Progress on relating optical auroral forms and electric field patterns

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Abstract. Ultraviolet auroral imagery and in situ electric field measurements from Freja are presented and used to identify signatures of the perpendicular electric field associated with three basic arc configurations. The auroral imagery is essential in identifying the two-dimensional characteristics of the discrete auroral forms for which electric field signatures are examined. The high-resolution data show the differences between the electric field signatures of the quiet and disturbed arcs (spirals) occurring as a single arc or as a part of a series of parallel arcs within the dusk and premidnight auroral distribution. The scale size of the arcs is given by their thickness, typically $\sim 100$ km. Common electric field signatures, such as a reduction in the convection electric field in the region of the arc and enhancements of the convection electric field at the boundaries of the arc, are observed. The electric field reductions dominating the signatures of quiet arcs occurring as a single arc indicate that these arcs are characterized with a weak field-aligned current. As inferred from the electric field enhancements dominating the signature of quiet arcs which are a part of a series of arcs, these arcs are characterized with a strong field-aligned current. Features which distinguish the quiet arcs from the disturbed arcs are the quasi-periodic fluctuations in the disturbed arc's electric field signature. The turbulence in the electric field indicates that shear structures and shear-driven plasma instabilities are involved in the formation of auroral spirals.

Introduction

Many satellite-based auroral imaging experiments [Anger et al., 1973; Frank et al., 1981; Anger et al., 1987] have demonstrated the scientific value in monitoring the auroral region on a global scale. In the form of auroral emissions, magnetospheric processes are mapped in both space and time into the ionosphere. Therefore auroral imagery can be used to remotely sense the magnetosphere. The Freja Mission [Lundin and Haerendel, 1993; Lundin et al., 1994], designed to examine fine structure plasma properties, consists of in situ plasma instruments and a remote sensing auroral imager. The experiments have been designed to achieve high spatial and temporal resolutions such that small-scale electrodynamic properties of many auroral processes can be examined. For example, electrodynamic signatures of optically observed auroral forms can be identified with in situ measurements and near simultaneous auroral imagery.

Discrete auroral arcs are associated with accelerated portions of the distribution of precipitating electrons (inverted-V electron precipitation) and hence upward field-aligned currents [Kamide et al., 1979]. Electric fields perpendicular to the local magnetic field are also an integral part of the electrodynamic structure of an arc and have provided information pertaining to the processes involved with discrete particle precipitation of the arc [de la Beaujardière et al., 1977, 1981; Marklund et al., 1982; Marklund, 1984; Brüning and Goertz, 1986; Timofeev, 1987; Opgenoorth et al., 1990; Aikio et al., 1993]. Signatures of this electric field, identified using high-resolution auroral imagery and in situ electric field measurements from Freja, are presented in this paper. Focussing on the small-scale electric field signatures of two-dimensional auroral forms, these data have the potential to provide new information pertaining to the electrodynamics of various arc configurations. Since this study constitutes one of the first comparisons of satellite-based auroral imagery and in situ electric field measurements, this method of identifying electric field signatures is evaluated and its limitations are assessed.

Electric field signatures of auroral arcs have been identified in the past by examining simultaneous electric field measurements, electron spectrograms, and/or ground-based auroral imagery [Marklund, 1984, and references therein]. Typically, electron spectrograms and auroral imagery have been used to locate regions occupied by auroral arcs or regions of particle precipitation characteristic of auroral arcs. Electric field signatures associated with the arcs were provided by electric field data from radar, rocket, and satellite.
experiments. As noted by Horwitz et al. [1978], a full understanding of electric fields in the auroral region requires high-resolution measurements over extended areas which are correlated with other geophysical data. These requirements are being fulfilled by satellite-based experiments as both temporal and spatial resolutions of the acquired data are improved. The spatial limitations experienced by radar and rocket experiments are also reduced by satellite-based experiments. Owing to the orbital characteristics of the satellite, extended regions of the auroral distribution can be monitored. The use of auroral imagery gives an indication of the two-dimensional nature of auroral forms and hence the associated auroral processes. Electron spectrograms present the auroral arc in one dimension, losing its two-dimensional characteristics. Although ground-based auroral imaging experiments have high resolutions, the imagery has a limited field of view compared to that of the satellite-based experiments. Therefore the use of high-resolution electric field measurements and auroral imagery from Freja will advance the identification of electric field signatures of various two-dimensional auroral forms.

The limitation in identifying the electric field signature of a particular arc through an examination of auroral imagery and in situ electric field measurements is the time difference between the acquisition of the two data types. A rapidly changing auroral form may be displaced during this time difference causing its location as given by the imagery to differ from that given by the in situ measurement. In the case of arcs which evolve at high rates, the time difference between data types may be significant. In order to evaluate the proposed method of identifying electric field signatures of auroral arcs, the time differences of the data and the evolution of the optically observed auroral forms are considered. Because the relationship between auroral emissions and particle precipitation is well known [Kamide et al., 1979; Rees, 1989], particle data corresponding to the optically observed arcs is consulted as a means of assuring that the location of the arc is as given by the imagery.

Characteristics of Electric Fields in the Vicinity of Auroral Arcs

As identified by earlier methods, perpendicular electric fields in the vicinity of auroral arc signatures represent the sum of the large-scale, convective electric field and an arc-associated electric field [de la Beaujardière et al., 1977, 1981; Marklund et al., 1982; Marklund, 1984; Brüning and Goertz, 1986; Timofeev et al., 1987; Opgenoorth et al., 1990; Aikio et al., 1993]. The source of the convective electric field is found in the coupling of the solar wind and magnetosphere [Akasofu, 1981] while that of the arc-associated electric field is found in the electrodynamic processes involved in the formation of the arc. More specifically, the arc-associated electric field is the field which ensures that current continuity is maintained in the vicinity of the arc.

Electric field signatures found to be coincident with auroral arcs tend to consist of an electric field antecorrelated with the particle precipitation of the arc [de la Beaujardière et al., 1977, 1981; Marklund, 1984] and/or an enhanced electric field directly adjacent the arc [Burch et al., 1976; Marklund, 1984; Brüning and Goertz, 1986; Opgenoorth et al., 1990; Aikio et al., 1993; Lewis et al., 1994]. When the strength of the electric field is antecorrelated with the intensity of inverted-V particle precipitation, the convection electric field appears to be reduced by an oppositely directed arc-associated electric field. With magnitudes between 20 and 50 mV/m [Baumjohann, 1983], the convection electric field has been observed to be directed from dusk to dawn within the auroral distribution and directed from dawn to dusk in regions poleward of the auroral distribution [Kelley, 1989], in a predominately north-south direction. Electric field enhancements found adjacent to the arc are also dependent on the direction of the convection electric field. Electric field enhancements at both the equatorward and poleward boundaries of the arc tend to be aligned with arcs occurring at the nightside reversal in the convection electric field [Burch et al., 1976]. As also observed by Burch et al. [1976], the enhancements are typically directed towards the region of inverted-V particle precipitation. The enhanced field is located at either the poleward or equatorward boundary of arcs found within a single convection zone (either northward or southward) [Heelis et al., 1981]. Within a northward directed convection electric field (dusk and premidnight sectors) a northward enhanced electric field is found equatorward of the arc. Similarly, within a southward directed convection electric field (dawn and postmidnight sectors) a southward enhanced electric field is found poleward of the arc [Brüning and Goertz, 1986; Opgenoorth et al., 1990; Aikio et al., 1993; Lewis et al., 1994].

The reduction in electric field within the boundaries of the arc has been associated with a polarization electric field directed across the arc (typically in the north-south direction). The enhanced particle flux and field-aligned current associated with an arc are accompanied by an enhancement in the ionospheric conductivity [Brüning and Goertz, 1986; Marklund et al., 1988]. Within the boundaries of the arc, current flow initiated by the combination of enhanced conductivity and convection electric field is balanced by an oppositely directed polarization electric field which ensures that the total current is divergence free [de la Beaujardière et al., 1977, 1981; Opgenoorth et al., 1990]. The polarization electric field is confined to the region of enhanced conductivity leading to the anticorrelation of the arc's auroral emissions and electric field.

Enhanced electric fields found near the boundaries of the arc have been observed with magnitudes of about 100 mV/m larger than the background convection electric field [Aikio et al., 1993]. Although asymmetries in the reduced or polarized electric field have been associated with latitudinal gradients in the convection electric field, typical gradients do not account for the enhancements which are larger than the convection field [Marklund, 1984; Opgenoorth et al., 1990]. Enhanced electric fields found near the boundaries of an arc have been found to be due to the three-dimensional current system of the arc. As given by current continuity, the upward field-aligned current in the region of enhanced conductivity must be balanced by the divergence of a height-integrated ionospheric Pedersen current [Aikio et al., 1993]. Therefore an ionospheric Pedersen current flows in the direction of the convection electric field. If polarization effects do not exactly balance the Pedersen current, the current must continue into regions adjacent to the arc. A downward field-
aligned current is expected to complete the current circuit of the arc. In these regions the conductivity is reduced due to the absence of particle flux and an enhanced electric field in the direction of the convection electric field ensures that current continuity is maintained [Oppenorth et al., 1990; Aikio et al., 1993]. For arcs at the dusk sector convection reversal, the convection field is directed towards the arc on both the poleward and equatorward sides, and two downward field-aligned currents can balance the upward field-aligned current. Pedersen currents flowing in the direction of the convection electric field joining the upward and downward field-aligned currents would require enhanced electric fields at both boundaries of the arc. When the arc is within a single convection zone, a single downward field-aligned current closes the circuit. Depending on the direction of the convection electric field and hence Pedersen current, this current is located on either the poleward or equatorward side of the arc.

These two arc-associated electric field sources and their variations have led to a variety of electric field signatures associated with discrete arcs. These signatures not only depend on the arc’s location within the auroral region (the variation of the convection electric field with magnetic local time) but on the influence of each source as well. Depending on the specific arc being assessed, the influence of one arc-associated electric field source may dominate the other. As found by Marklund [1984], when the convection electric field is large, polarization effects tend to dominate the electric field signature, and when the convection electric field is small, the effects due to field-aligned currents tend to dominate. Therefore electric field signatures of auroral arcs can be categorized and classified according to the dominating source of the arc-associated electric field and the orientation of the convection electric field (location of the observation). Marklund [1984] has provided such a classification scheme which is useful in interpreting electrodynamic characteristics of various arc configurations.

Instrumentation

Freja was launched in October of 1992 to investigate fine-structure plasma processes involved in the interaction of magnetospheric plasmas and the topside ionosphere. Detailed descriptions of the mission are provided by Lundin and Haerendel [1993] and Lundin et al. [1994]. The emphasis of this paper is the identification of electric field signatures of two-dimensional auroral forms as observed in ultraviolet auroral imagery. Auroral imagery, acquired by the ultraviolet imaging experiment [Murphree et al., 1994a], is used to identify and characterize various configurations of discrete auroral arcs. In situ electric field measurements associated with the observed arcs have been acquired by Freja’s double probe electric field experiment [Marklund et al., 1994]. The auroral imagery and in situ electric field measurements from these experiments are ideal for evaluating the proposed method of identifying electric field signatures of auroral arcs and suggesting electric field signatures of the optically observed arcs.

Freja’s ultraviolet imaging experiment consists of two cameras, one sensitive to atomic oxygen emissions (130.4 nm) and the other sensitive to the molecular nitrogen Lyman-Birge Hopfield band (130.4 to 2004 nm). Along with having the ability to image the auroral distribution under full sunlight, the resolution achieved by the instrument design and satellite orbital characteristics is comparable to that of ground-based instrumentation. The spatial and temporal resolutions of the imagery is 22 km and 0.37 s, respectively, with each image being acquired as often as every 6 s [Murphree et al., 1994b]. The enhanced temporal resolution and reasonable spatial resolution are improvements over other imaging experiments. The small-scale morphologies of auroral forms can now be resolved, and the related fine-structure plasma processes can be interpreted. Within the imagery from this experiment many examples of discrete auroral forms have been identified.

The double probe electric field experiment has provided electric field measurements coincident with the optically observed discrete aurora. The electric field is derived from a potential difference between six opposing probes lying in the spin plane of the satellite. The upper and lower limits of the electric field measurements are 1 and 0.03 V/m, respectively, with an expected accuracy of about 0.5 mV/m. The three components of the electric field vectors measured are one parallel to a model magnetic field, one directed magnetic eastward and one directed equatorward or southward. The eastward and southward components of the electric field vectors are used to investigate the perpendicular electric field associated with auroral arcs.

Data from Freja’s particle experiments are also consulted in order to confirm the locations of the auroral arcs at the time of the electric field measurements. Electron spectrograms are obtained from the two-dimensional electron spectrometer (TESP), [Boehm et al., 1994] which measures the full electron distribution function from ~ 20 eV to 25 keV. The ionosphere-mapped resolution achieved is about 200 m, which is what is required to resolve the structure at the edge of an arc. Since the electric field measurements and particle measurements are exactly simultaneous, electron spectrograms are used to assess if the locations of the forms of interest have changed during the time between electric field measurements and auroral imaging.

Freja orbits the Earth in an elliptical orbit with a perigee altitude of 601 km and an apogee altitude of 1756 km. The orbit is oriented such that the satellite maintains its apogee within the northern hemisphere [Lundin et al., 1994]. As the satellite orbits with an inclination of 65° it crosses the auroral distribution in a predominately longitudinal direction, often parallel to the auroral emissions. Data for this paper were acquired during a time period when the orbit was precessing from auroral crossings in the early morning sector (0100-0300 magnetic local time (MLT)) to the dusk sector (1300-2100 MLT).

Observations

This examination of imagery of auroral arcs and simultaneous electric field measurements consists of two parts. First, the optically observed auroral arcs are characterized in terms of locations, orientations, dimensions, and evolution. Second, a portion of the optical auroral arc observations are used to determine if electric field signatures of auroral arcs can be
deduced by the proposed method and to finally identify these electric field signatures.

Characterization of the Observed Auroral Arcs

All configurations of auroral arcs are the result of various magnetospheric processes. Owing to the ionosphere's role as a active mirror for magnetospheric processes, temporal and spatial characteristics of auroral forms are important in understanding the electrodynamics of an arc. For example, Borovsky [1993] reviews the validity of 22 theories for auroral arc formation by comparing the latitudinal extents or thicknesses of observed arcs and predicted arcs. The thickness of an arc effects the electric field patterns found to be aligned with the arc; a noticeable difference in the electric field patterns on spatial scales of 10 km and 100 km have been observed [Baumjohann, 1983]. An extensive examination of the auroral imagery acquired by Freja has provided many characteristics of the observed auroral arcs [Murphree et al., 1994b; Murphree and Johnson, 1996; Johnson, 1996]. Owing to the many possibilities of arc configurations and subsequent processes involved with their formation, it is important to specify which types of arcs will be associated with specific electrodynamical signatures.

As shown in Plate 1, the small-scale nature of various arc configurations are seen in the ultraviolet auroral imagery from Freja. Optical observations show that auroral arcs can take on configurations ranging from a streamline quiet configuration to a disturbed configuration, consisting of distortions in the spatial morphology and intensity of the arc. To give an indication of the scale size of these forms, the horizontal span of the images represent about 400 km. A quiet auroral arc is typically characterized as a longitudinally uniform, narrow band of emissions identified with a uniform sheet of current. Deviations from the quiet arc can be extreme, as in the case of substorm surges, or constrained to small-scale perturbations distributed along the arc. As shown in Plate 1, the disturbed arcs considered here consist of small-scale distortions, typically referred to as spirals [Hallinan and Davis, 1970; Davis and Hallinan, 1976, Waggner et al., 1983]. Identification of the distortions as spirals has been based on the spatial dimensions (~ 100 km diameter) and rotational sense (counterclockwise when observed parallel to the direction of the local magnetic field) of the forms. The auroral distribution is observed to be occupied by both single arcs and a series of parallel arcs separated in the latitudinal direction. Of the identified arcs, 40% were found to be apart of a series. The arcs have roughly the same intensity or one arc has a significantly higher intensity than those surrounding it. From the observed arcs the latitudinal spacing of a series of arcs ranges from the spatial resolution of the imagery up to 344 km with an average spacing of 105 km.

Plate 2 shows the locations of the observed arcs with respect to the magnetic coordinate system consisting of magnetic latitude (MLAT) and MLT. The apparent dependence on local times between 0000 and 2400 MLT is due to the trajectory of the Freja satellite during the fall of 1992 and the fact that the imager's field of view did not cover the full extent of the auroral distribution. The portion of the auroral distribution which has been imaged an approximate equal number of times extends from ~ 1400 MLT to ~ 0100 MLT covering all magnetic latitudes associated with the auroral distribution. As also shown in Plate 2, the arcs which are used in this examination of electric fields are located between 1330 MLT and 2318 MLT within the auroral distribution. The locations of the arcs are important since the expected electric field signatures are dependent on the orientation of the convection electric field which, in turn, is dependent on the local time of the observation.

Plate 1. Ultraviolet imagery from Freja of quiet and disturbed auroral arcs. In both of the images the longitudinal direction is approximately horizontal and corresponds to about 400 km. The images are displayed in color, with each color representing an auroral intensity. The upper end of the spectrum, reds and oranges, represents the highest intensities, while the lower end of the spectrum, blues and purples, represents the lowest intensities.
Plate 2. Observed locations of each discrete arc as a function of magnetic latitude and magnetic local
time. The boundaries of the region estimated to have been imaged equally (the boundaries of the region
which is approximately equally weighted) are indicated on the plot. The arcs for which an electric field
pattern corresponding to the arc is identified are shown in red.

As discussed by Borovsky and Susczynsky [1993] auroral
arcs can be classified according to their latitudinal extent
or thickness. Arcs are generally referred to as latitudinally
thin, and many attempts have been made to measure the
minimum thickness of an arc. Since the thickness of an arc
may be the result of its electrodynamic characteristics, it is
also important to specify the thickness of the arcs considered.
The thickness of each of the observed arcs is determined
from the auroral imagery. In the form of a histogram, the
distribution of 100 arc thicknesses is shown in Figure 1.
This distribution is similar to earlier results such as those
of Maggs and Davis [1968]. There is a significant increase
in the number of observed arcs with decreasing thickness.
The spatial resolution of the imagery, as indicated on the
plot, limits the observed arc thicknesses to about 22 km
and is probably the cause of the reduction in the number
of counts between 20 and 40 km in comparison with the
peak. Therefore the arcs for which the associated electric
field signatures are identified have thicknesses between the
spatial resolution of the imagery and 150 km, with an average
of 55 km.

These basic arc configurations are the focus of this paper.
Signatures of the perpendicular electric field associated with
both quiet and disturbed arcs occurring individually or as a
part of a series of arcs are identified. Both the quiet and
disturbed arcs occupy the dusk and premidnight sectors of
the auroral distribution and have average thicknesses of about
55 km. The differences between the electric field signatures
identified with the varying arc types provides information
pertaining to the electrodynamics of each arc configuration.

Owing to the fact that an image is acquired asynchronously
with respect to the continuous electric field measurements
and that the images typically view the satellite footprint at
times different from the in situ measurements, the two data
sets are not exactly simultaneous. In cases of stable arcs, that
is, arcs that are stationary and not altering their spatial charac-
teristics, the time difference will not affect the comparison of
the data. The time difference is important for cases in which
the arcs are not stationary or are changing their morphology.
Because this time difference is inevitable, the typical rates
at which the observed arcs translate or evolve are important.
When a specific auroral form is within the field of view of
the imagers for more than one image, the temporal behavior
of the form can be examined.

Quiet auroral arcs are typically observed to remain station-
ary within the limits of the spatial and temporal resolution
of the imagery. Arcs translating with a velocity less than
the minimum deducible from the imagery (~ 2 km/s) are
considered to be stationary. The motion, or in this case the
lack of motion, is seen in the intensity profile of an arc from
consecutive images. The intensity profiles, as shown in Fig-
ure 2, represent the intensity of a typical quiet arc along a path
approximately perpendicular to the arc (in the direction of
magnetic latitude). Discrete arcs, resulting from accelerated
discrete populations and thus localized peaks in energy de-
position, are identified by localized regions of high-intensity
auroral emissions. As evident from the peak in the intensity
profiles shown in Figure 2, discrete arcs are distinguishable
features embedded in the background diffuse emissions of
the auroral distribution. After subtraction of the background
emissions, deduced from the behavior of the intensity profile surrounding the peak (see dashed curve in Figure 2), the extent of the arc is easily identified. The significant drop in intensity on either side of the peak makes the boundaries of the arc easily distinguishable. The intensity of this arc drops by about 90% and by about 54% in 0.4° of latitude, or 45 km on the respective equatorward and poleward sides of the arc. The extent of the arc at each of the three image times has been indicated in Figure 2 by the vertical lines. As demonstrated in Figure 2, the boundaries of the arc are taken to be located at the points where the observed intensity profile deviates from the background intensity profile.

The evolution of the emissions within the arc does not affect its location or thickness (about 0.9° of latitude or about 100 km). Although the shape of the peak changed between images the location of the boundaries changed by only 0.05° of latitude or about 6 km. This is the typical behavior of the quiet arcs; they tend to remain stationary within the limits of the imagery. In the case of extremely disturbed arcs, such as substorm surges, translation of the discrete form is evident in the imagery.

The disturbed arcs, consisting of spirals, also remain stationary during the time in which they were imaged. Although translation of these arcs is not evident, evolution of the spirals is observed. As these arcs evolve the discontinuities either continue to rotate in the counterclockwise direction or they collapse. From earlier observations of these auroral forms, the typical life time of a spiral is about 10 min [Wagner et al., 1983]. Therefore the rotational velocity of a fully rotated spiral (360° or more) must be at least 0.6°/s. Equivalently, for spirals with an average diameter of 100 km, the tangential velocities of the motion are expected to be on the order of 30 km/s. From the growth and decay of spirals, Davis and Hallinan [1976] have also found that spirals with the observed diameter (~ 100 km) have typical rotational velocities of 0.3°/s or tangential velocities of 15 km/s.

Using the auroral imagery from Freja, the rotational velocity of the observed spirals is determined from the distance through which a specific point rotates between images, the apparent radii of the rotation and the time between images. From the rotation of 7 spirals the rotational velocity of these forms is found to range from 0.4 to 3.6°/s, with an average of 1.6°/s, and depends on the stage of the discontinuity's development. The earlier stages tend to evolve with lower rotational velocities, while the later stages tend to evolve with the higher velocities. If enough energy is available to the distortion process and the spiral becomes fully rotated at these rates, the growth of the spiral would require at least 4 min. The rotational motion of the disturbed arc is important to take into account when comparing auroral imagery and in situ measurements. The motion of the discrete emissions of the spiral will be evident in the data if the time between the acquisition of imagery and electric field measurements is on the order of the growth time. Electron spectrograms become very important in cases in which the satellite crosses disturbed arcs, or more specifically, the distortion point. The location of the arc at the time of the electric field measurements is easily confirmed by the associated electron precipitation.

Figure 2. Intensity profiles of an auroral arc from three consecutive images. The dashed curve represents the profile of the background diffuse emissions used in locating the boundaries of the arc as labeled.
Electric Field Signatures of the Observed Auroral Arcs

Electric field measurements associated with 11 auroral arcs, as indicated in Plate 2, are used to identify possible electrodynamic signatures of quiet and disturbed auroral arcs. The field measurements associated with these arcs are identified by considering the locations of optically identified discrete emissions as a function of the satellite's footprint and comparing their locations to the electric field measurements, which are also a function of the satellite's footprint. Note that the satellite's footprint is the satellite's trajectory mapped from the altitude of the satellite (≈ 1700 km for the data used) to 120 km. Similar to that shown in Figure 2, intensity profiles of the arcs, taken along the satellite's footprint, are used to determine the locations of the discrete emissions. The imagery of an arc, from which an intensity profile is extracted, typically consists of three images separated by 6 s. The intensity profiles are constructed by averaging the information from each of the images. The standard deviation of the average intensity is typically about 7 DN.

In each of the cases in which electric field measurements have been examined, the convection electric field is observed to be modified by the presence of auroral arcs. As expected, the convection electric field is directed towards the northeast or northwest within the dusk sector auroral distribution and directed towards the southeast or southwestern within the region poleward of the auroral distribution. In the following sections auroral imagery and corresponding electric field measurements for three cases are presented in order to demonstrate how this ambient electric field is modified by the electrodynamic structure of various auroral arc configurations. The three cases include a quiet arc, a disturbed arc and a series of quiet arcs and begin to suggest the difference in electric field signatures associated with these arcs configurations.

Quiet Arcs

Quiet arcs, extended in the longitudinal direction with a streamline configuration, are observed to occur both individually and as a part of a series of parallel arcs. The electric field signature of a quiet arc occurring as a single arc is seen in the data acquired during orbit 907 (December 13, 1992) of Freja. Imagery of this arc, a quiet arc which extends through about 5 hours of local time, is shown in Plate 3. This image has been constructed by averaging all the images acquired during the orbit. As shown by the satellite's footprint in Plate 3, the satellite crossed the auroral distribution near 1548 MLT in an approximately northeastward direction. The reference points along the satellite's footprint represent the satellite's position mapped to 120 km at the indicated times. Corrected to the time of the observations, the magnetic field model used in mapping these positions is the International Geomagnetic Reference Field (IGRF) 1990. Images of the afternoon satellite crossing were acquired at 2302:39, 2302:45, and 2302:51 UT. Electric fields corresponding to the region imaged at these times were measured between 2300:00 and 2303:30 UT. Therefore the maximum difference between the two data is about 2 min, 45 s. The intensity profile of the arc as a function of the satellite's footprint along with the corresponding measurements of the perpendicular electric field are shown in Figure 3. The electric field measurements include the eastward component, the southward component and the magnitude of the perpendicular electric field vector. The satellite reference times, as indicated in Plate 3, are included in Figure 3 as the numbered ticks on the horizontal axis.

Although the arc is a quiet arc and therefore generally stationary, the temporal changes of the arc were examined in order to assure that the location of the arc at the time of the electric field measurements is as indicated by the peak in the intensity profile. Examining the three images (covering 12 s) of this arc separately, the arc did not change. Further, the position of the arc as inferred from the electron spectrogram is aligned with the peak in the intensity profile. Since both the imagery and the electron spectrogram indicates that the quiet arc is stationary during the time between the acquisition of imagery and electric field measurements, the position of the arc is as indicated by the peak in the intensity profile.

As shown by the shaded region in Figure 3, the poleward boundary of this arc is located at the reversal in the convection electric field (from a northwestward field to a southeastward field). The boundaries of the arc as inferred from the peak in the intensity profile, are at 2300:36 and 2301:02 UT. In the region of the arc both the eastward and southward components of the electric field are reduced to near zero values. Although high-frequency, low-magnitude (≈ 7 mV/m) fluctuations are observed within the electric field that is reduced, the reduction of the field is generally a smooth reduction with its boundaries aligned with the boundaries of the arc. Equatorward of the arc, at 2300:32 UT, the magnitude of the electric field is enhanced to 70 mV/m in the direction of the convection field. This enhancement, directed towards the arc, may represent the enhancement expected in maintaining current continuity in regions of low-conductivity. The extent of the enhancement is consistent with that of earlier observations. Its extent of 42 km along the satellite trajectory is about 1/5 that of the arc (214 km). Although the magnitude of the enhanced electric field is larger than that of the convection electric field, its magnitude is not 100 mV/m larger as observed by Oppenorth et al. [1990], Aikio et al. [1993] and Lewis et al. [1994]. Unfortunately, a data gap occurred at the poleward boundary of this arc, and a similar electric field enhancement directed towards the arc could not be detected. In the additional cases in which quiet arcs are near the convection reversal, small enhancements of the convection electric field at the poleward boundary of the arc are observed.

Generalizing, the electric field signature observed to be associated with quiet arcs at the convection reversal consists of a reduction in the magnitude of the northwest convection field and exhibits very high frequency fluctuations with amplitudes less than 7 mV/m. This reduction in the magnitude of the electric field is consistent with an equal and opposite electric field referred to as a polarization field modifying the convection electric field. Small enhancements directed towards the arcs are found at the boundaries but do not appear to be consistent with the enhancements identified in earlier observations. The width of the enhancements are narrower than that of the arc (between 1/3 and 1/16 the width of the arc) as expected, but the magnitudes (25 - 70 mV/m) are slightly smaller than that expected (≈ 100 mV/m). In only
one case was the magnitude of the enhancement larger than that of the convection electric field.

Disturbed Arcs

Disturbed arcs observed throughout the data set consist of spirals or similar auroral forms distributed over the length of an arc. The electric field signature associated with this type of arc exhibits significantly different features than that of the quiet arc. These differences are clearly evident in the data acquired during orbit 908 (December 13, 1992). The disturbed nature of the arc is shown in Plate 4. The arc does not have a streamlined configuration but is rippled and has two significant distortions at ~ 1500 MLT and ~ 1700 MLT. Freja crossed this arc at ~ 1542 MLT, a point between the two distinct distortions. Images of this portion of the arc were acquired at 0051:41 and 0051:47 UT, while the electric field corresponding to this region was measured between 0048:30 and 0052:04 UT (maximum time difference between data of about 3 min, 14 s). The electric field and intensity profile associated with this arc are shown in Figure 4. Note that the absence of intensity data between 0052:03 and 0052:18 UT is due to the data gap in the imagery. Both the intensity profiles of the arc from the individual images and the electron spectrogram indicate that the arc is stationary and aligned with the peak in the intensity profile at the times of the electric field measurements. The region representing the arc extends from 0051:35 to 0052:01 UT, as shaded in Figure 4.

Similar to the quiet arcs examined, the poleward boundary of the disturbed arc is located near the reversal in the convection field. In this case the reversal is represented by the change in the electric field from a field with a magnitude of ~ 45 mV/m in the northwest direction to a field with a magnitude of ~ 5 mV/m in no particular direction because the satellite travelled along the convection reversal after crossing the arc. Within the region of the arc the electric field changes from a northwest to southeast directed field, and then back to northwest before settling into its poleward morphology. These variations actually appear as quasi-periodic variations in both components of the electric field, dominated by the reversal at 0051:54 UT. The magnitude and frequency of these fluctuations are 60 – 80 mV/m and 0.25 Hz, respectively. In this case, field enhancements at the boundaries of the arc are not observed and the boundaries of the arc in the electric field profile are not readily distinguishable. This type of signature is also observed when the satellite’s footprint crossed a spiral located during orbit 984 (December 18, 1992) (see companion paper by Marklund et al. [this issue]). Within the region of the arc the northeastward field is reduced to near zero values and exhibits fluctuations with a magnitude and frequency of 20 – 30 mV/m and 0.4 Hz, respectively. In this case, the electric field at the boundaries of the discrete emissions resumes the magnitude of the convection electric field.

Series Arcs

Auroral arcs also occupy the auroral distribution as a series of parallel arcs. Although in the imagery these arcs appear to be similar to arcs occurring individually, their electrodynamics may be affected by the surrounding arcs. As discussed previously, the separation of the parallel arcs can be of the order of the thickness of the arc. Within the electron spectrograms these arc configurations are represented by a very broad band of electron precipitation with varying energy. High-intensity emissions correspond to the electron precipitation with the highest energy, while the low-intensity diffuse emissions between the arcs correspond to a decrease in the energy of the precipitation or negligible electron precipitation. The data acquired during orbit 774 (December 3, 1992) and orbit 907 (December 13, 1992) illustrate the characteristics of the electric field signature of this type of arc configuration.

As shown in Plate 5, during orbit 774 the auroral distribution is occupied by a series of arcs of varying intensity. The images of these arcs were acquired at 2122:50 and 2122:56 UT, while the in situ measurements corresponding to these arcs were acquired between 2122:30 and 2125:00 UT (maximum time difference between data of 2 min, 7 s). The electric field measurements and intensity profile associated with the arcs are shown in Figure 5. As evident from the intensity profile of the arc, there are three distinguishable arcs in this series. The locations of these arcs, as inferred from the imagery, were confirmed by examining the electron spectrogram for this time period. Although the time difference between the imagery and in situ data was small, a difference between imaged emissions and electron precipitation was ap-

Figure 4. Perpendicular electric field and intensity profile associated with the disturbed arc observed during orbit 908 on December 13, 1992. The eastward component, southward component, and magnitude of the perpendicular electric field are included. The reference times of the satellite’s footprint, as indicated in Plate 4, are marked in order to compare the auroral imagery and electric field measurements. The shaded region indicates the times at which the disturbed arc was crossed by the satellite’s footprint.
In addition to the three arcs observed in the imagery, a fourth region of high-energy electron precipitation located poleward of the arcs in the imagery, is also observed. As deduced from the individual images, the arcs are in their developmental stages at the time of the imagery, and therefore the imagery represents the series of arcs in the first stages, while the electron spectrograms represent later stages of the arcs. Although there is a difference between the imagery and electron spectrogram, the arcs appear to be stationary since the arcs in the imagery are aligned with corresponding regions of high energy electron precipitation. The location of the arcs which are a part of the series are labeled in Figure 5. These locations have been inferred from both the intensity profile and the electron spectrogram.

The electric field signature corresponding to the broad region of arcs and electron precipitation consist of a general reduction in the convection electric field. The magnitude of the convection field (~ 35 mV/m) is reduced to about 10 mV/m. In comparison with the signatures described previously, the electric field in this case is not reduced to values as low as that of the quiet arcs occurring as a single arc. Considering each arc separately, this case demonstrates how each arc of a series of arcs is associated with a reduction in the magnitude of the electric field and in the regions between the arcs the electric field resumes the magnitude of the convection field or is enhanced above that magnitude (~ 50 mV/m). From the corresponding electron spectrogram and as evident from the imagery, the enhancements in the electric field are aligned with regions of negligible electron precipitation. In regions of low-conductivity large electric fields are required if Pedersen currents are to ensure the total current is continuous.

Another signature is observed during orbit 907 when the satellite’s footprint crossed the auroral distribution in a south-east direction at ~ 2000 MLT (see Plate 3) where arcs of low intensity were found in the region poleward of the most intense arc. A single enhancement of 100 mV/m appears to dominate the electric field signature of a broad region of parallel arcs. The electric field and intensity profile corresponding to this case are shown in Figure 6. Although the locations of the low-intensity arcs are not as distinct as that of the high-intensity arc, the corresponding electron spectrogram indicates that these arcs are associated with regions of significant electron precipitation separated by a region of reduced but not negligible electron precipitation. The electron spectrogram also indicates that there is a slight difference in the location of the emissions and the location of the associated electron precipitation. As indicated in Figure 6, the location of the arcs at the time of the electric field measure-

Figure 5. Perpendicular electric field and intensity profile associated with the series of quiet arcs observed during orbit 774 on December 3, 1992. The eastward component, southward component, and magnitude of the perpendicular electric field are included. The reference times of the satellite’s footprint, as indicated in Plate 3 are marked in order to compare the auroral imagery and electric field measurements. The shaded region indicates the times at which the arcs were crossed by the satellite’s footprint.

Figure 6. Perpendicular electric field and intensity profile associated with the series of arcs observed during orbit 907 on December 13, 1992. The eastward component, southward component and magnitude of the perpendicular electric field are included. The reference times of the satellite’s footprint, as indicated in Plate 3 are marked in order to compare the auroral imagery and electric field measurements. The shaded region indicates the times at which the arcs were crossed by the satellite’s footprint.
ments are shifted by about 6 s in the poleward direction (to the left).

As shown in Figure 6, a northeast enhancement of the electric field is clearly aligned with the region of negligible electron precipitation found poleward of the most intense arc. From earlier observations, this type of enhancement was expected to be located on the equatorward side of the arc and directed towards the arc [Opgenoorth et al., 1990; Aikio et al., 1993; Lewis et al., 1994]. In this case the enhanced field is directed towards the low-intensity arc poleward of the most intense arc. Also, the reduction expected to be aligned with the low-intensity arcs is not as prominent as in the case of the single quiet arc occupying the auroral distribution. Generalizing the observations of the field enhancements within a series of arcs, the enhancement of 100 mV/m is always observed on the poleward side of the most intense arc and is directed towards the lower intensity arcs.

Discussion

Signatures of the perpendicular electric field in the vicinity of three auroral arc configurations have been identified by examining auroral imagery and in situ electric field measurements. Owing to the nonsimultaneous nature of these two data types and the possible rapid evolution of auroral arcs, it was questionable whether small-scale electric field features can be associated with specific arc configurations using these data. As evident from the cases presented, this method is viable under certain circumstances. If the data are near simultaneous and the auroral forms are stationary with respect to the satellite’s trajectory, electrodynamic signatures of specific auroral forms can be deduced from in situ measurements. Electric field signatures associated with auroral forms which are a part of rapidly and somewhat randomly evolving forms such as substorms could not be identified.

Particle spectrograms have been used in evaluating this method of identifying electrodynamic signatures. Because the relationship between electron precipitation and auroral emissions is well known [Kamide et al., 1979; Rees, 1989], electron spectrograms which are simultaneous with the electric field measurements have been used to reaffirm that the location of the auroral form is as given by the imagery. Unless the auroral imagery and the in situ measurements are exactly simultaneous, the use of particle measurements is probably inevitable due to the possible rapid evolution of auroral forms. In the case of the series of arcs observed during orbit 907 (see Figure 6) a slight shift between the location of the auroral emissions and the associated electron precipitation was observed even though the arcs appeared to be stationary and the time difference between the imagery and in situ measurements was very small. Owing to the difference between in situ data and imagery and the arc’s evolution, this case may have been misinterpreted without the particle measurements.

With each improvement in resolution, exactly simultaneous electric field measurements and imagery or particle data will become increasingly essential to this type of analysis. As other experiments have demonstrated, auroral forms with scale sizes smaller than that observed in the Freja imagery do exist. Borovsky and Suszczynsky [1993] have measured arcs thicknesses on the order of 100 m. The evolution of these auroral forms may be significant on very small temporal scales, and therefore simultaneous data or a method of assuring that the location of the auroral form is as given by the imagery will be necessary.

For the cases in which it was possible to identify electric field signatures associated with auroral forms, the observations are consistent with earlier observations. Combinations of the anticorrelation of auroral forms and electric field and electric field enhancements at the boundaries of arcs have been observed. Many variations of electric field signatures have been associated with auroral arcs at various local times [Marklund, 1984]. Through the use of in situ electric field measurements and auroral imagery the new observations presented have been used to suggest the differences in electric field signatures due to differences in resulting auroral forms. The arc configurations which have been examined include quiet and disturbed arcs occurring as single arcs within the auroral distribution or as a part of a series of arcs within the auroral distribution. These dusk sector arcs have thicknesses of about 100 km and are typically stationary. As demonstrated by the imagery, the dominating evolution of the arcs consists of a rotational motion of the spirals observed along the disturbed arcs. The rate at which the arc has been found to rotated ranges from 0.4 to 3.6º/s. [Figure 8].
The signatures of the quiet arcs most resemble the signatures deduced from earlier observations. Within the region of the arc the magnitude of the corresponding electric field is reduced to values near zero and small electric field enhancements are observed at the boundaries of the arc. These observations are consistent with the interpretation that the arc-associated electric field consists of a polarization electric field and possibly an enhanced electric field generated in response to field-aligned current flow. Each of the quiet arcs examined were located near the dusk sector reversal of the convection electric field and therefore, the small field enhancements observed at both boundaries of the arc were expected. Enhanced electric fields at just one boundary of the arc are observed by Opgoenoorth et al. [1990], Aikio et al. [1993], and Lewis et al. [1994], but from the interpretation of their observed signatures it is feasible that enhancements at both boundaries is possible if the arc is located at the convection reversal as in the cases examined here.

The arc-associated current circuit which has been associated with the electric field signature observed in the region of the quiet arcs is shown in Figure 7. This schematic represents a plane containing the vertical and north-south axis of an arc. All parameters in the east-west direction, which is into the page, are taken to be constant. The sum of the arc-associated electric fields and the convection electric field, as observed, is shown on the right. The arc-associated polarization electric field reduces the convection electric field, while the small arc-associated field generated in response to the field-aligned current system enhances the convection electric field. Polarization effects are clearly associated with regions of high conductivity, while the field-aligned current effects are associated with regions of low-conductivity. The polarization electric field and hence current attempts to balance the Pedersen current which results from the enhanced conductivity in the region of the arc and the convection electric field. The small enhancements in the electric field at the boundaries of the arc can be interpreted as the response to the Pedersen currents extending into regions of low-conductivity such that the current circuit of the arc is closed via two downward field-aligned currents on either side of the arc. Because the observed electric field enhancements have magnitudes smaller than that previously observed, the arc-associated electric field of these arcs appears to be dominated by the polarization effects. Therefore these arcs are of the type characterized by a weak current flow associated with the particle precipitation which creates the arc [Marklund, 1984; Opgoenoorth et al., 1990].

When more than one quiet auroral arc is found to occupy the auroral distribution, the electric field signature associated with a single quiet arc appears to be affected by the surrounding arcs. Compared to the "single" arcs, the polarization effects in each of the observed series of arcs tends to be less effective and the influence of the current structure of the arcs is increasingly apparent in the electric field signatures. These arcs appear to be of the type of arc which is characterized by a strong upward field-aligned current [Marklund, 1984; Opgoenoorth, 1990]. From observations an enhancement in the upward field-aligned current is usually accom-
Plate 4. Auroral imagery from orbit 908 on December 13, 1992. The universal times of the individual images used to construct this image are 0051:41, 0051:47, 0054:11, 0054:23, 0056:41, 0056:47, 0056:53, 0059:10, 0059:22, 0101:40, 0101:46, and 0101:52. The footprint of the satellite at the indicated universal times is also indicated.

Plate 5. Auroral imagery from orbit 774 on December 3, 1992. The universal times of the individual images used to construct this image are 2120:30, 2122:50, and 2122:56. The footprint of the satellite at the indicated universal times is also indicated.
currents [de la Beaujardière and Vondrak, 1982]. As the Pedersen current extends into the low-conductivity regions surrounding the arc, enhanced electric fields ensure that the total current is continuous and give an indication of the location of the downward field-aligned currents. One interpretation of the electric field signature observed with a series of arcs is shown in Figure 8. Downward field-aligned currents are located equatorward of both the high-intensity arc and the series of low-intensity arcs which are not separated by regions of negligible electron precipitation, hence a downward field-aligned current. Pedersen currents flowing through both high- and low-conductivity regions connect the upward and downward field-aligned currents. Enhanced electric field are aligned with the regions of low conductivity, regions of decreased auroral emissions. The enhanced field with the largest magnitude is found equatorward of the series of low-intensity arcs. The large magnitude of this field enhancement can be associated with the strong Pedersen current and downward field-aligned current required to balance the upward field-aligned currents of the series of arcs. This electric field signature can then be taken as consistent with earlier observations.

A variation of the commonly observed electric field signature, such as that shown in Figure 7, has been observed to be associated with disturbed arcs consisting of auroral spirals. The variation is in the portion of the signature within the boundaries of the arc, the region of the polarization electric field. Both components of the electric field can be characterized with quasi-periodic fluctuations with magnitudes of ~ 50 and ~ 25 mV/m and frequencies of 0.25 and 0.4 Hz. These fluctuations can be interpreted as both temporal variations in the electric field or multiple spatial structures in the field. Low-frequency fluctuations similar to those observed have been found to play an important role in many processes associated with particle acceleration [Marklund, 1993]. Specific plasma processes have been related to distorted arcs such as that observed. Morphological characteristics of spirals have suggested that these processes include plasma instabilities which are shear driven [Murphree et al., 1989, 1994b]. Both velocity and magnetic shears provide a source of energy from which instabilities can grow and modify the spatial distribution of a plasma [Lotko and Shen, 1991]. Electrostatic turbulence has also been associated with shear structures and shear-driven instabilities [Horwitz et al., 1978; Earle et al., 1989]. Therefore the observed electric field fluctuations are interpreted as a manifestation of the shear structures responsible for spirals and give further support for their involvement in the formation of these auroral forms.

Summary

Observations of perpendicular electric field vectors and optical auroral emissions by Freja have been used to identify electric field signatures of both quiet and disturbed auroral arcs occurring as a single arc and as a part of a series. The auroral imagery has been used to identify not only the location of discrete emission but the configuration and characteristics of the auroral arcs as well. By comparing intensity profiles of the auroral arcs and electric field measurements, electric field signatures of three basic arcs have been successfully identified. As evident from these observations characteristics of the electric fields associated with specific arc configurations are crucial in interpreting the possible electrodynamic structures of the arcs.

The observed quiet and disturbed arcs were found within the dusk and premidnight sectors of the auroral distribution. These arcs have typical thicknesses of ~ 100 km and are separated by ~ 105 km when they are a part of a series of parallel arcs. During the time span when the arcs were imaged, their evolution was dominated by the rotation of the distorted portions of the arc. From the nature of the rotation and the spatial dimensions, the distortions have been identified as auroral spirals. The growth rate or rotational velocity of these auroral forms ranges from 0.4°/s to 3.6°/s and has been found to depend on the stage of the spiral's development.

The electric field signatures identified with the varying arc types are in agreement with earlier observations and interpretations of the electrodynamics of auroral arcs. The arcs are associated with both polarization effects related to the precipitation of electrons and a current system consisting of field-aligned currents and Pedersen currents. The electric field signatures of quiet arcs occurring as a part of a series of parallel arcs differs from that of the quiet arcs occurring alone. These differences have lead to the identification of the "series arcs" as arcs characterized by a strong upward field-aligned current, with the "single arcs" as arcs characterized by a weak field-aligned current. The differences in electric field signatures of the quiet and disturbed arcs are important in understanding the processes involved in the formation of the observed spirals. The quasi-periodic electric field fluctuations observed to be aligned with the distorted arcs indicate that shear structures and shear-driven plasma instabilities play a role in the formation of the disturbed arc.

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