Sounding rocket measurements of thermal electrons in active nightside aurora

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Sounding Rocket Measurements of Thermal Electrons in Active Nightside Aurora

BY

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DISSERTATION

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ABSTRACT

Sounding Rocket Measurements of Thermal Electrons in Active Nightside Aurora

by

Elizabeth MacDonald
University of New Hampshire, December, 2004

On January 14th 2002 the SIERRA sounding rocket was launched from Poker Flat Research Range, Alaska into active substorm expansion aurora and reached 735 km. For the first time, direct measurements of the cold ionospheric population in darkness were made by the UNH Thermal Electron Detector (TED). At these middle altitudes, understanding this population is important because the thermal electrons can carry currents coupling the lower ionosphere and the magnetospheric auroral source. This thesis, focusing on the development and analysis of this new instrument, incorporates the study of two distinct areas. One area is the direct measurement of the ambient thermal electrons which both form the background of the dynamic high latitude ionosphere and contribute directly to its behavior by modifying the plasma environment for other constituents. The second focus area is the concept that any attempt to measure thermal electrons must also be a careful study of potentials forming near conducting bodies in a plasma, a still poorly understood subject. The TED instrument response shows that a non-monotonic potential barrier can form in the sheath around the detector and prevent access to the core of the thermal electrons. A technique has been developed for reconstructing the plasma distribution which enables key measurements of temperature, density, and flow. Thermal electron core temperatures are seen to vary greatly, from as low as ~0.1 eV in the polar cap to a maximum of ~0.8 eV in auroral arcs. Outside
active precipitation the density agrees with an independent calculation from the HF wave receiver. This verifies the method used for estimating the payload potential. In the “inverted V” and Alfvénic regions the HF measure of density was used to normalize our results for the changing payload potential. The thermal data indicate that in the dark, the non-negligible auroral and secondary emission currents must be accounted for in order to understand what controls the spacecraft potential. Finally, it is shown that, given this understanding of the potential structure and a quantitative measure of the payload potential, the critical thermal electron drift should be measurable with this new instrument.
Chapter 1

Introduction

To the casual observer at high latitudes, the northern lights are a beautiful natural spectacle, usually observable on clear dark nights. To the general public, the aurora is visible only rarely during great geomagnetic storms when the auroral oval expands to lower latitudes. To the space scientist, the northern lights are not only beautiful but a visible manifestation of plasma processes at work over a continuous region between the Sun's corona and the Earth's atmosphere. The heliosphere, or region dominated by the Sun's magnetic influence, stretches from the Sun to more than one hundred AU, three times farther than Pluto. Embedded within the heliosphere is the Earth's magnetosphere which serves the planet as a protective bubble from the solar wind. The interaction of the Sun's magnetized plasma stream, the solar wind, with the Earth's dipolar magnetic field, gives rise to polar particle precipitation which stimulates the dance of the auroral lights.

The Sun's activity varies on timescales from 11 years to milliseconds, and causes variability in the solar wind speed, density, and magnetic field strength. This variation couples into the magnetosphere. Enhancements in energy inputs to the magnetosphere can generate geomagnetic storms with the potential to cripple satellites and ground power systems (Baker et al., 1998). Preventing such expensive failures in our increasingly technology-reliant society is one of the ultimate practical goals of the space physics field. Basic research efforts to understand, map, and model all parts of this system are actively pursued.

As early as the 1740's, the deviation of compass needles during auroral displays was
noted but not understood (Eather, 1980). Only within the last fifty years have scientists had the means to truly quantify the physical mechanisms and attempt to characterize the whole system. Figure 1-1 illustrates our present understanding of important global physical processes within the magnetosphere. Through our efforts to understand this system, layers of complexity have been peeled away only to reveal deeper and more intricate questions. How are energy, momentum, and information transported through this system? What are the carriers of the currents that thread it? How do our observations perturb what we hope to measure? Questions such as these form the subject of this thesis. We report an attempt to measure the ionospheric thermal plasma environment with in-situ observations on an auroral sounding rocket. We focus on the development of a new instrument for measuring the flux and distribution of the coldest ambient electrons which form the fabric of the ionosphere where auroral activity occurs.

Rocket observations provide a fast method of in-situ observations with multiple advantages. In general, the higher time resolution and slower velocity compared to orbiting satellites allow more detailed observations. Typical project completion times of three years allow students to make meaningful contributions over the whole cycle: instrument development through detailed event analysis. One possible disadvantage is that a flight takes measurements along one track of a unique event and only lasts approximately 10 minutes, although having a finite dataset can be an advantage for the graduate student!

1.1 The Ionosphere

We begin our study by building up a picture of the plasma environment surrounding the Earth, where our measurements and the aurora take place. The ionosphere is filled with a
Figure 1-1: Global 3-d cut-out view of the Earth's magnetosphere showing the major regions and the location of some of the primary physical functions. Our region of interest is primarily the midnight (anti-sunward) sector near the Earth where the field aligned current arrows enter and leave the ionosphere. (Picture used with permission of J. Burch, Southwest Research Institute, and adapted from Potemra (1984, p. viii).)
tenuous plasma. It exists at altitudes from ~80km to more than 1000km over the whole
globe. Different processes dominate at different latitudes. We shall begin by describing
the nature of the equilibrium ionosphere and then add the complexities of dynamic auroral
activity.

The equilibrium ionospheric state is a balance between the dense neutral chemistry-
dominated atmosphere and the virtual vacuum of space which is organized by species,
magnetic fieldlines, and electrodynamics. The catalysts to the interaction of these regions
are gravity and sunlight. The basic composition of the upper atmosphere is governed by
the absorption of the sun's ionizing radiation by the neutral atmospheric structure. The
ionosphere is a transition zone; its lower border is formed by a thinning of the dense neu-
tral atmosphere and its upper edge is dramatically heated and ionized by solar radiation.
Balance between sources and losses in various chemical reactions produces vertical stratifica-
tion of the abundances and temperatures of different neutral species. Different mechanisms
dominate at different altitudes where certain wavelengths of solar radiation are absorbed.

A plasma is defined as a collection of free positively and negatively charged particles
of approximately equal concentration. When a solar photon hits an atmospheric neutral
it causes the production of a free electron and an ion (which type depends on which type
of neutral is hit). As the radiation is further absorbed at lower altitudes, plasma produc-
tion decreases closer to the Earth. Combining this profile with the neutral density profile
produces a peak of plasma density at a middle altitude (Kelley, 1989). In the ionosphere,
recombination rates continuously drain the "ionized gas" of charge density, but on the sunlit
hemisphere the ionizing radiation source keeps plasma production high. At night, the upper
ionosphere maintains its density better because slower recombination rates dominate.
The bombardment of energetic particles to the atmosphere also causes plasma production and, at night, the visible light emissions of the aurora. These plasma production rates can be an order of magnitude higher at night than at noon. This production is more dynamic in time and spatially variable than that from photo-ionization. It also varies with altitude based on the incoming energy spectrum. The highest energies can deposit their energy deepest into the ionosphere. This causes different colored light emissions depending on what type of neutral particles dominate at that altitude.

Figure 1-2 shows typical height profiles of density, temperature, and characteristic parameters for the plasma particles. These values have been plotted for the date, time, and location of the SIERRA flight using the International Reference Ionosphere model (Bilitza, 2003). Thus, they typify a winter night at high latitudes. The dayside D region of the ionosphere is defined to be below 90 km, the E region from 90 - 150 km, and the F region from 150 - 500 km (Jursa, 1985). Our rockets fly at middle altitudes (up to 1000 km) in disturbed auroral conditions where chemistry can still be important but plasma processes dominate. For SIERRA, we will be focusing on the topside of the F region density peak. We will now describe the basic framework of auroral physics.

1.1.1 Auroral Physics

Many auroral satellites focus on higher altitude regions (1000 km to several Re) where the primary auroral acceleration occurs. The SIERRA project focuses on the often overlooked "gap" region between the collisional stable atmosphere and the collisionless dynamic magnetosphere. This "gap" cannot currently be incorporated into global system models because the physics is too dynamic and not well enough understood (Lotko, 2004). We first highlight

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Figure 1-2: The top plot shows the height profile of density for electrons, and major ion species (O⁺, N⁺, H⁺, and He⁺). The middle plot shows the temperature profile for the neutrals and the electrons and ions. Based on these ambient parameters the electron Debye length and gyroradius are calculated and shown in the third plot. These parameters will be important for later considerations of how to measure the thermal electrons. (Model results were obtained from the NASA National Space Science Data Center web page.)
some of the most relevant and dominant processes in nightside aurora primarily focusing on satellite altitudes since this is where most theory and observations have developed.

Rockets and satellites have probed the detailed microphysics at work in the auroral environment for over 50 years. The basic principles are now understood but the smaller spatial scale and faster time variations are still not clear. Much of the basic visible processes like substorms can be understood using multiple ground-based observing platforms. These ground observations have been ongoing for hundreds of years, but in-situ measurements were necessary to probe the physics.

The typical auroral arc is a sheet of current consisting of accelerated precipitation from the magnetosphere. Light is produced near 100 km when the atmosphere becomes dense enough to stop energetic particle precipitation. The ionosphere is not just a sink for the input energy. Ionospheric neutral particles, cold electrons, and ions can feedback and influence magnetosphere dynamics. Visible aurora is dynamic, multi-spectral, and organized over many scales. For our purposes, understanding arc generation mechanisms at the peak of an auroral substorm is important. A substorm is a common organized global phenomenon to release solar wind energy input to the magnetosphere through the ionosphere. Substorms have predictable patterns of activity, last over an hour and can repeat several times each day with most activity centered on the midnight sector. The substorm pattern includes a growth phase, followed by an arc breakup, then the expansion and recovery phases (Akasofu, 1964). Nightside auroral rockets are generally launched into the most energetic breakup and expansion phase arcs where much interesting electrodynamics remains unexplained.

Auroral arcs form to satisfy imposed magnetospheric current requirements. Detailed auroral microphysics can be understood and organized by different types of current systems.
The auroral field aligned current systems are upward current, downward or return current, and poleward boundary region currents. These correspond to regular arcs, "black aurora", and Alfvenically accelerated arcs. Figure 1-3 (provided by C. Carlson) summarizes the primary particle and wave signatures at play in the dominant current systems. As a low altitude sounding rocket passes northward through the auroral oval during a substorm peak it is likely to encounter arcs (upward current), ion outflow (downward current), and Alfvenic aurora on the poleward boundary before passage into the polar cap. Figure 1-4 (provided by C. Carlson) illustrates quantitatively the canonical signatures of the different current regions as measured by the higher altitude FAST satellite. The first panel shows the typical magnetometer signatures associated with the different current systems. These systems will be detailed next, though we will also concentrate on illustrating the differences in these signatures at FAST altitudes (thousands of km) with rocket altitudes, which represent the low altitude footpoint of the magnetosphere-ionosphere coupling. We also identify where SIERRA's measurements address open questions in auroral physics.

1.1.2 Upward Current Systems

Upward current systems (shown in blue in Figure 1-4) are defined by the precipitation of an accelerated flux of magnetospheric plasmasheet electrons. From the ground, these current sheets comprise the visible arcs which typically have extended East-West extent and narrower latitudinal extent. The in-situ observational name for typical upward current arcs is "inverted V's" because of their characteristic up-down appearance in energy flux spectrograms. This is evident in the blue shaded region in the third panel of Figure 1-4. These magnetospheric electrons have been accelerated by several kilovolts through an
Figure 1-3: FAST current system summary (Figure provided by C. W. Carlson and adapted from Carlson et al. (1998).)
Figure 1-4: FAST data composite typical of an auroral pass. This time range is discussed thoroughly in Paschmann et al. (2003, p. 96). (Figure provided by C. W. Carlson.)
extended U-shaped potential 2000 - 10000 km above Earth. The potential drop itself may not vary smoothly with altitude, and may be mostly contained within an oblique double layer (a localized potential drop) at the bottom of the acceleration region (Block, 1972; Ergun et al., 2000a). In the Figure 1-4 example we note that the FAST satellite is not within the potential drop itself since there are still secondary electrons and no upgoing ion beams.

In the well developed quasi-static picture, this potential structure maintains a parallel electric field which accelerates magnetospheric electrons and cold ionospheric electrons toward the ionosphere, where they stimulate light emission by ambient neutrals. In-situ measurements can determine the strength of the potential drop and the amount of current carried by the precipitating electrons. Magnetospheric electrons produce the main "V" while colder secondary electrons can sometimes cause the appearance of dispersive field aligned bursts or flickering aurora below the peak. While upward current regions can be more easily categorized as quasi-static and explained with time independent models, some variability and wave processes can be important also; in particular, with field aligned suprathermal electrons. Low perpendicular electric field wave power is evident in the second panel of Figure 1-4 and indicates the quasi-static nature of this region.

Upward current mechanisms have been well modeled (Knight, 1973; Chiu and Schultz, 1978; Ergun et al., 2000b) although it is still not certain to what extent the hot precipitating flux heats the ambient atmosphere. Secondary electron processes and wave mode modifications are less understood. Our sounding rocket altitude is definitely below the potential drop so we can observe how the precipitating flux transforms the ionospheric plasma, but we cannot sense the structure of the potential drop region itself.
1.1.3 Downward Current Systems

The importance of downward current systems has been recognized recently with superior satellite resolution (e.g., Freja, FAST) (Boehm et al., 1995; Marklund et al., 1997; Carlson et al., 1998). Return current regions close the current loop of the inverted V arc system currents. One reason that the physics of return current regions is important to understand is that much ionospheric ion outflow comes from these regions. Ion outflow plays an important role in populating the ring current and outer magnetosphere during major geomagnetic storm events. How does the ionosphere control its source and loss as a function of its global energy budget? A major goal of auroral sounding rocket studies is to quantify the mechanisms controlling outflow.

Downward current regions are characterized by upgoing ion conics that are transversely heated through a “pressure cooker” mechanism (Gorney et al., 1985). These are shown at the beginning of the sixth panel in Figure 1-4 (areas shaded in green) as bands of heated ions at symmetric pitch angles around 180°. Certain symmetries with upward current regions exist, but return current regions have unique characteristics, such as the larger role of wave-particle interaction even in modifying the equilibrium state. As shown in Figure 1-3, downward current regions typically display a broad energy spectrum of upgoing beam electrons. Peak upgoing electron fluxes can be ten times greater than typical downgoing “V” flux (Paschmann et al., 2003). A population of thermalized downgoing electrons is also present, although weaker and at lower energy. At rocket altitudes the downgoing field aligned electron population and upgoing ion conics are the primary observed particle signatures. The structure of the accelerating parallel fields in these regions is a subject of
present research. One unknown parameter is the low altitude, low energy initiation of this process. SIERRA's TED measurements are designed to probe the structure of the coldest and most difficult to measure particles which carry most of this current.

The observations in Figure 1-4 are typical for satellites with altitude greater than one Earth radius. A complete picture of the true nature and gradual transition of downward current region aurora at lower altitudes is not well-developed. Another open area of research regards the structure and formation of broad-band extra low frequency waves (called BBELF, for short). These waves, seen in the last panel of Figure 1-4 just prior to 16:48 UT, are associated with ion conics and seen at a wide range of altitudes and local times. The formation of these waves has been debated; they could be either Doppler-shifted spatial irregularities or shear-driven instabilities (Bonnell et al., 1996). Thermal electrons may play an important role in driving these instabilities.

1.1.4 Alfvénic Current Systems

Alfvénic aurora typically occur on the polar cap boundary of the auroral oval and can contain some of the most dynamic and optically exciting aurora (the red highlighted regions in Figure 1-4). Strong ion outflow is observed in this region, associated with variable current signatures (Tung et al., 2001). Similar to downward current regions, there can also be BBELF wave signatures and counterstreaming electrons. Electron signatures are broad in energy and extremely field aligned resulting from Alfvén wave acceleration. As Alfvén waves slosh energy between the magnetosphere and ionosphere, some energy is transferred to acceleration of the electrons. These accelerated electrons cause waves that then heat ions into conic outflow. Many different types of Alfvén waves can propagate in the ionosphere;
they are modified by the Alfvén speed height profile. SIERRA data address the dispersive Alfvén waves studied and modeled by Lysak (1991), Seyler et al. (1995), Chaston et al. (2004), and others.

Time dependent Alfvénic wave processes may cause filamentary currents with intense temporal and spatial gradients. SIERRA was designed to probe this small scale structuring of energy transfer between Alfvén waves, electrons, and ions. Alfvén waves can modulate the accelerating potentials of both upward and downward current regions.

Figure 1-4 highlights the major in-situ signatures of these three regions at satellite altitudes. At rocket altitudes, these signatures are modified and their behavior is less understood. It is crucial to understand the low altitude beginnings of ion outflow and current structuring in order to sort out the many mechanisms and causal relationships of magnetosphere-ionosphere coupling.

1.1.5 Thermal Electron Importance

Many of the open questions described above would benefit from clear observations of low energy, low altitude ambient electron distributions. As early as the 1960's, Hays and Sharp developed an instrument to measure the coldest electrons in the F region and below (Sharp and Hays, 1974). However, early measurements lacked sufficient time and energy resolution for determining the distribution of the thermals. In the 1980's, lack of knowledge of the thermal electron population was considered a critical gap in understanding both auroral wave-particle interaction mechanisms and how the current was carried in magnetosphere-ionosphere coupling (Cattell, 1981). More recently models of magnetosphere-ionosphere coupling need to know the behavior of the thermal electron population because of its role
in the important ion outflow processes which populate the magnetosphere with ionospheric ions (Schunk et al., 2004). Clearly, measuring thermal electrons is important, but the lack of a standard instrument emphasizes the fact that it is almost prohibitively difficult. Until now, the thermal electron population has never been measured effectively in darkness where the payload potential is several volts negative. Recent rocket flights have added to our understanding of thermal electrons and ions in the presence of sunlight and we shall introduce these observations in Chapter 3.

Thermal electrons play an integral role in the behavior of the ionosphere as both an active and passive partner in magnetosphere-ionosphere coupling. As the most numerous ambient particles, along with thermal ions, they are important in defining the basic underlying structure of the ionosphere. However, the electrons are highly mobile and play an important and dynamic role in modifying the auroral electrodynamics. The numerous thermal electrons can serve as a pathway for energy and momentum transport. Thus, it is critically important to measure the flux, energy distribution, and moments of the distribution. Knowledge of the electron temperature is important because it controls the ionospheric scale height. In order to have ion upwelling and feed ion outflow, quasi-neutrality dictates that the scale height must be increased so that the electrons are free to move also (Schunk, 2000). Directly measuring the amount of current carried by thermal electrons in various types of aurora, especially the return current and Alfvénic regions, is critical for determining the cause and effect in magnetosphere-ionosphere coupling mechanisms. For example, the drift of the thermal electrons has been proposed as key to field aligned current instabilities which cause BBELF (Cattell, 1981).

However, even basic properties of the thermal electrons are not known, such as how
energetic auroral precipitation and arcs may heat the core of the thermal electrons. Without direct measurements, it cannot be confirmed even that the core population is always Maxwellian. Thermal electrons in equilibrium are likely to be Maxwellian like the stable atmosphere. Indeed, radar observations work by scattering off the bulk Maxwellian thermal electron core. However, in some types of aurora, returned radar signals are not Maxwellian and not interpretable by standard theory. There are definite satellite observations of plasmasphere distributions which have a higher energy tail and are better fit by Kappa distributions (Kletzing et al., 2003). Since the ionosphere is a source for the plasmasphere, it is reasonable that some Kappa distributions may be important in ionospheric regions or altitudes.

Characterizing the thermal population distribution is the goal of our direct rocket observations. This first step is necessary for piecing together a more complete understanding of auroral dynamics. We are confident that direct observations of the thermal electron population will answer many questions in the complex processes of upward, downward, and Alfvénic current systems. This progress begins with figuring out how to make the measurements.

1.2 Particle Interaction with the Spacecraft Environment

Understanding spacecraft charging is key to understanding the problems encountered when attempting to measure thermal electrons. Here we provide background on this subject to prepare the reader for the detailed discussions to follow in interpreting the TED instrument response. For ionospheric sounding rockets, the magnitude of charging is not as severe as for the higher altitude satellites. In the outer magnetosphere, radiation belts, and solar wind,
spacecraft surfaces can charge to greater than 10 kV. Serious fatal problems can occur when such charges discharge through electrical components (Baker et al., 1998). This problem will not be considered in this work as severe spacecraft charging occurs in a much different regime of density and temperature than for the ionosphere. In the ionosphere, however, the problems can be just as detrimental since even a small amount of charging can interfere with the very low energies we are trying to detect.

Our goal is to describe the physics of how the spacecraft environment affects measurement techniques and alternatively, how the instruments and spacecraft themselves can bias the act of measurement. A successful instrument to measure the thermal electron distribution function needs to address this issue thoroughly since the typical magnitude of payload charging is well within the energy range of interest.

1.2.1 Spacecraft Charging

Why and how does a spacecraft charge? Spacecraft charge because they are conducting objects immersed in a plasma. In a very basic way we can understand that when plasma particles impinge on a charge-collecting metal in a plasma there is a need to maintain current balance to the object through attraction and repulsion of charges. Thus the potential on the object modifies the distribution of charged particles in the nearby vicinity. A plasma acts to shield out an applied potential, so the modifying potential as a function of distance will decrease to the plasma potential fairly close to the object. The scale size of this decrease is a function of the characteristics of the ambient plasma particles. The Debye length \( \lambda_d = \sqrt{\varepsilon_0 k T_e/\text{ne}^2} \) is the typical size of the sheath. For the simplest ideal case with spherical symmetry the potential generally falls off as an exponential raised to the negative
<table>
<thead>
<tr>
<th>Current Density</th>
<th>Incident / Emitted (I/E)</th>
<th>Current Source</th>
<th>Relative magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_e$</td>
<td>I</td>
<td>Ambient cold ionospheric electrons</td>
<td>1</td>
</tr>
<tr>
<td>$J_i$</td>
<td>I</td>
<td>Ambient cold ionospheric ions</td>
<td>$&lt;&lt;1$</td>
</tr>
<tr>
<td>$J_p$</td>
<td>E</td>
<td>Photoelectrons from photons hitting the payload skin</td>
<td>$\sim1$</td>
</tr>
<tr>
<td>$J_a$</td>
<td>I</td>
<td>Auroral particles, primarily accelerated precipitating electrons</td>
<td>$&lt;&lt;1$</td>
</tr>
<tr>
<td>$J_s$</td>
<td>E</td>
<td>Secondary, backscattered, and reflected electrons from the metal payload by impinging auroral particles</td>
<td>$&lt;&lt;1$</td>
</tr>
<tr>
<td>$J_r$</td>
<td>I</td>
<td>Rammed ions from payload motion through heavy cold ions</td>
<td>$&lt;&lt;1$</td>
</tr>
</tbody>
</table>

Table 1.1: List of terms which contribute to current balance for an object in a plasma and an estimate of their relative magnitude in importance for determining current balance.

Distance normalized by $\lambda_d$. For example, when an object is negatively charged the positive ions will be attracted by an exponential potential and the negative electrons will be repelled. This will leave an electric field in the sheath and a slight excess of positive ions. The Debye sheath acts to shield the charge from the plasma by canceling the electric field set up by the charging (Chen, 1984; Chapman, 1980).

What are the different types of current from particles fluxes that a spacecraft can encounter? The sheath and payload potential adjusts depending on the magnitudes of the different sources of charge in the plasma. For our case there are several positive and negative currents which contribute to the total current balance as:

$$I_e(\Phi) + I_i(\Phi) + I_p(\Phi) + I_a(\Phi) + I_s(\Phi) + I_r(\Phi) = I_t$$ \hspace{1cm} (1.2.1)

where $I_x = J_x A_x$ and $A_x$ is the relevant collector area and the collected current depends on the spacecraft potential. They are listed in Table 1.1 and divided into two major types.
depending on whether the current is incident to (I) or emitted from (E) the payload. An enforced potential can be applied, in which case we normally measure the total current drawn, $I_t$, or else the object is allowed to float to the potential where the current, $I_t$, equals zero. The magnitudes of the ambient thermal terms depend on their velocity, temperature, masses, and relative collected area. Since the electrons are so much faster the electron flux is $\sim 170$ times the thermal ion flux. For the simplest case with just these two thermal terms the higher electron mobility leads to the payload charging negative, since more electrons hit the payload per unit time. Any time sunlight hits the payload the third term becomes the dominant balance to the thermal electron flux. This flux of photoelectrons caused by photons hitting the payload and ejecting electrons can be so large that the thermal ion flux becomes insignificant and a spacecraft can even charge positive.

All of these terms involve to some extent, surface dependent elements. Terms which involve emissions from the surface are necessarily dependent on the surface properties. The role of the surface characteristics in determining current balance will be revisited in Chapter 3. For example, $J_s$ has lumped together in it three surface emission terms, from reflected, backscattered, and secondary components. According to Whipple (1981)

When an electron is incident upon a surface, it may be reflected or it may be absorbed into the material. Once it is in the material it may collide with scattering centers and eventually 'back-scatter' out of the material back into space. While the electron is in the material it loses energy and a portion of this energy can go into exciting other electrons which in turn may escape from the material. These three processes of reflection, back-scattering, and true secondary emission are usually treated as distinct processes.

Secondary emission is the largest of these three generally small contributors. The surface emission characteristics can vary greatly depending on surface cleanliness and are thus very
difficult to quantify (Whipple, 1981).

Another source of current to the payload is the additional electron current from the high energy auroral electrons. Because the auroral electrons are not nearly as numerous their contribution to the total spacecraft charging is generally thought to be small. However, since these high energy particles are not repelled by the thermal Debye sheath their fluxes to the surface can be significant in certain situations. Because of its sign, the pure addition of the auroral term drives the payload more negative. However, bombardment by auroral accelerated electrons can enhance secondary emission. The net effect is not obvious; driving the payload positive may be possible. The auroral term also includes a small contribution from incident lower energy particles, which are actually ambient secondaries produced from the auroral cascade of precipitation. The last term in Equation 1.2.1 is the effective current from collected rammed ions. This can be more important than the thermal ion flux on the downleg at low altitudes as the atmosphere thickens. There are possibly even smaller terms than those mentioned here. Excellent reviews of these subjects are given by Whipple (1981) and Garrett in Jursa (1985).

Going beyond this qualitative view to a quantitative model of how real spacecraft charge is much more complicated. Poisson's equation must be solved for the real self-consistent potential as a function of \( f \). Our specific case requires 3-d modeling with a magnetic field and with resolution on the order of the Debye length which is difficult because many simplifications cannot be used. We have not found any of the most sophisticated codes which can do all of this. So we are left with theoretical considerations of current balance and potential structure allowing for limitations caused by the necessary assumptions. This topic will be examined in detail in Chapter 3.
Many types of instruments probe the in-situ environment and measure charged particles. How do these instruments interact with the spacecraft charging situation and does the spacecraft charge affect the measurement being taken? We next consider these important questions which have serious repercussions for trying to measure thermal electrons.

1.2.2 Measuring Spacecraft Charge

How is the amount of spacecraft charging measured? Two key types of instruments, charge collecting and particle counting devices, are discussed here in terms of how they contribute to understanding the floating potential which balances all currents.

The Langmuir probe is the prototypical charge collecting instrument named after Irving Langmuir's groundbreaking experimental and theoretical work with laboratory vacuum chambers and their probes (Mott-Smith and Langmuir, 1926; Tonks and Langmuir, 1929). A Langmuir probe is usually a small conducting element with a simple geometry held away from the main payload or chamber walls and isolated from it. It works by applying a voltage which sweeps across positive and negative values. The range is chosen sufficiently large so as the probe can draw the full electron or ion saturation currents to it when biased positively or negatively, respectively. At intermediate voltages, the current drawn will vary roughly linearly as more electrons are retarded. The characteristic shape of the curve, which depends on the exact shape and area of the collector, is predicted from theory. From the magnitudes of the saturation current and the slope of the electron retardation region, the floating payload potential, electron temperature, and ion and electron densities can be derived. In a laboratory plasma, the floating potential and plasma potential relative to the chamber ground are determined while in space only a measure of the floating potential
relative to the plasma ground can be made. Drawbacks to this technique for rocket use, include the possibility of causing fluctuating potentials which can affect other measurements, typically floating electric field probes. Also, they must be ideal simple shapes, isolated, clean, and small so as to not affect the main payload.

Many different instruments are capable of measuring the energy and flux of charged particles. These observations can define some of the types of current collected by the spacecraft. This is most helpful for measuring the current from auroral electrons and the thermal ion current. These terms are easy to measure because they are less ambiguously affected by negative floating potentials. However, this does not provide a complete picture of the current balance and the overall float potential. Some thermal particle instruments measure the float potentials as a cutoff in their energy sweep. For example, for a payload charged negative with respect to the plasma, thermal ions will be accelerated into the detector. The nearly zero-energy particles will show up with energy equal to the spacecraft potential in the instrument frame provided the instrument has adequate response at the low energies. However, there was no thermal ion detector on SIERRA.

The act of attempting to measure the floating potential can affect its magnitude and any attempt at measurement can alter the environment from its natural state. These concerns and attempts to ameliorate them will now be discussed.

1.2.3 The Effect of Spacecraft Charge

How can the spacecraft charge affect our measurement? How can measurements affect the spacecraft charge? For particle counting devices the effect is an alteration of the detected energies by the payload potential. Since auroral particles have higher energies, their mea-
surement by an instrument biased by a few volts is minimally affected. However, for the subject of this thesis, a thermal electron detector, this question must be thoroughly considered because our energies are the same order as the spacecraft potential. This requires detailed efforts to quantify the variable spacecraft charging environment and the structure of the potential around the payload. Other complications arise from the fact that the detector size is similar to the Debye length, which affects trajectories and means neither a thick or thin sheath approximation is valid. Magnetic effects can also be important since the gyroradius is similar to the Debye length.

For current collecting instruments, the effect of payload charging is minimized by isolating the smaller probes from the main payload on long thin booms. The spacecraft potential disturbance is assumed to decrease radially out along the booms. However, the spheres often encounter interference at much longer boom lengths than the typical sheath size of a few Debye lengths. This is a fundamental problem and still not well understood (Eriksson et al., 2004; Pietrowski, 2000). Also, the spheres, no matter how isolated, cannot make a perfect connection to the plasma. For electric field measurements, measuring the differences between two spheres is not affected very much by an offset to both. The problem is less easily solved for Langmuir probes where this and surface contamination effects conspire to alter the derived quantities. In our special case, we encounter problems of both types, those typically seen on particle counting and current collecting instruments. Our efforts to combat these problems are central to the design and interpretation of our results.
1.3 SIERRA Mission Overview

The SIERRA mission was designed to probe the wave-particle interactions of active upward and downward current systems at middle altitudes. For this reason, we launched into the breakup of a substorm. The SIERRA acronym stands for *Sounding of the Ion Energization Region: Resolving Ambiguities*. The SIERRA mission reached new levels of payload and instrument design with coordinated multiple payloads and new capabilities for wave and particle measurements. The placement of the instruments on the three payloads is illustrated by Figure 1-5. The SIERRA mission served as proof-of-concept for yo-yo electric field booms and thermal electron detector designs. In addition, the multiple payloads contained a full suite of standard particle and wave instruments as can be seen in Figure 1-5. This suite was designed specifically to resolve questions about the temporal and spatial structuring of ion heating and associated wave phenomena, such as BBELF. The use of GPS receivers on the two sub-payloads enabled advanced interferometric calculations of wave properties with higher resolution than ever before. The new electric field sphere system with unwinding "yo-yo" wire booms is more compact, cost-effective, and electrically quiet than traditional rigid booms. Our focus, the TED detector, is a new attempt to measure thermal electrons in darkness, and extend the measurable energy range down to key low energies. Through the TED, we hope to gain critical missing information about thermal population itself, its connection to auroral parameters, and the low energy interactions between the payload environment and the detector.

After the flight, our goals were refined by the type of aurora encountered and the quality of the data. Fortunately both were excellent for SIERRA. Our focus has shifted to the Alfvén
Figure 1-5: Payload schematic, showing all types of instruments, and their mounting orientation for SIERRA. (Preliminary subpayload design shown. For flight the HEEPS-i was mounted on the opposite end of the subpayload. From *The Experimenter's Data Package*, Wallops Flight Facility.)
wave rich region we encountered with less emphasis on the return current region. The wave measurements are leading to new understanding of how different types of Alfvén waves transfer energy at small spatial scales (Klatt et al., 2004; Klatt, 2005). The primary focus of this thesis is the challenge to understand thermal electron measurements. The ultimate goal of the SIERRA mission is to understand the interconnected relationships between all the plasma particles and the waves, and how the processes at rocket altitudes contribute to the full magnetosphere-ionosphere coupling picture.

1.4 Thesis Statement

This thesis, focusing on the development and analysis of a new instrument designed to measure ionospheric thermal electrons, incorporates the study of two distinct areas. One area is the direct measurement of the ambient thermal electrons which both form the background of the dynamic high latitude ionosphere and contribute directly to its behavior by modifying the plasma environment for other constituents. Our study focuses on thermal electron detection in the region midway between the collisional chemistry-dominated atmosphere and the plasma processes of the higher altitude magnetosphere. The second focus area of this thesis is the concept that any attempt to measure thermal electrons must also be a careful study of potentials forming near conducting bodies in a plasma, a still poorly understood subject. Though spacecraft charging effects are not as extreme as for higher altitude satellites, the repercussions are equally as devastating to the sensitive detection of thermal particles.

These efforts are significant because clear progress must be made before quantitative forecasts and models of auroral behavior can be developed which realistically consider the
smallest scales, fastest variations, smallest energies, and lowest altitudes of magnetosphere-ionosphere coupling. The ionosphere is not a simple load on the magnetosphere, and its importance in influencing the larger system is recognized. For experimentalists the goal of developing standard thermal electron detection is crucial to advancing and testing these theories.

For the work of this thesis, a new instrument, the UNH Thermal Electron Detector, was calibrated, flown on the SIERRA sounding rocket in 2002, and analyzed thoroughly. This instrument tries to measure thermal electrons in darkness, a worthy but lofty goal. A significant result of our study is the realization that the nature of potentials near conducting surfaces in plasmas must be understood first in order to devise accurate measurement techniques. To truly understand the three dimensional potential structure around the TED sensor, equations for current balance, potential shape, and distribution function evolution must be solved self-consistently in order to allow for the real and underestimated effects of non-monotonic potentials. We have challenged traditional notions and learned about the fundamental nature of the boundary between the plasma and a charged body, showing that non-monotonic potential structures are to be expected near conducting surfaces. We apply this understanding of the potential structure to measure directly the temperature and density of the coldest particles and examine their connection to the larger auroral environment.

This thesis is structured with initial focus on pre-launch parameters, then detailed analysis of the TED instrument response, leading up to interpretation of real data. Chapter 1 is intended to provide a relevant introduction to the necessary space physics topics. Chapter 2 discusses the design of the TED and its expected ideal behavior, instrumentation of the rocket, conditions of the launch, and an overview of the flight data. Chapter 3 discusses
the techniques involved in interpreting the actual TED data, bringing in examples from previous thermal particle designs and considering current balance and spacecraft potential structure issues in more detail. Chapter 4 discusses the results from the analysis, in the context of thermal electron characteristics and also in conjunction with other particle and wave observations from the SIERRA mission. Chapter 5 will summarize the project as a whole and our key contributions and results.
Chapter 2

TED Design, SIERRA Instrumentation, Launch, & Data Summary

In this chapter we examine the instrumentation of the SIERRA rocket, concentrating on the new thermal electron detector. Additionally, this chapter will present a general summary of all the data obtained during the SIERRA rocket launch campaign of January 2002. These data will include pre-launch auroral parameters, vehicle performance and trajectory information, and an overview of data from the instruments onboard the rocket. We include a description of the overall geophysical environment at the time of launch, including how it was monitored by the science team, and what conditions were optimal for launch. We finish the chapter with a summary overview and archive of the SIERRA data from all instruments, focusing on introducing parameters which will be useful for comparison to the TED data in Chapter 4.

We begin with a detailed description of the many factors involved in a thermal electron detector design, including the expected ideal behavior of the TED. This initial discussion provides crucial background for a more technical interpretation of the actual flight data in Chapter 3. As we shall see, the actual flight data were quite different from what was expected.
2.1 Thermal Electron Detector

Sounding rocket particle measurements traditionally feature variations to an electrostatic analyzer (ESA) design, following the fundamental work of Carlson et al. (1983). At the University of New Hampshire, hemispherical ESA’s to measure primary auroral particles are called HEEPS-e for electron measurements, and HEEPS-i for ions. A variant including a magnetic deflection system for differentiating lighter ions from more massive oxygen is called BEEPS. SIERRA carried a swept energy HEEPS-e and BEEPS on the main payload. A fixed energy high time resolution HEEPS-i was on each of the payloads. The focus of this section is the two TED detectors on the main payload; the TED design is a modification of the traditional ESA that is specific to low energy electrons.

Our TED design directly measures the numerous thermal electron population in the ionosphere. This allows a complete measurement of current density through a kinetic approach, by summing up all the electrons over the full velocity distribution. This task is extremely difficult primarily because the low energy range makes the TED extremely susceptible to spacecraft charging effects. Also, the small electron gyroradius severely limits the geometry of effective detectors. As we will examine further in Chapter 3, a spacecraft skin normally charges negatively (~1 Volt) in the dark ionosphere because of the faster electron thermal velocity compared to ions and the need to maintain current balance to the body. This forms a Debye sheath; thermal electrons whose energy is less than the payload to plasma potential are repelled from reaching the detector. Thus an attractive potential is needed to overcome this repulsion. In the following, we will elaborate on the design problems which make measurement difficult, and a specific description of our design’s ability to
solve these problems.

### 2.1.1 Mechanical Description

The TED was designed (by M. Widholm, UNH) specifically to overcome the detection challenges and cleverly measure the full energy distribution (between 0.1 - 6 eV) and bulk flow velocity of these thermal electrons. The detector consists of a one dimensional pinhole electrostatic analyzer with a floating aperture potential actively biased to remain close to the plasma potential. The active sweep and bias control system seek out the peak in the measured electron spectrum and shift it to a set energy in order to optimize energy resolution around the peak and attract all the electrons. The anode has been cut to an annular shape that takes into account the curvature of the electron paths due to their gyroradius and pitch angle. This curved anode design optimizes energy resolution and geometric factor over the full range of desired energies and look angles.

An illustrative technical drawing of the TED instrument is shown in Figure 2-1. Also shown are representative ray tracing paths for different energy electrons. This figure illustrates the purpose of the specially shaped anode to compensate for the tight curvature of the coldest particles within the detector. Energy information is obtained by sweeping an analyzer voltage on the internal analyzer plate. Also shown in this figure is the collimator region and secondary electron trap region. The aperture area is \( \sim 1 \text{ mm}^2 \) and the collimator region is more hollowed out than shown to minimize bounce paths. The trap stops higher energy particles from bouncing into the exit slits.

On the main payload there were two TEDs mounted back to back on a one meter boom. Their orientation on the payload is illustrated by the cartoon in Figure 2-2. As the payload
Figure 2-1: 3-d view of one TED detector. Simulated paths of different energy electrons corresponding to different internal selection voltages are shown as they enter the detector and hit the specially shaped anode. Curvature in the XY projection is due to the electric field between the analyzer plate electrodes while curvature in the XZ plane is due to the Lorentz force. The TED was designed to work at all pitch angles; the 90° case is illustrated here to show the response for the most extreme magnetic field effects. All dark gray areas are at the skin bias. (Note: left-handed coordinate system. Ray tracing model M. Widholm. UNH.)
spins, all pitch angles are sampled and populations 180° different in pitch are measured simultaneously. The twin TED detectors are boom mounted to stay isolated from the large negative Debye sheath of the main payload. As shown in the figure the skin bias is applied relative to the payload ground. A wire from the circuit board foil is connected to a metal screw in the Aluminum TED casing.

The outer casing of the TED instrument is shown in Figure 2-3. The dimensions of the TED hammer-shaped head are 1.583 x 1.526 x 3.41 inches. The biased section of the boom is 6 inches long and 1.2 inches in diameter. The total TED surface area was approximately 0.02 m², approximately 0.45 - 0.6% of the estimated total payload surface area. There was a quarter inch plastic delrin ring isolating this section from the rest of the Aluminum boom.

The energy selection voltage was a 64 step exponentially spaced sweep applied to the top analyzer plate. The sweep values were chosen so that the potential difference between the plate and the skin would be between 0.08 - 6 V regardless of the skin bias value. Thus, the energy selection sweep is offset by the skin bias, with the coaxial center conductor tied to the analyzer plate and the outer wire tied to the skin. The top analyzer plate always applied a negative voltage to repel the electrons and bend them down towards the anode. The sweep period (0.064 seconds) is much shorter than the spacecraft spin period (~3 seconds). This means that the detector look direction is virtually stationary during each sweep.

The skin bias varies in one step per sweep linear increments between 0 - 4 V. After each sweep, an active feedback control loop notes the energy step of the peak in the count rate of TED #1 and varies the skin bias (for both TEDs) accordingly. Figure 2-4 indicates the intended movement of the peak to an ideal net acceleration of between 0.5 - 0.74 V, where the absolute energy resolution is optimal. In this region the spacing between the
Figure 2-2: The orientation of the TED detectors on the SIERRA payload is shown. At the spin phase when the boom axis is perpendicular to the magnetic field, TED1 measures particles flowing down the fieldlines and TED2 measures any particles flowing up. One quarter spin later, both detectors measure $90^\circ$ particles. Surfaces held at the skin bias outlined in yellow while surfaces at the spacecraft potential outlined in white.
energy steps is sufficient to resolve small changes in temperature and not so large that the peak would fall just into one step. The skin bias control seeks to lock in the skin bias to this preferred range. The skin bias control determined the peak as the step with maximum counts over an accumulation time of 1 ms. The count rate of this peak had to be above a minimum threshold of 4 kHz or else the skin bias would assume more bias was needed and increase automatically. The initial location of the peak depends on the payload potential as will be discussed in the next section.

The TED was coated with a thin layer of Aerodag G, a colloidal graphite suspension in an isopropyl alcohol aerosol applicator (Acheson). The covered surfaces included all of the biased boom, outer face, inner collimator, energy selection region, and analyzer plate. The purpose of the coating was to present a “black” surface to incoming particles and minimize their scattering inside and out. Also the coating was to ensure that a uniform work function and high conductivity were presented to the plasma. Aerodag was chosen because it has been used routinely for the HEEPS detector outer surfaces and is more convenient to apply than copper black. For the operation of the TED in a low energy plasma it is vital to investigate thoroughly how the surface properties might affect the intended measurement. Numerous tests were conducted to verify the conductivity and surface properties of the Aluminum-Aerodag layer. These will be described in the next chapter and also in Appendix A.

Planned Operation

Here we describe the expected operation of the TED, as a prelude to our discussions in Chapter 3 of the actual instrument response. The payload charges negative because thermal electron flux exceeds thermal ion flux to the surface; bombardment by hot auroral electron
Figure 2-3: Labeled photograph of the experiments which fit into the top of the nosecone. The TED and magnetometer booms are folded up. (Integration photo taken by S. Powell, Cornell.)
Figure 2-4: Energy vs. logarithmically spaced energy steps for the TED sweep (black points). Depending on the energy step of the peak in each sweep, the skin bias values adjust to move the peak into the ideal range, as shown by the red labels. Once the peak reaches the ideal range it locks for 4 sweeps and does not move in order to help keep a repeatable peak at a constant skin bias value. If the peak was found above 5.25 V it was assumed not to be a real thermal peak so the skin bias would increase.
precipitation increases this imbalance. As the payload becomes negative, the energy and charge of species a detector can collect will be altered. Positive charges are attracted to the payload and gain energy. Negative charges lose energy and therefore, low energy electrons (with energy less than the payload potential) are repelled, and cannot reach the payload. Higher energy electrons are retarded and lose energy but may still be detected.

The intended behavior of the instrument is best illustrated by considering the various cases of net potential at the TED with respect to plasma potential. The net potential generally refers to the sum of the payload potential and the applied skin bias as seen in the first panel of Figure 2-5. First, in the plasma frame, the full distribution, presumably a Maxwellian, shows up as a straight line of ln f vs. E in Figure 2-5, reaching down to the lowest energies. If the net potential is positive, the full distribution will be accelerated into the detector and appear in the energy sweep beginning at energy $eV_{net}$ (Panel C). If the net potential is less than the plasma potential, there will be part of the core which cannot reach the detector (Panel D). In that case, what we measure will be the tail of the core distribution. Zero energy particles in the detector correspond to plasma frame particles with energy just sufficient to reach the sensor despite the repulsive float potential.

Our instrument works to keep $V_{net} > V_{plasma}$ where $V_{net}$ equals the superposition of the natural negative spacecraft potential ($\Phi_{s/c}$ required for current balance in darkness) with the positive applied skin bias ($V_{SB}$). This negates the natural negative charging of the payload and creates a small positive charge to draw in all the electrons. The skin bias algorithm has an ideal positive acceleration of $\sim 0.5$ V. This allows us to image the core of the cold population shifted to a minimum energy of $0.5$ eV. The peak energy as seen by the TED is less than the applied skin bias. The position of the peak shifts throughout the
Figure 2-5: Different panels showing the planned operation and effect of the skin bias.
flight but the skin bias control adjusts the peak to within the ideal step range (see Figure 2-4). From this measure of the distribution we can calculate the temperature, density, and current carried by the thermal particles.

2.1.2 Testing

This section describes the calibration efforts, ray tracing modeling, and determination of the TED geometric factor. The TED was calibrated in-house during the summer of 2001. A prototype was built and characterized by the available low energy source in the Magnetosphere Research Lab vacuum chamber and test facility. This system was described previously by Lessard et al. (1998). A true known low energy source is difficult to produce and verify so early tests were designed as much for the purpose of finding the optimal particle source as for examining the response of the new instrument. For calibration and testing, the TED operates without the active feedback skin biasing. The lab computer sweeps the analyzer voltage linearly from 0 - 5 V in 256 steps and accumulates counts at each step. Several makeshift sources were tried. Much of our standard particle calibration uses an adjustable UV source electron gun whose absolute output flux is not known but can be used to characterize the relative response of the HEEPS detectors. The first TED tests were run using the UV source and chrome window gun. The chrome was biased a few volts negative while the TED skin was grounded such that the minimum energy of electrons reaching the detector equaled the accelerating potential between the chrome window and the detector skin. This source produced peaks as low as 1 eV but the count rates were very low despite the highest UV lamp intensity.

A homemade vacuum filament which emitted a larger flux of low energy electrons was
also used, though the absolute energy and flux output was not quantifiable. This filament
also produced counts at the expected energies, although a different contact potential energy
offset was observed. A major concern was the observation of repeatable high energy tails in
the measured peak distribution. Scattering inside the detectors was theorized to explain the
anomalous response. Ray tracing showed the particles that caused the tails were actually
lower energy particles which can bounce into the exit slit even though the analyzer was set
with a stronger field for higher energy steps. Previous ray tracing had not allowed particles
to bounce inside the detector. A short wall was added in front of the curved anode and
new lab and simulation tests run. The wall improved the symmetry of the peak and was
added to the flight configuration. Additional modeling tests were run to test the effect of
the wall on low energy detection and these tests indicated minimal effects due to the wall
(M. Widholm, personal communication, 2004).

Several filaments were tried, from an old vacuum tube to bare wires. My primary
involvement in the TED testing began at this time. Testing with a hot filament enabled
calculation of the analyzer selection factor, k. This was predicted to be 1.26 from the ray
tracing simulations but an average value of 1.2 was found by numerous runs with two TEDs.
The analyzer selection factor, k is found by varying the accelerating potential and detecting
in what energy step the peak was observed. Calculating the change in detected energy
with respect to the change in accelerating voltage determines the required energy selection
factor. In other words, k determines what actual plasma frame energy the sweep voltage
values correspond to. This is a constant factor regardless of energy for the energy range
we could test therefore it can be found even when the absolute source output is not well
known.
Figure 2-6: Monte Carlo ray tracing results showing the energy resolution of the analyzer at different selection energy voltages and pitch angles. (Plot: M. Widholm.)

Several key results from the calibration testing are listed as follows. First, we verified that the detector worked at all pitch angles with respect to the Earth’s strong field. A miniature magnetometer procured from Applied Physics Systems was used to verify the ambient field direction and strength in the chamber. Another result was the $\Delta E/E$ measured by plotting normalized counts versus normalized energy. At high energies it agreed with ray tracing and came out to $\sim 8\%$ while at the lowest input energy $\sim 0.6$ V, $\Delta E/E$ increased to around 25\%. It is not entirely clear whether this effect may have some origins in the stability of the low energy source used. After calibration testing, deformations were noted near the aperture in the Aerodag coating on both flight TEDs. The most likely source was the proximity of the aperture to the hot filament. This coating was touched up and reapplied prior to launch with no defects visible to the naked eye.

To the extent possible, the in-house testing verified that the TED worked as expected. Ray tracing was able to provide an additional dimension to the testing. Simple ray traces were shown in Figure 2-1. The Monte Carlo method inputs a random distribution of energies, positions, and angles to find the distribution of successful trajectories within the TED.
As described in the initial SIERRA proposal, [Figure 2-6] shows the relative count rate versus energy for trajectories that reach the anode with the selection voltage set for 0.10, 0.50 and 1.0 eV. These plots show that the energy resolution is about 9% for energies above 0.5 eV and degrades to a worst case of about 12% at 0.1 eV in a 0.4 Gauss magnetic field. The lower magnetic field strength at high altitudes will improve low energy performance (Kintner et al., 1998).

Simulation testing of this sort was useful for predicting the analyzer selection factor and modeling the very low energy response (not testable in the lab). More details on the calibration tests and ray tracing simulations can be found at Mark Widholm's testing page, http://www-ssg.sr.unh.edu/index.html?tof/Rockets/Sierra/sierra.html. Modeling also considered the effect of the finite electron gyroradius, where the TED detector body could block the entrance of certain particles at certain pitch angles. This effect was expected to degrade performance near 90° somewhat, but not have a significant overall impact.

Since our source magnitude is not completely quantified we cannot use the lab "calibration" to experimentally find the geometric factor, G. The geometric factor tells to what flux a certain number of counts corresponds. For a given flux, a smaller geometric factor means a smaller number of counts is obtained; therefore the detector is less sensitive or less "open" to detecting particles. Basic geometry considerations and ray tracing give a rough estimate of G. From the basic Monte Carlo-based ray tracing of the analyzer, done by M. Widholm, an estimate of 2.4 × 10⁻⁵sr cm² keV/keV for G at 0.5 eV was determined. We can also employ a very rough calculation of G by considering the area of the collimator region. With an aperture of 1 mm by 2 mm and 10 mm collimator length, we can calculate G = a (ΔE/E)ΔθΔΦ where a = area, ΔE/E = the energy resolution, and the angles...
Particle Instrument / (Reference Theses) | SIERRA Rocket Location | Geometric Factor [sr cm² keV/keV] | Energy Range [eV] | Time Resolution [s]
--- | --- | --- | --- | ---
HEEPS-e | main | 2e-4 | 7 - 14500 | 0.002
HEEPS-i (Pollock, 1987; Garbe, 1990) | main & 2 subs | 1e-3 | ~6 | 0.002
BEEPS (Lynch, 1992) | main | 5e-3 | 6 - 200 | 0.004
TED (MacDonald, 2004) | 2 on main | 3e-5 | 0.08 - 6.5 | 0.001

Table 2.1: Flight heritage and particle instrument specifications

refer to the solid angle acceptance range of an incoming particle. This consideration gives $G = 3.2 \times 10^{-5} \text{sr cm}^2 \text{keV/keV}$. A value of $3.0 \times 10^{-5} \text{sr cm}^2 \text{keV/keV}$ was used in the final calculations as it reflects an average of the estimate from multiple methods. The error is estimated to be +/- 20% although the value used is probably closer to an upper limit.

2.2 Other Instruments

2.2.1 Particle Detectors

The SIERRA rocket employed a full suite of standard electron and ion particle detectors. These instruments have a rich flight heritage at UNH and many graduate students have described the development of individual instruments for their theses. See Table 2.1 for a reference list as the previous work will not be repeated and this background will be only briefly discussed. This table also presents the specifications for the particle instruments on SIERRA.

The original hemispherical top-hat electrostatic analyzer design was developed by Carlson et al. (1983). More advanced versions have been developed at the Magnetospheric Research Laboratory by senior UNH engineers Mark Widholm and Dave Rau together with
Professors Arnoldy and Lynch.

Calibrations conducted at UNH during the summer of 2001 included standard tests designed to verify how counts in a detector's azimuthal look angle bins correspond to flux as a function of energy, pitch angle, and azimuth. All tests took place in the UNH vacuum chamber system with the standard UV source setup capable of producing a uniform beam of ions or electrons at detectable energies and a rotating positioning table to align the detectors relative to the beam (Lessard et al., 1998). Special care was taken to ensure uniform response from the identical ion detectors. The calibration tests can be broken into three main parts as discussed by Pollock (1987). In the first, the goal is to calibrate what acceleration voltage between the hemispherical plates allows what energies to pass through. Also we want to know the resolution of the peak, $\Delta E/E$. This step involves setting the gun to a certain energy and sweeping the plate accelerating voltage and also doing the reverse to calculate at what energies the response maximizes. From these tests we calculate $k$, the analyzer factor which transforms the sweeping plate voltages to actual energies and $\Delta E/E$ which gives the resolution for each step.

The angular response tests are designed to verify from where the counts that land in a certain bin originate and our uncertainty in that knowledge. The idea is similar to that of energy calibration except that the gun and plate voltages are fixed while the detector is rotated in three directions, pitch, yaw, and roll with respect to the beam direction. The last tests certify the overall sensitivity of each bin and account for possible differences in the collecting ability of each bin or anode. These tests verify whether the detector was constructed properly, addressing the physical tolerance, hemisphere alignments, grid transmitting properties, and MCP gain. For the SIERRA BEEPS, HEEPS-e and HEEPS-i.
Table 2.2: Wave instrument specifications

no major assembly problems were discovered and the response was generally as expected from previous flights and ray tracing experience.

2.2.2 Field Instruments

Electric and magnetic field instruments were a crucial part of SIERRA instrumentation. Table 2.2 gives specifications for these instruments. For more information on these measurements see Klatt et al. (2004), and Klatt (2005). For detailed analysis of HF wave data, see Samara et al. (2004), Samara (2005), and LaBelle et al. (2003).

The double probe electric field instruments on SIERRA consisted of 2 different types of instruments. The main payload had a standard 6 m tip-to-tip double pair Weitzmann boom system, and the two subpayloads had a new compact system called COWBOYS. The acronym stands for Cornell Wire BOom Yo-yo System. As described in the latest rocket proposal (Kintner et al., 2004)

The COWBOY boom system consists of a metal cylinder, about which 4 wire booms are wrapped. When released, the wires unwind while the cylinder rotates differentially (with respect to the payload structure) on a controlled magnetic
viscous brake. ... Differential voltage up to 1 kHz for each axis and each sphere-to-skin potential are measured. Plasma waves are measured differentially on both axes up to 20 kHz.

For SIERRA the main and one sub were operated in the so-called “cartwheel” orientation where the spin plane of the electric field spheres is parallel to the velocity vector and perpendicular to the background magnetic field. The Aft subpayload was in “propeller” mode where the spin plane is perpendicular to the direction vector.

On the main payload there were also special pre-amplifiers in the spheres which allow detection of the low frequency, medium frequency, and high frequency plasma waves at extremely high resolution. According to LaBelle et al. (2004), “The signals from the pre-amplifiers were fed into the Dartmouth College 5 MHz bandwidth receiver and subsequently transmitted in analog form to the ground where they were recorded first on video tape, then transferred to CDs with a final sample rate of 10MHz.” Automatic gain control ensures that the receiver captures a fully modulated signal. Through filtering the HF wave receiver measures waves at frequencies between 100 kHZ to 5 MHz. Previous designs are described by McAdams et al. (1999) and LaBelle et al. (1999).

The 3 axis fluxgate magnetometer used on all three payloads was a Billingsley Magnetics TFM100-G2 with a Vacquier sensor (Kintner et al., 1998). The size, range, sensitivity, and time resolution are ideal for studying fluctuations in the Earth’s magnetic field.

2.2.3 NASA Wallops Payload Instrumentation Support

NASA Wallops’ role in the suborbital experiment program is to provide everything necessary to put the experiments on a rocket and launch them into space. They provided the launch vehicle, experiment decks, power, telemetry and subpayload assemblies. The universities
provided the experiments and Cornell provided their own miniature GPS receiver for the subpayloads. According to NASA Wallops engineers (NSROC, 2000),

The 40.014 UE payload is a new design to be flown from the Poker Flat Research Range in January 2001 on a four stage vehicle. It consists of a cantilevered experiment structure covered by nose cone, telemetry, Space Vector attitude control system, two subpayloads with a deployable skin separating them, and a Nihka igniter housing. The nosecone ejects after third-stage burnout, and is laterally moved from the flight path. After fourth-stage burnout, the payload separates from the fourth-stage motor, and is pitched up by the ACS to deploy the first subpayload. Following the deployment of the first subpayload, the ACS then turns the payload 90 degrees and deploys the second subpayload, deploying the separating skin mid-maneuver. The payload is then despun by the ACS; and deploys a pair of fold down booms and two pair of Weitzmann booms. Each subpayload has a damped four wire boom system developed by Cornell University. The estimated weight, CG station, and length of the launch configuration is 653 pounds, 103 inches, and 175 inches; respectively.

Wallops also provided the personnel to integrate the experiments to the rocket and support the launch via testing, radar tracking, and all the other necessary components to make it fly. The SIERRA mission manager was Mr. William Payne.

2.3 Geophysical Launch Criteria

The rocket was launched at 08:23:05 UT on January 14, 2002 with a Black Brant XII 4-stage sounding rocket from Poker Flat Research Range (65.13° N, 147.48° W), outside Fairbanks, Alaska, USA. Optimally, we aimed to launch into a nightside substorm breakup arc system with poleward moving arcs on fieldlines coincident with the apogee of the rocket's trajectory (approximately over Kaktovik, Alaska). This section describes the desired auroral launch conditions, the available real-time data, and the actual launch conditions and outcome.
2.3.1 Auroral Environment

The Principal Investigator’s decision to launch the rocket is not an easy one; it ultimately involves both eyes and gut instinct as much as brain, experience, and knowledge. These qualities cannot all be gained by reading this thesis so we shall focus on processing and interpreting the plethora of global data which can serve as valuable tools to discern the appearance of the dynamic aurora. The goal is to make the best possible scientific estimate ("educated guess") of the auroral strength, duration, and location 15 to 30 minutes before the rocket reaches apogee. The launch countdown must be initiated and can be “held” 10 minutes from ignition of a 15 minute flight. Determining the best launch time for the rocket is an intricate problem involving using a full toolbox of available and relevant geophysical data to resolve the rapid spatial and temporal variability of aurora forms.

In the most naive approach a rocket could simply be launched when overhead activity is strong. In this case, one would likely miss the most intense activity at rocket apogee (500 km. away) as the aurora can be quite latitudinally and longitudinally confined in addition to its rapid motion or intensity changes.

In the following, we focus on correct interpretation of the available satellite and ground data in terms of the substorm phenomenology. A broad range of data are useful in verifying the position, phase, and intensity of auroral conditions in Northern Interior Alaska. Throughout Canada and Alaska a global network of observation points works together to detect the propagation of disturbances through the magnetosphere. The location of each station relative to the auroral oval at each time must be considered in interpreting its data.

As a means to develop the advanced knowledge of substorm development relevant for
the campaign, a website was created in November 2001 by the author in order to bring together real-time data from the variety of global sources to a centralized toolbox for use by the launch team. This website's URL address is: http://esp.sr.unh.edu/liz/mainpage.html and it is thoroughly described in Appendix B. The major elements of data described in this chapter are generally available at the website along with other supplementary sources.

Real-Time Satellite Data

In this era of fairly plentiful satellite coverage, three satellites, ACE and GOES #8 & #10, stand out for the most useful and advanced indicators of solar wind activity relevant to our purposes. Since the SIERRA launch, GOES #12 has now come online as the primary GOES geosynchronous satellite to replace GOES #8. Since the magnetosphere is so large and the precise timing of solar wind effects through the magnetosphere highly variable, forecasting ability could still be improved with a more extensive set of observation points. We are fortunate to have a near real-time upstream monitor of the solar wind in the Advanced Composition Explorer (ACE). ACE's location at Lagrangian Point 1 is advantageous to provide an approximately one hour warning of solar wind conditions near Earth. As is shown in Figure 2-7 for January 14, 2002, the direction and strength of the interplanetary magnetic field (particularly its southward component $B_z$), density, velocity, and bulk temperature are some of the quantities determined. These data are most useful in confirming the passage of shocks from magnetic clouds, compression of the magnetopause, favorable dayside reconnection times, and the strength of solar wind input to the magnetosphere. As can be seen on the day of launch the solar wind $B_z$ was slightly southward for over an hour beginning at 06 UT with an average speed of $\sim 490$ km/s. This is favorable for a moderate
Figure 2-7: ACE browse data for January 14, 2002: Solar wind speed, Proton density, $B_z$, $B_y$, and $B_x$. (Courtesy of the Ace Science Center.)
to small amount of energy loaded into the magnetosphere, conditions generally conducive to substorm growth.

If the solar wind data look promising, the GOES satellites can be monitored for further development. The geosynchronous placement of the GOES satellites is important. #8 is ~5 hours ahead of Fairbanks, and #10 is ~1 hour ahead. The GOES magnetometer coordinate system consists of $H_p$ (parallel to satellite spin axis, through North pole), $H_e$ (radially out from Earth in equatorial plane), and $H_n$ (in direction of $H_e \times H_p$). GOES also contains particle instruments useful in determining energetic proton events and storm radiation levels. On the dayside, if $H_p$ is negative, the magnetopause is strongly compressed to within geosynchronous orbit. The quiet-time sinusoidal $H_p$ shape corresponds to daily rotation with the Earth, with the field at the subsolar point ~2 times stronger than at midnight. On the nightside, a signature of the substorm growth phase tail stretching is decreasing $H_p$ and increasing $H_e$. The onset of a substorm, a suddenly dipolarized tail, is shown by the sudden reversal of this trend. On January 14th, the signatures of a substorm growth and onset near the time of launch are indicated in Figure 2-8. The signature is seen more clearly in GOES #10 because it was closer to the onset location although the fact that #8 also sees similar features indicates that this was a true substorm though fairly small and localized.

**Ground Based Magnetometer Data**

If signatures of growth phase or onset are measured by GOES, precise determination of the corresponding ground onset location must be made to determine if there will be conjunction with a rocket launched from Poker Flat. The CANOPUS magnetometer chains are useful for
Figure 2-8: GOES #8 and #10 magnetometer data plotted from the Space Physics Interactive Data Resource archive (NOAA.)
this. The X, Y, and Z magnetic field components are measured at each station and shown in Figure 2-10 for the day of launch. The directly driven currents and auroral electrojets are measured. The X component is most useful in identifying substorm onset via a substorm current wedge formation with a large negative deviation. When comparing the north-south chain the largest deviation often signifies the closest latitude to onset. In looking at the east-west chain the speed of westward propagation can be inferred. In Figure 2-10, notable features are the brief negative dips in the X component at Ft. Smith and Contwoyto Lake stations (67.9°, 73.5° N) around the time of launch. Clearly this disturbance was modest in size compared to the much larger event which occurred later in the day at 13 UT. Possibly it was seen only at a few stations because of its limited spatial extent coupled with the limited spatial magnetometer coverage. Also, in the Z component at these two stations large positive and negative bays were observed consistent with an electrojet current between these latitudes. The magnetogram from Kaktovik, which is right under the rocket apogee, shows a medium size bay of ~ 200 nT at the time of launch. Somewhat surprisingly, the Poker Flat and Ft. Yukon magnetograms show little significant ground magnetic perturbations at this time. Even though the movement of the discrete aurora was seen from these stations few currents were induced in their ground-based magnetometers.

Ground Based Imagery

Ground based optical imaging is a crucial piece of evaluating the auroral conditions for launch. Of most use are the all-sky and narrow field cameras (ASC, NF), and meridian scanning photometers (MSP) at three Alaskan sites along the launch trajectory. Examining the morphology of the aurora is not only beautiful but scientifically beneficial for researchers
Figure 2-9: The X (North) and Z (Down) components of the CANOPUS chain magnetometers. (Courtesy of the Canadian Space Agency.)

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Figure 2-10: Kaktovik magnetogram: H, D, and Z components correspond to north, magnetic east, and vertical magnetic deviations in a right-handed coordinate system. (Courtesy of the University of Alaska.)
in order to understand how various types of precipitation result in different optical displays. For example, the signatures of the phases of a substorm are very clear in ASC or MSP at the right location. At the time of the SIERRA launch the coverage of the all-sky camera network was much less than the currently planned expansion of the network underway for the ground component of the THEMIS satellite mission. Therefore we primarily used the Fort Yukon and Kaktovik all-sky cameras to verify activity at the zenith of the rocket’s intended trajectory. The narrow field camera located at Poker was pointed toward the northern horizon and was able to give some indication of the conditions to the North.

For scientific analysis the rocket’s trajectory can be mapped down the fieldline to 100 km where auroral light is produced. The images are digitized and the intensity, type, and direction of the auroral emissions can be compared to in-situ observations hundreds of kilometers above. The cameras were all operated in white light, without filtering to specific emissions, and at thirty frames per second. This sampling rate can limit the usefulness of typical cameras for rapidly moving aurora. The biggest drawbacks of ground-based optical imaging systems are their susceptibility to weather, background light and their remote locations, which make maintenance difficult. For instance, SIERRA was launched without full visibility at Kaktovik because of blowing snow.

2.3.2 Launch Conditions - A short story

Eight cold nights of observing (relatively weak) aurora, (bad) weather, and various mitigating circumstances (moose) passed at Poker Flat. During this time it was surprising to note that there were none of the prototypical substorm displays described by Akasofu and expected by this naive graduate student. On the ninth night, the weather finally cooper-
ated and allowed good visibility at all three all-sky camera sites, Poker, Fort Yukon, and Kaktovik. Researchers eagerly looked to the web for real-time ACE and GOES information and were supremely frustrated to find that the NOAA website had had a rare crash and was not operating. Calling the SEC in Boulder did nothing to alleviate the problem. This left no advance warning of auroral conditions. Graduate students (of little faith) despaired as the precious launch window hours passed. Suddenly there was auroral activity visible to the East. The P.I. looked out the observation window as an arc brightened and began to move West and poleward and (with great foresight) raised the count. The rocket was then launched at 08:23:05 UT into the poleward expansion of an active arc system, just after a classic substorm breakup with a modest ~150 nT bay. This proved once again that computers should never be relied upon or trusted as much as one's experience and instinct.

2.3.3 Payload Performance

The vehicle's performance was nominal in all respects. Figure 2-11 shows the trajectory of the SIERRA main payload over a geographic map. The trajectory was a few degrees west of planned but within normal dispersion circles. The right panel of Figure 2-11 shows the altitude as a function of time for the SIERRA payloads. At Poker Flat on January 14th, magnetic midnight was at ~11:11 UT.

The two subpayloads are referred to as the Forward and Aft given their relative initial positions on the payload stack. The Aft subpayload was ejected first to the north, then the payload did a rotation and ejected the Forward to the east. All three subpayloads were intended to be aligned in the plane perpendicular to the magnetic field at apogee. At apogee they were each separated by over 500 m, and by 800 seconds after launch they were almost
twice as far. Figure 2-11 also shows the altitude separation of the Main, Forward, and Aft at apogee (on the right axis, thin lines). Lastly, Figure 2-12 clarifies their relative heights and orientation with respect to a magnetic coordinate system.

The Main payload spun at 0.32 Hz with a slow 0.08 Hz cone rate. The subpayloads spun faster at 1.67 Hz with a shorter .85 Hz cone rate. The Main payload stayed within 3° of field aligned for the duration of the flight. The subpayloads began with similar 6 - 7° full cone angles which grew to 20 - 30° for the Forward and Aft, respectively.

Further discussion of the attitude and multi-payload orientation can be found in Klatt (2005), and on the Cornell website (http://sierra.ece.cornell.edu). All instruments worked and returned data flawlessly. The scientific dataset will now be presented briefly to give an overview of the types of aurora encountered. All wave data and attitude plots have been provided by Eric Klatt and Paul Kintner of Cornell and will be briefly discussed in the context of the auroral particle precipitation and as introduction for future use in conjunction with the TED data.

2.4 Data Presentation

We now begin presenting the data collected by the SIERRA flight, mainly focusing on a flight overview of the particle precipitation on the Main payload. A few examples of multipoint measurements will also be shown. The flight traversed strong auroral activity, characterized by many inverted V arcs and an extended region rich with Alfvénic precipitation and active waves. While typical return current region signatures such as transversely accelerated ions and broad-band ELF waves were not seen poleward of the upward current region, there is some evidence from the ion data that a strong return current region may be happening.
Figure 2-11: LEFT: The actual SIERRA trajectory is shown in blue, and the trajectory mapped down the fieldlines to a height of 100 km is shown in red. Marked points indicate altitudes of 600 km (on upleg and downleg), and apogee for reference. RIGHT: The thick black line and lower left axes show the trajectory of all three payloads, which are indistinguishable on this time scale. The thinner lines and top right axes show a closeup of the trajectory near apogee indicating the altitude separation between the 3 payloads. (Plots: E. Klatt, Cornell.)
Figure 2-12: Relative orientation of the three spacecraft at $t = 570$ seconds with respect to each other and the magnetic coordinates (Plot: E. Klatt, Cornell.)
<table>
<thead>
<tr>
<th>Period</th>
<th>Time Range (s)</th>
<th>Major Auroral Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>230 - 380</td>
<td>Large inverted V arc</td>
</tr>
<tr>
<td>B</td>
<td>380 - 455</td>
<td>Several smaller inverted V arcs</td>
</tr>
<tr>
<td>C</td>
<td>455 - 460</td>
<td>Gap between arcs?</td>
</tr>
<tr>
<td>D</td>
<td>460 - 530</td>
<td>Large inverted V arc</td>
</tr>
<tr>
<td>E</td>
<td>530 - 700</td>
<td>Alfvénic region</td>
</tr>
<tr>
<td>F</td>
<td>700 - 885</td>
<td>Polar cap</td>
</tr>
</tbody>
</table>

Table 2.3: Classification of major auroral types on the SIERRA flight

above the rocket during the Alfvénic region. This unusual observation is important to understanding the low altitude foot-points of magnetosphere-ionosphere coupling. In the following we will show the overview of the flight and discuss a few basic derived quantities. More detailed analysis of the different types of wave data can be found in Klatt (2005) and Samara (2005). Chapter 4 will be devoted to analyzing the TED data and looking at conjunctions with other observations introduced here.

2.4.1 Flight Survey

Figure 2-13 shows a basic summary of data from most major instruments, including electrons, ions, and waves on the main payload. The particle data are presented as spectrograms with count rate (proportional to differential energy flux) versus energy versus time. The particle energies are not corrected for the spacecraft potential as this is a small effect at most of the measured energies. Also note the logarithmic energy scales are an approximation to the true energy scale, which will be shown in Chapter 4 spectrograms. All pitch angles are summed. The DC wave data are generally filtered. A huge amount of data is summarized in this figure. The major regions are categorized for clarity in Table 2.3.
Figure 2-13: Survey plot of the SIERRA flight. The first three panels show DC electric and magnetic waves measured on the main payload and the Poynting flux derived from those measurements. The next three panels are particle spectrograms for the HEEPS-\(e^-\), BEEPS-O\(^+\), and BEEPS-H\(^+\), respectively, of total count rate (which is proportional to differential energy flux) summed over all pitch angles.
HEEPS Electrons

Starting with the fourth panel, showing the auroral energy HEEPS detector, we see varying energetic auroral precipitation over most of the flight. The SIERRA event began with several large inverted V arcs in periods A and D. At times the peak energy of the accelerated particles exceeded the energy range of the detector (maximum step at 14.5 keV) which is large but not unusually large for breakup arcs. Inverted V arcs are typified by an isotropic distribution with a loss-cone and "mono-energetic" peak (Kaufmann et al., 1978). The physical mechanisms of the stable arc are mostly well understood with upward current carried by energetic electron precipitation.

Some wave-particle mechanisms are less well understood, such as the embedded field aligned dispersive bursts (FAB) at energies less than the characteristic energy seen from 300 to 340 s. Their repetition frequency was ~1/s. Though FAB are frequently seen, their correlation to visual flickering aurora or "dancing rays", and the in-situ observations of corresponding waves are less understood. Particularly high time resolution is required for good separation and analysis of individual pulses. This was investigated with the PHAZE2 rocket which had 18 particle detectors with 125 Hz sampling (Arnoldy et al., 1999). A successful theory needs to describe the repetition, variability in dispersion signatures, height and range of the wave-particle acceleration region, and the cold parallel and perpendicular temperatures of the FAB. Our flight has only 1 swept HEEPS electron detector so our time resolution is not sufficient to permit detailed study of these bursts. Recent modeling efforts by Chaston et al. (2003) using the Alfvén wave framework have successfully shown detailed reproduction of these features.
Turning back to the broad-scale study of the precipitation we observe the large arcs in periods A and D are likely extended North-South arcs. It is more likely these arcs are not truly enormous E-W aligned arcs but active curling arcs aligned N-S at the time of the SIERRA encounter. Unfortunately we do not have camera data from Ft. Yukon or Kaktovik to confirm this interpretation although we can compare to measurements of the plasma flow. Period A ends with a typical arc edge field aligned enhancement accompanied by a moderate electric field reversal. Period B contains a series of faster arc crossings (perhaps more typically East-West elongated) with similar field aligned features to both earlier and later periods.

Next, a conspicuous short gap in auroral precipitation was traversed around 455 s. This gap could be a likely site for return current region activity with an oppositely directed potential drop above the payload. This region is an ideal spot to look for the current to be carried by thermal electrons. As we discuss other instruments’ observations we will return to this interesting albeit brief time period. Period D is another arc centered around apogee. It contains much more diffuse field aligned and lower energy components, as possibly faster time variations were aliased out.

In period E the precipitation changes as we emerge from traditional arc structures to active poleward boundary regions. Here, the precipitation is dynamic, strongly field aligned and broad in energy. This signature form is indicative of Alfvén wave accelerated particles and period E contains a rich variety of possible types of Alfvén waves. The wave-particle acceleration and coupling in this region is very complex and sophisticated models are required to understand the observables and identify specific types of Alfvén waves (Klatt et al., 2004; Chaston et al., 2004; Lysak, 1991). We will return to discussing
the wave observations of period E. The particles in this region exhibit signs of structured highly variable and striated current sheets and complex dispersion signatures.

Period F begins at 550 km altitude at ~73° latitude when SIERRA exited the auroral oval and entered the cold polar cap. Except for a very low energy precipitation polar rain event seen at 750 seconds only the cold ambient particles remain—not very exciting for most on-board auroral instrumentation other than the TED. Signal was lost at 888 seconds.

**BEEPS Ions**

Next we focus on the BEEPS swept energy ion instrument, summarized in the last two panels of Figure 2-13. Looking at Period C we see no evidence of transversely heated ion conics as would be expected in a return current region. In the inverted V arcs and the gap there are a few examples of lower hybrid solitary structures (LHSS) (Schuck et al., 1998; Schuck, 1999). These are very small spatial and sporadic low energy bursts at 90° which may contribute to ion outflow. More flux appears in the high mass oxygen channel than the low mass hydrogen as is expected at higher altitudes given their ionospheric abundances. In the Alfvén wave region very interesting ions were observed, at low and medium energies. Lynch et al. (2004) showed the pitch angle spectra of the low energy ions were consistent with ram energy plus a 2 km/s upflow.

The medium energy particles are downgoing and consistent with reflection off a higher altitude reverse potential drop. It is not clear how these ions correspond with electrons and waves at the same time. These ion signatures may be consistent with observations of Hultqvist (2002) and represent a new, or at least a less well recognized piece of the low altitude component of magnetosphere-ionosphere coupling. The initial process at low
altitudes by which ions are heated to eventually become conics at FAST altitudes is not well known. The downgoing ions we see may represent the remnants of what happens to ions which do not have enough energy to make it to conics and precipitate back down. More observations are needed in this altitude range to build up a better picture which meshes with the basic framework at satellite altitudes as discussed in Chapter 1.

Electric and Magnetic Waves

Figure 2-13 also shows the basic DC wave observations from the main payload. Little wave activity was seen as expected in the inverted V arcs as the primary mechanisms are quasi-static. In period C the electric field changes because of the lack of strong auroral current. In the Alfvén wave region, large spikes in electric field and fluctuations magnetic field are observed. Some of the magnetic field fluctuations appear quasi-periodic, with a period ~40 - 50 seconds. Throughout the flight it is possible to calculate the ratio of $E/B$ compared with the local Alfvén speed to confirm whether these are Alfvén waves. The results show that Period E is likely full of Alfvén wave structures (Klatt et al., 2004).

In Figure 2-13 a component of the Poynting flux, $\vec{S}$, is shown from the $\vec{E} \times \vec{B}$ measurements on the main payload. During Period E, several large negative spikes in $\vec{S}$ are observed indicating the bulk of the energy is going down the field lines. More detailed consideration of these waves and their correlation to observed dispersive electron structures is given by Klatt (2005). Note because of the orientation of the payloads, only two components of the electric field (relative to the magnetic field) are measurable although all three of the magnetic are measured.

Figure 2-14 shows a HEEPS spectrogram and two measures of current, one derived from
Figure 2-14: Field Aligned Currents ($\mu A/m^2$). MDFAC (black) and ESDFAC (purple) along with a HEEPS spectrogram as described in the text.

the three magnetometers separated by hundreds of km, and one estimate from the fluxes and direction of electrons detected. The excellent timing and spatial information afforded by GPS, coupled with the use of multipoint magnetometers, enables the estimation of field aligned current from the observed magnetic perturbations. More detail on this method and interpretation of its results is given by (Klatt et al., 2004). This calculation is very relevant to a discussion of the TED since the only way to directly measure the total field aligned current is to measure all the particles from 0 eV to the top of the auroral spectrum. Using Maxwell's laws and magnetic field measurements can also provide an estimate of the field
aligned current. Since a true gradient cannot be measured with only three points, additional assumptions must be made.

The method applied to the Cornell magnetometer measurements is described by Kintner et al. (2004),

The magnetic perturbations are calculated by solving for the attitude, then removing the IGRF model field from the measurements. Finally, the one-dimensional derivative is calculated from

\[ J_z = \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial z} \]  

(2.4.1)

where \( \partial x (\partial y) \) is given by the product of the north-south drift velocity (east-west velocity) with a time increment. This yields the FAC under the assumption that it exists as a two-dimensional arc oriented perpendicular to the ionospheric drift velocity in the payload reference frame.

This method measures one component of the field aligned current, essentially the gradient in the magnetic field across the flow vector with respect to distance along the flow. It cannot measure the gradient in the magnetic field along the flow vector with respect to distance across the flow. The resulting magnetometer-derived field aligned current (MDFAC) is shown in Figure 2-14 as a black line (4 second filter).

The current can also be estimated from the measured electrons. At this stage it is not possible to incorporate TED measurements of the coldest particles into the calculation so the electron spectra derived field aligned current (ESDFAC) will be incomplete. The ESDFAC is only the amount of current carried considering the pitch angle and flux of electrons measured between 7 and 14,500 eV. This current is shown by the purple line and the method is described in Appendix C. We expect that this is not the full current for multiple reasons. Outside arcs, it is reasonable that thermal electrons may carry current and the sense may be opposite. In the arcs, this calculation is most valid because we
expect the precipitating auroral particles to "carry" the upward current. We know that at the times of highest inverted V potential drop, our ESDFAC estimate is too low because the precipitation goes off scale at the highest energies. Thus, with caveats explained, a limited comparison can be made. It is also helpful to see the HEEPS spectra to check how the implied currents compare to the major auroral regions. The ESDFAC implies a fairly steady upward current in Periods A, B, and D of a few $\mu A/m^2$. We note the best agreement is where the ESDFAC is not underestimating the full auroral current, such as the edges of arcs and the later part of Period B. We note that the MDFAC indicates negative current during Period C, while the ESDFAC cannot confirm this as it simply decreases to zero. We also note a serious disagreement between the ESDFAC and the MDFAC in Period B. The magnetometers indicate a negative current at 380 seconds and beyond, while the HEEPS data appear to indicate a smaller auroral arc. This inconsistency may be due to the assumptions of the arc's orientation in the MDFAC calculation or there may be a return current. The TED data should be helpful to resolve this controversy.

In the Alfvenic region the MDFAC is likely more reliable since it can sense return currents. However the MDFAC technique may be limited for such dynamic current sheets. More study is needed to quantify the new MDFAC technique and measuring thermal electrons are an integral part of the solution. We see many differences and hope to shed additional light on this issue with the TED data. Note also in the Chapter 4 discussion of current balance we consider the full non-directional current from the impact of the auroral particles. This quantity is calculated like the ESDFAC only the pitch angle does not matter. For additional details on this and the ESDFAC method, see Appendix C.
$V_{ss}$

The electric field wave signals are also useful in other ways. The sphere-to-skin potential difference, $V_{ss}$ is monitored between each of the four spheres per payload and the payload "skin". Here, reference to the skin is not the same as the biased TED skin. For simple spin averaging, we just sum the four $V_{ss}$ signals and divide by 4. Comparing the averaged $<V_{ss}>$ signals between all three payloads shows they are remarkably similar despite the differences in probe type and payload size between the subpayloads and the main. The value of $V_{ss}$ is $\sim 0.9$ V $+/-$ 0.1 V for most of the flight. The measurement of $V_{ss}$ represents only the potential difference between the large payload and the small spheres. The connection between this value and the true floating potential of the payload is not obvious and will be discussed further in Chapter 4.

**HF Waves**

Data which will be extremely useful to the TED analysis are from the very sensitive HF wave receiver. Certain features are observed in the spectra which indicate the propagation of different wave modes. These data are studied extensively by Samara (2005) and LaBelle et al. (2004). From the shape of these cutoffs, the spin dependent plasma frequency can be picked out. From this we can calculate the total local plasma density over most of the flight where the plasma frequency is observed. Figure 2-15 shows the plasma frequency versus time. In Chapter 4, we will use extensively the "HF density" which comes from these values. The plasma frequency shows a strong and expected dependence on altitude. In Period E, the plasma frequency and hence density is extremely variable. These fluctuations seem to indicate a higher density than in the inverted V regions. The error in this frequency data
Table 2-15: Plasma frequency measured by the HF wave receiver (Hz). (Data from M. Samara, J. LaBelle, Dartmouth."

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Energy Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1200</td>
</tr>
<tr>
<td>200</td>
<td>1400</td>
</tr>
<tr>
<td>300</td>
<td>1600</td>
</tr>
<tr>
<td>400</td>
<td>1800</td>
</tr>
<tr>
<td>500</td>
<td>2000</td>
</tr>
<tr>
<td>600</td>
<td>2200</td>
</tr>
<tr>
<td>700</td>
<td>2400</td>
</tr>
</tbody>
</table>

is approximately a factor of two (M. Samara, personal communication, 2003).

Energy Flux

Figure 2-16 shows the total energy flux from the HEEPS detector, first from all HEEPS energies and second from only a low energy partial range between 7 - 100 eV. The purpose of separately looking at the flux in the secondary electrons is twofold: to see how it compares to the total flux, and for later comparison with TED data where the uppermost energies the TED detects may overlap with the lowest energies measured by the HEEPS-e. In the total energy flux, the largest features are the inverted V arcs in Periods A and D. The highest energy flux in the Alfvénic period is approximately half the highest overall flux.
Compared to the partial low energy flux, the temporal structure is very different. The partial low energy flux is very dynamic throughout and much larger in Period E. The turn-on of the field aligned bursts at 300 seconds is seen clearly. For both measures, the small amount of oscillations evident in the arcs is apparently a minor instrumental effect at the spin frequency regardless of blind spot averaging. The partial low energy energy flux is indicative of the variation in the secondary population which also affects the operation of the TED instrument.
Figure 2-16: TOP: total energy flux (mW/m²), BOTTOM: energy flux from energies 7-100 eV (mW/m²)
Chapter 3

Interpretation and Analysis of Instrument Response

This chapter presents the flight TED data in detail, with a focus on understanding the instrument response. First we describe the basic observations and present unanticipated behavior. The flight operation of the TED indicates the presence of a potential barrier between the TED sensor and the plasma despite the attractive skin bias potential. This potential barrier theory is developed and used to explain the unanticipated behavior. The rest of the chapter discusses the formation of the potential barrier, and its relation to payload charging, considering current balance and potential structure from different perspectives, increasing in complexity. These analyses are unique to the SIERRA TED measurement.

The positive biasing and low magnitude of spacecraft charging complicates the problem by requiring high precision in solving for potentials of less than one volt. We consider successively: simple current balance, simple numerical current balance, particle-in-cell (PIC) simulation, and extensive lab testing of surface properties. We also consider and evaluate the performance of previous designs first looking for relevant connections and dominant themes to apply in our unique case.
3.1 Actual TED Operation

The purpose of this section is to show the raw TED data and identify ways in which the data differ from the ideal operation outlined in Section 2.1.1. Minimally processed TED1 data are shown in Figure 3-1. The raw count rate (proportional to differential energy flux) is displayed as a function of energy step and time from launch. The correspondence of energy step to energy is shown in the double y-axis labels where one can see the close spacing of steps towards lower energy. The white line on the spectrogram shows the applied skin bias (relative to payload ground) mapped into the logarithmic energy step scale. The green lines indicate the boundaries for the skin bias control algorithm, as described in Section 2.1.1. The TED 2 data are very similar, with the only significant differences coming at the initial turn-on and at times greater than 700 seconds. Unless stated otherwise, the same analysis applies to TED 2 as TED 1.

The main unanticipated behavior is that the energy cutoff of the electron spectra matches the enforced skin bias voltage. In ideal operation, the cutoff should be at $eV_{\text{net}}$, as discussed in Section 2.1.1. For the cutoff to be at $eV_{SB}$ either the spacecraft potential equals 0 (very unlikely) or else a potential barrier prevents thermal core access to the detector. This will be explained further in the next section. Here we describe what the TED saw and identify the problems.

In the most basic terms, Figure 3-1 shows that the TED measured counts. There is a peak in these counts, such that counts generally do not exist below a variable cutoff energy. This cutoff consistently appears at the energy of the applied skin bias. The skin bias varies over the course of the flight. The skin bias was initially set to 4 V, and dropped
Figure 3-1: The TED data, energy vs. time with color corresponding to the count rate. The white line is the skin bias. The right y-axis scale is the step number of the energy bins.

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steadily to around 1.2 V by ~300 seconds. It fluctuated on very short time scales and also displayed long term variation. The skin bias reached a minimum steady value of ~0.75 V around 830 seconds. Also the skin bias dropped precipitously at times. Figure 3-1 shows the data from all pitch angles sampled as the payload spun. Pitch angle variation is seen only obviously in enhanced field aligned “stripes.” This 0° precipitation is coincident with field aligned secondary electron bursts seen at the lowest energies of the HEEP's data. These basic observations must be interpreted now in light of the detector's design.

Evident in the “raw” data are several unexpected and interrelated features which must be incorporated into our evaluation of the instrument response. First, while the data definitely show a characteristic peak, its location is generally at a higher energy step than it should have been. This could indicate that the core population has not reached the detector. This also indicates a problem with the feedback loop. The skin bias feedback control should have tried to move any absolute peak to an energy between steps 31 & 36 (dashed green lines). Further evidence of skin bias misbehavior is that it could not lock onto an ideal value and instead seemed to wander, generally between 1.5 V and 0 V. This can be explained by the very low overall count rate, which meant that the “smart” skin bias algorithm was unable to consistently recognize a real peak. This led to an up and down response, with the skin bias going up when no peak was found and generally down when a peak was found. Additionally, when the skin bias did change, it does not seem able to affect the position of the peak correctly. It was supposed to move the peak into the ideal range. Instead, the peak just traces the skin bias. We will return to examining this primary inconsistency with our picture of “ideal operation.” Other problems include a large reduction in sensitivity of TED2 as compared to TED1 on the downleg, at greater than 700 seconds (not shown). This
will be the subject of future work and does not affect the initial interpretation of results.

Figure 3-2 shows the cutoff energy in the TED compared to the applied skin bias. These data would seem to suggest that the thermals are always accelerated into the detector by the full applied skin bias. However, this is totally incorrect. Interpreting the peak seen as the full thermal core accelerated by the skin bias gives a calculation of the thermal density over three orders of magnitude too small. Thus we must infer that a significant fraction of the core population does not reach the TED sensor. The electrons seen at the peak of the measured spectra must not correspond to zero energy in the plasma frame. Zero to low energy plasma frame particles are apparently rejected from the TED sensing area. Next we discuss what sort of potential barrier could cause the observed spectral shape.

3.1.1 Justification of the Potential Barrier

We assume now that a potential barrier prevents access of the lowest energy electron population to the TED aperture, and that what we observed in the TED data is the part of the thermal distribution which can pass the barrier. Here we justify and explain this framework for interpreting the TED data. The keys to this framework are the data problems which imply that the superposition of potentials did not occur. In ideal operation as described in Section 2.1.1, the potential superposition means that the skin bias would have attempted to compensate for the payload potential. Then the sum of those potentials, $V_{\text{net}}$, would dictate the energy step where counts from zero energy plasma frame particles would appear in the instrument frame. Instead we have the key problem that the counts begin right at the skin bias energy (as shown by Figure 3-2).

To explain this, we invoke the potential barrier form shown in Figure 3-3, Panel A.
Figure 3-2: “Cutoff.” TED1 (black), TED2 (red), & skin bias (light blue) vs. time (linear scale).
This is much different than the expected monotonic potential where the spacecraft charging potential and the skin bias voltage would superpose to create an attractive potential above plasma ground. The next panels indicate how this potential form affects the thermals to produce the observed effects. As the particles travel towards the detector, the full distribution (Panel B) is “cut off” by the potential barrier (Panel C). Then the skin bias acceleration is encountered (Panel D) and the remaining tail is accelerated by the skin bias into the detector. Thus in the instrument frame the tail of the distribution appears (Panel D), beginning at the energy of the skin bias. Since we only observe the tail of the distribution, the count rate is significantly lower than for the full core. In fact because we know the skin bias is applied relative to the spacecraft ground, it is clear that the barrier magnitude is equivalent to the spacecraft potential. Notice that the net effect of the potential barrier still shifts the distribution around by the same net amount of $V_{SB} + \Phi_{s/c}$ but this theory explains why the counts begin at the skin bias. In Chapter 4 it will be necessary to know the magnitude of the barrier in order to accurately reconstruct the original distribution. To do this, we will need to quantitatively measure the true payload potential, which is equivalent to the barrier.

Using the concept of a potential barrier of magnitude equivalent to $\Phi_{s/c}$, quantitative reconstruction of the full distribution becomes possible and these quantitative results are shown in Chapter 4. First we explore different ideas for how and why the potential barrier forms. Why can’t the skin bias compensate for the sheath potential? These difficult questions we hope to illuminate by considering and testing various equations for characterizing the spacecraft potential and the field around a charged body. Though this quest may be ultimately inconclusive it is a useful and unique exploration since the typical instrument
Figure 3-3: Cartoon of the potential barrier and its interaction with the thermal electron core. A shows the hypothesized potential barrier. B shows the full thermal core in the plasma. C shows the effect of the barrier on the core. D shows the net effect of the barrier and the skin bias acceleration close to the detector.

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development process has not needed to consider this variety of effects. We will show how
traditional analysis does not lead to a potential barrier but reality proves otherwise. First,
we will begin by describing the results and problems encountered by previous thermal in-
struments: specifically the HARP, TECHS, and SPI analyzers on rockets beginning in the
1970's. Then we consider various aspects of current balance and spacecraft charging effects
and their possible repercussions on our thermal electron measurement.

3.2 Consideration of Previous Designs

Previous rocket flights have attempted to measure thermal particles but a standardized
instrumentation technique has not yet emerged. It is worthwhile to study these varied
designs and their net results in order to better assess the strengths and weaknesses of the
TED design. We wish to know if other designs exhibited similar problems. Why or why
not? There are very few cases of previous designs which directly overlap with SIERRA.
Usually several significant elements are unique to each case. For example, the first two
designs profiled here were either at a much higher or lower altitude, resulting in orders of
magnitude difference in density.

At the University of Michigan in the 1970's, Hays and Sharp pioneered one of the first
instruments to measure electrons less than 10 eV energy, (Hays and Nagy, 1973; Sharp and
Hays, 1974; Shyn et al., 1976; Sharp et al., 1979, 1981). The purpose of these experiments
was to study the low altitude flux of thermal electrons and atmospheric photoelectrons, a
primarily aeronomy interest important to determining the thermal energy budget of the
atmosphere. The instrument name HARP stood for Hyperbolic Analyzer of the Retarding
Potential type, and used channeltrons for 1-d particle acceptance and gain. The analyzer
was gridless and internally magnetically shielded by Co-Netic material. Externally it was coated with gold on stainless steel and aluminum (Hays and Nagy, 1973). Two different schemes were used for skin bias control: first, cycling through positive and negative preset values, and second, essentially the reverse of the TED skin bias selection algorithm. Instead of slowly varying the skin bias based on the location of the energy peak, they varied the skin bias over a wide range and analyzed the peak response at a certain energy step. An energy sweep was then taken at the value of skin bias which achieved maximum output (Sharp et al., 1981).

In aurora, they detected a Maxwellian thermal electron distribution with a peak flux of more than $10^{10}$ el/cm$^2$-s-st-ev at 0.5 eV (Sharp and Hays, 1974). At 124 km, the thermal temperature was $\sim 450^\circ$ K measured by the HARP and 750$^\circ$ K measured by a Langmuir probe (Sharp and Hays, 1974). This agreement is reasonable considering the notorious contamination problems which Langmuir probes have on sounding rockets (Sharp et al., 1979). They saw evidence of the low energy N$_2$ vibrational structure and photoelectrons. However, their apogee altitude was less than 300 km.

These results are severely limited by the lack of energy resolution. The fitted temperatures appear to be derived from 2 or 3 data points at the lowest energy steps, so it was very difficult to resolve the temperature and distribution accurately. Also, a lack of pitch angle resolution was compounded by the necessity of a forward mounting position. These two difficulties rule out sensing of the thermal electron drift velocity with this instrument. The low altitude and omnipresent sunlight make direct comparisons to SIERRA problematic. Great foresight was shown in the HARP's multiple detection modes, including active feedback and minimization of contact potential problems with the unique hyperbolic analyzer shape.
The main result of these flights was the demonstration that low energy detection was possible at low altitudes. The similarities to the TED operation include the use of an active feedback biasing system, superposition of potentials, and Liouville's theorem to correct the energy axis from the measured frame to the plasma frame.

In 1995, the TECHS instrument was flown on the SCIFER sounding rocket into the cusp. With an apogee twice as high as SIERRA (and almost entirely sunlit) this environment was significantly lower in density and dominated by sunlight-driven photoelectron flux. The TECHS design was a miniature top-hat spectrometer isolated on a 1 m boom (Pollock et al., 1996; Pollock et al., 1998; Adrian, 2002). The detector was coated with copper black and the skin bias cycled between +1V and -1V in five evenly spaced steps. The detector worked quite well, with the most useful data when the skin bias was at +1V. Derivations of electron temperature, density, and spacecraft potential yielded reasonable values independently confirmed by other SCIFER instruments and previous satellite observations. These results indicated both positive and negative values of spacecraft potential over the course of the flight.

A functional relationship was observed and modeled for the dependence of spacecraft potential on electron temperature and density (Adrian, 2002). Current balance to the payload was dominated by the thermal electron flux and by photoelectrons emitted from the payload. Escoubet et al. (1997) and others had shown that density was the strongest determinant for spacecraft potential for satellites in the sunlit positive spacecraft potential, low density regime. SCIFER results extended this result to higher densities and negative potentials, and showed that electron temperature is an important factor in determining spacecraft potential as well. Our SIERRA flight presents opportunities for analyzing this
relationship in the more complicated region of negative spacecraft potentials in the dark.

With several overlapping investigators and the closeness in time between the SCIFER and SIERRA flights, the TED design was directly motivated by some of the limitations of TECHS. It was felt that the stepped skin bias values sacrificed time resolution by spending too much time at non-ideal steps. This was the driver for the TED's "smart" skin bias adjustment scheme. Additionally, the top-hat design exhibited limitations at energies less than 0.7 eV indicating a possible gyroradius induced cutoff, so the TED design favored a more open one dimensional analyzer. As with TECHS, TED used a 1 m boom and utilized the superposition principle for the correction of measured energies to the plasma frame (Adrian, 2002; Griffiths, 1989; Jackson, 1999). The area ratio of TECHS to the SCIFER payload was ~1:1000. Higher ratios were a problem for later flights (M. Adrian, personal communication, 2003). Simple 2-d electrostatic modeling showed the formation of an attractive potential well in front of the negative main payload body. For SCIFER this was an advantageous potential structure and likely enhanced the TECHS field of view although quantitative effects were not detailed. Though TECHS worked on SCIFER, some unresolved questions remain. Its use on later missions was problematic (M. Adrian, personal communication, 2003) and it seems the design has not been successfully continued. We intended to build on TECHS' success and improve some of the shortcomings.

Another recent design which has shown promise is the SPI (suprathermal plasma imager) which flew on the GEODESIC flight in 2000. This instrument design can be used for ions or electrons at energies from the thermal core to hundreds of eV. Thermal ions became the primary thermal measurement on GEODESIC as a broken boom prevented analysis of the thermal electron data (Burchill, 2003). However, both thermal instruments used a unique
top-hat analyzer design incorporating a mesh inner hemisphere and phosphor screen for 2-d imaging of angle and energy. An internal energy sweep is not needed, as energy is imaged by radial distance from the detector center. This improves time resolution to ~100 Hz but can worsen imaging resolution at the lowest energies. This type of design is called the “Whalen Analyzer” (Whalen et al., 1994; Knudsen et al., 1998). The external bias of the thermal electron instrument was set to +5 V and the thermal ion instrument bias was set to -2 V (D. Knudsen, personal communication, 2003). Since this was a biased ion instrument the sensor-plasma potential was observable from the energy where the counts began. Throughout the flight this varied over a range from ~0.7 to ~4.5 V and displayed a trend of variation with respect to the payload velocity vector. Accounting for the -2 V ion instrument bias this gives values for the payload potential which are both positive and negative. These values are inconsistent at times with the measurement of “floating potential” directly from the electric field spheres which varied from -0.5 to -1.0 V (Burchill, 2003). This discrepancy was not understood and may be due to inaccuracies in either quantity. Chapter 4 will address this issue for SIERRA. Because this instrument looked at suprathermal ions which are generally accelerated into the detector it is difficult to surmise whether any evidence for non-monotonic potentials was found.

The external coating was Aerodag on all sensors and internal surfaces were gold blacked. On later flights all Aerodag was used (D. Knudsen, personal communication, 2003). A new version of this instrument will be flying on the Canadian ePOP satellite at 800 km and represents an excellent opportunity for extended in-situ evaluation of thermal and suprathermal particles at a variety of local times and latitudes (Liu, 2004). Unfortunately due to the mechanical boom failure on GEODESIC we cannot fully evaluate the design as
an instrument for thermal electrons. Other thermal ion instrument designs have also been successful (Pollock, 1987; Moore et al., 1996; Coffey et al., 1998). The GEODESIC example illustrates the use of a set attractive bias and the excellent time resolution and 3-d coverage possible with the mesh hemisphere design. Also this was an example of the use of Aerodag on detectors for both positive and negative species. Lastly, Burchill (2003) mentions the lack of adequate facilities for calibration of low energy detectors, a challenge particularly for electrons.

Considering the different circumstances and designs it is somewhat difficult to categorize the various problems with these previous attempts and identify the exact source of their difficulties as they relate to the TED. However, it helps to narrow down the most important type of problems which have plagued previous attempts. No one design appears to have our type of potential barrier although another type of non-monotonic potential was observed (for TECHS). Frequent discrepancy between measures of the payload potential by electric field or Langmuir probes are also common. Many possible causes for the TED potential barrier can be theorized. Since all of these ideas begin with the potential disturbance of the charged payload, we start our discussion with analyses of the spacecraft potential. Then we turn to more complex descriptions of the fields around charged bodies, and complications such as surface charging and potential barriers.
3.3 Structure of $\Phi(\tau)$

All solutions of the potential shape near conducting objects in a plasma must obey several equations (Jursa, 1985). First is the current balance equation:

$$I_e(\Phi) + I_i(\Phi) = I_t$$  \hspace{1cm} (3.3.1)

where $I_e$ is all contributions to electron current, $I_i$ is all contributions to ion current, and $I_t$ is total current flowing to the object. The various sources of current were discussed in Section 1.2.1. The currents to the surface are functions of the spacecraft potential and the spacecraft potential will float to where the sum of the currents equals zero and balance is achieved.

Next, Poisson's equation tells us the shape of the potential in the disturbed region around the charged payload subject to the local charge distributions:

$$\nabla^2 \Phi(r) = 4\pi e (n_s + n_e - n_i)$$  \hspace{1cm} (3.3.2)

where $n_s$ is the surface emitted electron density, $n_e$ is the electron density, and $n_i$ is the ion density.

Lastly the Vlasov equation:

$$\vec{v} \cdot \nabla f_i - (q_i/m_i) \nabla \Phi(r) \cdot \nabla_v f_i = 0,$$  \hspace{1cm} (3.3.3)

tells us the evolution of the distribution function in the presence of the potential as a function of space, and vice versa.

Without advantageous symmetry this set of equations cannot be solved analytically in three spatial dimensions. Fortunately, there are a multitude of ways to make this problem...
more tractable and several different techniques are considered here. For analytic solutions it is common to apply different approximations depending on the size of the Debye length, $\lambda_d$, relative to the object dimensions. For $r > \lambda_d$, a "thin sheath", space charge within the sheath must be considered. For $r < \lambda_d$, a "thick sheath", the particle trajectories within the sheath are important. For our case $R_{payload}$ is generally larger than $\lambda_d$, so the thin sheath approximation can be applied to the spacecraft potential. However, $r_{TED}$ is usually similar in size or smaller than $\lambda_d$ so both trajectory and space charge effects can be important around the sensor head. Increasingly complex methods of solving the $\Phi(r)$ equations are the focus of this section. Some are too simplistic to explain the observed potential barrier but are still useful for learning details of the potential structure around the payload and the instrument. We show that non-monotonic potential sheaths are quite possible and a reasonable explanation for our observations of a cutoff.

### 3.3.1 Analytic Current Balance Solution for $\Phi_f$

The simplest case considers only thermal ion and electron flux for current balance in Equation 3.3.1. In darkness, these are generally the primary contributions. In sunlight, the thermal ion term is usually disregarded in favor of the dominant photoelectron emission. Assuming an ideal spherical probe that remains slightly negative in a Maxwellian plasma, the electron and ion currents at the probe are given by Fahleson (1967) as

\begin{equation}
I_e = 4\pi r^2 n_e \sqrt{\frac{kT_e}{2\pi m_e}} \exp \frac{e\Phi_f}{kT_e} \tag{3.3.4}
\end{equation}

\begin{equation}
I_i \approx 4\pi r^2 n_e \sqrt{\frac{kT_i}{2\pi m_i}} \tag{3.3.5}
\end{equation}
where \( r \) is the probe radius, and \( \Phi_f \) is the float potential of the surface. These equations illustrate that the thermal electron current is proportional to density and is reduced by an exponential near the surface. The thermal ion current, also proportional to density, is approximated considering the current drawn to the object in the limit of a thin sheath. These relations solve Poisson's equation for spherical symmetry and yield a monotonic shape for the potential structure around the object. Assuming a thin sheath \( r > \lambda_d \), Equations 3.3.1 - 3.3.5 can give the potential at the surface of the body as

\[
\Phi_f = \frac{-kT_e}{e} \ln \left( \frac{\sqrt{kT_e}}{2\pi m_i} \right) \ln \left( \frac{\sqrt{kT_e}}{2\pi m_i} - \frac{l_i}{4\pi e^2 n_e} \right)
\]  

(3.3.6)

As long as \( I_e = 0 \), which is true for a payload without active control or Langmuir probes, no dependence on ambient density is needed. For the simplest case where no current flows and temperatures are isothermal we see that \( \Phi_f = (-kT_e) \ln(\sqrt{m_i/m_e}) \). The mass ratio depends on altitude; above 600 km, the ionosphere is mostly \( \text{H}^+ \) whereas below 600 km \( \text{O}^+ \) dominates. Therefore as a payload moves up in altitude, \( \Phi_f \) can vary from 5.18 - 4.9 kT. With \( T_i/T_e \) values more typical of the ionosphere (from the International Reference Ionosphere shown in Chapter 1), \( \Phi_f \) varies from -5.25 kT\( e \) to -5.04 kT\( e \) as altitude is increased. The value maximizes at the lowest ion temperature and highest electron temperature up to \( \sim 5 \). It is difficult to increase it much above that. The addition of an ion ram term which can exceed the ion thermal flux at low altitudes only serves to decrease the value. For example, adding the 3.5 km/s ram plus plasma flow typical for SIERRA at low altitudes decreases the value further to 4.19 kT\( e \).

In terms of applicability to SIERRA this simplistic derivation should hold best for the electric field spheres and roughly represents their floating potential. This derivation is
less useful for the biased TED because monotonic potentials are built into the solution because of the assumption of an exponential shape for $\Phi(r)$. This simplest derivation also does not consider the other sources of current, such as auroral precipitation, various types of secondary emission, backscatter, photoelectrons, etc. Next we improve upon this framework by considering the relative current the biased TED surface and main payload draw as a system. This more complex picture must be constructed numerically.

### 3.3.2 Numerical Current Balance Solution for $\Phi_{s/c}$

Our next tool for exploring the expected effects of our instrument is a numerical current balance analysis program. The text of the program can be found in Appendix D. Though rudimentary it illustrates the way changes to the environment affect the floating potential of the TED-payload body system. As in the previous section we assume an exponential shape for $\Phi(r)$. We applied the equation for limiting current balance drawn by different sections of the payload to a numerical program in order to estimate the natural float potential for a surface of this size with applied biases over fractions of the surface. Equation 3.3.7 approximates the ion and electron current terms for the main payload or biased subsurface as:

$$I_{x,o} = nev_{th,x} A_o W(-e\Phi)$$  \hspace{1cm} (3.3.7)

where $x=$species, $o=$object, $A=$area, $W(-e\Phi) = \exp(-e\Phi/kT)$ when $\Phi > 0$, & 1 otherwise. This equation applies appropriately to either species. It either applies the full saturation current or retards part of it. Each term in the current balance is a function of the potential. To solve for the float potential $\Phi_{s/c}$, the sum of the currents

$$I_{\text{main}} + I_{\text{main}} + I_{gTED} + I_{ TED} = I_{\text{tot}}$$  \hspace{1cm} (3.3.8)
is plotted as a function of $\Phi$. Where $I_{tot}$ crosses 0, the spacecraft potential $\Phi_{s/c}$ is found. This method cannot tell anything about the form of the TED potential barrier because monotonic potentials were built into the model by the assumption of an exponential shape for $\Phi(r)$. These equations are not strictly self-consistent solutions to Langmuir’s equations, but the results seem to be qualitatively sound and useful for the purpose of examining the spacecraft potential magnitude. To solve these equations it is necessary to estimate the TED size relative to the main payload. This estimate varies between 1:40, and 1:200. It is surprisingly difficult to estimate the total surface area of a payload like SIERRA with exposed decks and irregular shapes.

Despite these approximations, this program is useful for exploring how the strength of the applied bias and the size of the biased area affect the float potential. These effects are shown in Figure 3-4. We see that for the larger area ratio (shown with the green lines), an increased skin bias only decreases the payload potential more. However when the TED represents a smaller piece of the system it can only affect the skin bias to a certain point. Beyond that, increasing the skin bias does not decrease the spacecraft potential further. We hope that the real TED case is closer to the latter since we want to apply the skin bias to the TED probe without driving the payload potential further negative. However there is a real possibility that the area of the TED was too large and drove the payload. The model shows that as the size ratio decreases the saturation current to the biased TED surface occurs closer and closer to the full payload saturation current.

Table 3.1 shows the amount of difference in $\Phi_{s/c}$ caused by the application of $V_{sB}$ for numbers typical of the SIERRA flight. We see that the maximum difference in spacecraft potential was caused at the high density and low temperature case. These numbers provide
Figure 3-4: Current vs. Voltage–The zero crossing gives the $\Phi_s / \pi$ where the currents balance. From right to left the skin bias values are 0, .5, 1, 1.5, 4 V. The black lines have an area ratio of 1:200 and the green are 1:40.

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<table>
<thead>
<tr>
<th>Case</th>
<th>~Δt (s)</th>
<th>Area Ratio</th>
<th>n (#/cc)</th>
<th>T (eV)</th>
<th>Ie0 (μA/m²)</th>
<th>VSB (V)</th>
<th>Φs/c (V)</th>
<th>Φs/c no bias (V)</th>
<th>ΔΦ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250-320</td>
<td>1/40</td>
<td>4e4</td>
<td>.45</td>
<td>-2544</td>
<td>1.5</td>
<td>-2.54</td>
<td>-2.31</td>
<td>.23</td>
</tr>
<tr>
<td>2</td>
<td>450-650</td>
<td>1/40</td>
<td>2e4</td>
<td>.45</td>
<td>-1272</td>
<td>1.2</td>
<td>-2.43</td>
<td>-2.31</td>
<td>.12</td>
</tr>
<tr>
<td>3</td>
<td>450-650</td>
<td>1/40</td>
<td>2e4</td>
<td>.45</td>
<td>-1272</td>
<td>1</td>
<td>-2.39</td>
<td>-2.31</td>
<td>.08</td>
</tr>
<tr>
<td>4</td>
<td>450-650</td>
<td>1/200</td>
<td>2e4</td>
<td>.45</td>
<td>-1272</td>
<td>1</td>
<td>-2.33</td>
<td>-2.31</td>
<td>.02</td>
</tr>
<tr>
<td>5</td>
<td>700-790</td>
<td>1/40</td>
<td>4e4</td>
<td>.18</td>
<td>-1610</td>
<td>.9</td>
<td>-1.2</td>
<td>-.92</td>
<td>.28</td>
</tr>
</tbody>
</table>

Table 3.1: Output from the Float program showing relevant Φs/c for SIERRA-typical input values.

a baseline for comparison to the TED measurements of Chapter 4. We can see whether the absolute predicted Φs/c or just the ΔΦ are accurate. Though this discourse has identified the problem that the TED may be too large, the effect of this problem is unlikely to cause a barrier signature. If the spacecraft potential is just driven more negative we would expect to see just the retarded energies. Clearly this is inconsistent with our signature of no counts below the skin bias energy. This tool can be expanded to include contributions from other terms and these will be discussed in Chapter 4.

3.3.3 In-Situ Barrier Example

We have shown many solutions for the potential at the payload which assume a form for the potential as a function of r. These cannot tell us about the barrier which the TED data require. A full solution of Vlasov’s equation is needed to rigorously examine the Φ(r).

This section will demonstrate that some real-life examples of barriers clearly illustrate that a monotonic solution to Poisson’s equation is insufficient. An in-situ observation where a potential barrier was invoked was that of the particle detectors on the ATS6 satellite (Whipple, 1976; Olsen et al., 1981). According to Whipple,
The data indicate the presence of a potential barrier in the spacecraft environment which is as much as 50 V negative with respect to the spacecraft. The barrier turns back the low-energy spacecraft emitted electrons and prevents the low-energy ambient electrons from reaching the detector. It is argued that the magnitude of the observed barrier is too large to be explained in terms of a simple photoelectron or secondary electron sheath around a uniformly charged spacecraft. The most likely explanation is the presence of differential charging of the spacecraft surfaces.

The differential charging was due to the large insulated dish antenna on the satellite and the proximity of the particle package (Olsen et al., 1981). In sunlight (darkness), photoelectrons (secondaries) emitted off the payload were shown to be the dominant low energy electron source detected. Even with negative spacecraft potential, the barrier was more negative than the spacecraft. Using the NASA Charging Analyzer Program (NASCAP) to model the geometry of the satellite, they showed the insulated dish surfaces were capable of providing an extra source of photoelectrons and secondaries to the experiment apertures. They also ruled out other smaller insulating sources. This example illustrates the complexity of sheaths due to geometry and insulating surfaces and the ability of photoelectrons and secondaries to become trapped in a potential barrier (Olsen et al., 1981). It also highlights the need for electrostatic cleanliness. In this case the NASCAP code was useful. It cannot be used in our case because \( r \approx \lambda_d \approx r_g \). The problem of differential charging, caused by different surface materials is a more typical problem with larger magnitudes of spacecraft potential charging. Though NASCAP cannot be used, we can use other computational technology to bypass the limitations with the analytical and numerical techniques presented so far.
3.3.4 PIC Code Solution for $\Phi(r)$

The descriptions above calculate the float potential of conducting surfaces and relax the potential from these boundaries. These Laplacian solutions cannot form potential barriers. For this we need to consider the actual charge distributions in the volume near the payload surface. Next we improve upon the traditional Debye shielding picture with a more sophisticated particle tracing approach, considering the fields created by the particles in a self-consistent way. Analytic or numeric solutions for the potential in real-life geometries are intractable; though simple cases are useful there are obvious shortcomings. For our case there are several compelling difficulties: the gyroradii and Debye lengths are the same order as the probe size, and a positive bias is only applied to a small irregularly shaped piece of the payload-probe system. For these reasons, we explore a particle-in-cell (PIC) code previously used for predicting the potential around charged mesospheric dust, a problem with many similarities (Lapenta, 1999; Delzanno et al., 2004). The spherical 1d3v PIC code has many benefits but is still computationally limited. Delzanno (2004) showed that non-monotonic potentials can develop on micrometeoroid dust. Usually charged negative, the dust can actually charge positive due to the space charge effect of thermionic emission. The modeling is adaptable to the TED with the key change being that instead of thermionic emission providing a main term to current balance, the secondary emission from the Aerodag surface is used. This secondary emission is driven by the ambient thermal fluxes. Dr. Giovanni Lapenta of Los Alamos National Laboratory has generously adapted his code to our situation.

The secondary emission process is defined by the ratio of outgoing to ingoing electrons.
Table 3.2: Parameters for 1-d Lapenta PIC model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Density (cm⁻³)</td>
<td>2*10⁴</td>
</tr>
<tr>
<td>Electron temperature (eV)</td>
<td>0.1</td>
</tr>
<tr>
<td>Ion temperature (eV)</td>
<td>0.1</td>
</tr>
<tr>
<td>Biased area (m²)(rₑff)</td>
<td>0.02</td>
</tr>
<tr>
<td>Debye length λ_d (cm)</td>
<td>1.66</td>
</tr>
<tr>
<td>Mass Ratio (mₗ/mₑ)</td>
<td>100/1</td>
</tr>
<tr>
<td>Skin Biases (V)</td>
<td>0.5, 1</td>
</tr>
</tbody>
</table>

from a material as a function of incoming energy spectrum. This maximizes at some energy $E_{max}$ with the maximum emission ratio given by $\delta_{max}$. According to the SEE database Aquadag and related graphitic carbon have wide variety of $\delta_{max}$ (Brennison et al., 2001a) The most accurate value seems to be 1.34 so this was used for the simulation. Other parameters used for the simulation run are summarized in Table 3.2. The PIC simulation considers only thermal electron and ion fluxes and secondary emission of electrons from the object caused by the impact of those fluxes.

Because this model actually follows the particles it makes no assumptions that $r >>> \lambda_d$ or $r << \lambda_d$. However, the model is 1-d and does not include the interaction of the TED-payload system. Magnetic fields and also other current sources such as auroral precipitation are not included. Once the simulation is run the results for an isolated spherical TED-like object in a similar plasma show that a non-monotonic potential can easily appear. Figure 3-5 shows the potential as a function of normalized distance for a given applied skin bias. The parameterized quantity is the temperature of the emitted secondary electrons. Note that the potential well is not all that large but the relatively easy formation of barriers in the potential sheath around a plasma object is important. Most experimental rocket and satellite scientists fail to realize that such structures exist naturally, so ingrained is
the traditional view of an exponential Debye sheath. We plan to continue this interesting result by adjusting the model parameters to as close to reality as possible and including a higher energy auroral current term. It is expected that the auroral particles driving secondary emission will deepen the depth of the well. Also it should be possible to move to two dimensions, adding the magnetic field and considering the fully coupled TED-rocket body. Since Lapenta's model does not have all possible current sources it is difficult to say how important the secondary emission is compared to other sources of potential. But it does show that perhaps secondary emission should not be discarded so easily, especially in the dark where the thermal ion flux is limited. The fundamental result that space charge effects lead to a potential barrier is important and highly applicable to our problem. The PIC code results show that both the Aerodag surface itself and the secondary population are important for current balance. However, there are serious geometric idealizations in the PIC code. Therefore this result dovetails nicely with laboratory-based efforts to investigate the barrier formation and surface effects.

3.3.5 Laboratory Testing

Theoretical solutions for $\Phi(r)$ have numerous shortcomings leading us to consider an option with more similarities to the auroral flight. Additional laboratory testing of the prototype TED was undertaken post-launch in order to sort out the various instrumental effects and characterize performance in an ionosphere-like plasma. This testing occurred at the Naval Research Laboratory Space Physics Simulation Chamber (SPSC), a unique facility for simulating the space environment in a controlled fashion. The goals of the testing were to reproduce the flight barrier issues in a realistic lab plasma and, in the process, to learn more
Figure 3-5: Potential (normalized to the applied bias) as a function of distance (normalized to the linearized Debye length) for varying emitted secondary electron temperatures. Input to the PIC code shown in Table 3.2. (Plot provided by G. Lapenta.)
Table 3.3: Ionosphere - Space Chamber parameter scaling

<table>
<thead>
<tr>
<th>Particle Parameter</th>
<th>Ionosphere (250 - 1000 km)</th>
<th>Space Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Density ( cm^{-3} )</td>
<td>( 10^2 - 10^6 )</td>
<td>( 10^5 - 10^{11} )</td>
</tr>
<tr>
<td>Neutral density ( cm^{-3} )</td>
<td>( \sim 10^{10} - 10^5 )</td>
<td>( 10^{11} - 10^{13} )</td>
</tr>
<tr>
<td>Electron temperature (eV)</td>
<td>0.1 - 0.6</td>
<td>0.1 - 2</td>
</tr>
<tr>
<td>Magnetic field strength (G)</td>
<td>&lt; .5</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Debye length ( \lambda_d(cm) )</td>
<td>2 - 6</td>
<td>( 7 \times 10^{-4} - 0.7 )</td>
</tr>
<tr>
<td>Electron gyroradius ( \rho_e(cm) )</td>
<td>4 - 10</td>
<td>0.015 - 0.4</td>
</tr>
<tr>
<td>( \lambda_d/\rho_e )</td>
<td>0.2 - 0.6</td>
<td>0.005 - 50</td>
</tr>
</tbody>
</table>

about the Aerodag surface. The PIC code results suggest that the secondary emission from the Aerodag may be contributing to or causing the potential barrier. The unique benefits of laboratory testing are controllability, repeatability, precision, and capacity for multipoint measurements with high time resolution to investigate fundamental plasma physics (NRC, 2003). The testing occurred at NRL for one week in November 2003 under the direction of the Plasma Physics Division Space Chamber lab scientists Drs. Bill Amatucci and Dave Walker.

Given the fixed geometry of the TED, a very ionosphere-like plasma was desired with very little scaling. Table 3.3 compares typical in-situ ionospheric conditions with those achievable in the SPSC. Note that the density, temperature, and magnetic field the TED was designed specifically for are on the extreme low end of the SPSC range. This would have been manageable except for the additional requirement of low neutral pressure to prevent microchannel plate (MCP) breakdown at high voltage. In the UNH vacuum chamber, safe operation is achieved down to \( \sim 5 \times 10^{-6} \) T. In the SPSC, MCPs are not normally used as part of the diagnostic equipment. At NRL, at a pressure of \( 1.5 \times 10^{-6} \) T, the TED worked briefly and then suddenly stopped working, as presumably an arc occurred and blew the...
pre-amplifiers. Not much usable data was obtained up to this point as we were still adjusting the plasma parameters.

These technical difficulties altered the initial goal from complete lab characterization of the barrier issue and probing the potential sheath around the payload to only testing of the surface properties. To do this, we operated the TED like a Langmuir probe under a variety of surface and plasma conditions. It was possible to have the TED either float or be connected to the chamber ground, and to compare with the carefully calibrated heated NRL probe. This new focus also continues interesting NRL research on developing contamination-free Langmuir probes.

In previous work Amatucci et al. (2001) showed that the heated NRL probe was effectively free of surface contamination while other traditionally coated probes showed significant effects despite careful attention to the material, work function uniformity, and cleanliness. Their focus was on a novel and effective method of cleaning a probe to remove easily adsorbed neutrals, which can appear and contaminate a surface within 1 second of exposure to air at atmospheric pressure. The primary contamination effect is the hysteresis that appears in the current-voltage traces indicating differing amounts of collected current dependent on the direction of the voltage sweep. This hysteresis also had the effect of causing up to order of magnitude errors in the derived temperature and plasma parameters from the current characteristic curve. Ultimately the mechanism by which contamination causes the hysteresis, whether due to work function variability or some other effect, was undetermined.

We were able to revisit this problem with the TED probe and the results are shown in Figure 3-6. In these tests, the fields and pressures were higher, more typical for the SPSC
since the particle counting electronics were not used. Significant hysteresis was observed. For comparison, the NRL probe diagnostics from the same time are also shown. While the TED indicated 1.7 eV temperature, this differed by a factor of 20 from the NRL probe. As in the previous results, this does not prove exactly how the contamination is caused. This test was repeated with variable Aerodag surface condition and plasma parameters. Initially, the coating was old and quite worn with numerous scratches and one large defect, caused by an accident with isopropyl alcohol. Then, we carefully recoated the Aerodag and retested. With this fresher coat, the hysteresis was considerably lessened as shown in Figure 3-6. This indicates that oxidation or contamination on top of the Aerodag surface may prevent good contact with the plasma. Unfortunately, NRL testing was severely limited by time and many other interesting effects remain unresolved. Future laboratory testing of the TED (if a method can be developed to allow MCP operation at higher pressures) could prove invaluable to the many outstanding questions raised about the surface preparation of the TED.

The observations of hysteresis connected with the Aerodag coating prompted more in-depth examination of this material. As discussed in Appendix A, the properties of Aerodag were researched by numerous methods: contacting the manufacturer, obtaining NASA Space Environment Materials testing reports, and conducting simple in-house tests (Acheson; Brennison et al., 2001a,b). We attempted to explain how the contaminated surface causes hysteresis and what this can tell us about the formation of a potential barrier. Was the problem indicating a surface charging issue relating to abnormally high resistivity in the graphite? If so, this could mean the applied skin bias was actually reduced at the outer surface, which could possibly give some similarities to a barrier. However, all tests
Figure 3-6: Counterclockwise from top left: 1) NRL probe, $T = 0.098 \, \text{eV}$, $V_{\text{plasma}} \approx 0.3 \, \text{V}$, $V_{\text{float}} \approx -2 \, \text{V}$; 2) TED probe with "old" coating, $T = 1.7 \, (1.7) \, \text{eV}$, $V_{\text{plasma}} \approx 3.75 \, (7.6) \, \text{V}$, $V_{\text{float}} \approx -1.4 \, (0.2) \, \text{V}$; 3) TED probe with "new" coating, $T = 0.36 \, (0.32) \, \text{eV}$, $V_{\text{plasma}} \approx 0.5 \, (2.0) \, \text{V}$, $V_{\text{float}} \approx -1.4 \, (2.3) \, \text{V}$; 4) NRL probe, $T = 0.1 \, \text{eV}$, $V_{\text{plasma}} \approx 0.2 \, \text{V}$, $V_{\text{float}} \approx -3 \, \text{V}$.
and references indicate that while it is not a very good conductor, the skin bias is actually
applied from the Aluminum through the Aerodag coating. Because we were not able to test
the exact flight coating, we cannot verify whether the flight TEDs may have experienced
local potential variations to cause a barrier. Therefore, we conclude that the skin bias was
effectively applied although some Aerodag effects may be responsible for the hysteresis. We
feel confident that the Aerodag was not primarily responsible for problems with the in-situ
TED data. Secondary electrons emitted from the Aerodag surface may still be a major fac­
tor, and our limited laboratory testing was not able to illuminate this point. Unfortunately
the lab testing was not able to show why a barrier forms or how it is related to the observed
hysteresis. These questions are interesting and appropriate to investigate in a lab plasma
if possible. Ultimately, much more useful and complementary work could be done between
the sounding rocket and laboratory plasma communities—this may be explored in the future
with an NRC associateship project and new plasma chamber development at Dartmouth
College (MacDonald, 2004; Frederick-Frost, 2004).

3.4 Other Possibilities

There are numerous other examples of anomalous unexplained effects in which the tradi­
tional Debye sheath picture does not hold. One is the case of payload-induced interference
seen by electric field spheres. This problem has occurred on many rocket and satellite flights
and has never been adequately explained. The problem suggests that despite booms much
longer than the Debye length, the payload sheath finds a way to interfere with the current
collection of the electric field spheres. On SIERRA the main payload electric field spheres
see interference from within 10° to a maximum of 30° of field aligned (Klatt et al., 2003).
This observation indicates a sheath that is at least ~8 cm and possibly up to ~1 m. The nominal Debye length is only a few centimeters as was shown in Figure 1-2. A 1 m sheath could explain why the main payload spacecraft potential can easily obscure the aperture of the TED. If the sheath is only around 8 cm then it becomes necessary for the sheath to travel along the unbiased boom in order to possibly obscure the aperture. The actual details of how a sheath forms around various types of boom-payload systems are poorly defined. Therefore either scenario is equally likely. The wave measurements indicate this type of interference is only field aligned. Therefore, the isotropy of such a sheath would be questionable. Our observations indicate the barrier exists at all pitch angles leading us to conclude the barrier the TED sees probably has a different source than that causing interference in the wave signals. This electric field problem is largely ignored in the literature; simple compensation for the interference in the electric field data is the usual outcome.

Another possible explanation for the unanticipated TED behavior is that the real Debye length may be many times its theoretical value. Theoretical evidence for an abnormally large Debye length can be attributed to the core population following a non-thermal Kappa function instead of a Maxwellian (Treumann and Jaroschek, 2002). There is some evidence that the ionosphere may support a Kappa population since it is the source for the plasmasphere which does support a Kappa distribution (Kletzing et al., 2003; Dors and Kletzing, 1999; Dors, 1998). J. Scudder, (personal communication, 2003), also notes that “stratified plasmas with open boundaries to collisionless regions are generally non-thermal.” The implications for this statement to the auroral ionosphere are not well-known. On the other hand however there is overwhelming evidence from radar sounding that in most types of aurora, a Maxwellian population is accurate for high frequency plasma oscillations. It is beyond our
initial analysis scope to constructively test the Kappa function idea in reconstructing the data. The necessary addition of another free variable, Kappa, would make it very difficult to synthesize the available data to a reconstruction theory and obtain meaningful results. Nonetheless, this observation is useful to indicate how contentious many of the most basic properties of the thermal electrons are and how the these basic properties can significantly affect the Debye length which in turn affects our attempts to measure them.

3.5 Conclusions

At this point it is still difficult to explain how the potential barrier forms. However, barriers do exist and we have shown several examples. It is very difficult to apply ideal probe theory or even more sophisticated simulation techniques to solve for the potential structure around a complicated object like the TED and rocket payload. We have shown how a barrier cannot result from traditional current balance and potential energy approaches, although these can be useful for predicting the potential of a simpler object like an unbiased payload or electric field spheres. This is useful to tell us what factors control the magnitude of the payload potential and how it changes. We need an estimate of $\Phi_{s/c}$ because we know, based on the electronics of the instrument and the start of counts at the skin bias energy, that the barrier strength equals the spacecraft potential. Therefore, when we utilize the potential barrier concept to analyze the data in Chapter 4, estimating the payload potential will be of utmost importance in reconstructing the original distribution.

The mechanism causing the barrier is difficult to identify. A potential solution with a barrier requires space charge and a mechanism for maintaining the pileup of space charge. To accurately simulate this situation requires a particle-in-cell code, which actually follows the
particles and fields they create in a self-consistent way. However, the PIC code simulation lacks completeness, mostly because it is one dimensional. The PIC code implicates the secondary electrons produced off the Aerodag TED surface for causing the barrier. The surface properties were tested in a laboratory plasma. Ultimately this testing was unable to produce the right environment to test the TED. Therefore the culprit for the barrier remains at large. However, the testing indicated that the Aerodag surface may be susceptible to contamination. Unfortunately more testing will be required to understand this effect and its possible connection to the inferred potential barrier. Other possibilities may explain the formation of a barrier and have been considered but not identified as the definitive source of our problems. Despite the numerous possible sources for a small potential barrier, we believe the data are recoverable assuming a technique for reconstructing the data, and together with a framework where \( V_{\text{barrier}} = \Phi_s/c \).

Throughout this chapter we have explored many avenues to try to understand this apparent strange TED behavior. It is very difficult to evaluate quantitatively the shape and strength of the potential around a conducting object with the precision needed for this application, i.e. less than 1V. There are many sources of stray potentials of this size. Perhaps the best idea is to use the data and let that tell the story, as we will do next in Chapter 4. This can help to identify the source of the barrier uncertainties. Also as important is that despite these difficulties there is still much we can say about the geophysical quantities measured by the TED detector, given the framework of the reconstruction technique.
This chapter utilizes the theories developed in Chapter 3 to maximize the scientific data return from the TED. We focus on extracting the key moment parameters of thermal electron temperature, density, and flow. These calculations require an estimate of the spacecraft potential and its relation to the barrier strength. Given the problems encountered in interpreting the raw data (described in Section 3.1) and the trade-offs involved in managing these problems, we have developed two different analysis methods for shifting the energy of the measured population to the plasma frame. These two “shift methods” will be explained and their results evaluated in this chapter. Both methods rely on fitting the tail of the spectrum to a Maxwellian population and deriving the temperature, so the fundamental result of thermal electron core temperature is discussed first. The fitted core temperatures are important in their own right and can be derived without knowing the absolute energy axis.

In Shift Method 1, the form first described in Section 3.2, the barrier potential is equal to an estimated payload potential. The estimated payload potential is used to shift the energy spectra from the instrument frame to the plasma frame and allows the derivation of the reconstructed Maxwellian distribution density. These results are sensitive to accurate temperature fitting and knowledge of the sensor-plasma potential. The results of Method 1 are examined in conjunction with other data onboard the rocket, comparing the density response to varying auroral precipitation, and verifying the accuracy of the density by
comparison with the HF wave receiver measurement.

These comparisons motivate the development of Shift Method 2 which enables a quantitative evaluation of the $\Phi_{\text{shift}}$ measurement. Shift Method 2 does not assume the magnitude of the barrier or the payload potential is known, but calculates it explicitly by forcing the density result to equal our independent confirmation via the HF wave receiver. Each method has advantages which aid in producing meaningful results from an under-determined problem. Also, we can begin to derive flow from the difference in upgoing versus downgoing populations.

4.1 Maxwellian Thermal Temperatures

Transforming from raw counts to distribution function $f$ is straightforward. In this type of detector raw count rate is proportional to differential energy flux. Differential energy flux is itself proportional to $f/E^2$. Equation 4.1.1 shows the transformation from count rate to $f$, applying the geometry factor and other specifications given in Chapter 2.

$$f(E_{\text{plasma}}) = \frac{(CR)m_e^2}{2E_{\text{plasma}}^2G}$$

where CR is the count rate and G is the geometry factor (including $(\Delta E/E)$). For a thermal electron detector on a charged payload the transformation is complicated because $E_{\text{measured}} \neq E_{\text{plasma}}$. The distribution function will be corrected to the plasma frame in the next section. For now we need only realize that $E_{\text{measured}} = E_{\text{plasma}} + e\Phi_{\text{shift}}$. For an isothermal 3-d Maxwellian spectrum:

$$f(E_{\text{plasma}}) = n\left(\frac{m}{2\pi kT_e}\right)^{3/2} \exp\left(-\frac{E_{\text{plasma}}}{kT_e}\right)$$  

(4.1.2)
Table 4.1: Distribution of the fit qualities

<table>
<thead>
<tr>
<th>Fit Types</th>
<th>Good(%)</th>
<th>Ok(%)</th>
<th>Bad(%)</th>
<th>Secondary(%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TED1</td>
<td>447(53)</td>
<td>270(32)</td>
<td>83(10)</td>
<td>36(4)</td>
<td>836</td>
</tr>
<tr>
<td>TED2</td>
<td>219(26)</td>
<td>355(42)</td>
<td>213(25)</td>
<td>49(6)</td>
<td>836</td>
</tr>
</tbody>
</table>

\[
\ln(f) = \ln\left(n\left(\frac{m}{2\pi kT_e}\right)^{3/2}\right) + \left(\frac{-E_{\text{plasma}}}{kT_e}\right). \tag{4.1.3}
\]

Substituting for \(E_{\text{plasma}}\) we note a linear relationship between \(\ln f\) and \(E_{\text{measured}}\):

\[
\ln(f(E_{\text{measured}})) = \ln\left(n\left(\frac{m}{2\pi kT_e}\right)^{3/2}\right) + \left(\frac{e\Phi_{\text{shift}}}{kT_e}\right) + \left(\frac{-E_{\text{measured}}}{kT_e}\right). \tag{4.1.4}
\]

When plotting \(\ln f\) versus \(E_{\text{measured}}\), the slope of the line is equal to \(-1/kT_e\). Thus we can fit any portion of a Maxwellian population to a straight line and derive the core temperature from its slope. In our case, we can fit only the portion of the distribution that we were able to measure.

This line fit was done for all measured spectra of TED1 and TED2. Averaging was required to achieve significant counts above the 1-count noise level. This reduced the time resolution to 4 bin periods per spin. Calculating the fit involved an iterative approach to finding manually the best fits over at least a 0.5 eV energy range beginning near the skin bias. As shown in Figure 3-2 and discussed in Section 3-1 counts were only observed beginning at the energy of the skin bias. Spectra were categorized by eye into four categories according to the quality of the fit: good, ok, bad, and “secondary”. Table 4.1 illustrates the distribution of TED1 and TED2 data into these four types.

This method selected approximately 50% of the TED1 fits as good and suitable for further analysis. The “secondary” type generally means no cutoff was observed consistent with only seeing the hotter secondary electron population. This generally occurs at times...
Figure 4-1: Ln $f$ vs. $E_{\text{measured}}$ for good fits. Skin bias shown (red), 1-count line shown (blue), and fitted line shown (green). The temperature derived from the fit is shown in the top right of each panel. (Note the $f'$ quantity is proportional to $f$. A correction to the physical units is done in the calculation but not shown on these plots.)

when the skin bias has dropped steeply. Typical examples of each type are shown in Figures 4-1 and 4-2. Notice that the one count line effectively shifts depending on the magnitude of the skin bias. This means that at the lowest skin bias values, the one count can “cut off” the possibility of detecting the lowest energies.

Figure 4-3 shows the temperature derived from Maxwellian fits to “good” spectra from TED1 and TED2. These generally agree with each other except after 700 seconds, where TED2 is higher and more variable. Also shown in the figure is the auroral electron spec-
Figure 4-2: Ln f' vs. E_{measured} for ok (top), bad (middle), and "secondary" fits (bottom). Skin bias shown (red), 1-count line shown (blue), and fitted line shown (green). The temperature derived from the fit is shown in the top right of each panel. (Note the f' quantity is proportional to f. A correction to the physical units is done in the calculation but not shown on these plots.)
rogram, giving the characteristics of the auroral environment during the SIERRA flight. In comparison with the auroral data we see the TED measured the coldest ionospheric temperatures outside of auroral arcs (e.g. near 450 seconds, and after 700 seconds). At these times $kT_e$ was as low as 0.1 eV, which agrees well with standard ionosphere models considering the location, season, activity level, and altitude of the in-situ observation. During auroral precipitation, the temperature generally rose to between 0.3 - 0.8 eV. Based on examination of the fitted spectra, it is believed these are still heated core temperatures and not the secondary electron temperature. No clear transition in characteristic temperatures is seen between inverted V type arcs to Alfvénic arcs (after 530 seconds) although the temperature in the Alfvénic region seems more variable. Temperatures also seem to rise near 300 seconds coincident with the start of field aligned bursts under the inverted V energy. Very few noticeable angular trends are observed when looking at the good points separated by pitch (not shown). This indicates the barrier was fairly isotropic. At times, the temperature of the highest (non-core) electrons varied in sync with the field aligned auroral secondary population. These times are largely excluded from this plot as they fall into the “secondary” category. These temperatures will now be used for further analysis to aid in calculating other moments such as density.

4.2 Density

4.2.1 Shift Method 1

Despite the potential barrier problem the original distribution can be reconstructed assuming the thermal electron population has Maxwellian form and that a quantitative estimate
Figure 4-3: TOP (TED1) & BOTTOM (TED2): Fitted temperatures (black points, and blue smoothed line) versus time, MIDDLE: HEEPS count rate spectrogram (proportional to differential energy flux) and altitude versus time.
for the payload potential can be made. We also assume that the magnitude of the barrier is equal to the payload potential. Since no direct measurement is available, we first detail our calculation of the payload potential and then describe the full reconstruction technique. Note that Shift Method 2 will provide an evaluation of Shift Method 1.

Spacecraft Potential Estimation

The payload potential is frequently (though inaccurately) estimated by examining the spin-averaged sphere to skin potential difference (Vss) from the E-field instruments. The Vss measurement was discussed in the last section of Chapter 2. For the SIERRA main payload, this value was most often -0.9 +/- 0.1 V. As shown in Figure 4-4, all three spacecraft had similar Vss indicating that the main payload sphere-to-skin potential was not changed by the presence of the biased TED. However, the Vss measurement does not tell us anything about where the payload-spheres system sits with respect to the plasma ground. It only tells us the differential charging between the ideal spheres and the irregular payload. To anchor this system, we need to calculate the idealized float potential of the spheres.

By standard probe theory unbiased isolated spheres in a plasma should float 4 - 5 kT from the plasma potential. This result, described in Section 3.3.1, considers only the ambient isothermal and isotropic thermal fluxes and ignores contributions from other sources such as auroral current or secondary electrons. Thus, our first estimate of the spacecraft potential is assumed to be Vss - 5kTe. This is shown in Figure 4-5 based on the actual fitted temperature. This estimate indicates the payload potential was between ~ -1.5 and -4 V throughout the flight. This estimate falls within some typically quoted values of a few volts negative for payloads in the dark auroral environment. It is a little more negative than
Figure 4-4: $V_{ss}$ signals from all three spacecraft (Black=Main, Red=Forward, Green=Aft). Different panels advance in time.
other estimates of only ~1V negative, which are likely based on only the typical $V_{ss}$ values (and thus incorrect). Also shown is the skin bias which is generally more positive than $|V_{ss}|$ but not usually more positive than $|V_{ss} - 5kT_e|$. Note that this estimate for $\Phi_{s/c}$ does not include known contributions to the current balance equations such as auroral precipitation flux and secondary emission. However, we proceed towards a comparison with data from the HF receiver.

**Reconstructing the Full Distribution**

We can use the best derived temperatures and this estimate of payload potential to calculate the density of the thermal electron population as measured by the TED. We assume a Maxwellian distribution, i.e. Equation 4.1.2. Liouville’s theorem states that the distribution function must be conserved across the sheath boundary. Therefore, $f(E_{\text{measured}}) = f(E_{\text{plasma}})$ where $E_{\text{measured}} - e\Phi_{\text{shift}} = E_{\text{plasma}}$. To do this, we shift the spectra by the sum of the applied skin bias and the total payload potential, $V_{ss} - 5kT_e$. The strength of the barrier is $V_{ss} - 5kT_e$, our model of the spacecraft-plasma potential. This effectively shifts the distribution as was described in Figure 3-3, first by the barrier potential and then (in the opposite direction) by the skin bias. Figure 4-5 also shows $\Phi_{\text{shift}} = V_{SB} + \Phi_{s/c} = V_{SB} + V_{ss} - 5kT_e$. Note that the red points indicate the TED applied bias was not enough to raise it above plasma ground at any time. However the TED was positive with respect to the payload potential. The barrier picture still holds because of the location of the counts in the instrument frame.

We now use this calculation for $e\Phi_{\text{shift}}$ in our calculations of electron density. The natural log of Equation 4.1.2 yields an advantageous form for calculating temperature and
Figure 4-5: Skin Bias (black), $V_{ss}$ (green), $\Phi_{\text{S/C}} = V_{ss} - 5kT_e$ (blue), $\Phi_{\text{shift}} = V_{SB} - V_{ss} - 5kT_e$ (red).
density, Equation 4.1.4. When fitting $\ln f(E_{\text{measured}})$ versus $E_{\text{measured}}$ the y-intercept is related to the density:

$$y_{\text{int}} = \left( \frac{e^{\Phi_{\text{shift}}}}{kT_e} \right) + \ln(n_e) \left( \frac{m_e}{(2\pi kT_e)^{3/2}} \right)$$

and the slope is just $-1/kT_e$. Since we fit each spectra to find the y-intercept given a calculated $\Phi_{\text{shift}} (t)$, we can solve for density as

$$n_e = \frac{\exp^{-\Phi_{\text{shift}}/kT_e}}{(2\pi kT_e)^{3/2}}$$

4.2.2 Calculated Density from Shift Method 1

Figure 4-6 shows the density derived from each TED by Shift Method 1 (in dark gray symbols). Also shown on the graph is the density derived from plasma frequency points observed by the HF wave receiver throughout the flight. Our discussion of error analysis is reserved for Section 4.4 but here we discuss the relative discrepancies between the measurements of density. For TED1 the measurements are considerably lower than the HF measurements except at times greater than 700 seconds. Earlier the density from Method 1 seems as much as a factor of 10 too low though there is some agreement in the variation of density.

For TED2 the agreement is poorer, which is not surprising considering the abnormality in sensitivity observed after 700 seconds.

Compared to previous nightside auroral rocket flights to similar altitudes, the ambient density is fairly high. This indicated that the rocket did not reach into the auroral cavity or the potential drop region, usually located between 1000 km to 10000 km. One to one correlations between the ambient density and the auroral precipitation are not obvious. The dependence of density on altitude is clearly seen. The large density increase in the Alfvénic
Figure 4-8: TOP (TED1) & BOTTOM (TED2): Density assuming Shift Method 1 (gray points, and blue smoothed line) versus time, and density from HF wave receiver (red points). MIDDLE: HEEPS count rate spectrogram (proportional to differential energy flux) and altitude versus time.
region between 600 - 700 seconds is somewhat unusual and not strongly correlated with any other observations except possibly ions. Overall it seems our assumption for the spacecraft potential is most accurate at times outside active aurora and at lower altitudes. It is also reasonable to surmise that the auroral precipitation and possibly also other current sources affect the spacecraft potential and must be properly taken into account. Next we attempt to remove our a priori assumption for the form of the spacecraft potential.

4.2.3 Shift Method 2

In order to improve upon the results of Method 1 it is possible to use the same temperatures and calculate the necessary total energy axis shift to match the HF density exactly. This “HF shift”, $\Phi_{HFshift}$, can then be compared to our estimate of $\Phi_{shift}$. Thus we can compare our estimate of the spacecraft potential to an exact derived value. We set the density from Equation 4.2.2 equal to $n_{HF}$ and solve for the required shift potential as:

$$\Phi_{HFshift} = kT_e(y_{int} - (ln(n_{HF}(-\frac{m_e}{2\pi kT_e})^{3/2})))$$  \hspace{1cm} (4.2.3)

This method relies heavily on the accuracy of the HF density and further reduces the time resolution to only spectra very near times when HF density can be calculated. In applying this method pitch angle information is lost because the HF density is not directional. The benefit of this method is that it removes our estimate of the payload potential. Instead we directly compare what required shift we need, $\Phi_{HFshift}$, to our previously assumed function $\Phi_{shift}$.

Figure 4-7 compares the HF-derived shifts to the idealized $\Phi_{s/c}$ values. The top panel compares the shift values, $\Phi_{HFshift}$ and $\Phi_{shift}$ from the two methods. $\Phi_{HFshift}$ is generally
more negative than $\Phi_{shift}$, as it should be, since more shift is needed to increase the density to the real HF density values. After 700 seconds, the two generally agree, validating our initial assumptions that, outside auroral precipitation, the payload potential is $\approx V_{ss} - 5kT_e$. 

The next panel compares the two calculations for the spacecraft potential; $\Phi_{HFshift} - V_{SB}$, and $V_{ss} - 5kT_e$. The HF-derived $\Phi_{s/c}$ shows the potential was approximately $-4$ V, more negative than previously thought. If the payload potential is really this large then it should be possible to see accelerated thermal ions from such a large spacecraft potential. However the bottom energy step of the HEEPS ion detector does not see any such ions except from 600 - 700 seconds. There are several possible explanations for this inconsistency. The most likely is that our fitted temperatures could be too high. This would cause too large of an HF shift to be calculated to match the densities.

The difference between $\Phi_{HFshift}$ and our modeled $\Phi_{shift}$ for TED 1 and TED 2 is shown in the bottom panel of Figure 4-7. At the beginning of the flight as much as 1.5 V extra is needed to match HF density, while at the end only -0.5 V is needed. At the end there are even some positive values indicating that a reduction in density was required. TED 2 shows a much larger and more variable additional shift was needed at the end. The cause of this asymmetry is not certain at this time and thus generally we focus our discussion and conclusions on TED1. All in all, the difference between $\Phi_{HFshift}$ and $\Phi_{shift}$ will now be examined in terms of in what ways our assumptions of $\Phi_{s/c}$ for Shift Method 1 were insufficient.
Figure 4-7: TOP: Comparison of net shifts (TED1): HF shift (black) compared to \( \Phi_{\text{shift}} = V_{SB} - V_{ss} - 5kT_e \) (red). MIDDLE: Comparison of implied \( \Phi_{s/\ell} \) (TED1): HF shift - \( V_{SB} \) (black) compared to \( V_{ss} - 5kT_e \) (blue) and just \( V_{ss} \) (green). BOTTOM: Change in net shifts: \( \Phi_{HF\text{shift}} - \Phi_{\text{shift}} \), TED1 (black) TED2 (gold).
4.2.4 Comparison of Shift Method 1 and Shift Method 2 Results

This section will explore the nature of the difference between $\Phi_{HFshift}$ and $\Phi_{shift}$ in two parts: first an examination of the implied adjustment to $5kT_e$ which is required, and then the subsequent analysis of the dependence of this adjustment on the auroral environment.

First we study how the difference between $\Phi_{shift}$ and $\Phi_{HFshift}$ may be related to $kT_e$. $\Phi_{HFshift} - (V_{SB} + V_{ss})$ represents just the piece of the payload potential that should be proportional to $kT_e$. To examine directly what multiple of $kT_e$ may be required we have shown $(\Phi_{HFshift} - (V_{SB} + V_{ss}))/kT_e$ as a function of time in Figure 4-8. The plot indicates that a variable multiplying factor of 7 - 8 down to 4 - 5 at the end is necessary to account for $\Phi_{HFshift}$. Physically this suggests that in auroral precipitation it is necessary to increase the spacecraft potential from the usual value of $5kT_e$, while outside of the precipitation, $5kT_e$ works well. Another explanation could be that there was an additional source of contamination which contributed to this charging and weakened as the flight progressed.

A different way to explore this relationship is illustrated by a scatter plot of HF shift - $(V_{SB} + V_{ss})$ vs. $kT_e$. Given that:

$$\Phi_{shift} = V_{SB} + V_{ss} - 5kT_e$$ \hspace{1cm} (4.2.4)

and assuming that

$$\Phi_{HFshift} = V_{SB} + V_{ss} - xkT_e$$ \hspace{1cm} (4.2.5)

we can write

$$\Phi_{HFshift} - V_{SB} - V_{ss} = -xkT_e$$ \hspace{1cm} (4.2.6)

and plot this linear relationship against $kT_e$ to find $x$. The bottom panel of Figure 4-8
Figure 4-8: TOP: \( \Phi_{HFshift} - (V_{SB} + V_{ss})/(kT_e/e) \) vs. time (TED1: black; TED2, gold). BOTTOM: \( \Phi_{HFshift} - (V_{SB} + V_{ss}) \) vs. \( kT_e \) (TED1: colors described in the text).
shows this scatter plot color-coded to indicate the different regions of precipitation roughly delineated by time. The first period consists of the primarily upward current regions prior to 500 seconds (dark blue), then the Alfvénic region from 500 - 700 seconds (light blue), and finally the polar cap after 700 seconds (green). We note an excellent fit to a straight line with a consistent slope of 8.1 over time. This fit is predictable due to the proportionality inherent in the form of Equation 4.2.3. We also note that the intercept of this correlation is not zero. In fact, the intercept is ~0.46. At first, this result seems to contradict the previous plot which showed agreement to a variable integral of kT_e over time. In truth they are consistent as the previous plot did not allow for an intercept. If the intercept given by Figure 4-8 is incorporated then the slope of 8.1 is recovered. Our interpretation of this positive offset is that the sense is to oppose V_{ss} so actually the true sphere-to-skin potential is reduced. This reduction was probably caused by an overestimate of the sphere-to-skin potential because of the difference in contact potentials between the payload and the Titanium-Nitride electric field spheres.

In addition to the offset, the slope is much different from the 5kT_e figure predicted from the simple analytic solution. Explaining this difference and its implications for how far from the plasma the electric field spheres float will be a major part of the rest of this work. In Section 3.3.1 we first noted that the ~5kT_e value for the ideal spherical floating potential, \( \Phi_f \), is quite consistent over a typical ionospheric range of ion to electron temperatures and masses. Indeed it is difficult to reach above five by changing either mass or temperature ratios from reasonable values. However the net effect of auroral precipitation and secondary emission is difficult to quantify and was not included in these calculations thus far. Several more interesting correlations are now considered, some of which can shed light on the
Figure 4-8: TED 1 (colors delineate time as in Figure 4-8). TOP: $\Phi_{s/c}$-derived from Shift Method 2 ($V_{HFshift} - V_{SB}$) vs. log($I_{aur}$). BOTTOM: Change in $\Phi_{s/c}$ (($V_{HFshift} - V_{SB}$) - ($V_{ss} - 5kT_e$)) vs. log($I_{aur}$). Additional (blue) points from Float program.
complete consideration of all terms contributing to the current balance.

In particular we were interested in the effect of the auroral precipitation on the magnitude of the spacecraft potential. Using the HEEPS detector we can actually measure the amount of current carried by the auroral particles. Thus we tried plotting our measure of the true total spacecraft potential, HF shift - $V_{SB}$, as a function of $\log(I_{aur})$ in the top half of Figure 4-9. $I_{aur}$ is the non-directional total auroral current, and is related to the ESDFAC shown in Figure 2-14 and derived in Appendix C. Since it is omnidirectional the total auroral current striking the payload can be significantly larger (> 10$\mu$A/m$^2$) than the net field aligned current. The shape of the correlation in Figure 4-9 shows a functional relationship between the spacecraft potential and the auroral current which warrants further exploration.

The bottom of Figure 4-9 shows the additional shift needed to match the HF density as a function of the logarithm of the auroral current. This additional shift is also plotted versus time in the bottom panel of Figure 4-7 and represents the difference in calculated payload potentials from the first and second methods. A linear fit of this difference versus the logarithm of auroral current is seen with highest deviations occurring with highest auroral current, a totally independent quantity. Note we also are underestimating the auroral current when the peak of the largest arcs is not fully resolved by the HEEPS detector (such as 300 - 370 seconds, and 475 - 525 seconds). We believe correcting this would tend to improve the straight line fit.

Another interesting confirmation of this relation is shown by the blue points in the bottom half of Figure 4-9. These were derived from the simple current balance Float program (first described in Section 3.3.2). With these points we are plotting the change in calculated
payload potential as a function of an added term to the current balance to simulate the addition of auroral current. The additional current values used were between 0.1 – 5\mu A/m², and the initial spacecraft potential was -1.5V. While the actual magnitude of the payload potential is not consistent with our results the magnitude of the change in the payload potential seems generally consistent, another independent confirmation of this relation. We believe the reason the blue points decrease so steeply is because of some saturation problems in the model but nonetheless, the good agreement is heartening.

Figure 4-9 shows that the difference in payload potential implied by \textit{Shift Method 2} compared to the simplest estimate is driven by current contributors not properly taken into account in the \textit{Shift Method 1} approach; this includes both the auroral precipitation and other sources of current. To progress further in exploring the effect of these current terms on the resultant charging we can improve the equation for analytical current balance given by Equation 3.3.6 by allowing the auroral current to contribute and rewriting as:

\begin{equation}
\Phi' = -(kT_e/e) \ln\left(j_e/\left(j_i - I_{aur}\right)\right)
\end{equation}

where \(I_{aur}\) is the total auroral current, the thermal fluxes are \(j_x = nev_{thx}\) and the thermal velocity is \(v_{thx} = \sqrt{2kT_x/m}\). This equation contains the standard assumptions for an ideal sphere to calculate the current balance. The form of Equation 4.2.7 is useful because we can now calculate the right-hand side and compare it to our measure of the multiplicative factor from \textit{Shift Method 2}, \(\Phi_{HFshift} - V_{SB} - V_{ss}\). The magnitudes of \(j_e, j_i,\) and \(I_{aur}\) are shown in Figure 4-10. Note \(j_e\) is multiplied by 0.006 to fit on the same scale. Also note that for this plot, the ion temperature was chosen to equal 4 times the electron temperature, and the \(m_i\) to equal 9\(m_H\) (both typical for a mix of \(O^+\) and \(H^+\) in the ionosphere). Figure 4-10
shows that auroral current is comparable in size to the thermal ion current, and therefore should not have been neglected.

Next we can plot our measure of $\Phi_f$ from Equation 4.2.7 versus the HF-derived equivalent, $\Phi_{HFS\text{hift}} - V_{SB} - V_{ss}$ to see how well they are related. Since they both describe how far from plasma ground the electric field spheres float we would expect them to be equivalent. This is shown in the bottom half of Figure 4-10 where the fitted line has a slope of -1.8 and an offset of 0.23. The measured slope of 1.8 rather than 1 says that our model for $\Phi_f$ is still incomplete. This inaccuracy could be from ambiguity in the thermal ion flux term, the auroral current term, or from the fact that the measured auroral current does not include a correction for secondary emission.

First, we can calculate the necessary ion temperature for the thermal ion term to adjust the slope of Figure 4-10 to 1. Using a realistic mass ratio of 9*mass of hydrogen for most of the flight, we arrive at the ion temperature shown in Figure 4-11. Also shown is the implied ratio of $T_i/T_e$ required to produce these results. Previous thermal ion measurements have not found such high core temperatures (Moore et al., 1996; Moore et al., 1996; Lynch et al., 1999; Burchill, 2003). It is thus more likely that the differences in slope are caused by lack of completeness in Equation 4.2.7 since other sources are not considered such as the secondary electron emission which may affect the payload current balance.

Secondly, we can examine the relative importance of the auroral term. Without it, Equation 4.2.7 gives a smaller (less negative) floating potential. This makes sense because direct auroral current collection should move the payload more negative. Secondary emission should be coupled as it reduces the magnitude of the auroral term or even changes its sign, thus effectively reducing the overall floating potential. We can estimate the secondary
Figure 4-10: TOP: 0.006*$j_e$ (blue), $j_i$ (green), and $I_{aur}$ (black), BOTTOM: $\Phi_{HFshift} - V_{SB} - V_{ss}$ vs. $kT_e * \ln(j_e / (j_i - I_{aur}))$.

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emission necessary to improve the slope of Figure 4-10 to unity (not shown). This shows that in the largest arcs, the secondary emission would reduce the effect of the auroral current while in other regions, the auroral current proportional term would need to increase to nonphysical values. This is also indicated by the fact that for the slope of Figure 4-10 to change from -1.8 to -1 it is necessary to decrease the denominator in Equation 4.2.7: a direction contradictory to accounting for the secondary emission term. Thus it is likely that a more complicated combination of corrections to the secondary, auroral, and ion fluxes is needed to make our calculated estimates for these fluxes equivalent to the implied spacecraft potential of the floating spheres from Shift Method 2.
4.2.5 Debye Length

Using the basic results of Sections 2-1 and 2-2 we can calculate several other relevant parameters. The first is the nominal Debye length around the spacecraft versus time. Figure 4-12 shows $\lambda_d$ and the radius of the TED. The approximate distance from the aperture to the boom is ~15 cm. The Debye length changes by a factor of nearly 5 through the flight. At the end of the flight, because of the low temperature and higher density, $\lambda_d$ is less than the size of the two TEDs. At times of highest temperature the main payload Debye sheath traveling along the boom may be significant enough to obscure the aperture of the TED. The Debye length indicates the variability of the current balance equilibrium, which possibly can change from orbit motion limited to the space charge dominated regime over the course of the trajectory.
4.2.6 The Density - Payload Potential Relationship

In 2002, using TECHS derived data and models for temperature, density, and payload potential, Adrian (2002) showed a relationship which was consistent with the relation between density and payload potential observed for satellite data (Escoubet et al., 1997). These rocket data in positive and negative payload potential regions were consistent with the trend of satellite observations at higher positive potentials. Adrian (2002) also noted that at negative potentials, temperature was more important than density for determining \( \Phi_{s/c} \). The TED measurements can be compared similarly though with the caveat that the mission was in darkness and encountered no photoelectrons unlike SCIFER and satellite observations. Figure 4-13 shows density versus temperature and density versus \( \Phi_{HFshift} - V_{SB} \). Strong functional relationships are not observed. This lack of correlation indicates that the current balance situation in the dark is quite different than in sunlight; with no photoelectron generation, the spacecraft potential does not depend directly on density.

4.3 Flow

Deriving the current carried by the thermal electrons was a primary goal of the TED instrument. This is why the two TEDs looked in opposite directions at the same time. Unfortunately the low count rate and inaccurate density of Shift Method 1 makes it very difficult to calculate flow. At the end of the flight where Shift Method 1 works the best, TED 1 and TED 2 unfortunately cannot be compared directly without correcting for additional issues with the TED 2 response. Shift Method 2 fits all pitch angles to a unidirectional HF density so by necessity it cannot provide an estimate of the flow. If the count rate were
Figure 4-13: TED 1 (colors delineate time as in Figure 4-8). TOP: density vs. temperature. BOTTOM: density vs. $\Phi_{HFshift} - V_{SB}$.
higher and less averaging was required, and if Shift Method 1 yielded an accurate measure of density, the proper method for calculating current would be an integration of $n e v_{th}$ over all 3-d velocities. In the future, with improved TED performance this method should be very important for yielding information about the flow of thermal electrons. If the return current region carried an estimated current of 100 $\mu$A/m$^2$ in the thermal electrons, a drift velocity of $\sim$30 km/s would be evident in the TED.

Given the data we have available for SIERRA, a simpler way to check for flow is to compare density between the TEDs when they are both field aligned. We can also then calculate the drift velocity as

$$v_{drift} \approx \delta n < v_{th} > / < n >$$

(4.3.1)

where $\delta n$ is the field aligned difference in density, $< v_{th} > = 590 \sqrt{< T_e >}$[eV] is the average thermal velocity in km/s from TED1 and TED2 and $< n >$ is the average density from the HF density. In a very limited way we can do this for our TED measurement. Restricting to times when TED 1 looks toward 0° and TED 2 looks toward 180°, and both are good fits, limits the dataset to 61 samples. (In theory the reverse angles are also possible but a small programming error caused the averaged pitch angle bins to misalign so this example will only consider these pitches initially). Additionally we must exclude times greater than 700 seconds where the response of the two TEDs are not consistent.

Figure 4-14 shows the drift velocity calculation from Equation 4.3.1 along with the HEEPS auroral electron spectra. For the average density the HF density was used in order to reduce the sensitivities in Shift Method 1. There are a few times when there are more thermals flowing up than down which roughly correspond to gaps in auroral precipitation;
likely places of return current. It cannot be emphasized enough that the lack of good fits
when coupled with the restriction to conjunctive good times for TED1 and TED2 severely limits
the interpretation of these results. Because it is a difference it is also very sensitive to small
inaccuracies in the temperature fitting. Another limitation is the use of the Shift Method
estimate of payload potential for these points which we know is inadequate particularly
at the times we consider. The largest of these drifts are ~20 - 30% of the electron thermal
velocity. It is estimated that the minimum ratio of $v_{drift}/v_{thermal}$ to excite wave growth
would also be ~20 - 30% (P. Kintner, personal communication, 2004). More work is needed
to quantify the accuracy of our drift calculation.
4.4 Error Analysis

It is necessary to consider the uncertainties in our measured quantities and how these propagate and affect the results. We will consider three primary sources of error: calibration error due to imprecise knowledge of the geometry factor, uncertainties derived from the linear regression fit, and uncertainty in the measured density values from the HF wave receiver. We shall use the techniques of error analysis to derive how these errors can affect our results from both Shift Method 1 and Shift Method 2.

The error in the geometric factor $G$ is not a random error but rather a possible source of systematic error. We have examined the effect of $G$ being inaccurate by a factor of $g^*$. Because $G$ is directly inversely proportional to $f$, the effect is substantial. When plotting the natural log of $f$, if $G$ should be increased by $g^*$, then an overall offset equal to $\ln g^*$ will be subtracted from the plot. This affects the y-intercept found by this fit but not the slope. An offset of $\ln g^*$ to the y-intercept affects the calculated density of Shift Method 1. Since the natural log of the density is proportional to the y-intercept (see Equation 4.2.1) $g^*$ is inversely proportional to density. For example, if the geometric factor should be increased by $g^*$ then the density will decrease by a factor of $g^*$. Physically this makes sense because if the geometric factor increases and the detector is larger, it is easier to get more counts, so the same number of counts would correspond to a lower observed density.

The geometry factor also affects the $\Phi_{HFshift}$ calculation (Equation 4.2.3) by adding an offset of $-kT_e (\ln g^*)$. This also bears out physically because if the calculated density decreases then a larger $\Phi_{HFshift}$ is needed. Considering this result with real numbers, we see if our estimate of $G$ were off by a factor of 10, a $\sim0.5$ V error in $\Phi_{HFshift}$ would result.
Since this error is fairly small, and G is unlikely to be off by more than a factor of 10, this gives us some confidence in the magnitudes of our HF shifts.

Next, we independently consider the effect of random errors using standard linear regressions and least squares fitting methods. For any function $f$ of variables $x_i$, the uncertainty in $f$, $\Delta_f$ is calculated from the uncertainties in $\Delta x_i$, by

$$\Delta_f^2 = \sum (\frac{\partial f}{\partial x_i})^2 \Delta x_i^2$$  \hspace{1cm} (4.4.1)

We shall apply Equation 4.4.1 to two main results, the density calculation from *Shift Method 1* and the calculation from *Shift Method 2*.

To determine the error in the density calculated with *Shift Method 1*, we consider the uncertainties in three terms, the temperature, $y$-intercept, and $\Phi_{\text{shift}}$. Because $\Phi_{\text{shift}}$ already contains an uncertain estimate of the spacecraft potential we will not include its contribution. The IDL fitting routine calculates the uncertainties associated with the slope and intercept for its fits to $\ln f$ vs. $E$. From the error in slope, $\Delta_m$, the error in temperature is calculated using Equation 4.4.1, such that $\Delta_T = -\Delta_m/m^2$. The result for $\Delta_n$ is shown in Figure 4-15. The dominant term is from $\Delta_{y\text{-int}}$ which is slightly larger than the term from temperature. The error increases at the end of the flight because the densities increase while the temperature decreases and everything gets more sensitive.

Next we calculate the uncertainty in $\Phi_{HF\text{shift}}$ due to errors in temperature, $y$-intercept, and HF density using Equation 4.4.1. For the uncertainty in HF density we estimate $\sim 1e4/\text{cc}$. The result is shown in the second panel of Figure 4-15. Again the errors due to the fit parameters are small, probably because only the best fits were chosen for this analysis. The dominant term (by 4x) is the $\Delta_n$ from HF density. The uncertainties in
density and $\Phi_{HFshift}$ are fairly innocuous so we do not anticipate they change any key results.

In summary, for this first flight of the TED sensor, errors due to lack of precision in geometry factor are more problematic than uncertainties involved in the analysis techniques. For future iterations, more laboratory testing and modeling could refine the knowledge of the geometric factor and then minimizing uncertainties in other quantities would become more important.
Figure 4-15: Uncertainty in density (top) and $\Phi_{HFshift}$ (bottom) versus time.

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Chapter 5

Conclusions

In conclusion, this thesis has presented recent results from a new instrument designed to measure thermal electrons. This measurement is very difficult and the TED was cleverly designed to combat many of these inherent difficulties. Despite a unique design to provide better measurements than ever before we encountered previously unrecognized problems. However, we have interpreted the response of our instrument and developed a self-consistent model of the effects of a potential barrier on our detector. Based on the response of our detector, we can tell that the magnitude of the potential barrier around the TED is equal to the spacecraft potential. The effect of the barrier on our intended measurement of the core population is to repel the core from the vicinity of the probe. The particles which do reach the TED come from further out in the tail of the thermal distribution, have overcome the potential barrier and then been accelerated to the detector by the applied skin bias. From the piece of the distribution which we measure we are still able to probe the thermal properties and obtain meaningful results.

This recognition of the natural formation of non-monotonic potentials near a positively biased plasma probe in the absence of sunlight is a useful result which must be recognized for future experiments. The PIC code utilized by Lapenta (1999) rigorously illustrates the formation of potential wells in the sheath structure around different objects in a variety of plasma conditions. Further testing is required to understand the exact source and mechanism of the potential barrier formation in our case. It is interesting to note that ultimately
the effects of the barrier are to limit the current collected by the TED to what it would be if the applied skin bias potential were absent; in effect to shield it out. In light of this space charge dependent potential structure it is vital to know the magnitude of the barrier.

If the barrier is at the spacecraft potential then knowledge of the payload potential is paramount. Unfortunately, adequate techniques for estimating the payload potential are limited. Our analysis has shown that typical “rules of thumb” for spacecraft charging of a few kT negative, derived from simplistic analytic models, are limited in accuracy and misleading in active aurora. Additionally, utilizing only the sphere-to-skin voltage from the electric field spheres is also a poor indicator of the spacecraft potential. Our data indicate that in the dark, the current balance terms are complex and a complete accounting of the non-negligible auroral and secondary currents must be considered in order to understand what controls the spacecraft potential.

In the future, high importance should be placed on adequate knowledge of the spacecraft potential before low energy measurements can be successfully interpreted. In our case, the lack of knowledge of the spacecraft potential made absolute derivation of the thermal electron flux difficult though other independent confirmations of density could be used to lessen the problem. Thus, we have summarized the difficulties with this measurement and highlighted the need to carefully control and know the payload potential and other instrumental effects. We feel confident that we understand the effects of a potential barrier problem and can overcome them to shed light on auroral processes.

Our data suggest that the low energy electrons which play a vital and dynamic role in return current and Alfvénic wave-particle interactions and energy transfer at middle altitudes can be directly measured. Our preliminary results indicate cold temperatures
between 0.1 and 0.8 eV. This range is consistent with standard ionosphere models for the location, altitude and time of the SIERRA flight. Within the best Maxwellian fits, pitch-angle isotropy was largely observed. The coldest temperatures were in the polar cap and gaps between arcs. Though some of these are likely places for return currents, significant differences in the temperature depending on the TED aperture orientation up or down the fieldline were not found. The hottest core temperatures were observed coincident with auroral inverted V precipitation. The temperature was also elevated in the Alfvénic region in a similar manner. No discernible differences were evident between the inverted V and Alfvénic regions although perhaps more variability was evident in the smaller scale Alfvénic regions.

Density was difficult to determine without absolute accuracy in the knowledge of the payload potential. Outside of active precipitation the density agrees well with the HF density which verifies our techniques and method for estimating the payload potential. In the inverted V and Alfvénic regions it was necessary to rely on the HF density measurement to normalize our results. This indicated a fairly dense flight overall and particularly in part of the Alfvénic regions. The analysis techniques were a method of applying the HF density and the measured spectra to establish the payload potential. The reverse was also attempted but indicated inadequacies in the assumed form of the spacecraft potential in active precipitation.

Finally the limitations caused by the potential barrier have made accurate derivation of the thermal electron drift velocity extremely difficult and sensitive. For limited instances in the SIERRA data, there is a detectable difference between the density measured looking up and down the fieldline. These flows can be compared to the current measured by the new
multipoint magnetometer technique (Klatt et al., 2004) but both have significant problems. Nonetheless the progress toward a full measurement of current outside of the inverted V aurora is most exciting and both techniques will be refined in the future.

5.1 Future Work

Future work needed for the TED development includes: (1) further analysis of the second flight of the TED on the SERSIO payload; (2) continued laboratory testing and PIC modeling of the TED design; and (3) a continuation of the flight program for testing improvements to the TED design.

Using what we have learned about the TED problems and the best ways to combat them from the SIERRA TED flight we can consider the recent SERSIO sounding rocket which also carried a TED. In 2004, SERSIO was launched from Svalbard, Norway to 780 km in intense pre-storm cusp ion outflow. This payload contained two different designs for measuring thermal electrons and two identical but orthogonal top-hat thermal ion analyzers. In addition to the TED, another new instrument, the ERPA, was developed for detecting thermal electrons via an omni-directional retarding potential current collector. On the TED, the bias sweep and coating were altered to improve performance. SERSIO flew into sunlight whereas SIERRA was into total darkness. Unfortunately SERSIO data were severely limited by mechanical ACS problems which affected instrument deployment and orientation. Extensive ground-based radar observations, all-sky cameras, and satellite overflights should prove useful for facilitating quantitative comparisons at different altitudes. In particular, this flight allows a complete comparison between the remotely sensed EISCAT thermal parameters and their in-situ electron and ion counterparts. The performances of
the two TEDs can be contrasted with the aim of identifying differences due to changes in internal instrumental parameters versus external environment parameters. Also, the two different thermal electron designs on SERSIO, the TED and the ERPA can be compared.

Next we think it would be very beneficial to invest in further laboratory testing and modeling efforts to more fully verify and characterize the TED response. Being aware of the potential barrier, we would hope to more carefully figure out what triggers it, and how it can be avoided, which is a key for future versions of the TED. Further modifications of the PIC code could be developed to include many additional current sources. The model is capable of incorporating a 2-d geometry and accurate magnetic field. Modeling the exact shape of the floating payload and small biased boom element and probe would be extremely informative. Also, taking into full account the effect of the magnetic field on the plasma shielding is necessary and rarely done. Evaluating the full self-consistent effect of the auroral electron current and photoelectrons would be especially useful as well and highly applicable to our current data analysis efforts.

Further laboratory testing could be done at NRL or the new Dartmouth College vacuum chamber (MacDonald, 2004; Frederick-Frost, 2004). The goal would be to completely characterize the secondary emission, surface cleanliness, barrier, and TED low energy performance in an ionosphere-like plasma. Additionally, in preparation for future flights, NRL has proposed ameliorating the spacecraft charging problem by using a newly developed carbon nanotube emissive probe (NEP) technology. Emissive probes are a source of hot electrons until the payload reaches equilibrium and thus can sense and transmit information about the plasma potential. We have also proposed working on developing this new technology for application to future rocket use and to work in combination with an unbiased
TED (MacDonald, 2004). The steps of testing the NEP and TED in the NRL chamber are: (1) to characterize the performance of a suitably modified TED and sense the surrounding sheath structure with the NEP in an ionosphere-like laboratory plasma, (2) to evaluate the capability of the NEP for in-situ operation by thorough study of their properties in a wide range of laboratory plasma environments, and (3) to devise and test a method of using the two instruments together for ideal performance in lab or space, with real-time derivation of the payload potential to improve the TED operation.

The TED-emissive probe combination is also a key piece of a new proposed sounding rocket payload called DENALI (Kintner et al., 2004). DENALI stands for DC and low energy plasma in the Nightside AuroraL Ionosphere. The mission would explore the fundamental measurement issues the TED behavior on SIERRA has raised. Also, through multiple payload wave measurements, the low frequency and DC response of the magnetosphere-ionosphere system and the local payload environment can be explored in more detail. The whole mission would be designed around issues of controlling spacecraft charging with a new payload active neutralization system (PANS). This device would eliminate the spacecraft charging on one subpayload using hot emissive filaments and a current balance monitoring system. The three spacecraft would be instrumented similarly to SIERRA and SERSIO with the addition of a NEP array, a swept Langmuir probe, and the PANS. With this specific instrumentation, the questions of identifying the ideal methods for actively biasing the payload to the plasma potential, monitoring the plasma potential, and measuring the coldest thermal particles, could be closed.

For DENALI we would recommend flying a trajectory with significant portions of darkness and sunlight. Also it might be investigated whether to fly in simpler aurora or a more
active time. If a more active time was chosen it would be best to ensure active ion outflow during the rocket traversal, so as to maximize opportunities to observe thermal electrons carrying return current. A component of DENALI, conjunction with the new AMISR radar, is designed to do just that. AMISR is the new phased array radar system which will be installed in Poker Flat by the proposed time of the DENALI launch (Kintner et al., 2004). This radar will be capable of measuring the electron and ion temperature, and the electron and ion density and flow speeds in real-time with high temporal resolution. This will go far towards ensuring the ideal background for key new measurements and assist in providing another independent method against which to measure our results; both missing elements with SIERRA.

We have outlined several ideas which should aid in understanding the TED better in order to fly it more successfully again; specifically relating to better testing, modeling, and coupling to an active payload potential control system. Several other ideas are also recommended for the future use of the TED. Chief among these is changing the skin bias selection algorithm. Clearly, the skin bias did not have its intended effect on SIERRA. Preliminary results from SERSIO show different, but also ineffective, response of the skin bias to the measured spectrum. An algorithm similar to that used on HARP would probably be more effective to get higher flux to the detector. In this method, we would envision the skin bias to sweep through its range while the analyzer is selected at a given energy step. Then at the skin bias which garnered the maximum countrate, an energy sweep would be taken. Though more time-consuming, utilizing this technique should be considered for a TED on a future (not actively biased) payload. Another, much simpler approach, would be to also use a cycle of preset skin bias values, as with the TECHS instrument on SCIFER. On
an actively biased payload perhaps no TED skin bias would be required though the exact physical placement of a TED and a hot electron emitter would have to carefully consider anti-interference techniques. Secondly, a current monitor, which would in effect be operating the TED as a modified Langmuir probe would be crucial to understanding how much of the total thermal current the TED drew. Finally, as an extreme recommendation it is proposed that the feasibility of mating a single TED to a COWBOYS wire boom deployer be explored. Wire booms on compact subpayloads have shown significant noise reduction and proved a stable new technique. Perhaps a TED could fit in a balanced light-weight spherical package with an aperture in four different directions when deployed. The spherical shape would allow simpler deployment, modeling efforts, and operation as a modified Langmuir probe. The chief problem would probably be handling the number of coaxial connectors currently used to operate the TED. The width of the cable which makes up the wire boom can affect the system stability so this must be kept small. The reconfigurations required to envision a COWBOY-TED instrument are difficult but by no means insurmountable. The primary benefit would be obtaining the quietest possible environment in which make thermal electron measurements. In light of this great benefit the practical difficulties can be seen to surmount the mechanical concerns.

As this is an extremely difficult measurement to make, we recognize several iterations of the TED design may be required before all the problems are solved. It is important to continue forward momentum on the TED project and we believe the breadth of jumping-off points for future work ensures progress will continue. The sounding rocket program is integral to incubating innovative new instruments such as the TED. In the process of rocket-based, higher risk discovery, fundamental scientific progress is made as well. The
TED project has illustrated beautifully both of these points: the trials and tribulations of discovery, and progress in the pursuit of understanding the coupled magnetosphere-ionosphere-auroral zone system, our primary scientific goal.
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Appendices
Appendix A

Aerodag

Dag is the generic term for a coating used extensively on rocket instruments, particularly Langmuir probes and electrostatic analyzers. Historically, its use on UNH particle detectors has been for "blackness" and rejection of scattered light, uniformity of work function, and not necessarily low resistance (D. Rau, personal communication, 2003). The properties of Dag are investigated extensively here in order to illuminate unintended consequences for low energy electron detection. Aerodag is an aerosol application of a colloidal graphite suspension in alcohol. It can also be applied in a liquid form and "painted on" to a surface. In this form it is called Aquadag, which has been described in the NASA Space Environments and Effects (SEE) Materials Knowledgebase (Brennison et al., 2001a). The SEE database assimilates the results of extensive lab testing of space materials primarily done at Utah State University under Professor J. R. Brennison. Measured qualities of Aerodag and Aquadag are summarized in Table A.1. Both forms are more than 99.99% pure carbon. According to Brennison et al. (2001a) "colloidal graphite is crystalline graphite on 10-100's of nanometer scales. The crystalline nature of the powder gives the material similar properties to HOPG [highly ordered pyrolytic graphite] or crystalline graphite but without the long range order."

The resistive properties of the Aerodag are particularly interesting. Natural crystalline graphite is known to have 1000 times higher resistance perpendicular to the layered sheets of carbon bonds than interplanar (Brennison et al., 2001b). It was thought that an unusually
high resistance could be preventing the full skin bias from reaching through the Aerodag to the plasma. The SEE listing showed Aquadag to have somewhat elevated resistance, but it seems that our overall assumption of a highly conducting outer surface with no local potentials or insulating patches is theoretically valid. Additionally the SEE report noted low contamination, with less than 3% Oxygen adhered within the top monolayer.

Another possible problem is the possibility of an insulating oxide contamination layer on top of the Aluminum piece prior to Aerodag application. This was also tested with a simple lab setup. In flight, the voltage applied to the surface of the TED is connected by a wire to the inner surface and screws through the Aluminum, and is presumably applied to the outer surface. However with high resistance in between the Aluminum and the Aerodag, the voltage could be effectively reduced so that not as much was applied as we had thought. Our test involved measuring the resistance between the back of an Aluminum plate and the front which was coated with Aerodag. To verify the electrical connection between the Aluminum

<table>
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<tr>
<th>Parameter</th>
<th>Aquadag</th>
<th>Aerodag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Mean Atomic Number $&lt;Z_{\text{eff}}&gt;$</td>
<td>$(6.5 +/- .02)$</td>
<td></td>
</tr>
<tr>
<td>Bulk Resistivity $\Omega \cdot m$</td>
<td>$(5.0 +/- .2) \times 10^{-1}$</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td></td>
</tr>
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</tr>
<tr>
<td>$\delta_{\text{max}}$</td>
<td>$(1.34 +/- .02)$</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{max}}$ (keV)</td>
<td>$(.24 +/- .02)$</td>
<td></td>
</tr>
<tr>
<td>Density $(\text{kg m}^{-3})$</td>
<td>$(2.0 +/- .001) \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>Thickness (mils per coat)</td>
<td>$\sim1 - 2$</td>
<td></td>
</tr>
</tbody>
</table>

Table A.1: Relevant qualities of Aerodag and Aquadag from the SEE Materials Report and the manufacturer's Product Data Sheet specifications (*Brennison et al., 2001*).
and the Aerodag, one contact was made on a piece of brass atop insulating Kapton tape coated with the Aerodag and one on the back, only touching the Aluminum. Thus the only path for current flow is through the Aluminum, possible oxide layer, and Aerodag layer. A reading of 50kΩ was taken in air and rough vacuum (M. Widholm, personal communication, 2003). This indicated to us that the Aluminum and Aerodag are in good conductive contact. This value also represents an overestimate of the true resistance perpendicular to the plane of the thin film coating (M. Widholm, personal communication, 2004). Even considering this value of resistance, given the low currents that the TED collected, the voltage drop was not likely to be significant.

The various properties of Aerodag described here and in Table A.1 are very useful to consider in multiple areas of the TED design and operation which are pertinent to Chapters 2 and 3.
Appendix B

SIERRA Launch Real-Time Data Website

This appendix will list and describe the elements of the real-time data access website, created in 11/02 by Elizabeth MacDonald. The URL address for the site described is http://esp.sr.unh.edu/liz/mainpage.html. This page was designed specifically for predicting and monitoring auroral activity in preparation for a rocket launch from Poker Flat, Alaska. This page is especially useful for gathering the necessary data to call the launch to one central, easily navigable website. It can also be used by local observers in the central Alaska area or for educational purposes to understand the manifestations and monitoring of substorm dynamics and real-time aurora forecasting. At the Poker Flat Science Center, the rocket scientists typically have access to direct links and multiple dedicated monitors for each type of real-time data. In addition certain in-house data products such as live all-sky camera feeds and LIDAR scans can have their own real-time direct displays.

Because this page primarily links to other pages, it must be kept up to date with the constantly shifting addresses of all the sites it links. At this point, the page is somewhat out of date but the structure is still useful and could be updated easily. There is an index on the left of the browser window to navigate between different subject pages. Pages are grouped by similar types of measurements and time scales, so a logical progression can be made from page to page to track the substorm evolution. The site updates its real-time plots every 1 - 3 minutes and displays a real-time clock showing the Universal Time, Eastern Time Zone, and local Alaskan time.
Each page is described in the “About the Page” link and will be briefly summarized here. The data plots shown on the web pages are linked from various world-wide space agency sources. These are described further in the “All Data Credits” link on the index, along with links back to the actual data providers. Generally, each figure has a clearly marked link nearby to its original source. The basic layout and design of the website was used with the permission of Paul Kelley, whose Aurora Sentry website (http://aurora.n1bug.net) is specialized for predicting auroral effects for ham radio operators in the Northeast.

The first page, “Kp Index,” shows various displays of the Kp index over several solar rotation periods. As some active sunspots show up during several Carrington rotations, solar activity, and its solar wind and Earth effects can repeat every 27 days. Thus, one can begin to have a basic idea of whether the global auroral activity is likely to be high. Next, the “Solar Wind and Magnetosphere” page shows relevant data from the ACE and SoHO satellites monitoring the solar wind properties. The GOES satellite magnetometers at geosynchronous orbit show diurnal magnetic variations and faster variants due to the magnetosphere’s response to solar wind driving. Next are several groupings of ground-based magnetometer sites. These can be customized to show whichever may be most useful for the placement of the desired auroral activity. The “Other Ground Data” page shows some real-time all-sky camera images and links to other sites with all-sky camera, photometer, SuperDARN radar, and induction magnetometer ground-based data. The most useful, the University of Alaska all-sky cameras, have a separate real-time display and were not able to be included here. At the launch site, access to these data on dedicated monitors was readily available. Next, an assortment of satellite imager data is displayed. Generally these plots were infrequently in real-time operation, but could be useful to check for satellite
conjunctions with the rocket launch. Next, the “Oval Estimate” link showed a nice visual forecast from the CANOPUS magnetometers of the real-time auroral oval extent. Generally, this was not precise enough in longitude for locating activity and launching a rocket, but it is still interesting. “Solar Activity” shows various measures of the solar activity which could give advance warning of large geomagnetic events. Software to output satellite locations in real-time was desired but not readily available. Finally, weather forecast links were provided, as ultimately the launch must have clear skies.

The use of these data are discussed more in Chapter 2. For a general background to predicting space weather effects, please see Kivelson and Russell (1995). For more general real-time displays, the NOAA Space Environment Center webpage (http://sec.noaa.gov) and http://spaceweather.com are especially useful.
Appendix C

HEEPS Electron Data Current Calculation

A measure of the field aligned current can be derived from the electrons measured by the HEEPS detector. A kinetic approach, summing up the field aligned particles, can measure the current as the product of the density and the field aligned velocity moment:

\[ j_z = ne <v_z > \]  \hspace{1cm} (C.0.1)

In terms of the quantities we actually measure, we calculate \( j \) (via mathematical manipulation as in Williams (2002)):

\[ j_z = e/m \int (2E/m) \cos(\alpha) \sin(\alpha)f(E, \alpha, \varphi)dEd\alpha d\varphi \]  \hspace{1cm} (C.0.2)

where the distribution function is a function of energy, pitch angle, and azimuthal angle (assumed to be gyrotropic). The result is shown in Figure 2-14 and compared to a field aligned current measurement from the magnetometer data. It should be noted that this technique is limited by the energy range of the HEEPS. If there is a significant flux at higher or lower energies, our measurement can severely underestimate the true field aligned current. We see evidence of this at times of the largest inverted "V" arcs. Also, this method is incapable of sensing other types of current, such as the return current which may be carried by thermal electrons, or any kind of ion current. These caveats represent the fact that the use and comparison of this technique is limited to certain situations, and not necessarily indicative of an error.
To find the total omnidirectional current density to the payload from the HEEPS data, one needs to consider

\[ j_{aur} = ne < v > \]  \hspace{1cm} (C.0.3)

Mathematically, we just calculate

\[ j_{aur} = \frac{2e}{m} \int (2E/m) \sin(\alpha) f(E, \alpha, \varphi) dE d\alpha d\varphi \]  \hspace{1cm} (C.0.4)

Though this equation is very similar the difference in the trigonometric terms will ensure that the current is collected regardless of incoming angle.
Appendix D

Numerical Floating Potential Program

This Appendix presents the text of the Float program for the DOTSPad Macintosh programming language (created by M. Widholm). Figure 3-4 and Table 3.1 show sample input and output values.

---

-- Float Program (M. Widholm)---
-- Calculate net current to payload system with a biased probe

-- Saturation current densities in microA/m^2

\[ i_e = -850 \]
-- goes like \( \sqrt{T} \), lin. w/ n

- 600 0.1kT, 2e4/cc
- 60 0.1kT, 2e3/cc
- 30 0.1kT, 1e3
- 1300 0.5kT, 2e4
- 850 0.2kT, 2e4/cc

\[ i_i = -i_e / 170. \] -- ion current reduced because of mass ratio

-- Current Reduced by Retarding Potential Function

-- assume exp energy distribution.

\[ i_k t(v) = \exp(v / k_t) \text{ when } v < 0, 1 \]

-- \( v \) is thus \(-e*\phi\)

-- \( v / k_t = -e*\phi / k_t \)

-- argument should be pos for e-, neg for ions

\[ \text{phisc=X} \]-- X axis is payload potential wrt plasma

\[ \text{ppted} = \text{X} + \text{skin} \]-- TED probe potential

-- Current Balance

\[ \text{paye} = i_e * i_k t(\text{phisc}) \]-- e current to payload

\[ \text{payi} = i_i * i_k t(-\text{phisc}) \]-- i current to payload

\[ \text{payp} = 0 \]-- photo e- current from payload (areasun*photo(phisc))

-- or added auroral current

\[ \text{probeted} = \text{areated} * i_e * i_k t(\text{ppted}) + \]-- e current

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areated*ii0*ikt(-ppted) + -- ion current
areated*areasun*photo(ppted) -- Optional photo e- current

net = payi + paye + payp + probeted

--Photoelectrons (optional)----------------------
--photo= -0*ie0 -- try photo current of 10 percent of e- sat
-- positive current so change sign from ie0
--photo(v) = ip0*(exp(-v/photokt) when -v<0, 1) -- photo current
photo(v) = 50.8*exp(-v/2.4) + 1.5*exp(-v/12.6) when -v<0, 50.8+1.5
--ip0 = -ie0*1.1 -- photo current at 0
--photokt=2 -- assume 2eV photoelectron distribution

--Basic Parameters------------------------
kt=.2 -- electron temp
skin=-1:-- skin bias wrt payload
areated=1/100 --probe/payload area ratio
areasun = 0 --can add sunlit area

--Plotting-----------------------------------
Title="Net Current vs. Payload Potential"
Xsteps=800
Ylabel=" Net"
Xlabel="Phi_s/c with respect to plasma"
Xmin=-5;; Xmax=-0;;
Ymin=-5;; Ymax=6;;Ydiv=5

plot net -- zero cross is probe potential at equilibrium
plot paye+payi+payp --zero cross is potential w/o ted
plot net + skin --ted potential
label skin:-1
label ie0: -850
label kt: 0.2
label areated: 0.01
slabel "black is net to main, red is w/o bias"
slabel "ted is at skin from black crossing (green)"

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