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Abstract. The Langmuir plasma probe model is an important tool in spacecraft current collection and charging calculations. In ideal geometries, such as a sphere or an infinitely long cylinder, the model is well understood. However, the realistic geometries of current collectors, or spacecraft, are nonideal. An empirical formula for a Langmuir probe with a given nonideal geometry would be useful. We derive such a formula for the SCATHA satellite by using the SC10 potential data obtained during electron beam emissions. The satellite rotated perpendicular to sunlight with the SC10 booms in the equatorial plane. We choose one special mode of operation during a quiet space environment. In this mode the beam current increased continuously, while the energy remained constant. We analyzed the variations of the vehicle potential responding to the unique driving factor, the beam current. To provide physical explanation to the behavior of the SC10 potential data, we model the interactions between the beam, photoelectron, and ambient currents. We present an algorithm which successfully predicted by the improved Langmuir probe model compare favorably with the very few published measurements from the region.

1. Introduction

Ambient electrons and ions in space plasmas impact on the spacecraft. The surface potentials come to equilibria on timescales of milliseconds. The charging time is so short because spacecraft surface capacitances with respect to the space plasma are typically small. Some dielectric surfaces couple to subsurface materials. They may have higher capacitances and accordingly may take longer amounts of time to come to equilibria.

At equilibrium, a spacecraft behaves like a Langmuir plasma probe [Mott-Smith and Langmuir, 1926]. Since spacecraft are current collectors, their potentials are governed by the balance of currents as given in the Langmuir probe equation. The control of a spacecraft's potential differs from that of a laboratory Langmuir probe. In a laboratory, currents collected by Langmuir probes vary in response to the applied potential. In space, however, vehicle potentials float with respect to the ambient plasma. During charge-particle beam operations, a spacecraft's potential varies in response to the emitted current [Lai, 1989].

When the plasma density is high, the current density is limited by the Child-Langmuir's law. When the plasma density is low, such as at SCATHA altitudes (5–7 \( R_p \)), the current density from ambient plasma impacting on a spacecraft surface is not in the current-limiting regime. Instead, the current density is limited by the orbital angular momenta of the incoming charged particles. This, we refer to as the orbit-limited regime.

In the orbit-limited regime, the Langmuir probe equation

\[ \mu I_e(0) \left( 1 - \frac{q_e \phi}{kT} \right)^\alpha - I_i(0) \exp \left( -\frac{q_i \phi}{kT} \right) = 0 \]  

for \( e \phi > kT \). In (1), \( I_e(\phi) \) and \( I_i(\phi) \) are the electron and ion currents, respectively, which are collected from the local plasma by a probe charged to a potential \( \phi \) relative to the plasma, and \( T \) is the plasma temperature. In (1), \( q_e = -e \), and \( q_i = e \), where \( e \) is the magnitude of the elementary charge. The multiplicative factor \( \mu \) is unity if the probe is a perfect sphere and \( 2/\pi^{1/2} \approx 1 \) if it is an infinite cylinder; the power factor \( \alpha \) in (1) is unity and 1/2 respectively. Since the geometry of the probe is neither a sphere nor an infinitely long cylinder, \( \mu \) and \( \alpha \) have neither value.

Laframboise and Parker [1973] generalize the concept of orbit-limited motion to include spheroids. They conclude that prolate and oblate spheroids have an orbit limitation in the Laplace limit as long as the major-to-minor axis ratios are less than 1.653 and 2.537, respectively. They do not give \( \alpha \) values for specific ratios. Moreover, SCATHA is not a spheroid. Thus their work is not directly applicable here.

Equation (1) describes a balance in which the total current to the probe equals zero. When other currents are involved, (1) must be modified accordingly. For example, if there are currents due to secondary electrons \( I_s \), artificial beam emissions \( I_b \), and photoemissions \( I_{ph} \) due to sunlight, these terms have to be included:

\[ \mu I_e(0) \left( 1 + \frac{e \phi}{kT} \right)^\alpha - I_i(0) \exp \left( \frac{-e \phi}{kT} \right) = I_b + I_{ph} + I_s \]  

The magnetic field \( (-100 \text{ nT}) \) at SCATHA altitudes is weak. \( \mathbf{V} \times \mathbf{B} \) electric fields are negligible since they are much
To study in detail the oscillation behavior of the SC1O and CuBe, the outer sections of the SC1O booms should not be heated. The potential is controlled by the electron beam emission. During beam emissions, photoelectrons from the booms were attracted back toward the satellite. The beam current exceeded the ambient level. The spacecraft potential was controlled by the electron beam emission. Furthermore, the current beam was continuous, and the level of spacecraft charging was positive, in the range 0 to +170 V. The ion current can be ignored under these circumstances.

In section 2, we describe the SCATHA satellite and the SC10 instrumentation on board. The general characteristics of the oscillations of SC1O voltage measurements and the observations on March 11, 1981, are described in section 3. To study in detail the oscillation behavior on March 11, 1981, we present our theory in subsections 4.1, 4.2, and 4.3. In subsection 4.1, we model the photoelectron currents originating from the boom surfaces and flowing toward the satellite body. By using the measurements obtained, we determine the photoemissivity of copper-beryllium, the surface material on the outer segment of the booms. In section 4.2 we delineate three interaction regimes depending on the contribution of various currents to the satellite potential. In section 4.3 we choose the appropriate regime in which $\alpha$ is the only parameter to be determined, and we present an algorithm for calculating $\alpha$. With $\alpha$ determined, we have at hand an improved Langmuir probe formula for SCATHA. Applying this formula to the current-voltage measurements, we obtain the local plasma temperature and density. Finally, in section 5, we summarize the main findings of this paper and compare our plasma results with published ones obtained with different instrumentation and techniques under comparable environmental conditions.

2. SCATHA Satellite

SCATHA was launched in January 1979, to investigate natural and artificial processes controlling charging at high altitudes. Descriptions of the experiments on SCATHA are given by Fennell (1982). The satellite is about 1 m long and 1.6 m in diameter. It rotates about once per minute with a spin axis perpendicular to the Sun-Earth line. SCATHA is equipped with two 50-m booms (SC10) that are electrically isolated from the satellite ground. The surface material of the outer 20 m of each boom is made of an exposed copper beryllium (CuBe) wire. The inner segment is coated with kapton, an insulating material. The SC1O potential $\phi$ represents the difference between the potential $\phi_{\text{CuBe}}$ of the tip of a boom and that $\phi_s$ of the satellite ground (Lai et al., 1986). That is,

$$\phi = \phi_{\text{CuBe}} - \phi_s.$$  \hspace{1cm} (3)

An electron beam (SC4-1) could be emitted from SCATHA with various energies and currents. During quiet days in sunlight, SCATHA normally charges positively to a few volts. The emission of an electron beam tends to raise the satellite potential to a degree that depends on ambient conditions as well as beam energies and currents. When the satellite rotates in sunlight, the amount of solar illumination on boom surfaces varies sinusoidally, as does the photoelectron current from the booms to the spacecraft.

When SCATHA is in sunlight, with or without beam emission, SC1O potentials show oscillations at twice the satellite rotation frequency (Lai et al., 1986, 1987). When the satellite enters eclipse, the amplitude of oscillation decreases gradually; this evidence supports the contention that the oscillation is due to the effects of photoelectrons.

When SCATHA charged positively as a result of electron-beam emissions, photoelectrons from the booms were attracted back toward the satellite body (Lai et al., 1987). The booms form part of the satellite body's electrical environment. In this case, the satellite body not only interacts with its ambient plasma environment but also with the booms (Figure 1).

Because of the high secondary-emission coefficient of CuBe, the outer sections of the SC10 booms should not charge to high negative potentials, except in unusually energetic plasma environments (Lai, 1991). On quiet days, the potential $\phi_{\text{CuBe}}$ on SCATHA typically varies within $\pm 5\text{V}$ (Lai et al., 1986). When the spacecraft potential $\phi_s$ is high compared with $\phi_{\text{CuBe}}$, $\phi_s$ represents a good approximation of the spacecraft potential $\phi_s$, with the sign reversed, that is, $\phi \approx -\phi_s$. There are several instruments for measuring spacecraft potential on SCATHA (Fennell, 1982). They confirm that SC1O often provided good approximate measurements of the satellite potential. We assume that SC1O measured $\phi = -\phi_s$, where $\phi_s$ was of several tens of volts and was controlled by electron beam emissions.

3. Observations

We describe in this section the general characteristics of SC1O potential oscillations and the specific behavior of the oscillations on March 11, 1981.

3.1. General Characteristics

In sunlight, as the electron beam current increases from low values, the spacecraft potential increases. Furthermore, not only the maxima $|\max(\phi)|$ of the SC1O potential in an oscillation period but also the amplitude $|\max(\phi) - \min(\phi)|$ of oscillation increases. The extrema of the oscillation correlate well with the Sun angle of the beams (Lai et al., 1987). Minima occur at $\theta = 0^\circ$ and $\theta = 180^\circ$ and maxima at $90^\circ$ and $270^\circ$. Another instrument, SC2, also measured the potential of the spacecraft body. While still in operation, the oscillation frequency and phase of SC2 potential were identical with those of SC1O during electron beam emissions. This indicates that the oscillations are due to the variations of $\phi_s$.

In the rest of this section, we discuss three points on the SC1O potential data. The first one concerns whether the
boom (SC2 or SC10) potential oscillations always depend on vehicle potential modulation. The answer to this question is "no" under two extreme conditions of vehicle charging. In the first extreme, the vehicle potential relative to the space plasma is a few volts, and is nearly constant, as during quiet days in sunlight without beam emission. The booms may also be at a few volts relative to the space plasma. Under this condition, there is a twice per rotation modulation of the boom potentials. Such a modulation has been identified to be due to photoemission from the booms [Lai et al., 1986; Craven et al., 1987]. In the other extreme, the space plasma is so energetic and unusual that both the vehicle and the booms are charged to high potentials (a few kilovolts). This condition is rare [see Lai, 1991a, b] and did not occur on quiet days.

The second point to discuss concerns the use of SC10 rather than other measurements (SC2, SC5, and SC9) of vehicle potential on SCATHA. All measurements were approximate. Because of the short length (3 m) of its boom, the SC2 data were not accurate for measuring vehicle potential relative to the space plasma. The SC2 instrument failed early in 1979. The SC5 data below about 100 eV were inaccurate. The SC9 data, which measured vehicle potential by identifying the shift of the ambient electron distribution, were also inaccurate at low potentials and, besides, were sampled at a slow rate (once per 16 s).

The third point concerns the accuracy of SC10 data in representing the vehicle potential. At high-vehicle potentials, the Coulomb potential sheath may extend far beyond the 50-m booms, the data would merely reflect the potential difference between the vehicle and a point inside the sheath. For potentials below about 300 V, the error due to the Coulomb sheath is negligible.

3.2. Satellite Potential Oscillations

Figure 2 presents data acquired on March 11, 1981. The beam energy was constant at 300 eV. The beam current increased continuously from near zero to about 90 μA. There are several 30-s periods of calibration dropouts. Data taken during such periods are ignored in our study. Oscillations in the potential of SC10 detected on March 11, 1981, correlate with boom-Sun angle \( \theta \), with spacecraft potential

Figure 2. March 11, 1981, measurements on SCATHA. (a) SC10 \( \phi \) potential in volts, (b) electron beam current \( I_b \) in microamperes, and (c) SC10 boom Sun angle \( \theta \) in degrees are presented as functions of time. The electron beam energy is 300 eV. The dropouts at regular intervals are for calibration.
maxima occurring when the booms were parallel or antiparallel to sunlight direction and minima when the booms were perpendicular to it. Starting from zero beam current, the potential oscillation amplitude increased monotonically with beam current until a critical level of about 60 μA was reached. The amplitude decreased slightly with further increases in beam current.

4. Discussion

To provide a physical interpretation of these observations, we model the photoelectron current flowing towards the satellite body from the SC10 booms and delineate various regimes of interactions. We then provide an algorithm for determining the exponent α in the Langmuir probe equation (5).

4.1. Photoelectron Current Modeling

The photoelectron current $I_{ph}(\phi, \theta)$ from the booms is a function of the Sun angle $\theta$. Depending on the potential $\phi_s$ of the satellite body, some fraction $f$ of this current flows to the main body of the spacecraft. The satellite potential $\phi_s$ depends in a self-consistent manner on the photoelectron current $I_{ph}(\phi, \theta)$ received from the booms. In the low-density plasmas at SCATHA altitudes, the orbit-limited Langmuir plasma probe model applies for the collection of ambient currents. The current-balance equation for the satellite body is

$$
\mu I_s(0) \left( 1 + \frac{e \phi}{kT} \right) + I_{ph}(\phi, \phi_s) = I_b(\phi_s) - I_s(\phi_s)
$$

(4)

where

$$
I_{ph}(\phi, \theta) = 2d \int_0^{\pi/2} d\theta \int_0^R dr f(\phi(r)) j_{ph} \sin \theta
$$

(5)

and $d$ is the boom diameter $I_s(0)$ is the ambient current collected if the spacecraft potential $\phi_s$ is zero with no photoelectron or beam emissions. $I_b$ is the emitted electron beam current. If the beam’s energy is high and its current density low, all beam particles escape. However, if the beam’s energy is low and its current density is high, some beam particles return and the return current $I_b$ becomes nonzero.

For a spherical body, the power $\alpha$ of the orbit-limited current collection term in (1) equals unity; for an infinite cylinder, $\alpha$ equals 1/2. However, the SCATHA satellite is neither a sphere nor a long cylinder. Rather, it has a short cylindrical shape with nearly the same length and diameter. Thus the power $\alpha$ for SCATHA has neither value, and it may fall between them.

To model the photoelectron current $I_{ph}(\phi)$ from the booms to the satellite, we assume a photoelectron energy spectrum and a satellite sheath potential profile $\phi(r)$ as a function of distance $r$ from the satellite surface. Both laboratory and space experiments have shown that a Maxwellian distribution is a good approximation for describing the photoelectron energy spectrum [Hinterreisser et al., 1965; Whipple, 1981]. The photoemissivity $j_{ph}$ of the copper-beryllium boom surface material on a rotating satellite has been estimated to be between $2 \times 10^{-7}$ and $4 \times 10^{-7}$ A cm$^{-2}$ [Kellogg, 1980]. In this paper, we regard $j_{ph}$ as a parameter to be determined

$$
\phi(r) = \phi(0) \frac{R}{r + R} \exp \left( -r / \lambda_D \right)
$$

(7)

Here $R$ is the radius of the satellite body, and $\lambda_D$ is the Debye distance. For SCATHA environments, we assume that the Debye length $\lambda_D$ of the ambient plasma is about 45 m [Aggson et al., 1983], and the photoelectron temperature $T_{ph}$ is about 2 eV [Whipple, 1981; Lai et al., 1986]. Using this model, we have computed the photoelectron current $I_{ph}(\phi, 90^\circ)$ going toward the satellite body. The results appear in Figure 3.

The maxima and minima of the SC10 potential difference measurements of Figure 2, plotted in Figure 4, display the emitted beam currents as functions of the satellite potential. Data with photoemission (min $|\phi|$ with $\theta = 90^\circ$ or 270°) from the beams are plotted in Figure 5a, and those without photoemissions (max $|\phi|$ with $\theta = 0$ or 180°) are plotted in Figure 5b. At low-beam currents, each set of current-voltage data varies smoothly. The measurement trend suddenly deviates from the trend line at a critical current. Without photoemission, the critical current is about 60 μA with the spacecraft potential at about 220 V. With photoemission, the...
critical current is about 70 μA with the spacecraft at a potential of about 140 V.

The total photoelectron current \( I_{ph}(\phi, 90) \) is computed for a given value of photoemissivity \( j_{ph} \) using (5) and (6). This computed total photoelectron current \( I_{ph}(\phi, 90) \) is then added to the current in the maximum \( \phi \) (\( \theta = 0 \) or 180°) curve, which represents the spacecraft body potential when there is no photoelectron current from the booms to the spacecraft body. The result of this addition should represent the current collection of the satellite body during maximum sunlit conditions at the booms, that is, during \( |\phi| \) min (\( \theta = 90° \) or 270°). We find that the obtained curve fits best with the experimental data points of \( |\phi| \) min when the value of the photoemissivity \( j_{ph} \) is about \( 3.5 \times 10^{-9} \text{ A cm}^{-2} \) (Figure 6). This value of \( j_{ph} \) determined for the CuBe surfaces on the SC10 booms of SCATHA agrees with that (between \( 2 \times 10^{-9} \) and \( 4 \times 10^{-9} \text{ A cm}^{-2} \)) estimated by Kellogg [1980] for the CuBe surfaces on the Helios spacecraft.

4.2. Interaction Regimes

The satellite potential \( \phi_s(\theta) \) oscillates as the satellite and booms rotate in sunlight. The amplitude of the potential oscillation is given by \( \Delta \phi = \phi_s(\theta = 0 \text{ or } 180°) - \phi_s(\theta = 90° \text{ or } 270°) \). As the beam current \( I_b \) increases, so does the \( \Delta \phi \). When the satellite charges to near beam potential, the beam current does not escape completely [Olsen, 1989].

Three regimes of interactions 1, 2, and 3 can be identified in cases with and without photoemission (Figures 5a and 5b). In regime 1 and 2, the \( I_b \) is unsaturated, and the return current \( I_s \) is zero. In regime 1, some photoelectrons from the satellite body escape because the satellite positive potential \( \phi_s \) is low. The amount of photoelectron current leaving the satellite body is a function of satellite potential \( \phi_s \). In our model the current balance equation is

\[
\mu I_s(0) \left( 1 + \frac{e \phi}{kT} \right) + I_{ph} (\phi_s, \theta) = I_b(\phi_s) + J_{ph} (\phi_s, \theta)
\]

(8)
where $J_{ph}(\phi_s, \theta)$ is the photoelectron current leaving the satellite body.

In regime 2, the photoelectron current from the satellite body is very small because the satellite body potential energy $e\phi_s$ is high compared with the photoelectron energy:

$$\mu I_e(0) \left( 1 + \frac{e\phi}{kT} \right)^a + I_{ph}(\phi_s, \theta) = I_b(\phi_s)$$

By extrapolation [Gonfalone et al., 1979], the regime 2 curve intercepts the y axis ($\phi_s = 0$) at about 10 $\mu$A (Figure 5b). This determines $\mu I_e(0)$ to be approximately 10 $\mu$A in (4) which gives $I_{ph}(0) = \mu I_e(0) \approx 10$ $\mu$A at the intercept. Using the surface area $D = 9.05 \text{ m}^2$ of SCATHA and the average ambient current density $J_e = 0.115 \pm 0.10 \text{ nA cm}^{-2}$ obtained in a 45 days average in 1979 at SCATHA altitudes [Purvis et al., 1984], one obtains a result for the average current intercepted by SCATHA as $D J_e = 10.4 \pm 9.1 \times 10^{-6}$ A if $\mu = 1$ or $9.5 \pm 8.3 \times 10^{-6}$ A if $\mu = 1.1$. This average result is of the same order of magnitude as the $I_e(0)$ determined ($\approx 10 \mu$A), the ambient current intercepted by SCATHA on March 11, 1981.

In regime 1, the data points deviate from the curve extrapolated from regime 2, because of photoelectrons leaving the spacecraft body. On the other hand, very few of the photoelectrons from the booms can reach the spacecraft body, because of the low attraction offered by $\phi_s$. In regime 2, a multibody interaction occurs between the satellite body, the booms, the electron beam, and the ambient plasma. This regime will be discussed further in section 4.3. In regime 3, beam saturation occurs, and part of the beam current returns; this regime is not of main interest here. Physical processes characteristic of the three regimes are shown schematically at the bottoms of Figures 5a and 5b.

By differentiation, the slope of the straight line in Figure 6 equals $\mu I_e(0) \left( 1 + \frac{e\phi}{kT} \right)^a kT$. Therefore, the parameter $\alpha$ can be obtained from the slope, and then $\phi_s$ can be obtained from the intercept (at $e\phi = 0$) which equals $kT\alpha$.

Equation (12) is a simple formula enabling $\alpha$ and $kT$ to be determined. If the data $I_b(\phi)$ satisfy the Langmuir probe equation (10), they should satisfy (12). An algorithm based on (12) is as follows. Plotting the data $I_b/I_b^0$ as a function (ordinate) of $e\phi$ (abscissa) should yield a straight line with $1/\alpha$ as the slope. Once $\alpha$ is determined, the ambient electron temperature $T$ can be determined from the intercept (at $e\phi = 0$) which equals $kT/\alpha$.

Using data from Figure 5b, Figure 7 shows a plot of $I_b/I_b^0$ as a function of $e\phi$. In Figure 7 the data $I_b/I_b^0$ falls into a straight line for the potential range from $\phi = 25-160$ V. This linear dependence of $I_b/I_b^0$ on $e\phi$ is as predicted by (12). Outside this range, the current-voltage behavior deviates from the simple Langmuir probe equation given by (10). Below $\phi = 20$ V, some secondary electrons and photoelec-
trons from the spacecraft body escape, and above $\phi = 160$ V, some beam electrons return. Between the two critical values of potential $\phi$, $I_s/I_b$ falls on a straight line, as predicted by (12). From the slope of this line, we obtain the power factor $\alpha = 0.774$. This fitted value of $\alpha$ lies about halfway between the values for a sphere and an infinitely long cylinder.

After obtaining $\alpha$, one can obtain the ambient electron temperature $kT$ from the intercept in Figure 7. The intercept equals $kT/\alpha$ and gives $kT = 23.2$ eV. This value is comparable to $kT = 64$ eV [Whipple, 1981] which was measured by a different method on the ATS-5 satellite. Since the environment (e.g., plasma sheet and plasmasphere) is unknown, the comparison is not meant to be strict. We merely note that the measurements are of the same order of magnitude.

Taking $kT \approx 23.2$ eV and the ambient current $I_s(\phi = 0) \approx 10 \mu A$ obtained from the intercept (section 5), we can determine the ambient electron density $n_e$ by the following equation:

$$I_s(0) = \frac{1}{4} n_e e V_D = \frac{en_s D}{4} \left( \frac{8kT}{\pi m} \right)^{1/2} \approx 10 \mu A$$

which gives $n_e = 8.47 \text{ cm}^{-3}$ for $\mu = 1$ and $7.70$ for $\mu = 1.1$. We cannot determine $\mu$ without knowing $I_s(0)$ independently.

5. Summary and Conclusions

The equilibrium potential of a spacecraft is governed by current balance as given in the Langmuir probe equation. The power $\alpha$ in the Langmuir probe equation [Mott-Smith and Langmuir, 1926] is well known to be 1 or 1/2 for a spherical or infinitely long cylindrical probe, respectively. For most spacecraft, the geometry is neither a sphere nor an infinite cylinder. For improved spacecraft charging modeling, it is better to determine and use the correct value of $\alpha$ rather than taking $\alpha = 1$ as commonly practiced. This leads to a lower estimate of $kT$ and a higher estimate of the plasma density.

With beam emissions, the beam current emitted is likely known except when there is beam return. From current-potential measurements, it is then possible to deduce the value of $\alpha$. Before one can apply an algorithm to deduce the power $\alpha$, one has to identify and disentangle all the various interactions between the spacecraft body, the beams, the ambient plasma, and the beam emitted or even returned. We have taken the March 11, 1981, current-voltage measurements obtained on SCATHA satellite for a case study. The day was chosen because there was no storm and the period chosen was the only one in which the SCATHA electron beam current was increasing continuously instead of changing in large steps.

5.1. Key Observations

The SC10 potential difference measurements oscillated at twice the satellite frequency with their maxima occurring when the beams were parallel or antiparallel to sunlight ($\theta = 0^\circ$ or $180^\circ$) and the minima occurring when the beams were perpendicular. The amplitude of oscillation increased with the beam current until the satellite potential was near the beam energy.

5.2. Key Interpretations

When the beams were aligned with sunlight, there was no photoemission emitted from the boom surfaces. When the beams were perpendicular to sunlight, the photoemission from the beams was maximum. As the emitted beam current increased, the spacecraft potential increased. As a result, the spacecraft sheath engulfed part of the booms, and therefore some photoelectrons from the booms were attracted toward the satellite body. The amount of photoelectron current, and therefore the amplitude of oscillation, increased with the spacecraft potential. When the spacecraft potential was near the beam energy, the beam partially returned. We have identified three different interaction regimes (Figure 5). In regime 1, photoelectrons were emitted from the spacecraft body. Also, in this regime, the approximation $\phi = -\phi_b$ may not be accurate. In regime 3, partial beam return occurred. In between these two regimes, we have modeled the interactions.

5.3. Calculations and Results

1. Using a simple photoelectron current partition model to fit the measured oscillation amplitude, we found that the photoemissivity $I_{ph}$ of the boom surface was about $3.5 \times 10^{-9}$ A cm$^{-2}$.

2. The ambient current $I(0)$ can be deduced by extrapolating the regime 2 curve to intercept the $\phi = 0$ axis. From the intercept, we obtained the ambient current $I(0)$ intercepted by SCATHA as $10 \mu A$.

3. For Langmuir probe modeling, we chose the current-voltage measurements in regime 2, when the beams were aligned with sunlight. No photoemission from the beams was involved with these measurements. No partial beam return occurred in this regime. The spacecraft potential $\phi$ was a function of the beam current $I_b$, the ambient current $I(0)$, and the ambient temperature $T_e$ only (10). We plotted $I_b/I_s$ as a function of $\phi$. The slope gives $\alpha$ and the intercept $kT_e/\alpha$. The slope gives $\alpha = 0.774$, $kT_e = 23.2$ eV, and $n_e = 8.47 \text{ cm}^{-3}$ for $\mu = 1$ or $n_e = 7.70$ for $\mu = 1.1$.

5.4. Comparisons With Other Measurements

The calculated photoemissivity result agrees with the measurements by Kellogg [1980]. The ambient current value obtained agrees with the statistical measurements of Purvis et al. [1984]. It is interesting that the value of $\alpha \approx 0.774$ lies between the two known values 1 and 1/2, corresponding to a perfect sphere and an infinite cylinder, respectively. Since the geometry of SCATHA resembles a short cylinder, the $\alpha$ result seems reasonable. The ambient temperature $kT_e$ is comparable to the value $kT_e = 64$ eV obtained on ATS-5 [Whipple, 1981] at the geosynchronous environment by means of different instrumentation and technique. Since the environment is unknown, we merely note that our result, $kT_e = 23$ eV, is not unreasonable for near geosynchronous orbit, on a quiet day near dawn. At $5.5 R_E$ (perigee for SCATHA).

We compare our $n_e$ result with the statistical results of GEOS measurements obtained by means of relaxation sounding at $6.6 R_E$ [Higel and Lei, 1984]. During the period considered, the altitude of SCATHA was approximately 40000 km ($\approx 7.3 R_E$) at 0500 LT and the $2KP$ was $14^\circ$. At
the nearest values of $\Sigma Kp$, the GEOS plasma densities at 6.6 $R_E$ and 0900 LT were about 3 to 7 cm$^{-3}$ for $\Sigma Kp = 13$, 1 to 2 cm$^{-3}$ for $\Sigma Kp = 15$, and 8 to 9 cm$^{-3}$ for $\Sigma Kp = 21$ [see Higel and Lei, 1984, Figures 3E, 3A, 3B]. In this comparison, our local plasma density $n_e$ is on the high side.

5.5. Final Comments

We have assumed a Debye length $\lambda_D = 45$ m [Aggson et al., 1983] to fit the photoelectron current (top solid line in Figure 6). In retrospect, we use $\lambda_D = 12$ m ($kT_e \approx 23.2$ eV and $n_e \approx 7$ cm$^{-3}$) to fit (dashed line in Figure 6), yielding $j_{ph} \approx 6.5 \times 10^{-5}$ amp cm$^{-2}$. This photoemissivity value $j_{ph}$ is higher than Kellogg's [1980] estimate.

In our algorithm (12) we have avoided any photoelectron current flowing from the booms to the vehicle body by selecting the branch of SC10 potential data points (Figure 4) with Sun angle $\theta = 0^\circ$ or $180^\circ$. Any error in the initial estimate of plasma density, or Debye length, would not affect the algorithm for determining $I_e(0)$, $\alpha$, $kT_e$, and $n_e$.

Finally, we briefly comment that the presence of a satellite may affect its local plasma density. Enhancement of local plasma density has been observed by Olsen et al. [1981], who attributed the cause to possible potential barriers due to differential charging on the satellite surface. In our case, electron beam emissions may also be plausible reasons. For purposes of designing better experiments for improved determination of Langmuir probe parameters for spacecraft and the parameters of the ambient plasma, we suggest omitting a high-energy (several keV) electron beam at night. High-energy beam would generate less electrons in the vicinity of the spacecraft. Without photoemission from the spacecraft, the Langmuir probe current at $\phi = 0$ reduces to $I_e(0)$ regardless of the geometry, sphere, or cylinder. This would determine the ambient current without extrapolation or the ambiguity factor $\mu$ between 1 and 1.1.

Appendix

This appendix discusses the differences in functional forms of Langmuir probe current due to spherical and cylindrical geometries. The flux $J$ collected by a spherical probe is given by [Mott-Smith and Langmuir, 1926]

$$J = J_o \left( 1 + \frac{e^\phi}{kT} \right)$$

where $J_o$ is the random flux $n_o(kT/2m)^{1/2}$, $n_o$ is the plasma density at infinity, and $m$ is electron mass. The flux $J$ is related to the current $I$ by a multiplicative factor of surface area.

For a cylindrical probe, the flux $J$ collected is given by [Mott-Smith and Langmuir, 1926; Laramboise and Parker, 1973]

$$J = J_o (2/\pi)^{1/2} (\eta^{1/2} + g(\eta^{1/2}))$$

where

$$g(s) = \frac{i}{2} \pi^{1/2} \exp(s^2) \text{erfc}(s)$$

$$= \exp(s^2) \int_0^\infty \exp(-t^2) \, dt$$

and

$$\eta = -\frac{e^\phi}{kT} = 0$$

For $s = 0$, $g(0) = \pi^{1/2}/2$. For large $s$, $g(s) \to 1/2s$, one approximates $g(\eta^{1/2})$ in (16) by $1/2 \eta^{1/2}$, then approximates $1 + 1/2 \eta$ by $(1 + \eta)^{1/2}$ and obtains

$$J = \left( \frac{n_o}{\pi} \right) \left( \frac{2kT}{m} - 2e^\phi \right)^{1/2} = J_o \left( \frac{2}{\eta^{1/2}} \right) (1 + \eta)^{1/2}$$

The functions $[\eta^{1/2} + g(\eta^{1/2})]$ and $(1 + \eta)^{1/2}$ versus $\eta$ [Mott-Smith and Langmuir, 1926; Swift and Schwar, 1977] already show little difference for $e^\phi > kT$ and no visible difference at all for $e^\phi > 2kT$. This property further supports that our starting point of the data fitting (section 4.2) at about 30 eV (see Figure 7), below which the data deviate from the Langmuir probe form considered.

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References


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