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DATA ANALYSIS SUPPORT FOR THE SPREE INSTRUMENTS ON THE TSS-1 SHUTTLE FLIGHT

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This final report describes the scientific progress on Contract F19628-90-C-0133 entitled "Data Analysis Support for the SPREE Instruments on the TSS-1 Shuttle Flight" during the period June 29, 1992 to June 14, 1993. The objective of this contract is a scientific study of the interactions between the first flight of the Tethered Satellite System (TSS-1) and the ionosphere to increase understanding of the structure and current characteristics of high-voltage sheaths in the ionosphere. A paper describing the results of a review of the data sets for evidence of presheath heating around the subsatellite in included.

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1. INTRODUCTION

This final report covers the period June 29, 1992 to June 14, 1993, and describes the scientific progress on Contract F19628-90-C-0133 entitled "Data Analysis Support for the SPREE Instruments on the TSS-1 Shuttle Flight." The objective of this contract is a scientific study of the interactions between the first flight of the Tethered Satellite System (TSS-1) and the ionosphere to increase understanding of the structure and current characteristics of high-voltage sheaths in the ionosphere.

During the final year of this contract, we provided theory support for the SPREE team at the Science Operations Control Center, NASA/Johnson Space Center during the TSS-1 flight. We attended data review meetings. We reviewed the TSS-1 SPREE, SETS, and RETE data for evidence of presheath heating around the subsatellite. We prepared a paper that describes the results of the investigation.

We presented the high-voltage sheath calculations done during the second year of this contract at the Fall 1992 AGU Meeting in San Francisco, California, in December 1992. The abstract is in Attachment 1 of this report.

We prepared a paper describing the results of our review of the data sets for evidence of presheath heating around the subsatellite. The final version of this paper appears in Attachment 2 of this report.

The technical staff who contributed to the research described in this report are Drs. Ira Katz and Myron J. Mandell.

ATTACHMENT 1

A presentation was made at the fall 1992 AGU Meeting in San Francisco, California, in December 1992. The abstract follows.

Sheath Structure Calculations for the TSS-1 Subsatellite

The TSS-1 subsatellite (approximately a conducting sphere) was expected to attain positive potentials in the kilovolt range. Because the spacecraft velocity (leading to a wake structure) is approximately normal to the Earth's magnetic field (leading to sheath anisotropy), the sheath structure is inherently three-dimensional. Important issues in determining the sheath structure include the inherent instability of a collisionless sheath under these conditions, plasma heating in the ram region, magnetic field effects, and finite Mach number effects.

We used the DynaPAC computer code to calculate the self-consistent sheath structure for these conditions. With no magnetic field, the spacecraft potential would be strongly screened in the nonwake regions, but would extend well into the plasma-depleted wake region. The effect of the magnetic field is to transport electrons into the wake by $E \times B$ drifting, so that the spacecraft potential is screened in the wake region as well.

ATTACHMENT 2

The paper, "Observations of Ionosphere Heating in the TSS-1 Subsatellite Presheath", describing the results of our review of the data sets for evidence of presheath heating around the subsatellite follows.

Observations of Ionosphere Heating in the TSS-1 Subsatellite Presheath

Ira Katz, Enrico Melchioni, Myron Mandell, Marilyn Oberhardt, Don Thompson, Torsten Neubert, Brian Gilchrist

Abstract

The first flight of the Tethered Satellite System (TSS-1) was to investigate the mechanical and electrical dynamics of a conducting satellite deployed from the Orbiter via a tether whose core was a conducting wire [Dobrowolny and Melchioni, 1993; Dobrowolny, 1987; Dobrowolny and Stone, 1993]. In the TSS-1 system, the satellite is deployed from the Orbiter radially away from Earth. This configuration results in relative motion between the tether and Earth's magnetic field. A motional electromotive force (emf) results that is a product of Orbiter velocity, Earth's magnetic field, and the length of the deployed tether. Given the existence of this emf, a current can be driven in the tether. The satellite skin was conductive so that it could act as an anode in the TSS-1 circuit, collecting electrons that could be conducted through the tether to the Orbiter where they either went to Orbiter structural ground or were emitted into the ionosphere via active electron emission. This electron emission was accomplished during TSS-1 mainly by the 100 milliampere, 1 keV Fast Pulsed Electron Gun (FPEG) of the Shuttle Electrodynamic Tether System (SETS) [Williamson et al.,1988; Banks et al., 1993]. Potentials of the Orbiter with respect to the ambient plasma were obtained from measurements from the Shuttle Potential and Return Electron Experiment (SPREE) [Oberhardt et al., 1993], the SETS Tether Current Voltage Monitor (TCVM) [Thompson et al., 1993], and the Agenzia Spaziale Italiana (ASI) Deployer and Satellite Core Equipment (CORE) [Bonifazi et al., 1988; Bonifazi et al., 1993]. The FPEG electron emission was at levels much higher than that of either ambient ion collection at the Orbiter end or of electron collection at the satellite. Despite the limited tether deployment length of 268 meters, the TSS-1 system proved capable, during certain events, of generating satellite potentials sufficient to illuminate a previously unexplored aspect of plasma physics: that of an ion repelling, electron attracting, moving probe in a magnetoplasma. During such events, measurements were made of an apparent increase in the electron plasma temperature in the quasineutral ionospheric region beyond the satellite sheath. These measurements were made by the satellite boom-mounted Langmuir probe flown as part of the Research on Electrodynamic Tethers (RETE) experiment [Dobrowolny et al., 1993]. This apparent heating of the presheath

electrons was distinctly different from the acceleration of the electrons in the sheath, which could be observed when the sheath expanded such that the probe was completely in the sheath. We show that these observed electron temperatures are consistent with the formation of a Bohm stable electron collecting sheath.

1. Introduction

Current collection by a positive probe in a space plasma has been the subject of many studies. (See the review by Laframboise and Sonmor, 1993.) Most of this work was motivated by observations of the charging of electron emitting rocket payloads to potentials approaching (or even exceeding) the energy (typically ~1 keV) of an emitted electron beam. The reason for such charging is that space charge effects (Langmuir and Blodgett, 1924) and/or magnetic field effects (Parker and Murphy, 1967) limit return current from the ionosphere to values below the beam emission current, even for highly elevated potentials.

One of the goals of TSS-1 was to study electron collection by a positively charged orbital probe in the ionosphere [Dobrowolny and Melchioni, 1993]. Most of the preflight discussion of this process centered on whether electron collection by the satellite would be magnetically limited (as described by Parker and Murphy), or whether scattering across field lines would overcome the magnetic limiting and result in currents approaching the space charge limit (as described by Langmuir and Blodgett).

As a result, the data on current collection from the spherical TSS-1 satellite were awaited with great anticipation. A distinct difference with respect to previously flown experiments was that the satellite would travel at 7800 m/sec, roughly an order of magnitude faster than is normal for rocket payloads. This difference would help provide new insight to the current collection process.

In the actual flight, the maximum possible current collection (given by the induced emf divided by the tether resistance of 2200Ω) was about 0.02 amperes. This corresponds to the random electron thermal current to the ramward half of the 1.6 meter diameter satellite when the plasma density is about 6×10^{11} m^{-3}. Measurements were taken at densities ranging from 3×10^{11} to 1×10^{12} m^{-3}. Only at the very lowest of these densities is any substantial sheath enhancement needed, so that magnetic limiting never plays a role. At such low densities ($3\text{-}4 \times 10^{11}$ m^{-3}) measurements by the Langmuir probe on the

RETE experiment package indicate that collection of current approximating or exceeding the random thermal current results in satellite charging and enhancement of the electron temperature at the probe location.

In Section 2, we review the current collection results, introducing the measurements performed by the SETS TCVM and the CORE satellite ammeter, as well as the SPREE Orbiter potential measurements. In Section 3 we present the RETE Langmuir probe measurements. In Section 4 all the measurements are brought together to illustrate a set of six typical charging events, some of which display the electron heating phenomenon. In Section 5 we show that this heating is a result of an instability caused by the penetration of ram ions into the electron collecting sheath. This heating in turn leads to substantial enhancement of electron current collection by the satellite beyond that predicted by classical theories. Results are summarized in Section 6.

2. Current Collection During TSS-1

The TSS-1 circuit, shown in Figure 1, drops the motion induced emf across four circuit elements: the tether resistance, the electron collecting sheath at the satellite, the ionosphere, and either the ion collecting sheath or the FPEG at the Orbiter. Because during the actual TSS-1 flight the maximum tether length was 268 meters (rather than the planned 20 kilometers) only modest satellite potentials were achieved, and the satellite sheath was always thin compared with its 0.8 meter radius. Also, for the low currents actually collected, the ionosphere resistance was always unmeasurably low, and is ignored in the analysis.

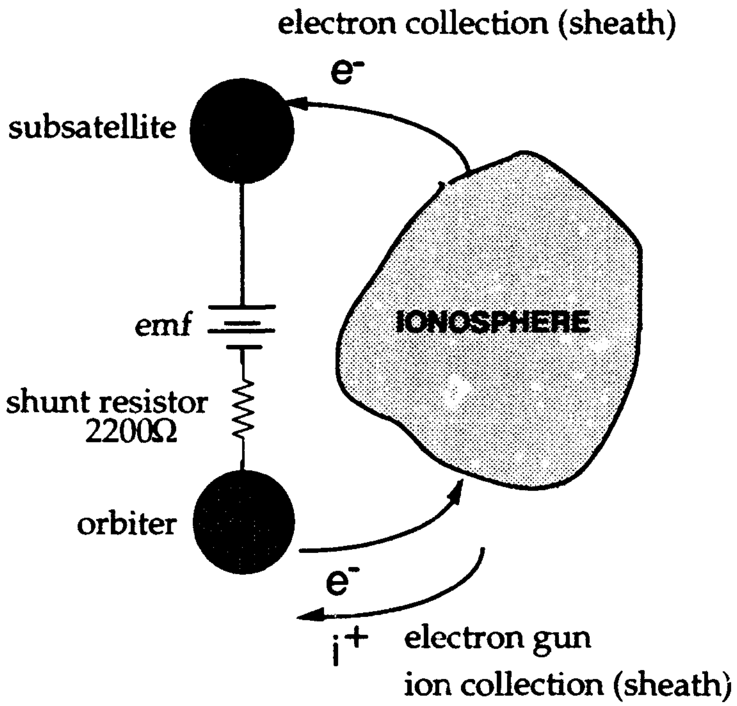

Figure 1. TSS-1 circuit model. The motion induced emf, v×**B**•**L**, is dropped in part through the tether resistance (2200 Ω), in part through the orbiter sheath (whose current is composed of incident ram ions and FPEG-emitted electrons), and in part through the sheath of the electron-collecting subsatellite.

Note that the circuit current always flows through the entire tether, so that the tether resistance is independent of the amount of tether deployed. For most of the day side observations nearly all the induced emf was dropped through the tether resistance. This was the result of low emf combined with the high ionosphere plasma density. The most interesting data from TSS-1 was obtained when the ionosphere density was low, and the plasma currents were well below the tether resistive current limit. Longer tether length would have generated higher voltages, leading to higher sheath impedances at both the Orbiter and satellite.

The events reported in this study all occurred during the Deployment 1 operating cycle (DEP1), which is composed of 4 steps:

(1) Step 1 had the satellite electrically isolated from the Orbiter and the FPEG pulsing at various frequencies. Measurements of the Orbiter potential in

conjunction with the FPEG emission could then be made while the scientific instruments on the satellite made measurements of the local plasma.

(2) In Step 2 the tether was connected to the Orbiter ground through a resistor bank while the FPEG fired a DC beam.

(3) In Step 3 the resistors were cycled with no FPEG emission. Given the low induced voltage, during Steps 2 and 3 only the lowest (shunt) resistor value (15Ω) allowed a significant current to flow in the system.

(4) DEP1 Step 4 was passive, with the satellite electrically insulated, no FPEG emission, and no cycling of the resistors.

To characterize the current collection, we use nearly simultaneous measurements obtained during different steps of DEP1 cycles, as shown in Table 1.

Shunt	FPEG	Measurement
∞	Off	Induced emf
15Ω	Off	Saturation ion current to orbiter
15Ω	On	Electron current to subsatellite

Table 1. Three nearly simultaneous measurements used to determine enhanced electron collection.

The vxB induced emf is measured as the open circuit voltage, during DEP1 Step 4. The ion current measurement during Step 3 (shunt + FPEG off) allows us to calculate whether a substantial sheath potential is required for ion collection on the Orbiter. We find this to be a good indicator of low plasma density conditions which, in turn, lead to satellite charging during the 2nd DEP1 Step (shunt + FPEG on). Finally, we use the electron current measurement during Step 2 to correlate with direct measurement of electron temperature near the satellite by the RETE Langmuir probe. We now describe in more detail the tether circuit during the Step 2 and 3 of the DEP1 cycle.

2.1 FPEG Off

During Step 3 of DEP1 cycles, when the FPEG is off and the tether is connected to the shuttle ground by means of the shunt resistor, the Orbiter is observed by SPREE [Oberhardt et al., 1993] to charge to negative potentials. The ion current collection at the Orbiter during this step follows classical theory, so that the current to the Orbiter is simply the ram ion current times the Orbiter's effective collection area. Whatever is happening at the satellite, it is able to collect enough electrons to balance the Orbiter current without a significantly elevated potential. If we assume the satellite remains near plasma potential, as confirmed by RETE potential measurements, we can calculate the negative potential achieved by the Orbiter as the difference between the IR drop across the tether resistance and the magnetic emf:

$$\Phi_{Orbiter} = I_{tether} R_{tot} - \Phi_{vxB}$$

where Φ_{body} is the potential of the body (orbiter or satellite) with respect to the ionosphere, Φ_{vxB} is the induced potential and R_{tot} is the total resistance of the tether (including the resistance from the bank). During the shunt period, R_{tot} can be well approximated by the tether resistance of 2200 Ω. In this case we find the calculated sheath potentials in good agreement with estimates based on ram ion energies measured by the SPREE particle detectors [Davis et al., 1993].

2.2 FPEG On

When the FPEG electron gun is firing it has been experimentally observed [Oberhardt et al., 1993; Thompson et al., 1993; Oberhardt et al, 1993] that the Orbiter potential with respect to the ionosphere is either zero or positive, depending on the plasma density. An order of magnitude computation to find the upper density limit to observe Orbiter charging during FPEG operation is the following. With 20 mA of tether current and 100mA of gun current, there are 80mA of electron current left to be collected from space. Assuming a ionospheric temperature of 0.1 eV and the Orbiter engine bells collecting area of $25 m^2$, the threshold density below which positive Orbiter charging is required is about 6×10^{11} m^{-3}.

Since, from experimental data, it turns out that the satellite potential cannot in general be neglected as in the FPEG off case, the equation of the tether circuit when the gun is on becomes:

$$\Phi_{vxB} = I_{tether} R_{tot} + \Phi_{satellite} - \Phi_{Orbiter}$$

where, again, both the satellite and Orbiter potentials are referred to the ionosphere. The satellite potential is determined by the condition that it collect sufficient electrons to balance the tether current. For the low currents supported by the emf across the tether resistance, only very modest satellite potentials are required. By contrast, the Orbiter potential is determined by the condition that collected electrons balance the difference between the tether current and the current emitted by the gun. As a consequence, although the potential difference between satellite and Orbiter is rather small due to the low induced voltage, the actual potential of the two tether ends depends on how much the Orbiter must charge to neutralize the effect of the 100 mA, 1 KeV electron beam.

The above speculations are sustained by experimental data. For all the measurements presented here, the IR drop nearly equals the magnetic emf. This is in contrast to the FPEG off results, when the IR drop was as little as 20% of the emf and the Orbiter ion collecting sheath dropped most of the potential.

Finally, we notice that, in most of the cases presented here, during the FPEG operation the Orbiter was near the plasma potential, so that no large satellite charging is achieved.

3. RETE Langmuir Probe Measurements

The RETE experiment was designed to provide data for the understanding of the satellite sheath physics [Dobrowolny et al., 1993]. Relevant for the discussion presented here are the data obtained from the Langmuir probe and the satellite potential measurement.

The RETE Langmuir probe (LP) was located on a canister mounted on the tip of one of the TSS-1 deployable booms, in the upper hemisphere at about 80 degrees from the satellite's direction of motion. The collecting surface of the probe was a hemisphere of radius 0.5 cm. During the measurements of interest here this surface was positioned about 10 cm from the satellite skin in the vicinity of the spacecraft equator. The canister was electrically isolated from the satellite by means of a pentode, and the potential difference between the canister and the satellite itself was measured (DCBP potential).

Analyzing the current voltage characteristic of the LP [Melchioni et al., 1993] it is possible to obtain the ion and electron plasma density, the electron temperature, the local potential of the plasma around the probe, and the potential of the canister with respect to the ionosphere (Melchioni et al., 1993). Combining the DCBP potential with the canister-plasma potential satellite potential with respect to the ionosphere is recovered.

The shape of the LP characteristic is generally the one expected for a probe in a Maxwellian plasma drifting at the orbital speed. On some occasions, during the highest satellite charging events, a cold energetic electron population is clearly distinguishable. The latter indicates that the probe has been engulfed in the satellite sheath. In the analysis presented here, the measurements taken inside the sheath are not considered.

4. Ordering the data

As will be described in the next section, electron heating should be observed in the presheath region, close to the sheath edge. We must therefore find an indicator of satellite sheath formation. A useful quantity to build this indicator would be the satellite potential, but the instrumental error associated with the DCBP potential measure (1.27 V) is too large compared to the satellite potentials actually obtained.

A good satellite sheath importance indicator can be constructed reasoning as follows. Let us start with the ion current measures taken during the DEP1 Step 3. The maximum current which can flow in the tether circuit is:

$$I_{max} = \Phi_{vxB} / R_{tot}$$

and is obtained when no sheath is required both on the Orbiter or on the satellite. We note that the random electron thermal current to the ramward half of the satellite is only moderately larger than the ram ion current to the estimated Orbiter effective area. We can therefore expect that if a sheath forms around the Orbiter during Step 3, the same should happen to the satellite during Step 2, when FPEG is on. Only when the ram ion current is considerably less than I_{max} do we have a chance of observing interesting electron sheath physics.

We define the sheath importance parameter, S, as the ratio of the current the tether could carry to the ion current the ionosphere can provide during Step 2:

$$S = I_{max} / I_{tether} = \Phi_{vxB} / I_{tether} R_{tot}$$

The larger S, the more important is sheath collection in determining the observed tether current.

In the above formula, however, the density variations between steps 2 and 3 are not considered. Since each step lasts about 100 seconds, this variation can play an important role. Since the LP provides independent measurements of the plasma electron density during the two operations, we can construct a corrected indicator, S1, by multiplying S by the ratio of the measured electron densities:

$$S1 = S\, Ne_{off} / Ne_{on}$$

Another indicator can be constructed using the tether current measured during DEP1 Step 2 and the corresponding ionospheric density estimated with RETE data. We define S2 as the ratio of the measured tether current to the electron thermal current to the ramward half of the satellite:

$$S2 = I_{tether} / 2\pi r_{sat}^2 J_{th}$$

where r_{sat} is the satellite radius, and $J_{th} = eNe_{on}(eTe/2\pi m)^{1/2}$ is computed with the measured ambient electron density and temperature. Whenever S2 >1 a sheath is required to sustain the current in the tether.

Table 2 shows the measured emf, tether current, plasma density, and derived sheath importance parameters obtained during six typical events. S2 in the table is computed using $T_e = 0.3$ eV, which is the temperature usually measured by RETE during quiet periods. As we shall see below, observation of enhanced electron temperature are well-correlated with S1 and S2.

DEP1 start time GMT	emf V	I (off) A	Ne (off) m^{-3}	I (on) A	Ne (on) m^{-3}	S1	S2
218/00:25:12	33.3	0.013	7.0×10^{11}	0.016	6.6×10^{11}	1.23	0.41
218/02:18:24	38.5	0.004	2.7×10^{11}	0.019	2.4×10^{11}	4.92	1.34
218/02:25:08	43.8	0.006	3.4×10^{11}	0.022	3.1×10^{11}	3.64	1.20
218/02:31:49	50.5	0.011	3.4×10^{11}	0.025	3.5×10^{11}	2.03	1.21
218/02:38:32	55.5	0.012	3.8×10^{11}	0.027	5.3×10^{11}	1.51	0.86
218/02:45:16	56.0	0.017	5.3×10^{11}	0.027	4.5×10^{11}	1.76	1.02

Table 2. Data from SETS, DCORE, and RETE measured during TSS-1. The last two columns are derived values of the Orbiter charging when FPEG was off, and S, the sheath importance parameter.

Figures 2a and 2b refer to the first 2 events in Table 2, which are the 2 most extreme cases considered in this analysis. In both figures, the lower panel shows the tether current, measured by the Satellite CORE equipment (Bonifazi et al., 1993), during FPEG firing. The middle panel contains the electron temperature and the upper panel the reconstructed satellite potential. The large fluctuations associated with the satellite potential are due to the 1.27 volt quantization error of the DCBP potential measurement.

Figure 2a shows data collected when the plasma density was relatively high (6.6×10^{11} m^{-3}) and the sheath importance parameters (S1 = 1.23 and S2 = 0.41) were low. The electron temperature shows no correlation with the tether current or the satellite potential. The electron temperature average value (~ 0.3 eV) is higher than what is usually assumed for the ionosphere at shuttle altitudes.

In Figure 2b we display the results of the analysis for a case of low ambient density (2.4×10^{11} m^{-3}) and the sheath importance parameters (S1 = 4.92, S2 = 1.34) were the highest among the considered events. The probe was probably right at the edge of the satellite sheath; some of the characteristics (data derived from them do not appear in the plot) bear the evidence that the probe is occasionally inside the sheath during this event. A sharp electron temperature increase is observed, in very good agreement with the theoretical explanation given in the next section.

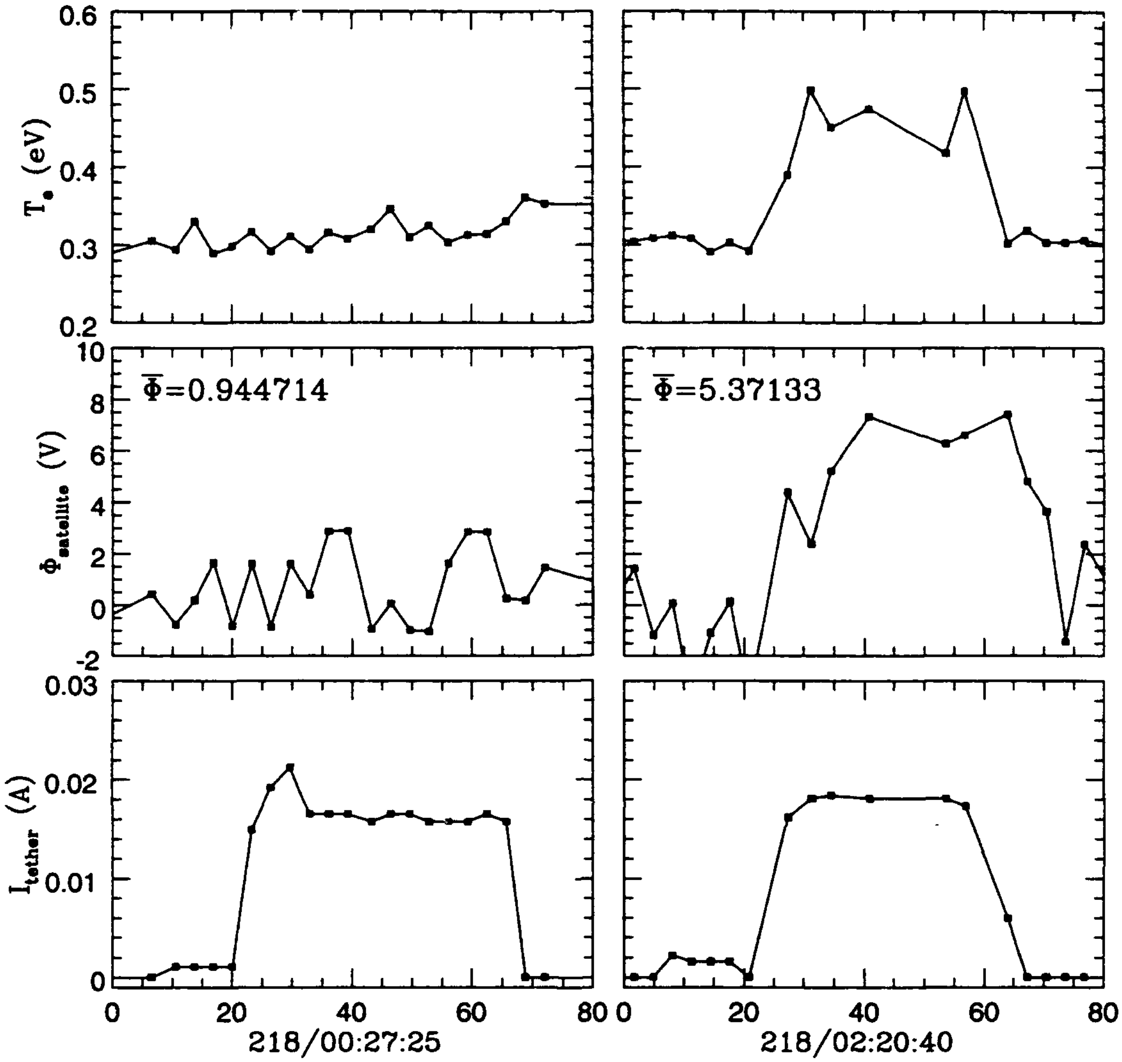

Figure 2. Temporal correlat.o.. between tether current (lower panels), satellite potential (central panels) and electron temperature (upper panels) during the first 2 DEP1 cycles reported in Table 2.

Figure 3 shows the same quantities as Figure 2 for the remaining 4 events in Table 2. (Note that the GMT times reported in Figures 2 and 3 are referred to the beginning of the plot window, and not to the start of the associated DEP1.) As we can see, whenever S2 >1 (Figures 3a, 3b and 3d), an increase in the electron temperature correlated with the tether current is observed. In Figure 3c, on the other hand, no heating appears. This figure corresponds in fact to event five in Table 2, which is characterized by S2 = 0.86 and S1 = 1.51, the second lowest value in the table.

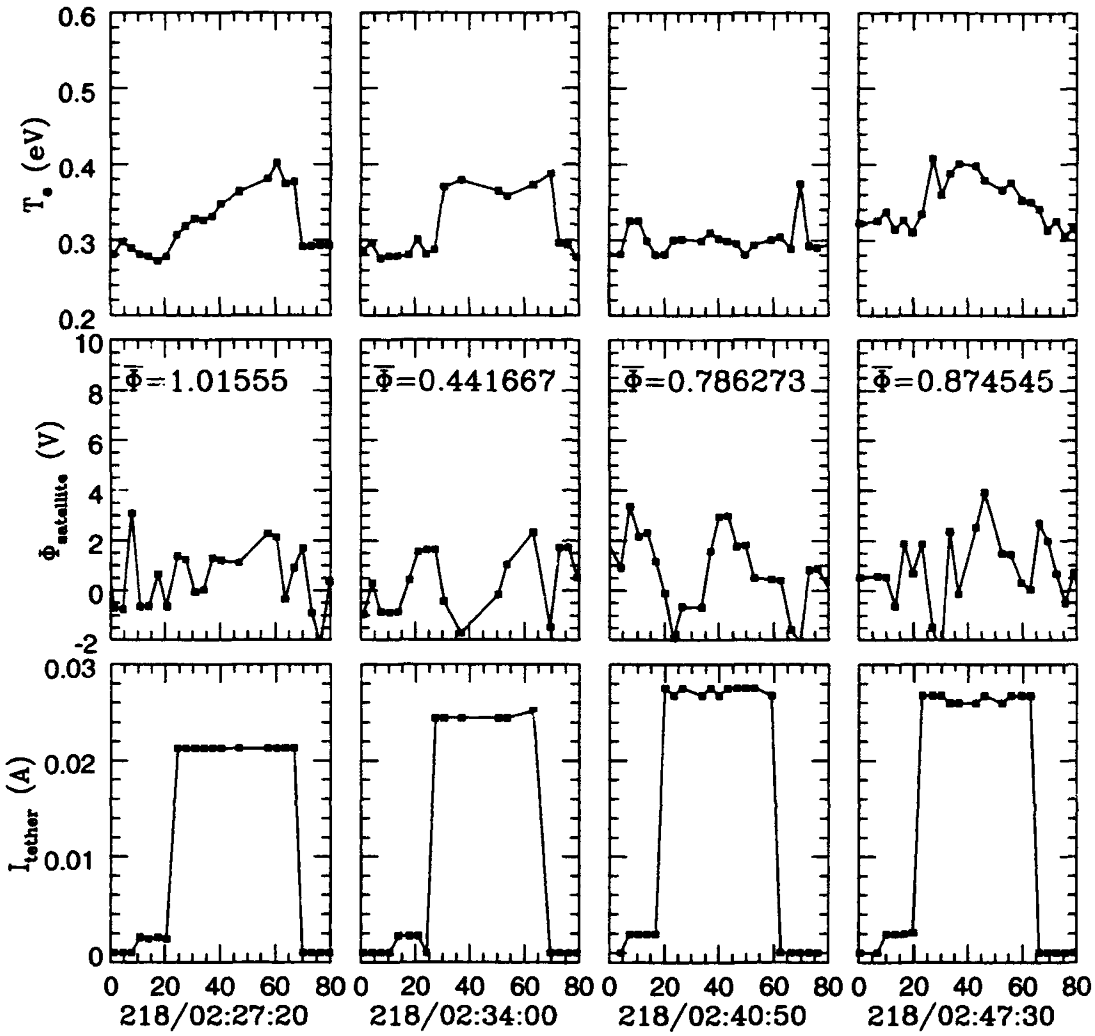

Figure 3. Temporal correlation between tether current (lower panels), satellite potential (central panels) and electron temperature (upper panels) during the last 4 DEP1 cycles reported in Table 2.

5. Theory

When a large, highly charged probe is immersed in a dense plasma, a sheath of opposite charge forms around the probe. The space charge in the sheath shields the bulk of the plasma from the probe charge. The necessary conditions to form a stable sheath were first set forth by D. A Bohm (ref) and are the subject of a recent comprehensive review by K-U Riemann, entitled "The Bohm criterion and sheath formation."

The Bohm condition has a very simple physical interpretation. When a charged probe is put into a dense, neutral, plasma, two things happen. First, charges of opposite sign are attracted towards the probe, and second, charges of like sign are repelled from the probe. In a stable sheath the density of attracted charges (opposite sign) is everywhere greater than the density of repelled charges (like sign). This condition is very easy to satisfy near a highly charged probe, because at large potentials the repelled species density decreases exponentially, while the attracted species density varies much more slowly. However, near the edge of the sheath, as the potential approaches the local plasma potential, the acceleration of the attracted species can reduce the attracted species density faster than the repelled species density. This

> "renders shielding impossible unless the 'Bohm criterion' is fulfilled. This condition for sheath formation demands that ions enter the sheath region with a high velocity, ... (A corresponding condition for an electron sheath in front of a positive wall is easy to fulfill but without practical importance)."

Both issues addressed in above quote from the Riemann article are relevant to TSS-1. The TSS-1 subsatellite forms an electron sheath, and electrons must be accelerated into the sheath in order for shielding to occur.

TSS-1 poses a very difficult problem because the earth's magnetic field limits electron motion and also because the subsatellite is moving fast compared to ion thermal velocities and slowly compared to electron thermal velocities (mesothermal). In order to get handle on collection, we first develop a simple theory of sheath current for a stationary electron collecting sphere immersed a dense plasma without a magnetic field. Using the lessons from the simpler case, we then develop an even more approximate approach to the TSS-1 mesothermal, magnetic limited, electron collection.

5.1 No Motion, No Magnetic Field

Acceleration of electrons by long ranged presheath potentials permits a stable electron collecting sheath to form around stationary sphere immersed in a dense plasma in the absence of a magnetic field. This problem has been solved exactly by Parrot, Storey, Parker, and Laframboise (1982 Phys. Fluids 25, 2388). The approach below is a simple, fluid-like treatment which illuminates the basic physical principles. It also gets a presheath enhancement that agrees within a few percent with the published exact solution.

Adjacent to the sphere there is a thin space charge sheath, that is a region of electron charge where the potential varies rapidly according to Poisson's equation. For large spheres, short Debye lengths, and low potentials (e.g. TSS- 1), the thickness of the sheath is very small compared with the sphere radius. Outside of the sheath is a much larger, quasi-neutral, region where the potential varies gradually on a scale of the sphere dimensions, with the maximum potential about one-half the electron temperature (i.e., less than a tenth of a volt in the ionospheric environment). This region, called the presheath, causes electrons to converge while repelling ions, so that from the undisturbed plasma inward to the sheath edge (at which the potential begins to rise so rapidly that all electrons are absorbed while ions are excluded) the ion and electron densities are equal (quasineutral). Furthermore, the presheath region is stable in the sense that a small, local potential increase will lead to negative local space charge.

The presheath modifies the current collected by a spherical probe by a focusing factor, f_{ps}: $I_e = f_{ps} A j_{th}$ where A is the area of the sphere and j_t is the one-sided thermal current: $j_{th} = ne (e\theta/2\pi m_e)^{1/2}$ We now present a simple argument why, in the absence of motion or magnetic effects, the value of f_{ps} is about 1.5.

For a positive potential probe we will need to develop expressions for the ion density and the electron density and current at the sheath surface. Under reasonably general conditions, if we have a Maxwellian plasma at infinity, the ion density is described by an exponential: $n_i = n_e{}^{-(\phi/\theta)}$. For the electron current, in spherical geometry, we will assume the well-known "orbit-limited" formula, $j_e = j_{th} (1 + \phi/\theta)$ which comes from considering energy and angular momentum conservation, provided the potential drops no more rapidly than r^{-2}. The same arguments, when used to calculate the electron density, lead to an incomplete factorial function. Rather than resorting to numerics, we make the following simpler argument:

(1) In undisturbed plasma, we define v_{th} by $n = 2\, j_{th} / v_{th}$ where the factor of 2 results from electron thermal current crossing a plane from both directions.

(2) At the sheath surface the electron angular distribution remains uniform over the incoming hemisphere, but vanishes for the outgoing hemisphere. The velocity

distribution, however, is an accelerated Maxwellian (which leads to an incomplete factorial function when we integrate to obtain density). We make the approximation that the mean acceleration of the velocity component normal to the sheath is by the factor $(1 + \phi/\theta))^{1/2}$. It follows that $n_e = j_e / [(1 + \phi/\theta))^{1/2} v_{th}]$.

(3) Using the orbit-limited value for j_e, we obtain the electron density at the sheath surface: $n_e = 1/2\, n\, (1 + \phi/\theta))^{1/2}$, where ϕ is the sheath surface potential.

The charge density, ρ, vanishes everywhere outside the sheath. Plotting $\rho = e(n_i - n_e)$ as a function of assumed sheath potential (Figure 4), we find that the charge density vanishes for $\phi/\theta = 0.49$. This means that $\phi = 0.49\theta$ is the sheath surface potential necessary to simultaneously satisfy the conditions that (1) outbound electrons vanish; (2) inbound electrons are accelerated and isotropic; and (3) electron density exactly balances exponentially attenuated ion density. Using the orbit-limited current formula, we then find the presheath enhancement factor to be $f_{ps} = (1+\phi/\theta) = 1.49$. (Parrot et al. find the same sheath surface potential, but a slightly reduced current enhancement of $f_{ps} = 1.45$ because the consistent presheath potential is slightly steeper than inverse square.)

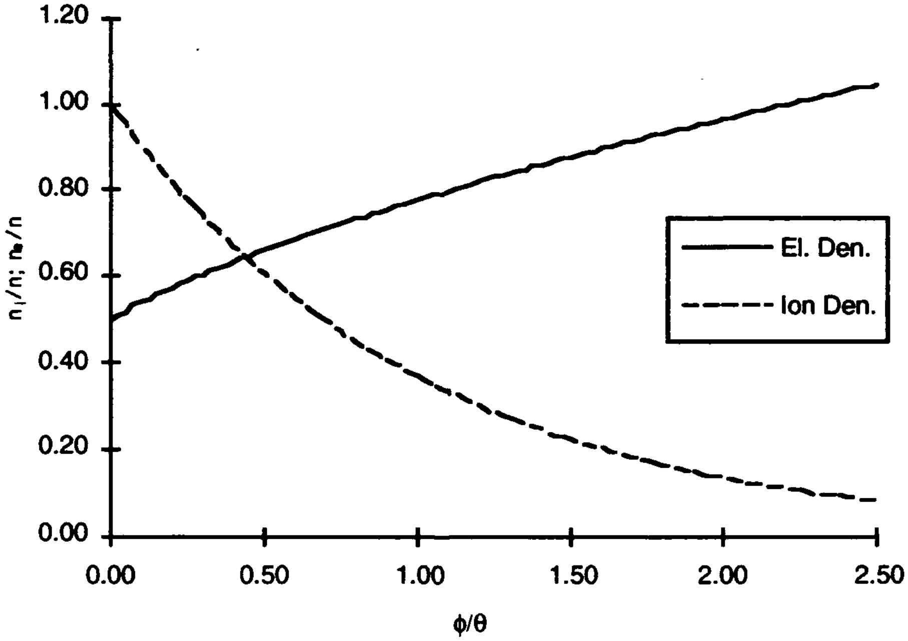

Figure 4. Sheath surface electron and ion densities as a function of assumed sheath potential. Quasi-neutral condition is satisfied for $\phi/\theta = 0.49$.

The above result is for a stationary sphere with no magnetic field. For TSS-1, we will show that the presheath enhancement of the electron current density is even larger.

5.2 Moving Sphere, Magnetic Field

The Riemann paper lists the following four processes which can occur in the presheath to satisfy the Bohm criterion:

1. geometric current concentration;
2. collisional friction;
3. ionization;
4. magnetic deflection.

In the previous example without motion or magnetic field, geometric current concentration due to enhanced potentials dominated the presheath.

In the absence of a magnetic field, current converges linearly with presheath potential. A strong magnetic field (electron Larmor radius small compared with the sphere radius) substantially reduces convergence of the plasma electron current. For very low gas pressures, ionization can't be important. This leaves collisional friction (scattering) as the only mechanism left in order to satisfy the Bohm criterion in the presheath. There are many instabilities than can give rise to scattering; however, for the discussion below we investigate the enhancement to collected current which occurs if scattering plays a major role in the presheath. The result is a presheath factor which enhances the electron current by more than a factor of two.

Unlike the previous example, the sheath potential is determined from the energy of the fast moving ions. If we assume that the presheath scattering affects electrons only, the sheath potential necessary to exclude ions is given by $\phi_s(\alpha) = E_i \cos^2 \alpha$ where α is the angle between the local sheath normal and the ram direction, and E_i is the energy of the ram ions in the sphere frame. For TSS-1 the ions have 5 electron volts of energy. This leads to sheath potentials averaging 2.5 volts, far larger than the 0.049 volt sheath potential for the non-moving, non-magnetic example under ionospheric conditions. We expect the much larger presheath potentials to lead to larger electron currents; the question is how much larger currents?

5.3 Temperature Enhancement by Collisional Presheath

If a quasi-neutral plasma has an electron scattering mechanism characterized by a scattering rate ν, the plasma electrical conductivity will be given by $\sigma = \varepsilon_0 \omega_p^2/\nu$. As we must include the diffusive flow of electrons due to pressure gradients, the plasma current is given by $j = -\sigma \nabla \phi - (\sigma/n)\nabla(n\theta)$.

The steady-state condition, $\nabla \bullet j = 0$, then leads to an elliptic equation for the presheath potential: $-\nabla \bullet \sigma \nabla \phi - \nabla \bullet (\sigma/n)\nabla(n\theta) = 0$, which is amenable to numerical solution.

We must also consider the temperature field in the presheath. The heat flow (which has a conductive and a convective term) and the ohmic heating rate are given by $Q = -3/2\ \sigma\theta\nabla\theta - 5/2\ \theta j$ $\nabla \bullet Q = j^2/\sigma$ so that $-3/4 \nabla \bullet \sigma \nabla \theta^2 - 5/2\ \nabla \bullet (\theta j) = j^2/\sigma$

The elliptic equations for temperature and electrostatic potential must be simultaneously and self-consistently solved. Note, however, that every term in both the above equations is proportional to σ (or to ν^{-1}). It follows that the temperature and potential fields, for a given set of boundary conditions, will be independent of the scattering rate, while the current will be inversely proportional to the scattering rate.

Before we can apply the above electron transport equations, we need an estimate of the ion density in the presheath, taking the spacecraft motion into account. (A ram ion density enhancement would lead to increased conductivity and therefore increased current.) To do this, we note that the potential equation, being elliptic, will give rise to a long-ranged potential. The density field for Mach 7 ions (5 eV ram energy and 0.1 eV temperature) in a Coulomb potential (taken as a typical long-ranged potential) is shown in Figure 5. The maximum density enhancement on the ram side is 30%. Consequently, we assume that, for the purpose of these calculations, it is adequate to assume a uniform ion density except in the wake of the subsatellite.

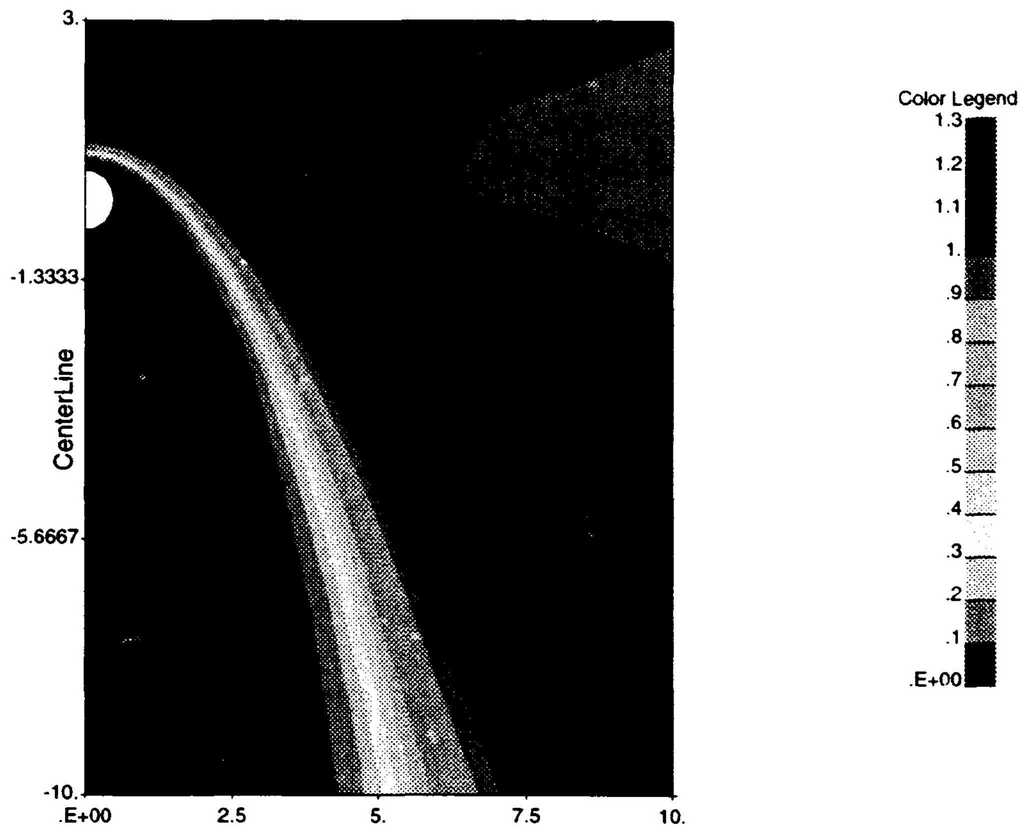

Figure 5. Ion density for a positive coulomb potential moving at Mach 7. For a long-ranged potential, ion density is nearly uniform outside stagnation surface. At Mach 7, Coulomb potential gives peak density enhancement of 30%.

Now we are ready to calculate the temperature and potential external to the subsatellite. We take the computational space to be the region external to a hemisphere (representing the ramward side of the subsatellite) capping a cylinder (representing the spacecraft wake. The ambient density and temperature are taken as 2×10^{11} m^{-3} and 0.1 eV respectively. The plasma scattering frequency was taken to be constant. In keeping with the thin sheath assumption, we apply the boundary condition $\phi = E_i \cos^2\alpha$ on the hemisphere. The resultant plasma potential and temperature fields are shown in Figure 6. The peak temperature is 1.7 eV; at the angular location of the RETE probe the electron temperature ranges from ~0.5 ev down to ambient, depending on the radius. Note that the absolute value of the temperature just outside the sheath scales with ram ion energy, and is independent of background plasma temperature.

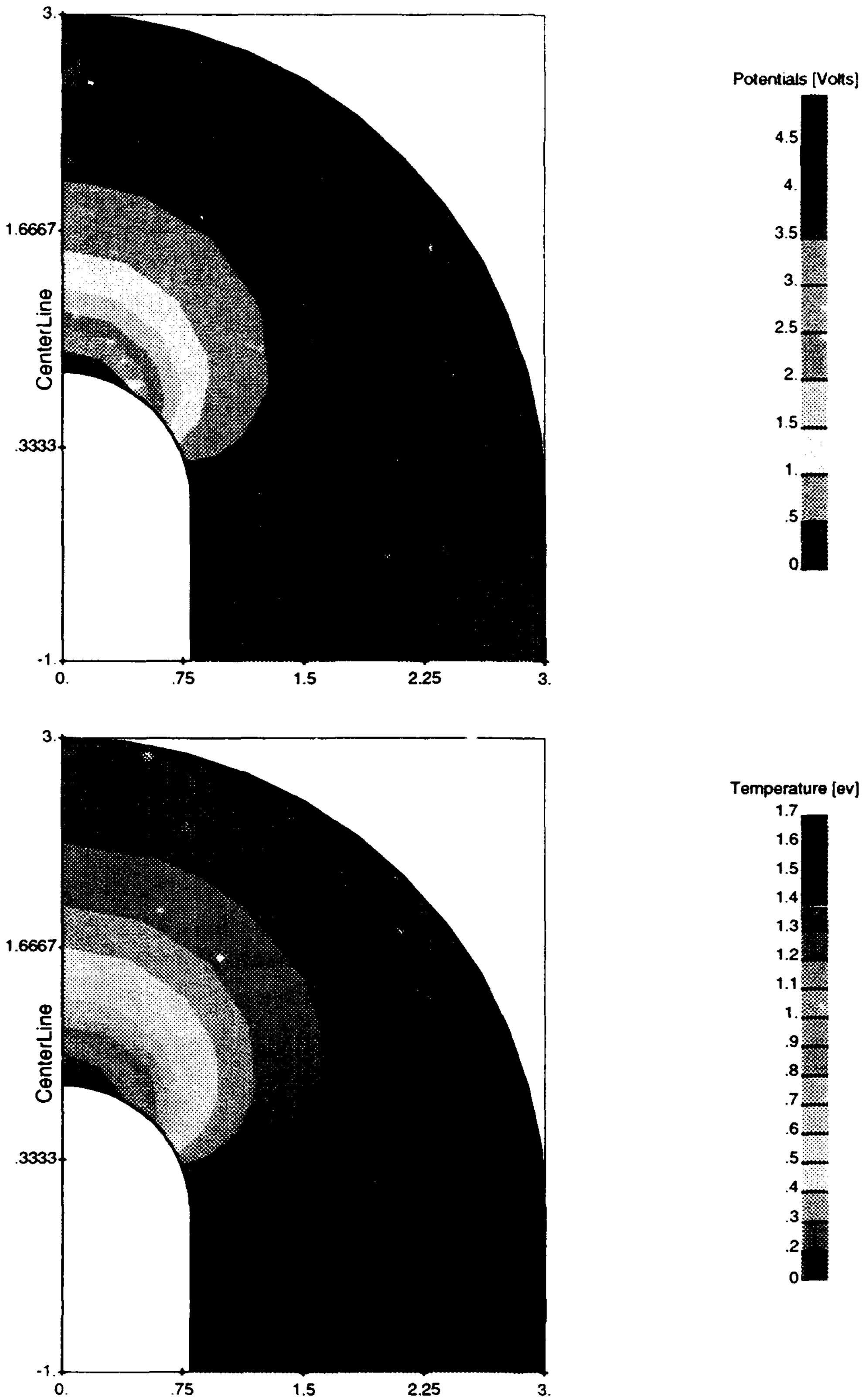

Figure 6a & 6b. Plasma potential and temperature in the TSS-1 subsatellite collisional presheath. (Dimensions in meters.)

To obtain the electron current to the subsatellite, we integrate the plasma thermal current (using the enhanced local temperature) over the ramward surface of the subsatellite. For this solution, the current is 15.2 milliamperes, an enhancement by a factor of 2.2 over the 6.8 milliamperes collected with no heating or presheath enhancement.

6. Summary

During TSS-1, enhanced electron temperatures were observed in the satellite presheath when the FPEG clamped the Orbiter potential to plasma potential and there was current flow in the tether. Due to the low induced voltages, these observations occurred when the ambient plasma density was low. These enhanced temperatures are due to resolution of a Bohm unstable sheath by a collisional mechanism. For a stationary spherical ionospheric probe with no magnetic field, this instability would be resolved by a convergent presheath electron current. For the TSS-1 satellite the ambient magnetic field precludes collisionless electron convergence, so that anomalous scattering saturates the instability. The theory described here indicates that an increase in the electron temperature at the RETE Langmuir probe location to 0.5 eV is to be expected. This is in good agreement with the observations, which show temperatures in the range of 0.4-0.5 eV.

TSS-1 resulted in only very few examples of large, high voltage, electron collecting sheaths around the satellite. However, the low potential data provides interesting information on the nature of an electron collecting presheath around a sphere moving through a magnetized plasma. Understanding the presheath,and therefore knowing what currents enter the sheath, is required before addressing whether space charge limited (Langmuir-Blodgett) or magnetic limited (Parker-Murphy) sheath theory applies in the ionosphere.

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