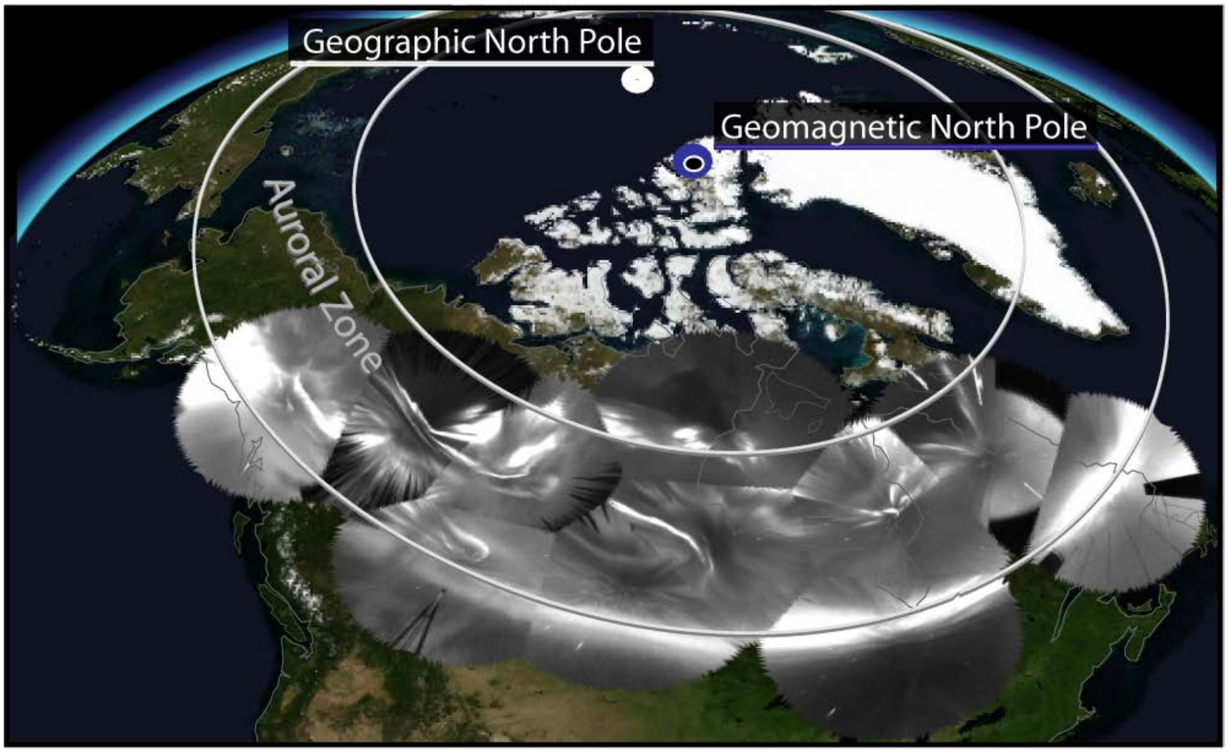
2020 Solar-Terrestrial Science Roadmap

June 4, 2020

Prepared by the Solar-Terrestrial Science Advisory Committee with community consultation



"Ensure Canada's leadership in acquiring and using space-based data to support science excellence, innovation, and economic growth; Supporting space science to study Earth and beyond (e.g. space weather)." *[***Canadian Space Strategy, 2019***]*

Revision History

Rev.	**Description**	**Initials**	**Date**
1.0	2009 Canadian Space Environment Community LTSP Roadmap [RD-01]	-	Nov 17, 2009
2.0	Updated to reflect 2017 Solar-Terrestrial Science Community Workshop [RD-02] and 2019 Canadian Space Strategy [RD-03]	STSAC	June 2, 2020

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1 Introduction

As a nation, Canada confronts many challenges. Among these challenges is the growing potential for space weather-related disruptions to Canada's increasingly technological society following explosive releases of energy from the Sun. In addition, because of climate change, the large-scale structure of the atmosphere is changing, and the Earth's climate is evolving. Of particular importance and relevance is the fact that both the solar and the terrestrial environments are also changing rapidly. Developing a fundamental understanding of the physical processes which control the evolution of these coupled terrestrial and space environments is key to assessing both the future evolution of our planet, and for addressing and mitigating the adverse impacts of space weather. Overall, our community proposes a scientific voyage of discovery to the next space plasma research frontier. We will directly address the challenges of the solar impacts on our changing planet, forecasting and mitigating the potentially catastrophic impacts of extreme space weather. Understanding space plasma environments is a key aspect of space situational awareness, addressing the threats posed by space radiation to crewed and robotic exploration of deep space.

Numerous processes act to control the response of the magnetosphere-ionosphere-atmosphere to solar forcing. These highly coupled processes operate at a system level, and a detailed understanding of the physical processes which control the dynamics of the terrestrial environment is fundamental to understanding their evolution. Similar processes act to couple the Sun to other planetary systems inside the heliosphere and understanding their evolution and related space radiation consequences will be key for Canadian ambitions for future robotic and human exploration of lunar and planetary bodies in the solar system. In the context of anthropogenically driven terrestrial climatic change, disentangling these system-level connections on a changing Earth and in the atmosphere of a changing Sun is of crucial importance. For example, the Earth's magnetic pole is migrating, and the strength of the magnetic field has diminished by 9% over the last 200 years on a global average. Changes in the dominant solar magnetic field in space similarly have given rise to conditions unprecedented in the Space Age, yet we lack fundamental understanding of their causes. Whilst the recent periods of global warming are clearly driven primarily by anthropogenic factors and not changes in the Sun, understanding and quantifying solar impacts remains a very important endeavour for scientific discovery and for higher fidelity forecasting of the system's coupled response to changing internal and external conditions. All these evolving systems require not only ongoing continuous monitoring, but in order to mitigate the adverse impacts of space weather, a more detailed and refined understanding of the dynamic Sun/Earth system is essential.

Canada is a country rich in opportunities. Among these opportunities is Canada's contribution to the advancement of our knowledge-based civilization. To continue Canada's leadership in world economy and science, to ensure Canada's continuing prosperity and security, investment in science and the people who advance scientific knowledge is a priority for the Government of Canada. The Canadian solar-terrestrial scientific community is globally recognized for scientific leadership and discovery with national impact through technological development and commercial spin-offs. Canada's world-leading solar-terrestrial scientific research, with a long history of instrument development, has had the direct consequence of growing Canada's high-tech space engineering sector. A key element of the solar-terrestrial research program is for trainees to work on all stages of development of flight hardware. These trainees have moved forward with an entrepreneurial spirit and have been significant contributors to Canada's space sector. Notable examples of commercial spin-offs include Calian SED, ITRES Research Limited, Keo Scientific, and Wildy Enterprises.

It was the nascent Canadian solar-terrestrial science community that led Canada to become the third country in space with its own satellite: Alouette 1. Since then, thanks to the efforts of our early pioneers and the many who followed in their footsteps, Canada has emerged as a sought-after partner in international solar-terrestrial science projects and missions. These include missions developed in collaboration with the Japan Aerospace Exploration Agency (JAXA), the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and, most recently, the Chinese Academy of Sciences (CAS).

Canadian researchers have from the start taken advantage of the unique perspective afforded by space to observe the impact of space weather on the Earth. The pioneering success of Alouette 1 led to missions which also used radio sounders to probe the ionosphere from above, including ISIS 2, whose auroral photometer made the first images of the aurora from space just a decade later. These early observations showed how variable the space environment can be and were among the first to demonstrate the global extent of space weather. Canadian researchers not only made many observational firsts but, more importantly, established research trends that significantly advanced international understanding of space weather impacts on spacecraft and terrestrial technological systems.

Canadian researchers in universities and government have continued not only to work with satellites, but to take advantage of the unique perspective afforded by Canada's location under active space weather regions. Extensive arrays of instruments deployed from coast to coast and across the Canadian North represent the world's largest and most powerful ground-based network for observing the impacts of space weather. These instruments enable observations of space weather that are impossible to make from space and provide a vital context for space-based observations. Long an important tool for solar-terrestrial science, the arrays of instruments deployed across Canada are drawing increased interest by government (NRCan, DND/DRDC, DFO, etc.) and industry (Hydro-Québec, TransAlta, NovAtel, etc.) as they seek to increase their resilience to the impact of space weather.

In identifying strategic directions and priorities for the program, the solar-terrestrial science community was guided by the vision enunciated in the New Space Strategy for Canada [RD-03]. That vision acknowledges space as a strategic national asset requiring a whole-of-government effort to ensure that Canada can rely on space to meet national needs. Just as a sea-faring nation relying on the sea needs to understand the sea, a space-faring nation needs to understand the space environment. It is this drive to understand the space environment that is at the heart of the Canadian solar-terrestrial science program. Canada's foray into deep space as a partner in the Lunar Gateway only increases this need. Astronauts who leave the protective shield of the Earth's magnetosphere to go to the Moon or into deep space have always been at risk of far higher radiation doses than those working in low Earth orbit at the ISS.

Space is a vital factor in both the present and future of humanity. Space science research, fundamentally, develops the essential knowledge through which humankind establishes its position in the Universe and formulates the best strategy for the survival and continuing progress of human civilization. In this context, the value of our science will last for as long as humankind continues to push the envelope of its existence. For this reason, among many others, solar-terrestrial science matters to Canada.

2 References

RD	Title and links
RD-01	2009 Canadian Space Environment Community LTSP Roadmap (Livelink)
RD-02	2017 Solar-Terrestrial Science Community Workshop – Executive Summary (Livelink)
RD-03	Exploration, Imagination, Innovation: A New Space Strategy for Canada
RD-04	Understanding space weather to shield society: A global roadmap for 2015–2025 commissioned by COSPAR and ILWS (Livelink)
RD-05	Solar and Space Physics: A Science for a Technological Society (Livelink)
RD-06	Cosmic Vision: Space Science for Europe 2015–2025 (Livelink)
RD-07	Space Weather Socioeconomic Impact Study on Canadian Infrastructure 2019 (Livelink)
RD-08	CSA Deep Space Gateway Space Radiation and Health Study Team Report 2018 (Livelink)
RD-09	Report of the Planetary Exploration Topical Team on Planetary Space Environment 2017 (Livelink)

3 Solar-Terrestrial Science

Canada's solar-terrestrial science community seeks to advance our knowledge and understanding of the dynamics of the Sun and its effects on the atmospheres, ionospheres and magnetospheres of the Earth and other planets, and to advance our capability to forecast and mitigate the resulting impact of these effects on society. The community further seeks to apply our knowledge to understanding related impacts for space exploration, both crewed and robotic, and for the evolution of the environments of other planets in the solar system.

As the Sun's ionized outer atmosphere expands through interplanetary space, its ever-present and constantly varying plasma – the solar wind – interacts in a multitude of ways with every object in the solar system. Surfaces and atmospheres of bodies that lack a strong magnetic field, such as the Moon, are subject to direct scouring and erosion by the solar wind. The Earth and other magnetized objects are shielded from direct bombardment but are coupled strongly to the solar wind through electromagnetic forces and fluid mechanical interactions. The result of these influences is a complex and variable space environment, comprising distinct regions that range from cool, quiescent ionospheric plasma to highly dynamic populations with temperatures hotter than the surface of the Sun. Importantly, these regions are coupled strongly through electrical currents, transport, and collisions, acting together to channel terawatts of solar wind power through the magnetosphere and ultimately into the upper atmosphere. At the same time, atmospheric forcing and mass flows couple back to the magnetosphere. These phenomena are important both because they serve as up-close examples of processes that are at work throughout the cosmos, and because they are known to affect satellite communications and navigation systems, radio communications, aviation safety, electrical power grids, and even climate. As our society depends increasingly on space technologies, and as our environment affects our daily life more than ever before, solar-terrestrial interactions have increasingly significant economic and societal relevance to Canada.

Physical processes in near-Earth space are studied via direct *in situ* observation of the plasma and electromagnetic fields, and via remote sensing. Remote sensing provides a powerful means of tracking the evolution of the near-Earth space environment on a global scale. Canada's land mass spans the largest and most interesting portion of the polar cap, auroral zone, and sub-auroral region. This Canadian Advantage has shaped Canadian solar-terrestrial science from its inception in the mid-nineteenth century.

Early Canadian researchers gained international prominence in the emerging space sciences by deploying ground-based instruments to monitor the ionosphere and neutral atmosphere remotely. International leadership in those studies fostered a rich science program that grew to incorporate *in situ* observations on sounding rockets and satellites and made solar-terrestrial science a major driver of Canada's space presence. The first Canadian satellite Alouette 1, which made Canada the world's third space-faring nation, was dedicated to ionospheric studies, delivering numerous scientific firsts encapsulated in many refereed publications and the training of highly qualified personnel, and leading to the establishment of a world-class space instrumentation capability. The solar-terrestrial science program relied heavily on sounding rockets and contributed to the development of the Canadian Black Brant rocket which remains a workhorse for international suborbital space research.

In more recent years, solar-terrestrial science has continued to maintain international prominence – and leadership – in many areas of space science. We have utilized our Canadian geographical advantage in creating the world's foremost networks of ground-based instrumentation. Our space-based *in situ* and auroral imaging activities have continued, delivering new instruments that have placed Canadian science at the very front lines of the multi-billion-dollar international program of space-based solar-terrestrial science. Canada has also witnessed rapidly developing strength in terms of concerted theoretical and numerical modeling initiatives for solar and space plasmas. Our science and supporting technology are recognized internationally for ingenuity and innovation. Significant outcomes of our activities include the ability to generate new technologies, and the recognition of Canada as an important contributor of transformational space science instruments. While our scientific leaders carry out high-impact development and science, they create an outstanding environment for space-related training and provision of opportunities for the next generation of scientists and engineers.

High impact spin-off companies have been formed, serving the needs of the Canadian government, technological innovations of ground- and space-based instrumentation.

As an example of scientific productivity, an extensive literature search found that the GO Canada initiative enabled 1174 peer-reviewed publications between 2007-01-01 and 2017-12-31 (Figure 1). Of those publications, 470 (or 40%) were authored by Canadian GO Canada Principal Investigators (PIs) or Co-Investigators (CoIs) while the rest were authored by other scientists who are not directly involved in the GO Canada initiative, indicating the broad impact of GO Canada. Figure 1 illustrates the high level of use of GO Canada data by both Canadian and by international scientists. Other solar-terrestrial science projects, including THEMIS, Swarm and e-POP, have also been highly effective in generating peer-reviewed publications.

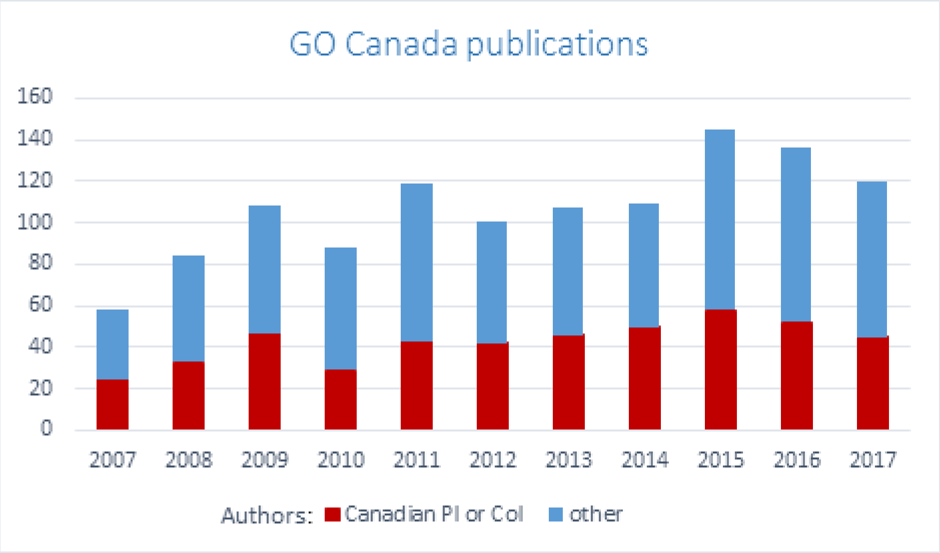

Figure 1 – Peer-reviewed GO Canada publications, 2007-2017

4 Science Questions

In establishing the scientific questions listed in this section, the Canadian community took into careful consideration the international context [RD-04, RD-05, RD-06], the relevance to the Canadian Space Strategy [RD-03], and the potential to make significant progress in solving fundamental problems. Our community is poised to make significant advances on the following science questions.

4.1 How does the Sun vary?

As the ultimate source of energy that controls Earth's environment and climate, the Sun represents a central focus for the community. Scientifically, solar variability comprises the following questions:

- What is the physical origin of the solar magnetic activity cycle?
- What is the role of magnetic field in solar atmosphere and coronal processes?
- What physical processes govern the production and evolution of CMEs, active regions, coronal holes, flares, and shocks?
- What processes are responsible for the acceleration and characteristics of the fast and slow solar wind?
- What processes govern the propagation and evolution of solar wind disturbances?
- What physical processes accelerate energetic particles in the solar environment?
- What plasma physical processes are responsible for reconnection, dissipation, and turbulence in space plasmas?

4.2 What physical processes control the space environment?

Upon entering the space environment around the Earth or other planets, the mass and energy from the Sun undergo a complicated process of transport and dissipation. Understanding this process entails investigation on the following questions:

- What role does multiscale coupling play in space environment dynamics?
- How are mass, energy, and momentum transported through space environments?

- How does structure arise in space plasmas?
- What are the physical processes that couple magnetospheres, ionospheres, and atmospheres?
- What physical processes cause terrestrial and planetary aurora?
- What plasma processes are responsible for the acceleration and loss of energetic particles in space environments?
- How does the Sun affect space environments?
- What role do magnetic fields play in the evolution of planetary environments?
- How can we use the space environment as a laboratory?

4.3 How does space weather affect society and human activities in space?

Disturbances associated with energy transport in the space environment manifest themselves often as space weather. Over the last decade, the risk from space weather on the increasingly advanced technological systems which underpin 21st century society is increasingly understood to be both of high likelihood and high impact [e.g., RD-04, RD-05, RD-07]. With the increasing use of space to serve the needs of humanity, including through commercial operations and within the New Space Economy, mitigation of adverse space weather effects is becoming ever-more important. Mitigation and forecasting of space weather effects depends on improved understanding of the fundamental processes which generate space weather effects. Critical to mitigating the impacts on vulnerable systems therefore includes the answering the following questions:

- How does space weather affect GPS navigation and RF communication?
- How does space weather affect terrestrial weather and climate?
- How does space weather affect the operations of satellites in Earth orbit?
- How does space weather affect our ability to explore near-Earth space, other planets, and beyond?
- How does space weather affect electrical power grids by geomagnetically induced currents (GICs)?
- How does space weather affect the safety and security of Canadians?
- Can we use our advancing fundamental knowledge of the space environment to improve our ability to predict space weather?
- How can we mitigate space weather effects on society, keeping pace with advancing technology and the needs of Canada in space? Technologies that we take for granted have advanced far more quickly than our understanding of space weather and hence our ability to cope with any out of normal events.

5 Canadian Strengths

The Canadian solar-terrestrial science community is committed to addressing the research questions listed above, and resolves to carry out a scientifically rich and compelling, strategic, innovative, cost-effective, and sustainable program of instrument development, observation, data assimilation and modeling, analysis, and data mining and distribution in support of that research. Through these activities we will continue to build and further strengthen Canadian capacity in solar-terrestrial science.

Canada’s technical and scientific contributions to solar-terrestrial science date from the inception of the field in the mid-nineteenth century. Our research capacity has been developed over decades with significant funding from federal and provincial agencies, including the CSA, NSERC, and CFI. Specific areas in which Canada has demonstrated capabilities and, in many cases, ranks as or is well positioned to become a world leader have been identified previously [RD-01, RD-02] and are as follows:

Ground-based instrumentation

- Magnetometers
- All-Sky Imagers
- Optical interferometers for high-altitude high-altitude wind measurements
- Photometers
- Riometers
- Coherent scatter radars
- Incoherent scatter radars
- Ionosondes
- GPS ionospheric scintillation and TEC monitors
- Solar radio monitoring

Ground-based networks and facilities in the polar, auroral, and sub-auroral regions

- Geospace Observatory (GO) Canada
- SuperDARN Canada National Research Facility
- THEMIS Ground-Based Observatories (THEMIS-GBOs)
- Athabasca University Geophysical Observatory (AUGO)
- Athabasca University THEMIS UCLA Magnetometer Network (AUTUMN)
- Expanded Canadian High-Arctic Ionospheric Network (E-CHAIN)
- Resolute Bay Incoherent Scatter Radar (RISR)
- Transition Region Explorer (TREx)
- National Research Council's Solar Flux Monitor
- Natural Resources Canada's Geomagnetic Observatories

Space-based instrumentation

- Optical and UV imagers
- Optical neutral and ion wind interferometers
- Low-energy (<keV) electron, ion, and ion composition analyzers
- High-energy (~MeV) electron and ion instrumentation
- Radio transmitters and receivers
- Magnetometers
- GPS receivers

Data assimilation, and modeling (with applications to space weather forecasting)

- Advanced numerical methods and algorithms for solar and space plasmas
- Models of the solar dynamo, solar cycle, solar modes, solar wind, and CME initiation and propagation
- Models/simulations of global and local dynamics of the magnetosphere, ionosphere and neutral atmosphere
- Nowcasting and forecasting models for space weather services
- Low-dimensional dynamical models

Virtual Observatories and Data Mining

- Swarm-Aurora
- AuroraX
- The Empirical-Canadian High Arctic Ionospheric Model (E-CHAIM)
- Canadian Ionosphere Atmosphere Model (C-IAM)

6 Roadmap

This roadmap articulates a path by which Canada, both independently and in partnership with other nations, will make significant strides toward the resolution of the science questions listed in Section 4. To implement this plan we must both utilize and expand our capacity in experimental, simulation, and theoretical science. The key to such an expansion is to provide a hierarchy of opportunities that stress hands-on training opportunities in the near term, allowing successful students and postdoctoral researchers the opportunity to take on roles of increasing responsibility. The successful training of these HQP will also be key for Canada to exploit commercial opportunities within the New Space economy.

Overall, the Canadian community has the proven track record, innovation, and overall capacity to conceive of, develop, and implement new space-based instrument programs and satellite missions, and new ground-based instruments in support of space missions. Furthering our science objectives is not only an essential ingredient for the long-term health of solar-terrestrial and space weather science in Canada, but also a necessary outcome for Canada to address evolving and increasingly important space weather challenges.

This roadmap is organized in terms of the strategic vision of the community, strategic community priorities, and recommendations for near, medium, and long-term investments.

6.1 Strategic Vision

The Canadian solar-terrestrial and space weather research communities propose that the CSA develop a balanced, integrated and laddered program of investments which focus on discovery and enable innovative space science research and training. This should focus on the niche and internationally recognized strengths of the Canadian community. By making targeted strategic investments in the opportunities which deliver the maximum scientific return, this will deliver significant international impact and a high profile for Canadian space science and related space weather applications.

Specifically, CSA should leverage Canada's international leadership in ground-based, suborbital and orbital instrumentation and mission development, by making strategic investments in a balanced and integrated program spanning: ground-based instrument arrays; suborbital programs (balloons and sounding rockets); payload and instrument development program, for national and international ride shares and flights of opportunity; and the development of domestic nano- and micro satellite projects, where possible exploiting funding partnerships with appropriate co-funding agencies and collaborators.

These activities should be underpinned by targeted data analysis programs, and supported as appropriate by integrated theory, simulation and modelling. Where appropriate this should be at the national facility level and could involve Environment and Climate Change Canada, Defence Research and Development Canada, and Natural Resources Canada.

To deliver a viable program, the CSA must support direct investments which maintain the capacity and competitiveness of the Canadian space research and training community. Only through such ***dedicated and continuous CSA investments*** will the Canadian community continue to be invited to partner in future international space missions and activities. Appropriate direct CSA support to Canadian excellence will naturally facilitate successful partnerships which bring additional funds from partners such as NSERC and CFI to the Canadian space program.

Overall, to be successful and maintain solar-terrestrial science capacity, this requires a ***continuous CSA strategic investment in current and future strengths and opportunities***.

The Solar-Terrestrial Sciences Community feels very strongly that to sustain and grow a robust and globally relevant Space Science sector in the Canadian academic community, Canada needs a **space flight opportunity *program*** which is **open and transparent**. By this, we mean that all six scientific disciplines should have the opportunity to compete for spaceflight opportunities, and that the winners of such competitions would have the opportunity to develop the mission from Phase A through to Phase E. The terms of reference of these competitions could be developed to lead to a stronger academic space sector, but the overarching objectives of the program should be opportunities (be they instruments on international missions, or stand-alone satellites) that lead to globally relevant excellent science. The CSA has the resources to carry out such a program, especially if it is willing to adopt a more risk-tolerant approach. We believe such a program would have obvious benefits to Canadian industry, and if opportunities came at a fast-enough pace, they should ignite excitement across the Canadian public.

We have included the Space Science Life Cycle (Figure 2) for projects under the umbrella of the CSA for two reasons. First, the program we envision and that is described in this roadmap includes all of these life cycle elements. Second, areas where the CSA can provide better support, such as modeling and data analysis, figure prominently in this vision for a program.

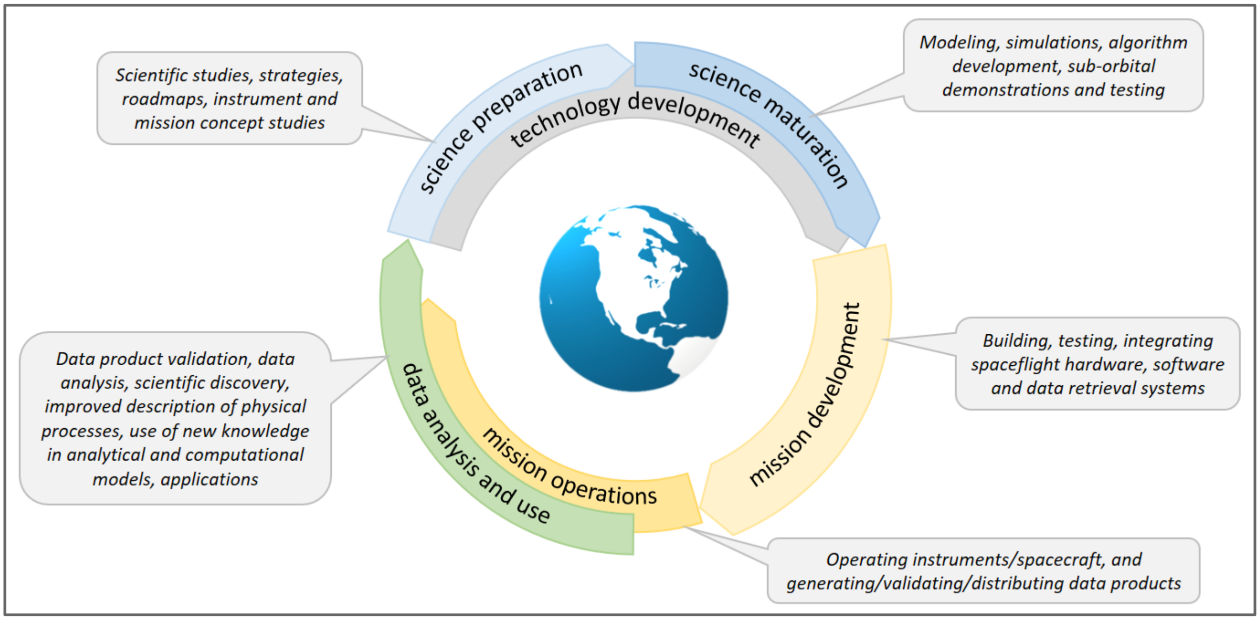

Figure 2 – Space science life cycle.

6.2 Strategic Community Priorities

The community has developed the five following strategic priorities to represent the strategic vision.

1. Niche Excellence of the Canadian Multi-instrument Ground-based Arrays. The community recommends that the CSA ***continue to support and enhance Canada's ground-based observatory programs***. The Geospace Observatory (GO) Canada arrays of more than 120 university-operated instruments and the THEMIS ground-based observatories (GBOs) take advantage of Canada's northern location to observe space weather over Canada and unlock the value of observations made by space weather research satellites. More than any other CSA initiatives, GO Canada, its predecessors, and the THEMIS GBOs have been responsible for the national and international successes of the Canadian solar-terrestrial science community. The community has leveraged this experience and expertise into many new opportunities, both ground- and space-based.

2. Instrument Development. The community recommends that the CSA support ***flight opportunities (e.g. international missions of opportunity, lunar LEAP/Gateway, etc.) for instruments already under development,*** and the ***future development of new instrument concepts***. The community appreciated the value of previous programs such as the CSA's Space Technology Development Program which enabled researchers to develop instruments for future space flight opportunities; with the narrowing of the scope of STDP to focus on internal CSA technology needs, a new funding line to support scientific instrument development is essential. Growing Canadian and international interest in CubeSat platforms has further stimulated several groups to modify their existing heritage designs so that they can fly on these smaller platforms. The community sees such programs as vital to bridging the gap between the CSA's FAST program and high-profile scientific flight opportunities.

3. Access to Space for Solar-Terrestrial Science. The community recommends that the CSA supports ***recurring opportunities for access to space***. Regular and inexpensive flight opportunities are necessary both for science/technology development and for research and training. The community has seen the value of suborbital and pre-space demonstration platforms such as CaNoRock and strongly supports a new partnership with Norway called CaNoSat that is modelled after CaNoRock and could be a model for launching future CubeSats for scientific research and training, in addition to the Canadian CubeSat Program (CCP). Future additional opportunities for low-cost access to space include through the ***ESA SCOUT mission program***, as well as through ***flights and missions of opportunity*** of instruments on national and international space agency satellites (potentially also including on commercial vehicles). A new opportunity which is of significant interest to the community is the possibility to fly solar-terrestrial payloads in the lunar vicinity, for example via hosting on the Lunar Gateway. Addressing the impacts of space radiation has also been identified as an opportunity for partnership between the solar-terrestrial community and the space exploration and space health divisions of the CSA, with a 2018 CSA Topical Team on "CSA Deep Space Gateway Space Radiation & Health Study Team" identifying a series of collaborative projects which could deliver high impact science return [RD-08], and additionally consistent with the 2017 report from the Planetary Exploration Topical Team on Planetary Space Environment [RD-09].

Low-cost access to space via extensive suborbital and nanosatellite constellation infrastructure is expected to open a new window for solar-terrestrial science. Such capacity is expected to serve as a technology incubator for industrial and commercial exploitation in near-Earth space for Earth-observation, communications, environmental monitoring, and sovereignty applications, for the benefit of Canadians, especially in the Arctic north. Indeed, future new technology will make suborbital scientific and commercial operations an increasing reality of space science in the 21st century.

4. <u>Exploitation of dense arrays of ground-based and satellite data</u>: Canada has developed an international reputation for high impact science resulting from the deployment and operation of dense multi-instrument networks of ground-based instrumentation, and the analysis of its data together with that from conjugate satellite missions. The continued operation of networks such as GO Canada, THEMIS-GBO, AUGO/AUTUMN, SuperDARN, and RISR-C, as well as newly funded research facilities such as TREx, will ensure the ongoing vitality and impact derived from the analysis and exploitation of data from these arrays, and from supporting partner satellite missions. The focus of these data analysis programs will be investigations of multiscale geospace processes including the aurora, and the interaction of space plasma processes and the upper atmosphere. The addition of data from next generation all-sky imagers, wind interferometers, proton auroral photometers, meridian scanning riometers and other new radio remote sensing instruments will further position Canadian researchers at the forefront of this discovery research. Ongoing funding for the analysis of Canadian data is crucial for Canada to derive maximum benefit from its prior investments in scientific infrastructure. It further underpins Canadian leadership roles in global international science initiatives such as PRESTO, ILWS, CEDAR, GEM, and DASI, and facilitates partnerships with existing and future domestic and international solar-terrestrial science satellite missions such as ePOP, Swarm and SMILE.

5. <u>Dedicated Simulation and Modelling Program/Projects.</u> The community emphasizes that a world-class space research program must include a ***strong modeling, data assimilation, simulation, and theory component***. Such models are particularly important in the solar-terrestrial sciences because only some aspects of the space environment are visible to remote sensing instruments. Models and simulations make it possible to exploit unique Canadian observations of the Earth's space environment to explore the multiscale dynamics of the Sun-Earth system, and enable the application of the derived new fundamental understanding to predict and forecast space weather. The CSA has a unique role to play in bridging the gap between the development of scientific models and the application of those models by government and industry to mitigate against the impacts of space weather. An important example of these dynamics is the upward and downward coupling between the atmosphere and geospace. New opportunities in partnership with CSA Planetary Science and Space Exploration could include applications relating to lunar, Martian, and planetary environments, for example within the Lunar Exploration Accelerator Program (LEAP) and/or in partnership with the Lunar Gateway.

6. <u>Open and Transparent Process for International Mission Participation.</u> The community recommends that the CSA introduce internal processes which facilitate the ***timely development of opportunities for partnership in international missions***. The community appreciates the

challenge facing the CSA when it is solicited to support Canadian participation in international missions. Such requests often come with little notice and have significant implications for the CSA. The community would prefer to have a defined CSA process for proposed Canadian hardware involvement in such high-profile partnerships.

6.3 Strategic Investments

Achievement of the community's strategic priorities is accomplished through the following investments: support two immediate opportunities, and provide flight opportunities and funding to enable the implementation of a longer term integrated strategic plan. The community specifically proposes that the CSA invest in delivering a balanced, integrated and laddered program of investments which focus on discovery and enables innovative space science research and training. This program, addressing the community's near-, medium- and long-term needs, would leverage high-profile national and international partnerships to deliver high impact science return for Canada.

Immediate Strategic Investments. The community has identified the following opportunities to deliver high profile international impact from **immediate CSA investment:**

a. Commit to a Foundational Level of CSA Funding for *GO Canada* of at least $1.5M annually. More than any other CSA initiatives, GO Canada, its predecessors, and the THEMIS GBOs have been responsible for the national and international successes of the Canadian solar-terrestrial science community. The Final Report of the GO Canada External Review Committee concluded that it "makes vital contributions to the fundamental understanding of the complex physical processes underlying space weather. They note that the many types of unique and fundamental observations made by GO Canada instruments within the high latitude and polar regions of Canada are important to a broad range of international scientific programs and space missions." The community has leveraged this experience and expertise into many new opportunities, both ground- and space-based, including numerous national and international mission partnerships and funding from external partners including CFI, NRCan, NSERC, DRDC, the US Air Force, and others. The proposed 30% reduction of the future GO Canada grants from the CSA, without the guarantee of partner funding, is extremely risky and could represent an existential threat which strikes at the core of the community's highest priority program. Without due planning and preparation, this represents an unacceptable risk to the future of community research in this area of high impact, niche Canadian expertise. The proposed approach may further prevent the growth and/or expansion of projects with the GO Canada consortium, with the impact that the arrays current internationally unique capabilities are degraded and Canada's leadership position in this niche area eroded – perhaps catastrophically. For this reason, the community identifies the immediate restoration of GO Canada funding as a very high priority for immediate investment.

b. Support the development to flight of the *RADICALS satellite mission.* The RADiation Impacts on Climate and Atmospheric Loss Satellite (RADICALS) will be a low-Earth orbiting satellite mission targeting the transport of space radiation into the atmosphere, and the subsequent impact on Earth's climate. Accurately quantifying the climatic response to anthropogenic forcing, and constraining models of future trends, urgently requires the comprehensive measurements enabled by RADICALS. The RADICALS will therefore be an internationally unique space-based laboratory infrastructure with high-impact science goals. The RADICALS mission exploits and builds on niche capacity at the multiple Canadian proposing institutions and brings together a consortium of six of Canada's leading space research universities, with world-leading expertise in microsatellites and space instrumentation. In partnership with industry (Honeywell, Magellan) and government departments, the consortium will draw on federal, provincial, and institutional budgets and capacity to deliver an innovative high impact, low-cost mission. The RADICALS mission represents an entirely “made-in-Canada” solution to a high priority international science question, strategically aligned with high priority federal government and international research goals. Overall, the project focuses on miniaturized space technology to deliver exceptional research and training, new data, new knowledge, and socio-economic benefits including commercial opportunities in the New Space economy. At the present time, the RADICALS mission is the subject of a $20 million CFI proposal submitted and currently being assessed and reviewed in the 2020 CFI Innovation Fund competition. If the proposal is supported by CFI and the Provincial partners, this would require a CSA contribution for a 20% partner contribution of around $CAD 4 million.

Ongoing and Future Strategic Programmatic Initiatives. The community further emphasizes the value of an integrated longer-term strategic program to be implemented in the near- to medium-term. Five thrusts of activity are identified and staggered support with a regular cadence of funding opportunities at known intervals is essential for robust community involvement. This ensures the community can plan and strategize for proposals with suitable lead times. The community is able to respond quickly to the implementation of any of these elements as a significant augment to the ongoing funding of existing activities. **The community recommends that at least one additional new element of this program should be funded as an addition to the existing program within the next two years**. The community further recommends that all of the following high-profile opportunities be implemented as part of an integrated longer-term strategic program in the near- to medium-term.

a. Maintain and enhance an integrated multi-instrument ground-based program. This leverages the Canadian advantage, based on the location of the magnetic pole and of having the most accessible polar regions in the world. This should encompass maintaining and expanding the GO Canada initiative, and not only continuing to utilize extensive support from CFI and other partners, but also to expand these partnerships further to support, for example, new instruments, new players, new technology, upgraded infrastructure, expanded arrays, etc. This will naturally create opportunities for high profile Canadian science leadership through future partnerships with domestic and international satellite missions.

b. Leverage opportunities for the flight of Canadian solar-terrestrial instrumentation in lunar orbit. Examples include the SWEPT energetic particle telescope, or the further development of Canadian niche instrumentation such as auroral imaging from a lunar platform. The community has benefited significantly from prior CSA investments in instrument development. These represent prime candidates for utilization in the lunar environment, especially following very recent CSA-funded concept studies and science maturation contracts for flights on the Lunar Gateway and in the lunar vicinity over recent years. For example, the detailed characterization and understanding of radiation in deep space is crucial for the safety and success of future crewed and robotic exploration missions to the moon, Mars, and other planetary systems. This is a great opportunity for Canada to make a significant contribution to the international lunar and planetary exploration effort, and connects the expertise of the Canadian Solar-Terrestrial Science community with the priorities of the science communities supported by the Human Spaceflight and Space and Planetary Exploration divisions of the CSA. Hosting solar-terrestrial science payloads on the external payload bays on the Lunar Gateway is an especially attractive proposition.

Funding could also be provided in support of lunar modelling studies in preparation for, and in support of, Canadian interest and involvement in the Lunar Gateway, and in preparing for the return of astronauts to the lunar surface.

c. Instigate an integrated mission and instrument development program. The community highlighted the importance of ongoing instrument development opportunities in order to maintain key Canadian capacity and international competitiveness in niche measurement technology, and as a platform for the integration of new scientific innovation. Such developments are essential if Canada is to continue to take advantage of international ride-share and mission opportunities. With recent changes to the eligibility and scope of the STDP funding line, introducing a new dedicated instrument development program would enable Canada to maintain and expand upon its high international profile and impact in this area.

Unlike the FAST program, with its focus on HQP development, short duration awards, and limited funding envelope, the community envisages the implementation of a laddered and integrated program delivering niche science-grade Canadian instrumentation. To be successful, this would need to be implemented with a funding envelope that enables the development of internationally competitive instruments and helps to secure and support their flight on orbital and suborbital platforms. These should span from international missions of opportunity on large, medium and small satellite missions (e.g. in the NASA Explorer or ESA Cosmic Visions class), to dedicated domestic micro- and nano-satellites, and sounding rocket and balloon missions.

Specifically, this integrated program could include the following elements:

- Instigate a ***standing instrument development program***, including the innovative development of miniaturized technology for flight on small platforms.

- Instigate an open and transparent competition for ***new micro-satellite mission concept studies*,** with defined opportunities in a new cross-agency competition which will lead to a guaranteed development to flight for the selected successful mission concept(s).

- Instigate a ***nano-satellite research program***, perhaps leveraging either the CaNoSat CubeSat partnership or the ESA SCOUT program for flight.

- Instigate a ***suborbital research program*** (balloons and sounding rockets).

- Instigate an open and transparent competition for ***new micro-satellite mission concept studies*,** with defined opportunities in a new cross-agency competition which will lead to a guaranteed development to flight for the selected successful mission concept(s).

d. Develop a robust data analysis, data assimilation and modelling program. Full value of observations from ground-based instruments and networks and satellite missions is only achieved through robust data analysis and modelling. Atmosphere/ionosphere general circulation models which include the atmosphere and ionosphere provide a unique basis for interpreting multi-instrument observational data, and for assessing the implications and impact of observed phenomena. Such models provide the basis for data assimilation systems which merge observations and simulation and form the basis for forecasting phenomena in near-Earth space, including space weather. In addition, detailed models are needed to explore and understand specific phenomena, and/or identify missing physics, essential for advancing fundamental understanding at the system level.

The following elements are essential to this thrust:

- Maintain and expand a multi-instrument and multi-satellite ground- and space-based ***data analysis program***. This includes support for data exploitation of Canadian ground- and space-based observations, building upon the recent CSA funding opportunity for data analysis in support of existing satellite missions, with an emphasis on Canadian instruments such as Swarm and ePOP, although other international data sources are also valuable.

- Establish and maintain a ***national model of the coupled whole atmosphere/ionosphere*** system. This effort could involve collaboration between Environment and Climate Change Canada where current expertise in general circulation modelling exists and the academic community where the understanding of the background theory and necessary algorithms exist. This model would be run on the national Compute Canada facilities and output would be available to the community. Natural Resources Canada could be interested in the space weather applications of such a model. The community has identified the importance of undertaking a feasibility study examining the establishment of a national modelling/assimilation capability for the atmosphere/geospace. Such a model would provide a framework for understanding the system level upward and downward coupling processes and which are a critical component of ionized and neutral atmosphere coupling. With appropriate consultation with the community, competitive funding for such a feasibility study could be released immediately representing an important concrete step toward achieving this goal.

- A ***data assimilation and modelling program*** targeted at specific processes in the coupled magnetosphere-ionosphere-thermosphere, and encompassing comparative planetary and lunar atmospheres, ionospheres, and magnetospheres should be supported and maintained. Global scale models are only as accurate as the fidelity of the physical processes which they contain, so integrated data assimilation and modelling efforts at the process level are key for future improvements to larger scale model accuracy and prediction efficiency.

e. Exploit multidisciplinary opportunities in space research to deliver innovative training of HQP. The community notes that all its past and anticipated successes are built on the development and effective use of a talented and motivated human resource base. Many of the future opportunities require Canada to make significant new investment in human capital. There is an important need to create an environment in which early-career scientists assume a larger and more independent role in conceiving and leading appropriate research projects, in order to best utilize our existing human resources. To fully realize the potentials identified in this report, as well as those that will undoubtedly emerge in the future, the size and capacity of our community must grow significantly. Our goal is to increase the rank of faculty members (or equivalent) engaged in solar-terrestrial science research, create better career stability and more rewarding career profiles for research associates and post-doctoral fellows, and increase our student population. Furthermore, given Canada's lack of a federally funded institute for space research, it is essential that we maintain a critical mass of research engineers and instrument specialists through a combination of projects, concept studies, and consortium activities. This enables the effective custodianship of Canada's capacity for ongoing and future space science and engineering capacity, including in science innovation and in instrument development, and suborbital orbital mission development, operation, and management.

Mechanisms for achieving these goals include, but are not limited to

- Providing support for faculty renewal in space physics, perhaps including dedicated CSA Research Chairs or funding similar to Killam Research Fellowships where a grant facilitates teaching relief for university professors enabling them to concentrate on research full time.

- Expanding the FAST program such that PhD students and early career engineers and technicians are eligible for funding under the HQP training quota, and by opening applications to all University-designated PIs, including those holding adjunct appointments.

- Supporting the attendance of students, post-doctoral fellows, and early career scientists at national and international conferences such as the yearly DASP workshop.

- Renewing the ***CaNoRock*** training program for another five years (2022–2027).

Training HQP with transferable skills for the aerospace sector will be an additional major benefit from the implementation of an integrated and expanded solar-terrestrial science program in Canada and addressing an urgent training need. For example, in 2012 David Emerson led the 2012 Aerospace Review mandated by the Government of Canada which assessed the state of the Canadian aerospace sector. The Emerson report highlighted that "*the highly skilled workforce that has been the backbone of Canadian aerospace is aging, raising the spectre of critical skills shortages.*" Training in the solar-terrestrial sciences also produces trainees who are qualified to pursue careers in space science and engineering in academia and industry, including in the rapidly expanding NewSpace sector of the aerospace industry.

The respective elements of the Canadian solar-terrestrial science roadmap are summarized and depicted in Figure 3 on the next page.

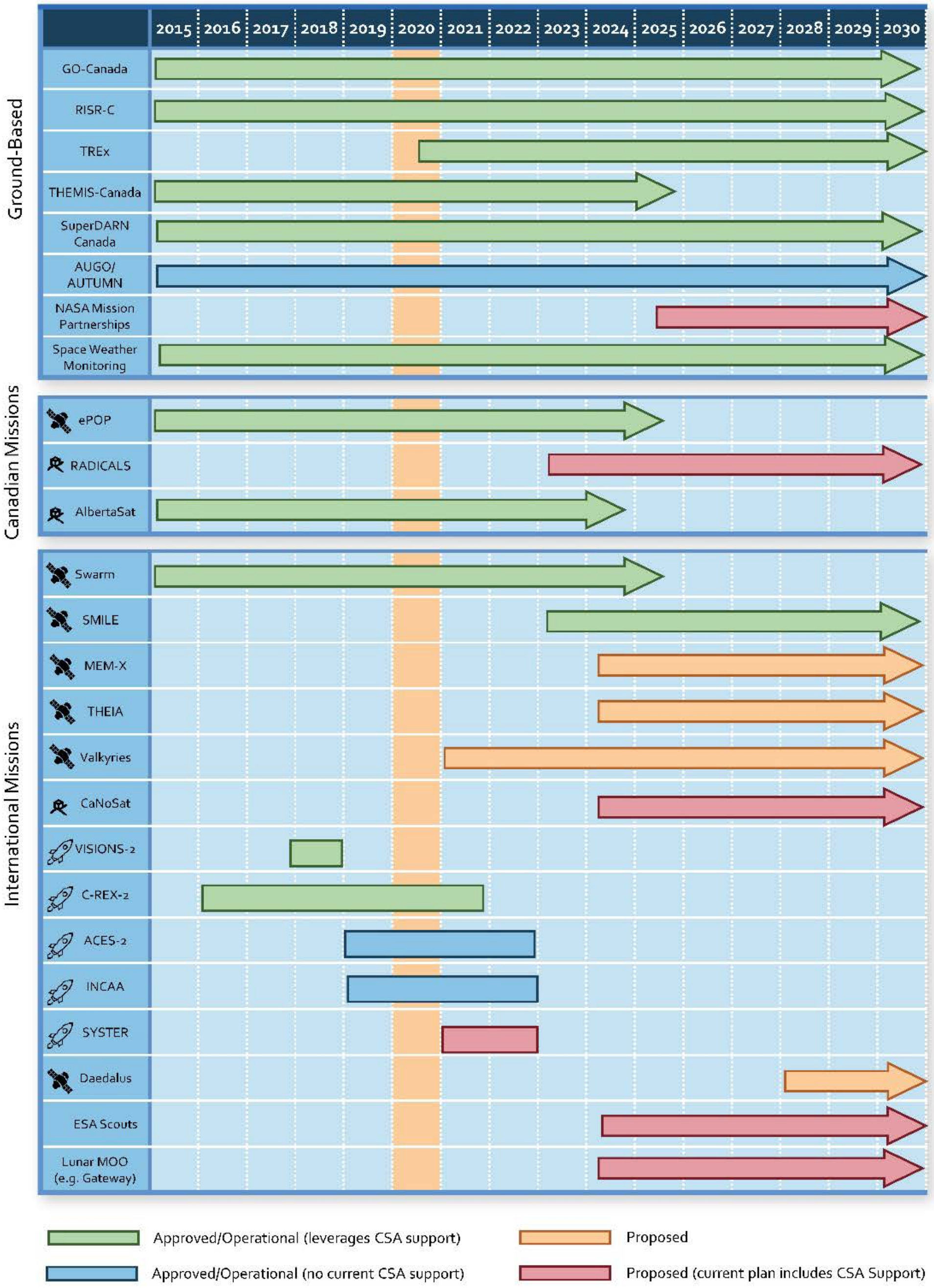

Figure 3 – Solar-terrestrial science roadmap, showing approved, planned, proposed, and to-be-proposed activities in the period of 2015–2030.

This roadmap presents a balanced spectrum of small versus large, near-term versus longer-term, and primarily Canadian versus international projects, with strategic connections between the different elements in the map consistent with the goal to "Ensure Canada's leadership in acquiring and using space-based data to support science excellence, innovation, and economic growth" by "Supporting space science to study Earth and beyond (e.g. space weather)" in the Canadian Federal Space Strategy [2019;

RD-03]. Experience dictates that compelling new opportunities will arise as well. The success of future projects – those on the roadmap and those that are not – will be determined by their level of excellence as assessed in competitive reviews.

7 Outcomes

The community fully supports the idea of accountability and achievement of tangible outcomes recognizable by the Canadian taxpayer, aligned with the Canadian Federal Space Strategy [2019; RD-03]. Metrics to be developed in the next year will quantify our attainment of these outcomes, which with adequate support will maintain and enhance our strong standing internationally. We identify four top-level strategic outcomes for which we hold ourselves accountable:

1. Be an internationally recognized contributor of forefront knowledge about the space environment around the Earth and other solar-system bodies in which Canada has an interest. This outcome is measured in the quantity and quality of scientific publications, and frequency at which Canadian data are used in the scientific literature. GO Canada metrics cited above attest to our current high standing, which will be enhanced as our plan unfolds.
2. Be an internationally respected contributor of solar-terrestrial science missions and/or instruments enabling such missions. This outcome is measured in the number of successfully implemented solar-terrestrial science experiments (including suborbital experiments).
3. Be an internationally significant contributor of space weather applications and capabilities. This outcome is measured in the amount of useful information delivered to clients sensitive to space weather effects in Canada and elsewhere.
4. Be an internationally attractive training ground for the next generation of researchers. This outcome is measured in the number of graduate students trained through solar-terrestrial science projects. Our performance goal in this instance is expressed in terms of sustainable growth of the community and supply of highly qualified personnel (HQP) to space-related endeavours in Canada.

Reaching our performance goals set forth above requires that the following conditions exist:

1. A policy framework and corresponding integrated program spanning ground-based, sub-orbital, and orbital opportunities, including mission concept developments that result in definite flights for the missions which succeed in transparent and open competitions, and that recognize the importance of solar-terrestrial science to Canada.
2. A decadal funding envelope that is consistent with the capacity possessed and opportunities available to the community and attached to the program opportunities.
3. An efficient, competition-based mechanism to select the right missions and projects to implement.
4. An instrument development capacity (both ground and space-based) that looks beyond the decadal horizon to proactively place Canada in a leadership position in future space science experiments.
5. A collaborative research environment in which Canadian expertise and resources in data analysis, assimilation and modeling are synergized.
6. An internationally significant polar scientific research infrastructure and capability (which may align with other national goals including strategic and geopolitical goals).
7. A capability to place instruments in deep space to meet the need of extraterrestrial exploration (e.g., Lunar Gateway).

8. A smart and sophisticated approach to international cooperation that is responsive and has short lead-time, to maximize scientific opportunities and minimize the cost per opportunity for Canada. This approach calls for much expanded cooperative relationships with both traditional space agency partners and emerging space powers such as China and India.

8 Conclusion

Approximately 10 years from today, a wave of solar-terrestrial science missions will usher in a new era of discovery. Canada is well positioned for this anticipated renaissance. The era will be marked by a major expansion of scientific capabilities and ambitions on two fronts. The first is system-level understanding of how structures emerge and change dynamically; the second is focused experimental studies of fundamental and universal processes on spatial and temporal scales of their occurrence. Additionally, searching for potential impact on climate and atmospheric conditions of geospace processes will elevate the policy relevance of our research. This roadmap gives the best collective vision of the solar-terrestrial science community as we survey the unfolding landscape 10 years down the road. Although our path may go through unexpected turns as dictated by the circumstance, our overall goal will remain unchanged, that is, to be a significant player and driver of the next wave of solar-terrestrial science research worldwide. In aiming to realize this goal, the community has expended major efforts to align its activities with government priorities and to pool its resources to develop scientific capabilities of bona fide international importance. In return, the community expects commensurate support from the Government of Canada to fully realize this potential.

9 Appendix

This appendix presents a list of the acronyms used in, or relevant to, this document.

AUGO	Athabasca University Geophysical Observatory
AUTUMN(X)	Athabasca University THEMIS UCLA Magnetometer Network (eXtension)
CEDAR	Coupling Energetics and Dynamics of Atmospheric Regions
CFI	Canadian Foundation for Innovation
CGSM	Canadian GeoSpace Monitoring (earlier CSA-sponsored program)
(E)CHAIN	(Expanded) Canadian High Arctic Ionospheric Network
CME	Coronal Mass Ejection
CSA	Canadian Space Agency
DASI	Distributed Arrays of Small Instruments (US NSF-funded projects)
DASP	Division of Atmospheric and Space Physics (of the Canadian Association of Physicists)
ePOP	Enhanced Polar Outflow Probe
GEM	Geospace Environment Modeling
GBO	Ground-Based Observatories
GIC	Geomagnetically Induced Current
GO Canada	Geospace Observatory Canada
GPS	Global Positioning System
HQP	Highly Qualified Personnel
ILWS	International Living with a Star
ISIS	International Satellite for Ionospheric Studies
ISS	International Space Station

JAXA	Japan Aerospace Exploration Agency
keV	Kilo Electron Volt
MeV	Mega Electron Volt
NASA	National Aeronautics and Space Administration
NSERC	Natural Science and Engineering Research Council
PI	Principal Investigator
PRESTO	Predictability of the Solar-Terrestrial Coupling (SCOSTEP program)
RADICALS	RADiation Impacts on Climate and Atmospheric Loss Satellite
RISR	Resolute Bay Incoherent Scatter Radar
RISR-C	Canadian portion of RISR
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
STSAC	Solar-Terrestrial Science Advisory Committee
TEC	Total Electron Content
THEMIS	Time History of Events and Macro-scale Interactions during Substorms
TREx	Transition Region Explorer
UCLA	University of California at Los Angeles
US	United States
UV	Ultraviolet