Small-Scale Structures and Motions of Auroral Signatures as Observed From the Ground: A Planned Field Study Using Camera and Radar Observations

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1: Background and Motivation

The aurora borealis or northern lights is a beautiful and richly complex phenomenon, which has been studied for many years. Theories exist to explain the plasma physics processes related to the aurora, but many more questions still exist. It will be the purpose of this thesis to examine a small portion of the auroral plasma physics processes, namely that of ionosphere-magnetosphere coupling through small-scale structuring and dynamics.

There are two parts to the study of auroral physics. The first one involves understanding the structure and evolution of auroral features. This includes describing complex auroral forms in terms of much more simplified models. Theories and models have been developed, based on observations, which contain assumptions and make predictions about how the auroral structures form and evolve. The main mechanism for coupling together all of these auroral processes are currents flowing in the ionosphere and magnetosphere. It is therefore very important to understand and be able to measure these currents.

The second aspect deals with the question of how these auroral features can be quantified and measured in order to test against the theories and models. There are many ways to observe the aurora including cameras, radars, rockets, and satellites. The aurora, being so dynamic and involving such a large range of scales, makes measuring and quantifying the structures very difficult. The main methods used for making such measurements are ground-based instruments, sounding rockets, and constellations of satellites.

1.1: Ground Observations

Ground-based observations of the aurora are useful for providing an overall picture of the ionosphere and the visible aurora. This method of observation is frequently used because it is usually the easiest and least expensive. It is limited in its capabilities since remote sensing techniques must be used. Examples include cameras to record auroral activity, radars to probe ionospheric density profiles, and magnetometers to indicate ionospheric currents. A benefit of using ground-based observations is that a 2-D picture of the aurora can be examined and changes in time can be distinguished from motions in space.

1.2: Sounding Rockets

Sounding rockets improve on the ground-based observations by providing in-situ plasma measurements, but they are limited in that they are usually only a single point measurement with a very limited field of view. The CASCADES rocket (described below) was to use more than one payload to get multi-point in-situ data. This could then be used to measure the signatures of propagating Alfven waves, to investigate proper motions and shears in pre-midnight auroral break-up arcs associated with poleward
boundary intensifications, and to measure and make the distinction between charge sheets and current sheets, which are thought to be responsible for producing the auroral curls and auroral spirals seen in the ground optical data. With the in-situ multi-point plasma measurements and the ground cameras, a much more complete analysis of the structure and dynamics of the auroral features could be conducted.

1.2.1: CASCADES Sounding Rocket Campaign

The CASCADES (the Changing Aurora: in Situ and Camera Analysis of Electron precipitation Structures), 40.017, sounding rocket campaign was designed to examine the small-scale structure and dynamics of auroral features. The payload consisted of 5 separate parts (4 sub-payloads in addition to the main payload), which would come apart and form an array in flight. This was done to try to resolve the differences between changes in time and changes in space of the auroral structures that it would fly through. The main payload was instrumented with a magnetometer, an ion detector and 2 electron detectors, one of which was specifically designed to measure down-going field-aligned electrons. It also included a low-light imager looking down the magnetic field at the visible aurora. Two of the sub-payloads were PFFs (Particle Free Flyers) carrying a magnetometer and an electron detector. The other two sub payloads were COWBOYs (Cornell Wire Boom Yo-yo), where each had a magnetometer, wire electric field booms extending 12 m tip to tip, as well as a small thermal electron detector, the ERPA (Electrostatic Retarding Potential Analyzer). All 5 payloads were equipped with a Cornell GPS receiver to allow very precise timing and position information between the payloads. This array of payloads was arranged such that the two COWBOYs would separate by a large distance (a few km) along the magnetic field direction. The two PFFs would go out perpendicular to the magnetic field and at right angles to each other and also have smaller separations (few 100’s of meters). The array was set up this way to examine the structure and dynamics of parallel and perpendicular auroral gradients, where parallel and perpendicular refers to direction with respect to the magnetic field.

CASCADES was launched from Poker Flat Research Range (PFRR), AK at 10:31:17 UT on 6 March 2005 into active auroral arc structures. However at 33.2 seconds into the flight, the third stage motor failed to ignite, resulting in the payload reaching an apogee of only 29.5 km. The payload, which struck the ground 21.9 km downrange was recovered about 2 days later and brought back to PFRR. This motor ignition failure resulted in receiving no scientific data from the rocket borne experiments. Since there is no chance for an immediate re-fly, we must turn to modified means to address questions that CASCADES was designed to answer. We recover some of the original perpendicular science goals by using ground-based instrumentation, such as real-time (30 frames per second) auroral imaging cameras, radars, and magnetometers.

1.3: Satellite Constellations

Sounding rockets are limited to case studies with limited field of view. Using a large constellation of orbiting satellites making many in-situ measurements throughout the ionosphere and magnetosphere would be the most accurate way to gain a larger
picture of the auroral structure and dynamics. This however is very costly and very difficult logistically. Therefore very small spacecraft are needed, where there will be limited space for instruments, allowing only the most important to be installed. Having a magnetometer on such a payload is very important since it is the currents which connect the different regions together, therefore the magnetic influence of the payload must also be known and accounted for to get accurate measurements.

1.4: Overview

This proposal will first cover the ground-based instrumentation that will be used for this study, including cameras, radars and magnetometers. Next the subject of magnetic cleanliness of small spacecraft will be discussed, with the example of the PFFs and COWBOYs from the CASCADES sounding rocket campaign. The science questions and goals to be addressed by this study will then be outlined and discussed.

2: Ground-Based Instrumentation

Studies of auroral perpendicular structure, gradients, and motions can be made using an array of ground-based instrumentation. This study however is not a replacement for an in-situ rocket-based study, but rather a complementary study with the constraints and benefits of ground-based observation, the results of which can be compared to in-situ observations.

2.1: Imagers

The most important tool for quantifying auroral structure and motions is the auroral imager, which images in real time at 30 frames per second. There are two different types that will be used for this study, all-sky and narrow-field imagers.

The all-sky camera uses a fish-eye lens to produce a 2-D picture of the sky from horizon to horizon. This gives a large-scale picture of the auroral activity visible at that location. However, near the horizons, below elevations of 20 or 30 degrees, the image is severely distorted making data from that part of the image un-quantifiable. The all-sky image is a projection of the whole sky onto a circle, so care must be taken when computing structure scale size and motion because the perspective is different for different regions of the image. The region near the center of the image most accurately reproduces what the aurora really looks like, as this is an angular projection. The altitude of the auroral structures must be modeled in order to make estimates of sizes and speeds. A constant altitude of 100 km is typically used for observations directly below, viewing the bottom of the structures. For observations near the horizons, the altitude extent of the structures can be inferred, but the distinction between horizontally and vertically extended structures cannot be made using the all-sky image. The University of Alaska at Fairbanks (UAF) operates 3 all-sky cameras that will be used for this study, which are located at Poker Flat, Fort Yukon, and Kaktovik. Figure 2.1 shows the locations of these three sites on a map of Alaska.
Figure 2.2 is an image from the all-sky camera at Kaktovik, which shows an active auroral arc structure that was moving from southwest to northeast. In this image, north is down and east is to the right. The height of the letters on the image would represent about 5 km near the center. Many different auroral features can be identified in the image with one of the most notable being the large dark stripe passing through the structure. There are smaller structures visible as well, but the structure size resolution is, at best, a few kilometers in the center, and many kilometers near the edges. In order to image the smaller scale (sub-kilometer) structure, a different type of camera, one with a smaller field of view, is needed.

The second type of auroral imager to be used in this study is the narrow-field camera. This camera has a field of view of 12 x 16 degrees allowing for a high-resolution image of a much smaller piece of the sky. It can resolve very small-scale (sub-kilometer) auroral features near the zenith and kilometer scale features near the horizons. In order to observe vertical extent in auroral structures, they must be viewed in the perpendicular direction, near the horizons. An advantage of this camera over the all-sky camera is that when observing near the horizon, the vertical extent of auroral features can be observed, while in the all-sky image, the area near the horizons is distorted. Imaging auroral rays perpendicularly allows for a larger dataset of ray sizes and speeds to be collected and quantified. One narrow-field camera, also operated by UAF, is currently located at PFRR. A second narrow-field camera can also be taken to Kaktovik if needed, and possibly Fort Yukon.

The narrow-field camera is equipped with a red filter in order to block out the most dominant auroral emission, the green line at a wavelength of 557.7 nm. This is
done because the excited state of atomic oxygen, which produces this green line, has a lifetime of 110 seconds, while the excited state that produces the 630 nm red line has a lifetime of 0.74 seconds. Therefore by observing the red structures at low altitudes (~100 km), it can be assumed that they will form in the same place where they will be observed since the red light will be emitted very rapidly. The green structures will drift and move around because of the much longer lifetime of the excited state. This results in the green structures being spread out and not representative of their generation mechanisms.

![Image](image.png)

**Figure 2.2:** Image from the all-sky camera at Kaktovik on 06 March 2005.

The narrow-field camera(s) will be the primary source of the high-resolution images of the auroral features to be used in this study. The all-sky cameras will provide a larger scale auroral context for the narrow-field images.

### 2.2: Radars

The use of ground cameras to complement the in-situ data was part of the original plan for CASCADES but the use of radars was not. For this study the optical data will be complemented with radar data, to quantify the ionospheric response to the auroral activity. There are potentially 3 different radars that can be used for this study.

The first one is the 30 MHz imaging radar located near Anchorage, AK which is operated by Cornell University in collaboration with UAF. This radar can image the E layer ionosphere over a large area of Alaska including Poker Flat and Fort Yukon. It is a coherent scatter radar at 30 MHz. This means that the scattered returns are from
irregularities in the plasma that have a scale size on the order of 1/2 of a wavelength, or about 5 m. One of the questions to be addressed is the nature of these irregularities, because there is little consensus about their identity. Each image pixel spans 2.5 km in range and between 3-5 km in azimuth depending on the range (0.4 degree azimuth resolution), and the integration time for each image is 5 seconds.

Another radar that may be useful for this study is the superDARN (super Dual Auroral Radar Network) radar station located on Kodiak Island, AK. This radar can observe the F-region ionosphere above Poker Flat, and measures line-of-sight flow velocities. This can be useful for determining the large-scale convection over Alaska and provide a context for the 30 MHz imaging radar observations. Unfortunately, there is no other superDARN station that can observe this area, therefore vector 2-D flow velocities cannot be computed.

The third radar that would be very useful for this study is the AMISR (Advanced Modular Incoherent Scatter Radar) that is currently being constructed at Poker Flat, where the radar can look from the zenith down to 30 degrees elevation in the north, and 30 degrees east and west of north. This radar would be able to observe the E-region ionosphere above Fort Yukon, thus allowing the radar to observe the perpendicular motions there. It is still questionable how much of this AMISR will be operational this coming winter, when we are planning the optical observations. Nevertheless, whenever the Poker Flat AMISR comes into operation, data collected with it will complement this study. This radar is set up as a phased array of panels, so that steering of the beam can be done almost instantly. AMISR works by scattering off of the bulk plasma, giving information about density as well as line-of-sight flow speeds. AMISR will be a very big antenna array, allowing the detection of small signal returns with high time resolution. This will allow for the detection of the small-scale density enhancements and depletions expected with the light and dark auroral features. The motion and size of these small-scale structures can be quantified and then compared to the optical data. One major question to be addressed with AMISR, with its high resolution, is the existence, or not, of large amplitude small-scale fluctuations in the ionosphere. Such fluctuations cannot be detected by existing radars, because their spatial resolution is too coarse, therefore averaging out the small-scale structures.

2.3: Magnetometers

Magnetic field changes observed on the ground are an indicator of currents flowing in the ionosphere. For this study we will use the magnetic field measurements made on the ground at the locations of the cameras. There are, however magnetometers operated by UAF at all of the locations shown on the map in Figure 2.1.

The largest changes in the magnetic field values correspond to times when the auroral activity overhead intensifies. An equivalent horizontal ionospheric current can be calculated from the magnetic field perturbations, but there are many assumptions that need to be made. It can be shown that vertical field-aligned currents produce no magnetic perturbation on the ground, assuming that the ionospheric conductivity is uniform. This is because the Pedersen current, the current connecting the field-aligned currents, flows horizontally in the ionosphere, producing a magnetic perturbation that exactly cancels the perturbation caused by the field-aligned currents. The magnetic
perturbation measured on the ground is assumed to be mostly due to the Hall current, which flows perpendicular to both the field-aligned and Pedersen currents (Kelley, 89).

For the purposes of this study the equivalent horizontal ionospheric currents will be estimated from the measured magnetic perturbations. The effects of ionospheric modification by auroral activity will be investigated. The conductivity is changed by the intensified activity, which violates the previous assumption, and thus the magnetic perturbation observed contains contributions from field-aligned and non-isotropic Pedersen currents.

Estimating ionospheric currents from ground-based magnetometers is not very reliable and based on assumptions that may not always be accurate. The magnetic perturbations observed on the ground are ambiguous and could be caused by a lot of very different current systems. Therefore making magnetic field measurements in-situ with spacecraft puts more constraints on the type of currents present, and allows for more accurate estimates of the current structures associated with the auroral activity. However, the ground-based magnetometers do provide a very good indicator for the intensity of the auroral activity.

3: Magnetic Cleanliness of Small Payloads

3.1: Background

Measuring the Earth's magnetic field, and its perturbations, has long been of interest to scientists. However, the more accurately it is measured, the more difficult it becomes to do so without significantly disturbing it in the process. The instrument used to measure the magnetic field, and its supporting electronics and structure produce a disturbance to the background magnetic field. Often this disturbance can be measured and calibrated out, so that the output is an accurate measure of the external magnetic field in the vicinity of the magnetometer. This external field however is not just the geomagnetic field, as it also contains the sum of all the local magnetic field sources. These sources can include current carrying wires, as well as any magnetic materials nearby, all of which are usually contained in the electronics that power and read out the magnetometer. When measuring the geomagnetic field on the ground, this problem can be eliminated by placing the magnetometer in a remote area and attaching it to the control electronics using long (10s of meters) cables. This works very well because the magnetic field magnitude falls off as the inverse cube of the distance, therefore any of the magnetic effects of these local sources will be virtually undetectable at the magnetometer at those distances. However, when measuring the geomagnetic field from spacecraft, there is a limit as to how far away the magnetometer can be placed, usually only meters or less. At these distances the magnetic effects of the rest of the spacecraft and electronics can be detected by the magnetometer. It is the purpose of this study to investigate the effects of having a magnetometer on a very small spacecraft where it must be close to everything and therefore measures the interference effects of the spacecraft itself.

The magnitude of the geomagnetic field at the Earth's surface is about 30,000 nT (nanoTesla) at the equator and about 60,000 nT at the poles. These values decrease as the inverse cube of the distance from the center of the Earth, so for spacecraft it is very
important to be able to measure small changes in the geomagnetic field. For example, sounding rockets need to detect 10s out of 10s of thousands of nT, or 1 part in $10^4$, whereas some satellites need to detect few nT changes out of few nT fields. This requirement is driven by the need to accurately measure current structures in the ionosphere and magnetosphere. These current structures produce magnetic fields, which alter the background geomagnetic field due to Ampere’s law, 

$$\mathbf{\nabla} \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t},$$

which relates curls in magnetic field to currents and time rate of change of electric field. For the frequency ranges involved in the auroral processes, the changing electric field term is negligible compared to the current term. The small changes in the background magnetic field contain all the information about the current structures. The accuracy with which current structures can be measured from spacecraft is limited by their ability to accurately measure small changes in magnetic field.

Single spacecraft like FAST, Freja, and POLAR make single point measurements as they pass through a structure making it impossible to tell the difference between changes in space, changes in time, and motions in space of the structures through which they are flying. In a field-aligned system, where it is assumed that there are no changes in the field-aligned direction, 3 separate payloads are sufficient to resolve these ambiguities. However in the full 3-D space, a minimum of 4 spacecraft flying in a constellation are needed. The CLUSTER mission accomplishes this with 4 fairly large and very expensive spacecraft. The CLUSTER array can make one measurement in space, assuming linear gradients that are larger than the spacecraft separation. The next step to study the magnetosphere in detail is a large constellation of satellites like the upcoming DRACO mission with 50-100 very small satellites. This would provide many measurements throughout the volume, again assuming linear gradients. They would have to be very small and very cheap to make it feasible for them to be built and put into space. However, having magnetometers on very small satellites means that the magnetometer has to be close to everything else, and therefore the payload disturbance to the magnetic field must be characterized and accounted for in the data.

### 3.2: CASCADES and PFF Design

The CASCADES sounding rocket mission involved the design and construction of two small autonomous sub payloads, Particle Free Flyers (PFFs). The PFFs were designed to be as magnetically clean as possible, by the use of non-magnetic connectors, no nickel plating on certain parts, and the placement of the batteries (nickel-cadmium) as far away from the magnetometer as possible. Each PFF weighed about 21 pounds in its final flight configuration and was contained inside a 9” diameter, that of the wrap-around antenna, with the magnetometer sticking up on a bracket about 0.4 m from the base, (Figure 3.1).

During the design of the PFFs many of the parts and components were characterized using the magnetic calibration (magcal) facility and an astatic-magnetometer, both at Wallops Flight Facility (WFF) in Wallops Island, VA. The magcal facility can null out the Earth’s field to produce a region of zero magnetic field magnitude accurate to 1 or 2 nT. It can then produce any specific magnetic field up to a magnitude of 60,000 nT in any direction. There were 2 main types of magnetic
contamination identified.

Figure 3.1: Photograph of a PFF with the magnetometer (black rectangular box) mounted upright to place the sensor end as far from the rest of the payload as possible.

The first type was due to intrinsic or (hard) magnetic material, such as iron and nickel, which have a constant magnetic field regardless of any external field (Primdahl, 97). The net result is that of a simple dipole magnet producing a constant offset to the geomagnetic field at the location of the magnetometer. This can be measured and calibrated out in the magcal facility. A note of caution here is that these hard magnetic materials exhibit hysteresis. When large enough external fields are applied their magnetic moment can be changed. During the testing at WFF many of the identified magnetic components were subjected to magnetic fields of +/-60,000 nT, which is larger than they would experience on the ground or in flight, there was no noticeable change in their measured magnetic moment. Therefore, it appears that much higher fields are needed to change the magnetic moments of these hard magnetic materials. It is then reasonable to assume that these magnetic moments are not a function of external field strength for the range of magnetic field values experienced in flight.

The second type of contamination was due to inductive or (soft) magnetic material that has no intrinsic magnetic moment but produces a magnetic field when placed into an external one. This type of material produces a disturbance to the geomagnetic field at the location of the magnetometer that is dependent on the field
strength and direction at the location of the material (Primdahl, 97). For example, when the payload is spinning, the soft magnetic material sees a varying field direction, and therefore produces a different disturbance to the magnetic field at different angles. This disturbance will then be spin-dependent, and would be evident in the data if the effect is large enough.

Part of the magnetic calibration for the PFFs was to characterize the extent to which these soft magnetic materials would influence the data quality of the PFFs. The PFF data were compared to the COWBOY data, which have had flight history on the SIERRA (Sounding of the Ion Energization Region: Resolving Ambiguities), 40.014, and SERSIO (Svalbard EISCAT Rocket Study of Ion Outflows), 35.035, sounding rocket missions. The SIERRA magnetometer data are known to be fairly free of contamination and therefore of good science quality. Two COWBOYs were built for the CASCADES mission, allowing for a good comparison between the COWBOYs and the PFFs, because the variation between the two COWBOYs and the variation between the two PFFs can be examined and compared to the variation between the PFFs and the COWBOYs.

3.3: Calibration Procedure

The same magnetic calibration procedure was done for all five payloads (2 PFFs, 2 COWBOYs, and the main payload) and the data that will be used for this comparison study is from what is called the linearity test. This test procedure involves placing the spacecraft in the magcal facility and stepping the magnetic field value by 5,000 nT steps from -60,000 nT to +60,000 nT in each of the three axes. However, for the purpose of this study only values between +/- 45,000 nT will be used due to some saturation issues with the PFFs. Figure 3.2 shows an example from PFF#2 where the x-axis was being stepped. During this procedure the spacecraft is powered from the internal batteries and the data is received through the telemetry (TM) just as it would be in flight. The magnetometer data was sampled at 1000 samples per second. Each of the steps in the data last for about 0.5 sec, in order to avoid the transients from the changing magnetic field. Two hundred samples were taken from the center part of each step and averaged to give the number of TM counts that corresponds to that magnetic field value. These 19 points were then fit to a line to get the scaling and offsets to convert TM counts to nanotesla. The effects of any hard magnetic materials are contained in the offset values obtained in this step, so they effectively are no longer an issue. An assumption here is that all of the magnetic field is going in the applied direction and nowhere else. As can be seen from Figure 3.2 some of the applied field in one direction shows up in the other two as well, but in all of these cases it amounts to only about 3% or less of the total field. This must be assumed in the beginning since it is uncertain if this effect is from misalignment or soft magnetic material effects. This assumption results in the possibility of having the absolute magnetic field measurements slightly incorrect, however changes in magnetic field values are still measured correctly. This overall offset shift can later be corrected, once the non-orthogonality and misalignments are accounted for.

The amount of the applied field that shows up in the orthogonal directions is the net result of a number of effects. These include misalignment or non-orthogonality of the sensor elements with respect to the housing of the magnetometer, misalignment of the magnetometer mounting to the payload, misalignment of the payload to the magcal
facility's axis, and the effects of any soft magnetic material.

![Graphs showing magnetometer data for x, y, and z axes](image)

Figure 3.2: Magnetometer data showing all three axes (Bx, By, Bz) while the magnitude of the field in the x-direction was being stepped from -45,000 nT to +45,000 nT. The y-axes are in nT and the x-axes are time in seconds.

Accurately untangling the contribution from any one of these effects from the others would be virtually impossible given the capabilities of the magcal facility, so another way of characterizing the soft magnetic material effect is needed. The method used here involves constructing a 3x3 gain matrix, which relates the known magnetic field (from the magcal facility) to the measured engineering units (from the magnetometer). The matrix equation is:

\[
\begin{bmatrix}
E_1 \\ E_2 \\ E_3 \\
\end{bmatrix} = 
\begin{bmatrix}
C_{11} & C_{12} & C_{13} \\
C_{21} & C_{22} & C_{23} \\
C_{31} & C_{32} & C_{33} \\
\end{bmatrix}
\begin{bmatrix}
B_1 \\ B_2 \\ B_3 \\
\end{bmatrix}
\]

Here E is the field measured in the engineering units, B is the magnetic field, and the C’s are the unitless constants of the 3x3 matrix (Zheng et al., 03). This gain matrix will have 1’s on the diagonal (due to the assumption that all of the field is in the applied direction), and should be anti-symmetric with small numbers for the off diagonal terms. These off diagonal terms represent how much of a given axis shows up in another axis, and these can be calculated from the linearity data. These were calculated in two ways, first, by taking the ratio of the different components at each step and then averaging these 18 values (excluding the zero nT value), or second, by plotting the values at each step from
one axis against the values at the same steps from the axis that was being stepped, then fitting to a line and taking the slope. For example, for the data plotted in Figure 3.3, the y and z components would be plotted against the x-component. Both of these methods give very similar numbers for the constants, as shown in Table 3.1.

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Table 3.1: The gain matrix constants for all 5 payloads calculated using the averaging method, and the fitting a line (plotting) method.

The magnitude of these off-diagonal terms gives a measure of the net misalignment, nonorthogonality, and soft magnetic materials effects. If the contribution to these numbers was purely from misalignment and nonorthogonality then it would be expected that, for example, $C_{12} = -C_{21}$ exactly. If a given field is applied in the x-direction and a small contribution is picked up in the y-axis, then, when the same given field is applied in the y-direction, the same small contribution should be picked up in the x-direction, and similarly for the other 2 pairs of axes. Any difference between the magnitudes of the opposing pairs of constants must be coming from the soft magnetic materials influence, assuming that the magcal facility's axes form an orthogonal system. Even if this system were not orthogonal, a comparison between the PFFs and the COWBOYS could still be done since they would both have the same relative errors, and it is the differences between their respective constants that are of interest. For the purpose of this study the opposing pairs of constants were added together. For example, $C_{12} + C_{21}$ give a number that we refer to as the cross-sum, and $(C_{12} + C_{21})/(C_{12} - C_{21})$ give a number that we refer to as the relative cross-sum. For a system that only has misalignments the cross-sum would be zero, so the magnitude of the cross-sum is a good estimate of the effect of the soft magnetic material. Table 3.2 shows these cross-sums and relative cross-sums for the three planes of each payload.

From these data it can be seen that the cross-sums of the PFFs are mostly less than the cross-sums of the COWBOYS, indicating that there is generally less soft magnetic material influence on the PFFs than on the COWBOYS. There is however less variation between the two COWBOYS than there is between the two PFFs. This indicates that the
construction of the COWBOYs is more repeatable than that of the PFFs, which makes sense given that there have been several COWBOYs constructed prior to this mission.

<table>
<thead>
<tr>
<th></th>
<th>Cross-sums</th>
<th>Relative Cross-sums (%)</th>
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<tbody>
<tr>
<td></td>
<td>1,2 (x,y)</td>
<td>1,3 (x,z)</td>
</tr>
<tr>
<td>Averaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFF#1</td>
<td>2.214</td>
<td>-5.203</td>
</tr>
<tr>
<td>PFF#2</td>
<td>-1.391</td>
<td>3.257</td>
</tr>
<tr>
<td>COWBOY#1</td>
<td>7.074</td>
<td>-27.841</td>
</tr>
<tr>
<td>COWBOY#2</td>
<td>6.925</td>
<td>-27.915</td>
</tr>
<tr>
<td>Main</td>
<td>1.051</td>
<td>9.864</td>
</tr>
<tr>
<td>Plotting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFF#1</td>
<td>2.145</td>
<td>-5.226</td>
</tr>
<tr>
<td>PFF#2</td>
<td>-1.569</td>
<td>3.108</td>
</tr>
<tr>
<td>COWBOY#1</td>
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<td>-27.811</td>
</tr>
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<td>COWBOY#2</td>
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<td>-27.916</td>
</tr>
<tr>
<td>Main</td>
<td>1.051</td>
<td>9.864</td>
</tr>
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</table>

Table 3.2: The cross-sums for each plane of each of the five payloads, also calculated using the averaging method, and the fitting a line (plotting) method. The values for the cross-sums are \((10^{-3})\) times the value given in the table. The values for the relative cross-sums are given in percent.

The values for the actual constants are much lower for the COWBOYS than for the PFFs indicating that the alignments of the magnetometers with respect to the payloads, as well as the alignments of the payloads to the magcal system, were better for the COWBOYS. There should not be any significant difference between the alignments of the magnetometer sensor elements because the magnetometers were exactly the same model from the same vendor (Billingsley Aerospace, model: TFM100G3).

The main payload also has the same model magnetometer but due to space constraints it had to be mounted right on top of the electronics box, so it was expected that the main would be a little worse than the PFFs. The values for the main are still on the same order as the other payloads, showing that an entirely different mounting for the magnetometer results in similar values for the cross-sums.

The large values for the cross-sums on the COWBOYs are most likely caused by the proximity to a large number of the nickel-cadmium batteries as well as a magnetic damping mechanism, all of which are located within the COWBOY sub-payload itself. These materials are on the order of 0.5 m to 0.75 m from the magnetometer.

In conclusion, the PFFs constructed as they were would have been capable of producing good science quality magnetic field data down to the few nanotesla level. There was however an interference problem with the GPS board that was next to the magnetometer conditioning circuit. The GPS board added significant digital noise to the magnetic field data, with the most prominent being a 110 Hz and a 220 Hz signal. The cause of this problem has since been identified and will be remedied for future missions, however all of the magcal data that exists for the PFFs has this extra noise on it, limiting
its usefulness for higher resolution analysis, since it must be averaged out. It is very unfortunate that neither the PFFs nor the COWBOYs produced any useful in-flight data during the short flight of CASCADES, preventing a more accurate comparison.

4: Scientific Goals

There are many interesting auroral and plasma physics questions that can be investigated with the data from this array of ground-based instrumentation. This study aims to collect as much data as possible during a two-week observing period to ensure that many features, from a range of auroral conditions, are quantified. The goal of this study will be to compare the quantified observations to models and theories, in order to test their results and assumptions.

4.1: Scientific Questions:

By examining the camera data collected during the sounding rocket campaign, a preliminary list of science questions was constructed. When more data are collected, including radar observations, more questions will likely be raised.

These questions can be grouped into 3 main categories. The first group is related to auroral morphology questions and their implications, which involve quantifying structures observable in the camera data.

1. Does auroral ray size correlate to perpendicular ray speed?
2. Are “quiet arcs” really quiet, or do they have small-scale structure when examined closely?
3. Do arcs always “ray-up” before breaking up into substorm onset, and what implications does this have on substorm sequencing?

The next group deals with questions related to return current region, inverted-V arcs, and statistics of the light and dark auroral features, to quantify any relations between spatial structure and time evolution of the structures.

4. How intense are small-scale structures when viewed with high resolution?
5. What differences are observed between the light and dark auroral features, and what can this reveal about ionospheric electric fields and plasma density?
6. Can large flow fields exist at very low altitudes, and on small scales, due to ionospheric modification?

The last group contains questions dealing with observations that can be used to compare to models that have coupling to the ionosphere through the auroral footpoint (Streltsov, 04; Lysak, 90; Seyler, 01).

7. Why do some features resist moving, while others move fast?
8. How do proper motions compare to the ion acoustic speed, and can this lead to dragging of potential structures?
9. Are there observable spatial features that are causal or necessary to the evolution and dynamics of the structures themselves? Does the spatial structure determine the time evolution of the features, or is it the other way around?

The remaining questions deal with camera observations being used in conjunction with other observations to investigate observational parameters and limitations.

10. Can ionospheric currents be estimated better using the camera images to place limits on the size of the region carrying most of the current?
11. By using the cameras and radars together, can insight be gained into what the coherent radar is actually scattering from? Could it be density irregularities, gradients, shears, or something else?

4.2: Potential Studies:

Three potential studies that can be done using this collected data are described below. Others may evolve once all the data is collected. The aim of this study is not to produce a model, but to quantify data about the structure and dynamics of auroral features and compare to assumptions of existing models, as was done in (Hallinan, 76), where auroral spirals and curls and their directions of curling were compared to theories of current and charge sheets that cause these structures.

4.2.1: Auroral Ray Motion Study

During the breakup or poleward expansion of an arc, the magnetospherically driven field aligned currents intensify. This causes localized areas of enhanced or depleted electron density in the ionosphere, associated with upward and downward current regions, and diverging or converging electric fields. This results in sheared (EXB) flow that then curls up into the rays, or curls depending on the viewing geometry. It is reasonable to expect that whenever there is an intensification in the aurora rays should exist as well. The existence of rays in the aurora can be verified accurately by using the camera data, and the implications on substorm theory will be investigated. The model of (Seyler, 01) investigates scale sizes near the electron inertial length, which is around 50 meters in the E-region ionosphere. Small-scale structures the size of a few electron-inertial lengths can be investigated using this data, which will be compared to the model output.

There is some preliminary observational evidence to support the theory that ray size, meaning perpendicular extent, correlates to the perpendicular speed of the ray. For example, rays observed to be 1 km wide moved about 2 km/sec and rays about 2 km wide moved about 6 km/sec. However this data set consists of only a few examples, therefore many more examples are still needed to examine this correlation statistically. If a correlation is found to be statistically significant, it can be checked for consistency against the (Seyler, 01) model, which develops small-scale structures resembling auroral rays.
4.2.2: Return Current Region Study

A major goal of the return current region questions is to investigate the statistics of the light and dark auroral features in the all-sky images, and predict what a satellite pass, for example, the FAST satellite, over this region would measure for the electric field structure of the arcs. This data will then be compared to data from a recent statistical study, (Hwang, et al. 05a,b), which investigated many auroral zone crossings of the FAST satellite. They quantified the auroral arc electric fields structure and compared that with the upgoing electron energies to determine how much of the potential structure is closing below the satellite. This then reveals how much of the electric field is of ionospheric origin. This study can then be used to compare against their results, since this study will be investigating the visible auroral structures and how they relate to ionospheric motions and structure. This study has an advantage over the FAST study, in that this study can investigate the time evolution and spatial shapes of the auroral structures, where FAST can only make a single point measurement. Another goal of this study is to investigate the time evolution of the auroral structures, for example, do the straight and twisted up arcs evolve into one another or do they form independently.

4.2.3: Ionospheric Feedback Model Comparison Study

This study aims to investigate the validity of models of magnetosphere-ionosphere coupling that have the ionosphere as an active part of the feedback mechanism, for example, (Streltsov and Lotko, 04). Their model indicates that large ionospheric electric fields and currents can be generated on small scales. Another major goal of this study is to use the camera and radar data to look for the existence of such small-scale large amplitude structures at low altitudes (100-120 km). For example, the model has a lower ionospheric boundary of 120 km, and this study will determine if significant ionospheric modification occurs below this altitude, which could affect the feedback more than the model indicates. Another model to be investigated is (Lysak and Song, 02), which presents a mechanism for producing narrow auroral arcs by allowing the ionosphere to be active and modified in the feedback mechanism. Other work relating to ionospheric feedback mechanisms and observations include (Semeter, 05, and Doe, 93).

These questions will be addressed with the data collected during this study, with the principal data source being the optical camera data, to be complemented with ground magnetometers, and whatever radar data is available during that time.

5: Plans and Scheduling

The observations for this study will take place during the winter of 2006 from Alaska. These optical observations can only be made when the moon is not visible at night, because the moonlight will saturate, and can damage, the low-light imaging cameras. This limits the observations to about a week on either side of the new moon.
There are 3 potential observing windows, at the ends of January, February, and March. It has not yet been decided which one will be used for this study. Some of this uncertainty is because AMISR is currently being constructed, and it is not yet known how much of it will be operating in each particular month this winter. During the February or March windows there will be a greater chance that more of AMISR will be in place, however the January window will allow for longer observation periods due to the extended darkness.

These data will then be used to address the science questions previously described, with the intent of gaining useful insight into the structuring and dynamics of small-scale auroral processes and how they affect ionosphere-magnetosphere coupling. This analysis will be done in collaboration with modelers including Seyler, Streltsov, and Lysak, to better compare these results to the models. Further analysis will also be done on the magnetic cleanliness study to better characterize the influence of soft magnetic materials on small spacecraft.

5.1: Academic Timeline

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<th>Term</th>
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<th>Research:</th>
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Acknowledgments:

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References:


