., 113, doi:10.1029/2007JD009690, 2008.

- Sergeev, V. A., Kubyshkina, M. V., Baumjohann, W., Nakamura, R., Amm, O., Pulkkinen, T., Angelopoulos, V., Mende, S. B., Klecker, B., Nagai, T., Sauvaud, J.-A., Slavin, J. A., and Thom- sen, M. F.: Transition from substorm growth to substorm expan- sion phase as observed with a radial configuration of ISTP and Cluster spacecraft, Ann. Geophys., 23, 2183–2198, 2005.

- Skone, S., K. Knudsen, and M. de Jong, Limitations in GPS receiver tracking performance under ionospheric scintillation conditions, Phys, Chem. Earth, 26, 613-621, 2001.

- Skone, S., The impact of magnetic storms on GPS receiver performance, J. Geodesy, 75, 457-468, 2001.

- Skone, S. and V. Hoyle, Canadian GPS network for ionosphere monitoring (CANGIM), GPS Solutions, 9, 59-62, 2005.

- Skone, S. and R. Yousuf, Performance of satellite-based navigation for marine users during ionospheric disturbances, Space Weather Journal, 5, 9 pages, doi:10.1029/ 2006SW000246, 2007.
- Smith, A. M., C. N. Mitchell, R. J. Watson, R. W. Meggs, P. M. Kintner, K. Kauristie, and F. Honary, GPS scintillation in the high arctic associated with an auroral arc, Space Weather, 6, doi: 10.1029/2007SW000349, 2008.
- Strickland, D., J. Jasperse, and J. Whalen, Dependence of auroral FUV emission on the incident electron spectrum and neutral atmosphere, J. Geophys. Res., 88, 8051, 1983.
- Uritsky, V. M., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K. H. Glassmeier (2009), Longitudinally propagating arc wave in the pre-onset optical aurora, Geophys. Res. Lett., 36, L21103, doi:10.1029/2009GL040777.
- Uritsky, V., Eric Donovan, T. Trondsen, D. Pineau and B. Kozelov, Data-derived spatio-temporal resolution constraints for global auroral imagers. Submitted to J. Geophys. Res, 2010.
- Watkins, N., M. Freeman, S. Chapman, and R. Dendy, J. Atmos. Solar-Terr. Phys., 63, 1435-1445, 2001.
- Yahnin, A., M. V. Malkov, V. A. Sergeev, R. J. Pellinen, O. Aulamo, S. Vennerström, E. Friis-Christensen, K. Lassen, C. Danielsen, J. D. Craven, C. Deehr, and L. A. Frank, Features of steady magnetospheric convection, J. Geophys. Res., 99, 4039-4051, 1994.

Appendix B: Technical References

- Carbary J.F., Sotirelis T., Newell P.T., Meng C.-I. Correlation of LBH intensities with precipitating particle energies, Geophys. Res. Lett. V. 31. L13801, doi:10/1029/2004GL019888. 2004.
- Frey, H. U., S. B. Mende, C. W. Carlson, J. C. Gérard, B. Hubert, J. Spann, R. Gladstone, and T. J. Immel, The electron and proton aurora as seen by IMAGE-FUV and FAST, Geophys. Res. Lett., 28, 1135, 2001
- Frey, H. U. et al. Summary of quantitative interpretation of IMAGE Far Ultraviolet auroral data. Space Sci. Rev. 109, 255–283 (2003)
- Gérard, J.-C., B. Hubert, M. Meurant, V. I. Shematovich, D. V. Bisikalo, H. Frey, S. Mende, G. R. Gladstone, and C. W. Carlson, Observation of the proton aurora with 155IMAGE FUV imager and simultaneous ion flux in situ measurements, J. Geophys. Res., 106(A12), 28,939–28,948, 2001.
- Germany, G. A., M. R. Torr, D. G. Torr, and P. G. Richards, Use of FUV auroral emissions as diagnostic indicators, J. Geophys Res., 99,383, 1994.
- Germany, G. A., D. G. Torr, P. G. Richards, M. R. Torr, and S. John, Determination of ionospheric conductivities from FUV auroral emissions, J. Geophys. Res., 99, 23297, 1994.
- Hubert B., J.C. Gérard, D.S. Evans, M. Meurant, S.B. Mende, H.U. Frey and T.J. Immel, Total electron and proton energy input during auroral substorms: remote sensing with IMAGE-FUV, J. Geophys. Res., 107, doi: 10.1029/2001JA009229, 2002.
- Lummerzheim, D., M. H. Rees, J. D. Craven, and L. A. Frank, Ionospheric conductances derived from DE-1 auroral images, J. Atmos. Terr. Phys., 53, 281, 1991.

- Monchick, L., M. J. Linevsky, C. I. Meng and S. Favin S. Chakrabarti and F. Paresce, Some auroral properties from far ultraviolet observations, Planetary and Space Science, Volume 33, Issue 2, p. 175-181, 1985.

- Torr, M. R., D. G. Torr, M. Zukic, B. Johnson, J. Ajello, P. Banks, K. Clark, K. Cole, C. Keffer, G. K. Parks, B. Tsurutani, J. F. Spann, Jr., A far ultraviolet imager for the International Solar-Terrestrial Physics Mission, Space Science Reviews, 71, 329-383, 1995.

- Wanliss, J. A., and K. M. Showalter, High-resolution global storm index: Dst versus SYM-H. J. Geophys. Res.., 111, doi:10.1029/2005JA011034, 2006

- Zukic, M., D. G. Torr, J. F. Spann, Jr., M. R. Torr, Vacuum Ultraviolet Thin Films. 2: Vacuum Ultraviolet All-Dielectric Narrowband Filters, Appl. Opt., 29, 4293, 1990.

- Zukic, M., D. G. Torr, J. Kim, J. F. Spann, Jr., M. R. Torr, Filters for the International Solar Terrestrial Physics Mission for Far Ultraviolet Imager, Opt. Engrg., 32, 3069, 1993.

Appendix X – CDRL PM1 (Initial Release)

Document No. PCW-UVI.CDRL.PM1.0001. Initial Release
Rev 0001
February 16, 2010

Project Management Plan

PCW-UVI (Phase 0)
CDRL PM1

Contract No. XXXXXXXX
Prepared for:
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1 Introduction

1.1 Project Objectives

The technical goal of Phase 0 is to develop a viable conceptual design that efficiently meets the Measurement Needs derived from the Scientific Objectives. The design must be technically realistic, physically compatible with PCW (given the information available during Phase 0) and reasonably risky. In the course of accomplishing this, the contractor will meet all requirements detailed in PHEMOS RFP, including the on time delivery of all CDRL deliverables.

These objectives must be met on time and on budget, and it will be the job of the Project Manager at UofC (Prime Project Manager, PPM) to create an environment in which this happens. This will be done by applying generally recognized project management techniques. Six key project management knowledge areas have been identified as especially critical for the work outlined in the Proposal (Global Auroral Imaging on PCW): project cost, scope, schedule, quality, communications and risk. The methods and systems to be used to control these parameters are addressed below.

1.2 Scope

The scope of Phase 0 has been clearly defined in the Work Breakdown Structure (WPS, Figure 1) and Work Packages (WP) in the Proposal. The WBS was developed in conjunction with Routes AstroEngineering, the major subcontractor on the project. The detailed Work Packages associated with the WBS are included in Appendix B and will play a critical role in managing the scope of the project.

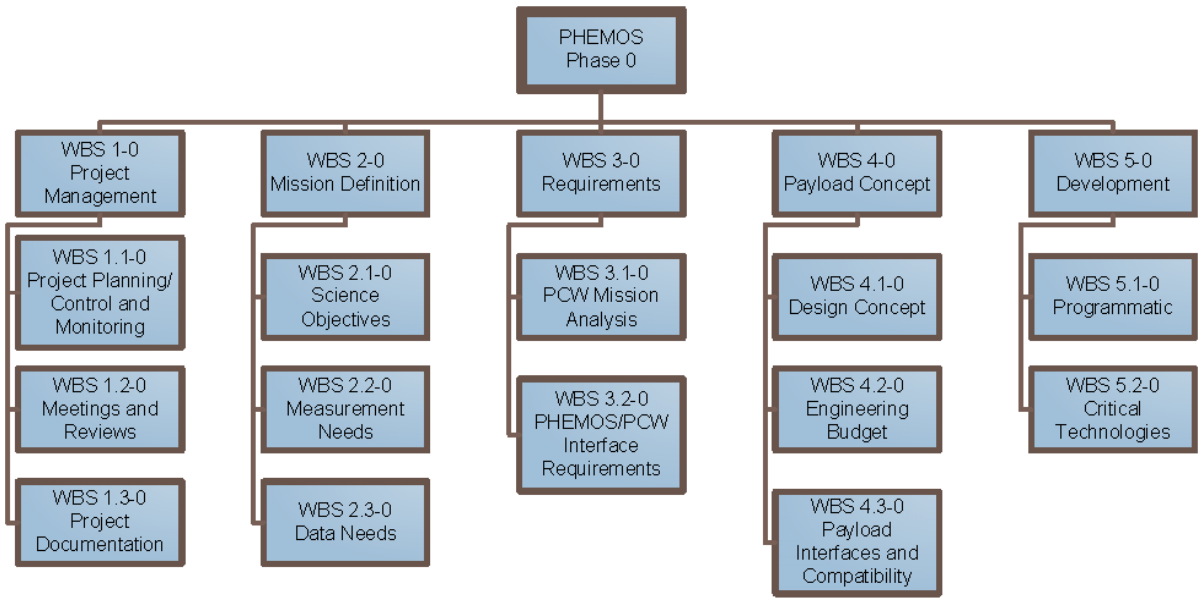


Figure 1: The Phase 0 Work Breakdown Structure

1.3 Applicable and Reference Documents

Dr. Eric Donovan, *Global Auroral Imaging on PCW*, Proposal in Response to PWGSC Solicitation No. 9F007-09-0217/A

2 Project Management Plan

Phase 0 will be managed by the Prime Project Manager (PPM, Greffen) located at the University of Calgary (Contractor) and reporting to Dr. Eric Donovan (Principle Investigator). The PPM will employ standard Project Management techniques (as detailed in *A Guide to the Project Management Body of Knowledge, Fourth Edition*) and discussed here to monitor and control the project cost, scope, schedule, quality, communications and risk.

The PPM is strategically placed in the project Organizational Chart (Figure 2) to facilitate effective management of the project. All project communications, including progress reports, requests for change and action items, will flow through the PPM. Communications between the Science Team and UofC Project Manager (Greffen) will be facilitated by the Deputy PI (DPI, Spanswick). The Technical Lead (Trondsen) will play a similar role on the technical side.

The PPM will be responsible for coordinating the efforts of, and facilitating communications between, all of the project stakeholders (including the CSA and PWGSC). The PPM will be accountable to the PI (Donovan) for all non-science aspects of the project, including the budget, scope, schedule and quality of output.

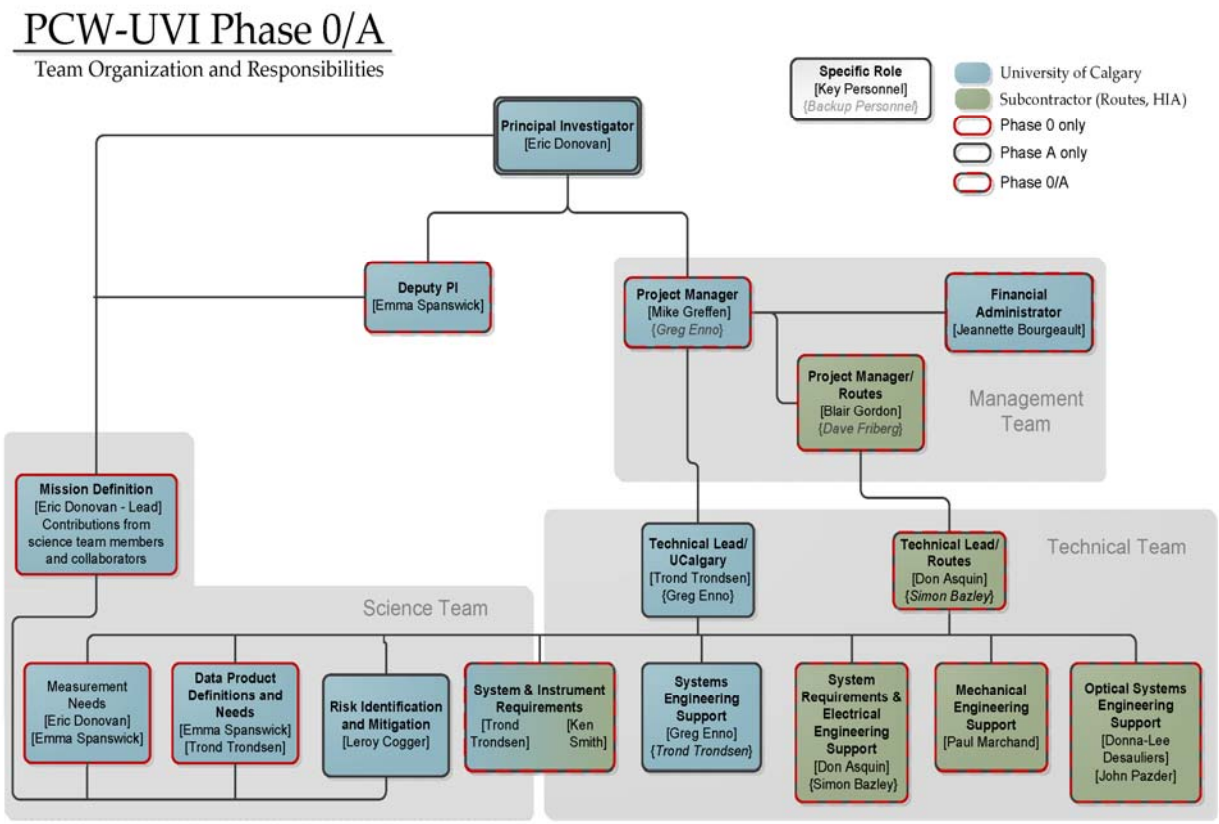


Figure 2: The Organizational Chart of the PCW-UVI team during Phase 0 and A

2.1 Cost Management

The Financial Bid contains a detailed cost breakdown by WP for Phase 0. The Actual Cost of the project will be reviewed on a monthly cadence by the PPM and the Financial Administrator (Bourgeault). It will be compared to the Planned Value as well as Earned Value (Earned Value Management, EVM), which will be calculated using a simple technical performance model. Due to the fact that Phase 0 is Fixed Price, cost overruns will impact other identified project parameters and will be largely dealt with using the appropriate tools (for example, a projected cost overrun may impact the scope and/or the schedule of the project but will not affect the total budget). The Contract Plan and Report Form (Appendix A) will be used to track and report costs to the CSA.

2.2 Scope Management

A Work Breakdown Structure (WBS) is a standard Scope Management tool that plays a key role in the Project Management Plan (PMP). A detailed WBS has been developed for Phase 0 in heavy consultation Routes AstroEngineering. The WBS will be updated on a monthly cadence throughout the lifetime of the project. All scope change requests will be directed to the PMP who will access the impact

on the project (most critically cost and schedule), seek appropriate approval and communicate any resulting changes to the WBS to the stakeholders. The monthly progress meetings, the review and acceptance of deliverables and he scheduled reviews all provide excellent opportunities to verify, and modify if necessary, the scope of the project.

2.3 Schedule Management

The project schedule has been created in some detail in Microsoft Project, and will be updated monthly (the schedule for Phase 0 positive float). EVM and/or PERT analysis will be used to access variances from the planned schedule and monitor the critical path. In addition to this, formal performance reviews will act as milestone opportunities to analyze schedule performance. In the event of negative schedule variance fast tracking will be employed to correct the issue (due to the fixed project budget crashing the schedule will only be done in an extreme case). Do to the nature of the work there are several good candidate Work Packages for fast tracking.

2.4 Quality Management

In order to achieve the goals of the project it is critical that quality of the project output is satisfactory. Specifically this section addresses the quality of the conceptual design and resulting requirement documents that will be used as inputs to Phase BCD. The quality of the deliverables will be assessed by determining their compliance with the instrument and mission requirements. To this end it will be the job of the PPM to facilitate the creation, documentation, and communication of the instrument requirements as well as closely monitor the WPs associated with PCW mission requirements. An internal design review will be held as part of the trade-off analysis in Phase A to check the compliance of the candidate design against the instrument requirements and ultimately the Science Objectives.

2.5 Communications Management

The three major stakeholders in the project are separated by geography and each has a unique enterprise environment. Clear communication between these diverse organizations (and all other stakeholders) will play a critical role in the successful conclusion of the project. Information distribution will occur through the scheduled meetings and required deliverables. It will be the job of the PPM to access if further information distribution tools are required and put them in place. The PPM will also work with stakeholders to meet their needs and address issues as they occur.

2.6 Risk Management

Risk management is the primary job of the PPM. All of the techniques listed above are ultimately about reducing and managing project risk. It is important to note that project risk and business (science/technical) risk are separate entities. It is possible to complete a project on schedule and budget

but have a non-functional product at the end. The PPM will be primarily responsible for managing project risk, but will also facilitate the management of technical risk.

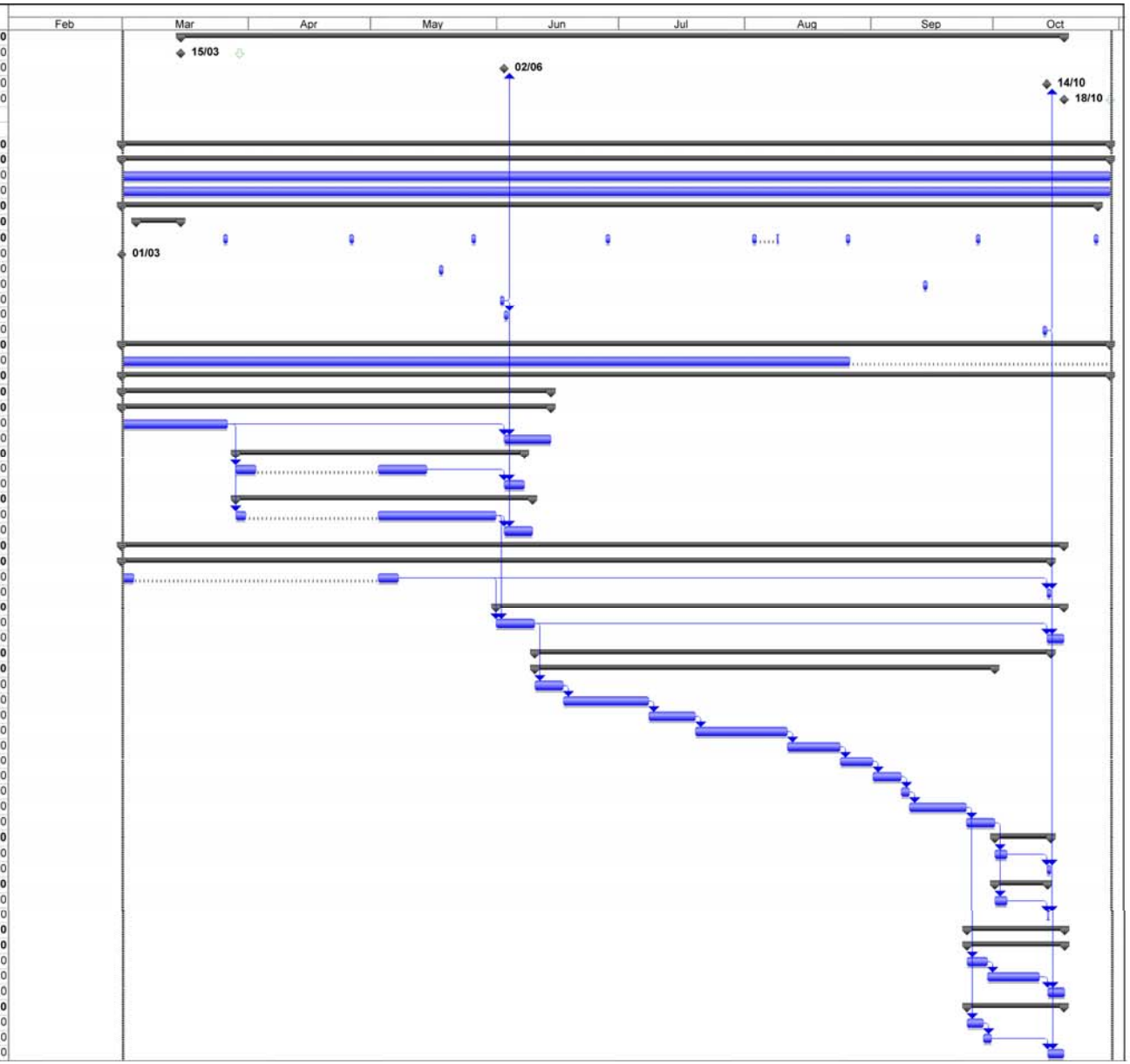
Preliminary management and technical risk assessments have been accomplished as part of the proposal process. The risk assessment (and reassessment) process consists of identifying risks, analyzing and prioritizing, and developing a response to them. Risk reassessment will occur extremely early in Phase 0 and on a regular basis throughout the project (continuous risk management). The PPM will participate in technical risk reviews and work closely with the Technical Lead (Trondsen) to monitor and control technical risks. The PPM will also work with the Deputy PI (DPI) to manage science risks that is risks that threaten the Science Objectives. The project manager will be responsible for managing reserves as part of the risk response strategy.

3 Schedule and Milestones

3.1 Phase 0 Schedule

A detailed Phase 0 schedule has been created in Microsoft Project (MSP) in heavy consultation with Routes AstroEngineering. The schedule contains positive float. Prior to the start of the project, critical path and PERT analysis will be done on the schedule. MSP will be used to track the actual progress of the schedule and to perform Earned Value Management (EVM) periodically during the Phase. Requested changes to the schedule will be processed by the PPM and tracked and communicated to stakeholders accordingly.

ID	Task Name	Start	Finish
1	**Milestones**	**15/03/2010**	**18/10/2010**
2	Kick-off Meeting	15/03/2010	15/03/2010
3	MTR	02/06/2010	02/06/2010
4	PCR	14/10/2010	14/10/2010
5	End/Closure of Phase 0	18/10/2010	18/10/2010
6			
7			
8	**WBS 1-0: Project Management**	**01/03/2010**	**29/10/2010**
9	**WBS 1.1-0: Project Planning, Control and Monitoring**	**01/03/2010**	**29/10/2010**
10	CWBS (Scope) and Schedules (Time)	01/03/2010	29/10/2010
11	Cost, Quality, Risk and Communications Manageme	01/03/2010	29/10/2010
12	**WBS 1.2-0: Meetings and Reviews**	**01/03/2010**	**26/10/2010**
13	**Kick-off Meeting (proposed location Ottawa)**	**04/03/2010**	**15/03/2010**
16	**Monthly Progress Meeting**	**26/03/2010**	**26/10/2010**
25	*PCW Phase A MRR*	01/03/2010	01/03/2010
26	PCW U&ST #1 (location - Ottawa)	18/05/2010	18/05/2010
27	PCW U&ST #2 (location - Ottawa)	14/09/2010	14/09/2010
28	PHEMOS Mission MTR Meeting (CSA - 1 day)	02/06/2010	02/06/2010
29	Technical Interchange Meeting (Routes)	03/06/2010	03/06/2010
30	PCR Meeting (CSA - 1 day)	13/10/2010	14/10/2010
31	**WBS 1.3-0: Project Documentation**	**01/03/2010**	**29/10/2010**
32	UofC CADM	01/03/2010	29/10/2010
33	**CDLR Deliverables**	**01/03/2010**	**29/10/2010**
82	**WBS 2-0: Mission Definition**	**01/03/2010**	**14/06/2010**
83	**WBS 2.1-0: Science Objectives**	**01/03/2010**	**14/06/2010**
84	Science Objectives (input to CDRL SC1, IR for MTR	01/03/2010	26/03/2010
85	Finalize Science Objectives (input to CDRL SC1, F t	03/06/2010	14/06/2010
86	**WBS 2.2-0: Measurement Needs**	**29/03/2010**	**07/06/2010**
87	Measurement Needs (input to CDRL SC1, IR for M	29/03/2010	14/05/2010
88	Finalize Measurement Needs (input to CDRL SC1, F	03/06/2010	07/06/2010
89	**WBS 2.3-0: Data Needs**	**29/03/2010**	**09/06/2010**
90	Data Needs (input to CDRL SC1, IR for MTR)	29/03/2010	31/05/2010
91	Finalize Data Nees (input to CDRL SC1, F for PCR)	03/06/2010	09/06/2010
92	**WBS 3-0: Requirements**	**01/03/2010**	**18/10/2010**
93	**WBS 3.1-0: PCW Mission Analysis**	**01/03/2010**	**15/10/2010**
94	PCW Mission Analysis (documentation input to CDR	01/03/2010	07/05/2010
95	Finalize PCW Mission Analysis (input to CDRL EN1	14/10/2010	15/10/2010
96	**WBS 3.2-0: PHEMOS/PCW Interface Requirements**	**01/06/2010**	**18/10/2010**
97	PHEMOS/PCW Interface Requirements Document (	01/06/2010	10/06/2010
98	Finalize Interface Requirements Document (input to	14/10/2010	18/10/2010
99	**WBS 4-0: Science Payload Concept**	**10/06/2010**	**15/10/2010**
100	**WBS 4.1-0: Design Concept**	**10/06/2010**	**01/10/2010**
101	Payload Architecture, Block Diagram	10/06/2010	17/06/2010
102	Optical Design (Baffles, Mirrors, Coatings)	17/06/2010	08/07/2010
103	Mechanical Packaging	08/07/2010	19/07/2010
104	Electronic Design	20/07/2010	11/08/2010
105	Payload Performance Analyses	11/08/2010	24/08/2010
106	Orbit Analysis	24/08/2010	01/09/2010
107	Concept of Operations (nominal, contingency, mitiga	01/09/2010	08/09/2010
108	Compliance Matrix against Science & Mission Requ	08/09/2010	10/09/2010
109	Payload Conceptual Design Documentation (input to	10/09/2010	24/09/2010
110	Finalize Conceptual Design (input to CDRL EN2, F)	24/09/2010	01/10/2010
111	**WBS 4.2-0: Engineering Budget**	**01/10/2010**	**15/10/2010**
112	Engineering Budget (input to CDRL EN2, IR for PCF	01/10/2010	04/10/2010
113	Finalize Engineering Budget (input to CDRL EN2, F	14/10/2010	15/10/2010
114	**WPS 4.3-0: Payload Interfaces and Compatibility**	**01/10/2010**	**14/10/2010**
115	Develop Payload Interfaces (input to CDRL EN2, IR	01/10/2010	04/10/2010
116	Finalize Payload Interfaces (input to CDRL EN2, F)	14/10/2010	14/10/2010
117	**WBS 5-0: Development Plan**	**24/09/2010**	**18/10/2010**
118	**WBS 5.1-0 Programmatic**	**24/09/2010**	**18/10/2010**
119	Preliminary Development Plan (input to CDRL MM1	24/09/2010	29/09/2010
120	Cost & Schedule (Phase BCD, input to CDRL MM1,	29/09/2010	12/10/2010
121	Finalize Development Plan (input to CDRL MM1, F)	14/10/2010	18/10/2010
122	**WBS 5.2-0: Critical Technologies**	**24/09/2010**	**18/10/2010**
123	Critical Technologies Identification (input to CDRL M	24/09/2010	28/09/2010
124	TRL Assessment (input to CDRL MM1, IR for PCW)	28/09/2010	30/09/2010
125	Finalize Technologies Documentation (input to CDR	14/10/2010	18/10/2010



3.2 Phase 0 Milestones

The major project milestones under the planned Phase 0 schedule are tabulated below along with their corresponding deliverables.

Milestone	Date	Deliverables
Kick off Meeting	15/03/2010	Project Management Plan (CDRL PM1, F) CWBS and Work Package Descriptions (CDRL PM2, IR) KoM Agenda (CDRL PM3) KoM Minutes (CDRL PM4)
Monthly Progress Meetings	Monthly	Monthly Progress Reports (CDRL PM8)
Mid-Term Review	02/06/2010	Mid-term Review Data Package (CDRL PM6, IR) Science Objective and User's needs Definition Document (CDRL SC1, IR) MTR Agenda (CDRL PM3) MTR Minutes (CDRL PM4)
Science Payload Concept Review	14/10/2010	Science Objective and User's needs Definition Document (CDRL SC1, F) Preliminary Interface Requirements Document (CDRL EN1, IR) Science Payload Conceptual Design Document (CDRL EN2, IR) PHEMOS Mission Preliminary Cost & Schedule Estimates (CDRL MM1, IR) PCR Agenda (CDRL PM3) PCR Minutes (CDRL PM4)
Phase Closure	29/10/2010	Action Items Log (CDRL PM5) Phase Closure Report (CDRL PM9, F) Crown Assets List (CDRL PM10, IR) Preliminary Interface Requirements Document (CDRL EN1, F) Science Payload Conceptual Design Document (CDRL EN2, F) PHEMOS Mission Preliminary Cost & Schedule Estimates (CDRL MM1, F)

4 Appendices

4.1 Appendix A – Sample Contract and Report Form

Part 3 – Contract Plan and Report Form

File No.: 9F007-080599
Contractor: UofC, Donovan
Date: November 10, 2009

	FY 2009/2010												Task Cost		
Work Package	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Actual to Date (FY)	Projected (next quarter)	Planned (FY)
WP1100 (Management)	1,042	905	798	677	675	988	1,198	1,198	1,197				5,085	3,593	15,500
Greffen	*455*	*423*	*422*	*407*	*405*	*405*	*405*	*405*	*405*				*2,516*	*1,215*	*5,400*
Trondsen	*286*	*286*	*280*	*270*	*270*	*270*	*270*	*270*	*270*				*1,664*	*811*	*3,500*
Simmonds	-	*195*	*97*	-	-	-	-	-	-				*292*	-	*3,000*
Bourgeault							*210*	*210*	*210*				-	*630*	
Coop	*301*	*NA*	*NA*	*NA*	*NA*	*312*	*312*	*312*	*312*				*614*	*937*	*3,600*
WP1200 (Materials)	1,065	959	844	721	-	312	210	210	210				3,900	630	9,710
Trondsen	*763*	*763*	*747*	*721*	-	-	-	-	-				2,995	-	*3,110*
Simmonds	-	*195*	*97*	-	-	-							292	-	*3,000*
Bourgeault							*210*	*210*	*210*				-	*630*	
Coop	*301*	*NA*	*NA*	*NA*	*NA*	*312*							614	-	*3,600*
WP2100 (Mech Fab)	573	573	561	4,925	-	-	-	-	-				6,631	-	2,750
Trondsen	*573*	*573*	*561*	-	-	-							1,706	-	*1,750*
Materials and Supplies	-	-	-	-	-	-							-	-	*1,000*
Subcontracts	-	-	-	*4,925*	-	-							4,925	-	-
WP2200 (Elec Fab)	1,437	573	561	451	451	901	900	900	2,900				4,372	4,700	16,750
Trondsen	*573*	*573*	*561*	*451*	*451*	*901*	*900*	*900*	*900*				*3,508*	*2,700*	*1,750*
Subcontracts	*864*	-	-	-	-	-			*2,000*				*864*	*2,000*	*15,000*
WP2300 (Optical Fab)	1,955	4,615	1,588	270	28,197	700	1,000	-	-				37,326	1,000	43,730
Trondsen	*1,622*	*1,622*	*1,588*	*270*	*451*	*451*							*6,004*	-	*5,730*
Coop	*241*	*NA*	*NA*	*NA*	*NA*	*250*							*491*	-	*3,000*
Materials and Supplies	*92*	*2,992*	-	-	*27,747*	-	*1,000*						*30,831*	*1,000*	*35,000*
WP2400 (Assembly)	4,790	1,428	1,010	1,987	2,971	4,232	4,850	4,850	4,850				16,418	14,550	61,200
Trondsen	-	-	-	*1,892*	*2,433*	*1,982*	*2,000*	*2,000*	*2,000*				6,307	*6,000*	*30,800*
Coop	*2,168*	*NA*	*NA*	*NA*	*NA*	*2,250*	*2,250*	*2,250*	*2,250*				4,418	*6,750*	*26,400*
Materials and Supplies	*2,258*	*1,191*	*703*	-	- *0*	-	*500*	*500*	*500*				4,152	*1,500*	*3,000*
Shipping	*364*	*237*	*307*	*95*	*539*	-	*100*	*100*	*100*				1,541	*300*	*1,000*
WP2500 (Spares)*													-	-	-
WP3100 (Calibration)													-	-	-
WP3200 (Deployment)													-	-	-
Overhead	98	-	-	1,627	-	-	2,000						1,724	2,000	4,500
Planned Cost	9,300	8,500	6,600	6,677	5,050	37,187	10,158	7,158	9,157					**26,473**	**154,140**
Actual Cost	10,959	9,051	5,361	10,657	32,294	7,134							**75,457**		

Original Estimate
Completed
Revised Estimate

*Due to the nature of the purchasing and accounting systems at the UofC, it is impossible to separate 'Spares', and as such they are included in WP2100 through WP2400.

4.2 Appendix B: Work Packages

PROJECT: PCW-UVI [PHASE 0/PHASE A]	**WBS Ref: WP 1.1-0/A**
Work Package Title: Project Planning/Control and Monitoring	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:** T0 /T1+8/10 mths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Mike Greffen
Estimated Effort:0/26 *(81/74c)*hrs	**Resources:** Mike Greffen, Blair Gordon

OBJECTIVES:

- Finalize Project Management Plan
- Maintain CWBS and Schedule
- Complete Phase 0/A on time and on budget with a high quality product

INPUTS:

- CDRL PM1 Initial Release

TASKS:

- Update and finalize the proposed Project Management Plan (CDRL PM1) with emphasis on changes in resource availability, the Responsibility Allocation Matrix, the Project Risk Assessment Matrix and the budget and timeline.
- Review and update the CWBS and the Work Package Descriptions at the start of the phase and prior to each Monthly Progress Meeting. (scope verification)
- Define all stakeholders' roles and responsibilities. Manage the stakeholder's expectations to keep the project on scope. Facilitate stakeholder communication via regular meetings and an effective Configuration and Document Management office (communications management).
- Continually track project progress using Earned Value Management or equivalent. Monitor and control the timeline, budget and scope and quality of all Phase 0 work (schedule, cost, scope and quality control). Maintain schedule, update in Monthly Progress Reports (CDRL-PM8/PM18).
- Monitor and control project management risks. Track risks identified in the preliminary management risk analysis and identify new risks as appropriate. Update or develop mitigation strategies for identified risks. Monitor the contingency reserves in the project (risk management)
- Facilitate all communication with CSA.

OUTPUTS AND DELIVERABLES:

- CDRL-PM1/PM11 (Project Management Plan) delivered Final at Kick Off Meeting
- CDRL-PM8/PM18 (Monthly Progress Reports)
- CDRL-PM2/PM12 (CWBS and Work Package Descriptions)

PROJECT: PCW-UVI [PHASE 0/PHASEA]	**WBS Ref: WP 1.2-0/A**
Work Package Title: Meeting and Reviews	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:** T0/T1+8/10mnths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Mike Greffen
Estimated Effort: 0/106 *(220/157c)* hours	**Resources:** Mike Greffen, Eric Donovan, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers

OBJECTIVES:

- Stay connected with the progress of the PCW work currently underway
- Communicate project progress to the CSA and other stakeholders

INPUTS:

- PHEMOS RFP (Solicitation 9F007-090217/A)

TASKS:

- Arrange and attend project meetings listed in the PHEMOS RFP, either in person or by teleconference or videoconference.
- Attend PCW mission meetings listed in the PHEMOS RFP. Communicate latest mission level information to the project team.
- Conduct PHEMOS reviews listed in the PHEMOS RFP.

OUTPUTS AND DELIVERABLES:

- None (see WP 1.3-0/A)

PROJECT: PCW-UVI [PHASE 0/PHASEA]	**WBS Ref: WP 1.3-0/A**
Work Package Title: Project Documentation	**Sheet:** 1 of 1
Scheduled Start: T0/T1 **Scheduled End:**T0 /T1+8/10mnths	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 44/306 *(230/231c)* hours	**Resources:** Emma Spanswick, Mike Greffen, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers, Eric Donovan

OBJECTIVES:

- Provide configuration controlled versions of all CDRL documents listed in the PHEMOS RFP (solicitation 9F007-090217/A).
- Foster clear communication of project progress to all stakeholders.

INPUTS:

- PHEMOS RFP (solicitation 9F007-090217/A)

TASKS:

- Receive inputs to CDRL documents from appropriate Work Packages.
- Integrate inputs into Data Item Description compliant documents and place under Configuration Control.
- Distribute CDRL documents to stakeholders.

OUTPUTS AND DELIVERABLES:

- Preliminary, Initial Release and Final (as required) versions of all project CDRL documents.

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 2.1-0**
Work Package Title: Science Objectives	**Sheet:** 1 of 1
Scheduled Start: T0 **Scheduled End:** T0+75.5days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Eric Donovan
Estimated Effort: 15 *(26c)* hours	**Resources:** Eric Donovan, Emma Spanswick

OBJECTIVES:

- To detail the science concept and objectives of the mission in sufficient depth to allow for the specification of measurement and data needs.

INPUTS:

- Preliminary CDRL SC1 submitted with PCW-UVI Phase 0/A proposal

TASKS:

- Review (and if necessary revise) the preliminary science concept and objectives description contained in the preliminary CDRL SC1 submitted with the PCW-UVI Phase0/A proposal. This includes a review (and complete documentation) of the science concept, objectives and prioritization.
- If necessary, review and revise the science objectives and prioritization (initiated by MTR or WP4.1-0) and iterate towards a finalized science concept and objectives document.

OUTPUTS AND DELIVERABLES:

- Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0, WP2.2-0, WP2.3-0].
- Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 2.2-0**
Work Package Title: Measurement Needs	**Sheet:** 1 of 1
Scheduled Start: T0+20 days **Scheduled End:** T0 + 71 days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 32 *(33c)* hours	**Resources:** Emma Spanswick, Eric Donovan, Blair Gordon, Ken Smith, Don Asquin, Donna-Lee Desaulniers

OBJECTIVES:

- To detail and prioritize the mission measurement needs in sufficient depth to enable instrument conceptual design (WP4.1-0)

INPUTS:

- Preliminary science objectives contained in CDRL SC1 from WP2.1-0

TASKS:

- Based on the science objectives section contained in the preliminary version controlled CDRL SC1 (initial output from WP2.1-0), identify and name the key measurement needs. These will include (but are not limited to): observational area of interest, measurement quantities, energy resolution and daytime viewing needs.
- Determine values/ranges for measurement needs based on the science objectives output from WP2.1-0.
- Prioritize measurement needs based on the prioritization of science objectives output from WP2.1-0.
- If necessary, review and revise the measurement needs and/or prioritization (initiated by MTR and/or WP4.1-0) to iterate towards a final release of CDRL SC1.
- Provide a preliminary set of instrument requirements (ie. FUV spectral range, resolution, etc.) to enable conceptual design (WP4.1-0)

OUTPUTS AND DELIVERABLES:

- Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0, WP4.1-0]

- Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 2.3-0**
Work Package Title: Data Needs	**Sheet:** 1 of 1
Scheduled Start: T0+20 days **Scheduled End:** T0 + 73 days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 60 *(20c)* hours	**Resources:** Emma Spanswick

OBJECTIVES:
- To detail and prioritize the data needs of PCW-UVI

INPUTS:
- Preliminary science objectives and measurement needs contained in CDRL SC1 (initial output from WP2.1-0 and WP2.2-0).

TASKS:
- Based on the output of WP2.1-0 and WP2.2-0 review (and if necessary revise) the list of potential PCW-UVI data products.
- For each data product, identify the needs of potential end users. These will include (but are not limited to): data availability, turn-around-time, and image mapping requirements.
- For each data product, identify its relationship to the PCW-UVI science objectives and prioritize data needs based on the prioritization of science objectives output from WP2.1-0.

OUTPUTS AND DELIVERABLES:
- Input to CDRL SC1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0]
- Input to CDRL SC1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 3.1-0**
Work Package Title: PCW Mission Analysis	**Sheet:** 1 of 1
Scheduled Start: T0 **Scheduled End:** T0+164days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 24 *(68c)* hours	**Resources:** Emma Spanswick, Ken Smith, Don Asquin

OBJECTIVES:
- Achieve a full understanding of the operational environment of the Science Payload

INPUTS:
- PHEMOS proposal concept
- Available PCW mission documentation from CSA

TASKS:
- Thorough analysis of all available documents on PCW to achieve objective.

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN1 [delivered to WP1.3-0, WP3.2-0]
- Input to CDRL EN1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0]
- Input to CDRL EN1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 3.2-0**
Work Package Title: PHEMOS/PCW Interface Requirements	**Sheet:** 1 of 1
Scheduled Start: T0+64days **Scheduled End:** T0+164days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Emma Spanswick
Estimated Effort: 30 *(48c)* hours	**Resources:** Emma Spanswick, Blair Gordon, Ken Smith, Don Asquin

OBJECTIVES:
- Produce a list of instrument requirements for the PCW satellite

INPUTS:
- PCW Mission analysis from WP3.1-0
- Preliminary PCW-UVI concept design from proposal
- Instrument requirements section from initial release of CDRL SC1

TASKS:
- Based on the measurement requirements in the initial release of CDRL SC1 determine the associated interface requirements on PCW. These will include, but not be limited to; pointing accuracy, pointing stability, distribution of instrument suite across available satellites, and telemetry rate.

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN1 (Initial Release), prior to the Midterm Review [delivered to WP1.3-0]
- Input to CDRL EN1 (Final), prior to science Payload Concept Review [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WBS 4.1-0** **WP Ref: WP 4.1.1-0**
Work Package Title: Design Concept	**Sheet:** 1 of 1
Scheduled Start: T0+71days **Scheduled End:** T0+153days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 440 *(164c)*hours	**Resources:** Trond Trondsen, Blair Gordon, Ken Smith, Don Asquin, Paul Marchand, Donna-Lee Desaulniers, John Pazder

OBJECTIVES:
- Develop a validated science payload conceptual design based on the measurement requirements of the science objectives

INPUTS:
- Initial conceptual design from PCW-UVI proposal
- Measurement/Instrument requirements from initial release of CDRL SC1
- PCW mission constraints from initial release of CDRL EN1

TASKS:
- Perform conceptual design, including optics, detectors, electronics, controls, data storage and handling
- Define interfaces and any common resources
- Perform analysis given measurement requirements (from initial release of CDRL SC1)
- Develop preliminary Concept of Operations

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0, WP5.1-0, WP5.2-0]
- Input to CDRL EN2 (Final) [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 4.2-0**
Work Package Title: Engineering Budget	**Sheet:** 1 of 1
Scheduled Start: T0+140days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 12 *(13c)* hours	**Resources:** Blair Gordon, Ken Smith, Paul Marchand

OBJECTIVES:
- Determine mass, volume, power, dataflow, and thermal budgets

INPUTS:
- Conceptual design from preliminary CDRL EN2 (output from WP 4.1-0)

TASKS:
- Perform radiation analysis for specified orbit
- Estimate mass, volume, power, dataflow, and thermal budgets from refined conceptual design
- Iterate design if required (initial design exceeds conceivable S/C resources)

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0]
- Input to CDRL EN2 (Final) [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 4.3-0**
Work Package Title: Payload Interfaces and Compatibility	**Sheet:** 1 of 1
Scheduled Start:T0+140days **Scheduled End:**T0+149days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 12 *(15c)* hours	**Resources:** Blair Gordon, Don Asquin, Ken Smith, Paul Marchand, Donna-Lee Desaulniers

OBJECTIVES:
- Produce preliminary interface design

INPUTS:
- Conceptual design contained CDRL EN2 (output WP4.1-0)
- Data needs from initial release of CDRL SC1

TASKS:
- Determine power, command/control, data output, mechanical (mass, mounting, structural, volume), thermal requirements and characteristics

OUTPUTS AND DELIVERABLES:
- Input to CDRL EN2 (Initial Release), prior to the Payload Concept Review [delivered to WP1.3-0]
- Input to CDRL EN2 (Final) [delivered to WP1.3-0]

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 5.1-0**
Work Package Title: Programmatic	**Sheet:** 1 of 1
Scheduled Start: T0+135days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 40 *(84c)* hours	**Resources:** Blair Gordon, Ken Smith, Don Asquin
OBJECTIVES: ▪ Program Cost and schedule estimate for Phases BCD	
INPUTS: ▪ Mission & Instrument Requirements contained in CDRL SC1 ▪ Concept Design and analyses from WP4.1-0	
TASKS: ▪ Prepare PHEMOS Preliminary Cost & Schedule estimate	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL MM1 (initial release) at PCR [delivered to WP1.3-0] ▪ Input to CDRL MM1 (final) [delivered to WP1.3-0]	

PROJECT: PCW-UVI [PHASE 0]	**WBS Ref: WP 5.2-0**
Work Package Title: Critical Technologies	**Sheet:** 1 of 1
Scheduled Start: T0+135days **Scheduled End:** T0+150days	**Accountable Manager:** Mike Greffen **Accountable Resource:** Blair Gordon
Estimated Effort: 8 *(12c)* hours	**Resources:** Blair Gordon, Ken Smith, Don Asquin
OBJECTIVES: ▪ Identify Critical Technologies and establish initial TRL Level	
INPUTS: ▪ Mission & Instrument Requirements contained in CDRL SC1 ▪ Concept Design and analyses from WP4.1-0	
TASKS: ▪ Map key instrument requirements to the performance of key technologies ▪ Assess Criticality of Key Technologies ▪ Assess current technology TRL level	
OUTPUTS AND DELIVERABLES: ▪ Input to CDRL MM1 (initial release) at PCR [delivered to WP1.3-0] ▪ Input to CDRL MM1 (final) [delivered to WP1.3-0]	

Appendix XI – Sample Contract Report Form

Part 3 – Contract Plan and Report Form

File No.: 9F007-080599	Task Cost		
Contractor: UofC, Donovan	Actual to Date (FY)	Projected (next quarter)	Planned (FY)
Date: November 10, 2009			

	FY 2009/2010														
Work Package	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**			
WP1100 (Management)	1,042	905	798	677	675	988	1,198	1,198	1,197				5,085	3,593	15,500
Greffen	*455*	*423*	*422*	*407*	*405*	*405*	*405*	*405*	*405*				*2,516*	1,215	5,400
Trondsen	*286*	*286*	*280*	*270*	*270*	*270*	*270*	*270*	*270*				*1,664*	*811*	*3,500*
Simmonds	-	*195*	*97*	-	-	-	-	-	-				*292*	-	*3,000*
Bourgeault							*210*	*210*	*210*				-	*630*	
Coop	*301*	*NA*	*NA*	*NA*	*NA*	*312*	*312*	*312*	*312*				*614*	*937*	*3,600*
WP1200 (Materials)	1,065	959	844	721	-	312	210	210	210				3,900	630	9,710
Trondsen	*763*	*763*	*747*	*721*	-	-	-	-	-				2,995	-	*3,110*
Simmonds	-	*195*	*97*	-	-	-							292	-	*3,000*
Bourgeault							*210*	*210*	*210*				-	*630*	
Coop	*301*	*NA*	*NA*	*NA*	*NA*	*312*							614	-	*3,600*
WP2100 (Mech Fab)	573	573	561	4,925	-	-	-	-	-				6,631	-	2,750
Trondsen	*573*	*573*	*561*	-	-	-							1,706	-	*1,750*
Materials and Supplies	-	-	-	-	-	-							-	-	*1,000*
Subcontracts	-	-	-	*4,925*	-	-							4,925	-	-
WP2200 (Elec Fab)	1,437	573	561	451	451	901	900	900	2,900				4,372	4,700	16,750
Trondsen	*573*	*573*	*561*	*451*	*451*	*901*	*900*	*900*	*900*				*3,508*	*2,700*	*1,750*
Subcontracts	*864*	-	-	-	-	-			*2,000*				*864*	*2,000*	*15,000*
WP2300 (Optical Fab)	1,955	4,615	1,588	270	28,197	700	1,000	-	-				37,326	1,000	43,730
Trondsen	*1,622*	*1,622*	*1,588*	*270*	*451*	*451*							*6,004*	-	*5,730*
Coop	*241*	*NA*	*NA*	*NA*	*NA*	*250*							*491*	-	*3,000*
Materials and Supplies	*92*	*2,992*	-	-	*27,747*	-	*1,000*						*30,831*	*1,000*	*35,000*
WP2400 (Assembly)	4,790	1,428	1,010	1,987	2,971	4,232	4,850	4,850	4,850				16,418	14,550	61,200
Trondsen	-	-	-	*1,892*	*2,433*	*1,982*	*2,000*	*2,000*	*2,000*				6,307	*6,000*	*30,800*
Coop	*2,168*	*NA*	*NA*	*NA*	*NA*	*2,250*	*2,250*	*2,250*	*2,250*				4,418	*6,750*	*26,400*
Materials and Supplies	*2,258*	*1,191*	*703*	-	- *0*	-	*500*	*500*	*500*				4,152	*1,500*	*3,000*
Shipping	*364*	*237*	*307*	*95*	*539*	-	*100*	*100*	*100*				1,541	*300*	*1,000*
WP2500 (Spares)*													-	-	-
WP3100 (Calibration)													-	-	-
WP3200 (Deployment)													-	-	-
Overhead	98	-	-	1,627	-	-	2,000						1,724	2,000	4,500
Planned Cost	9,300	8,500	6,600	6,677	5,050	37,187	10,158	7,158	9,157					**26,473**	**154,140**
Actual Cost	10,959	9,051	5,361	10,657	32,294	7,134							**75,457**		

Original Estimate
Completed
Revised Estimate

*Due to the nature of the purchasing and accounting systems at the UofC, it is impossible to separate 'Spares', and as such they are included in WP2100 through WP2400.

Appendix XII – Preliminary Concept Sensitivity Analysis

TABLE 1: PHEMOS Modeled UV Imager Sensitivity

	Item	LBH-short	LBH-long	OI(1304Å)	Units
Exposure	Rows on square CCD	1024	1024	1024	pixels
	Binning factor	**3**	**3**	**3**	pixels/bin
	Binned rows on square CCD	341.33333	341.33333	341.33333	pixels
	Total FOV	**20**	**20**	**20**	deg
	IFOV	0.059	0.059	0.059	deg/pixel
	Exposure time	**20**	**20**	**20**	s
Optical Efficiency	Single mirror reflectivity in UV	0.85	0.85	0.85	wrt unity
	Number of mirrors	**3**	**3**	**3**	
	Total resulting reflectivity	0.614	0.614	0.614	wrt unity
	Single mirror reflectivity in solar spectrum	0.05	0.05	0.05	wrt unity
	Solar spectrum rejection due to mirrors	1.25E-04	1.25E-04	1.25E-04	wrt unity
	Intensifier window material	SiO_2	BaF_2	CaF_2	
	Intensifier window transmission	0.82	0.76	0.5	wrt unity
	Photocathode material	CsI	CsI	KBr	
	Photocathode QE	0.21	0.15	0.26	wrt unity
	MCP efficiency	0.6	0.6	0.6	wrt unity
	Optics and intensifier transmission in UV	0.0635	0.0420	0.0479	wrt unity
	Aperture area	1.58	1.58	1.58	cm^2
	Aperture diameter	**14.2**	**14.2**	**14.2**	mm
	Pixel Omega (square pixels)	1.05E-06	1.05E-06	1.05E-06	sr/pixel
Signal to Noise Ratio	Radiance-kR conversion factor	7.96E+07	7.96E+07	7.96E+07	counts/cm^2/s/sr/kR
	Calculated Sensitivity	8.343	5.524	6.299	counts/s/kR/pixel
	Counts/R/pixel/exposure	0.167	0.110	0.126	counts/(R*pixel*exp)
	Minimum detectable signal	1	1	1	Counts
	Noise Equivalent Signal (NES) - desired = 10, max = 30	**5.99**	**9.05**	**7.94**	R/exposure
	Minimum good SNR	2.5	2.5	2.5	:1
	Brightness required for SNR	**37.455**	**56.576**	**49.613**	**R/exposure**
Spatial Resolution	1 RE (radius of earth)	6.38E+06	6.38E+06	6.38E+06	m
	Satellite altitude [RE] (geocentric)	7.26	7.26	7.26	RE
	Derived Altitude [km above ground]	39938.8	39938.8	39938.8	km
	Full Earth angle seen from above altitude	15.83	15.83	15.83	deg
	Nadir resolution element	**40.8**	**40.8**	**40.8**	**km**
Detector and Optics Interface	Detector (space qualified) active diameter	25	25	25	mm
	Focal length required	70.89	70.89	70.89	mm
	f-ratio	5.00	5.00	5.00	:1
	CCD pixel size	13	13	13	µm
	Binned CCD pixel size	39	39	39	µm
	CCD dimension	13.312	13.312	13.312	mm
	MCP to CCD taper ratio required	1.88	1.88	1.88	:1
	MCP resolution (MTF)	22	22	22	lp/mm
	MCP line pairs across diameter	550	550	550	lp
	Spatial sampling factor	2.4	2.4	2.4	samples per lp
	Maximum useful pixels across MCP diameter	1320	1320	1320	pixels

TABLE 2

Nadir Spatial Resolution as a function of binning (1024x1024 CCD) and FoV

Binning / FoV	18 deg	20 deg	22 deg	24 deg
1:1	12 km	14 km	15 km	16 km
2:2	25 km	27 km	30 km	33 km
3:3	37 km	**40 km**	45 km	49 km
4:4	49 km	55 km	60 km	65 km
5:5	61 km	68 km	75 km	82 km
6:6	74 km	82 km	90 km	98 km
7:7	86 km	95 km	105 km	114 km
8:8	98 km	109 km	120 km	131 km

Table 3

Rayleigh sensitivity as a function of binning and FoV (40 sec exposure time)

Binning / FoV	18 deg @ 40 s	20 deg @ 40 s	22 deg @ 40 s	24 deg @ 40 s
1:1	208 R	170 R	139 R	117 R
2:2	52 R	42 R	35 R	30 R
3:3	23 R	19 R	15 R	13 R
4:4	13 R	11 R	9 R	7 R
8:8	3.5 R	2.6 R	2.2 R	1.8 R

Table 4

Rayleigh sensitivity as a function of binning and FoV (20 sec exposure time)

Binning / FoV	18 deg @ 20 s	20 deg @ 20 s	22 deg @ 20 s	24 deg @ 20 s
1:1	416 R	340 R	278 R	134 R
2:2	104 R	84 R	70 R	60 R
3:3	46 R	**38 R**	30 R	26 R
4:4	26 R	22 R	18 R	14 R
8:8	6.5 R	5.3 R	4.4 R	3.7 R

Table 5

For a 38 R aurora (highlighted above), SNR varies with Exposure Time as...

T (s)	20	18	16	14	12	10	8	6	4	2	1
SNR	2.5	2.4	2.3	2.1	2.0	1.8	1.6	1.3	1.2	0.8	0.6

Minimum useful SNR depends on application and must be empirically determined. Common values are 2.5, 1.0, and sqrt(2)=1.4.