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Satellite particle collection during active states of the Tethered Satellite System (TSS)

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SATELLITE PARTICLE COLLECTION DURING ACTIVE STATES OF THE TETHERED SATELLITE SYSTEM (TSS)

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Abstract

The reflight of the Tethered Satellite System (TSS-1R) was carried aboard the Space Shuttle *Columbia* on February 22, 1996. After deploying a day later than planned, the satellite almost reached its full deployed distance before the tether broke. Data was collected for over 5 hours during deployment out to a distance of 19.7 km. Maximum emf attained during deployment was 3700 V while the maximum current achieved was just under 0.5 A. The current collected was factors of 2 to 4 greater than the predictions of the conventional Parker-Murphy theory. The microscopic view of the collection process at the satellite showed exotic behavior with the existence of 100 – 200 eV suprathermal electrons and significant spin phase modulation of the electron fluxes. Although the data set acquired from TSS-1R was considerably less than planned, the quality of the data allows one of the main goals of the mission to be met—characterizing the system I-V response. A "quick look" assessment of the data has already shown that an understanding of the TSS-1R electrodynamic behavior will require modification of the standard picture of current collection in space plasmas.

Introduction

Background

Several tether-related flights have been accomplished in the past few years with the orbital missions occurring most recently—two Tethered Satellite System (TSS) missions and the Plasma Motor Generator (PMG) mission. Excellent reviews of the past, present, and the potential future of tethers in space can be found in volumes 1–3 of the Proceedings of the Fourth International Conference on Tethers in Space (Smithsonian Institute, Washington D.C., April 10–14, 1995) and in the executive summary of the 1994 International Summer Workshop on Space Tethers for Ionospheric-Thermospheric-Mesospheric Science (University of Michigan, July 6–8, 1994).

TSS and some of the previous tethered flight experiments, including sounding rockets, share common electrodynamic goals such as the characterization of the system I-V response. However, the TSS goals are more extensive and include additional scientific objectives; e.g., the characterization of the physics of the satellite sheath, of current collection, and of overall current closure. These extensive goals of TSS are enabled by

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the precise control of the system parameters, coupled with the fact that orbiting tether systems inherently involve longer duration missions that allow for the accumulation of a considerable database. In addition, the orbital motion of the tether through the geomagnetic field allows orbiting tethered systems to generate a much higher emf.

System Description

The TSS is a Shuttle-based system designed to deploy, control, and retrieve satellites on long, gravity-gradient stabilized tethers. It consists of two major systems—a deployer system, developed by NASA, and a satellite specially designed for tethered deployment, developed by the Italian Space Agency (ASI). Details of the deployer and satellite capabilities, and the science objectives for the TSS mission are available in Dobrowolny and Stone, 1994.[1] Here, we need only mention that, as configured for TSS-1R, the deployer carried 21.7 km of conducting tether with a total resistance of 2100 ohms. The satellite was a sphere (0.8 m in radius) and had a highly conductive thermal control coating over an aluminum skin, with a collection area of 8 m^2, that was connected directly to the conductor in the tether. By comparison, the Orbiter's collection area (essentially limited to the engine bells) is approximately 40 m^2. Instruments for current control, for monitoring the tether current and voltage, and for measuring the plasma electron and ion fluxes and energy distributions were mounted in the Orbiter's payload bay. The satellite carried instruments to measure plasma ion and electron fluxes and energy distributions, magnetic and electric fields, and the tether current. In addition, a low-light-level TV was carried in the aft flight deck of the Orbiter and ground sites, instrumented to detect TSS-generated RF and hydromagnetic plasma wave emissions, were positioned at several locations along the orbital track.

The TSS was in an electrodynamic configuration; that is, it used a tether with an insulated conductor in its core, and the satellite was deployed upward—away from the Earth. In this configuration, an emf is produced by the motion of the conducting tether through the Earth's geomagnetic field with its polarity such that the satellite receives a positive bias. The emf, in turn, drives a current in the tether. The motional emf is given by,

$$\text{emf} = q\,(\mathbf{V}_0 \times \mathbf{B}) \cdot \mathbf{L}\,, \qquad (1)$$

where q is the electronic charge, $\mathbf{V}_0$ is the velocity of the Orbiter relative to the corotating plasma, $\mathbf{B}$ is the geomagnetic field, and L is the tether length. For TSS, the $\mathbf{V}_0 \times \mathbf{B}$ electric field is on the order 0.25 V/m. A deployment of 20 km can produce a maximum emf of about 5000 V across the tether as the system moves through the geomagnetic field. It was anticipated that, under these conditions, the satellite would become highly biased and extract on the order of 500 mA of electron current directly from the ionospheric plasma. This current, after traveling down through the tether, was to be emitted back into the ionosphere at the Orbiter. Closure of the current flowing through the tether then had to occur within the conducting ionospheric plasma.

Science Instrumentation

A functional schematic of the TSS system, with its motional emf and ionospheric current system, is shown in Fig. 1. Diagnostic instrumentation is located on both end bodies and the tether current is controlled by a resistor bank and/or electron guns located on the Orbiter. Operational modes for the data shown in this paper are: (1) the tether current flows through one of several control resistors in the Shuttle Electrodynamic Tether System (SETS) experiment[2] to Orbiter electrical ground and is neutralized by the collection of ionospheric ram ions to the Orbiter engine bell surfaces and (2) the tether current flows directly to the cathode of the Deployer Core (DCORE) electron gun and is accelerated back into the ionosphere using the available tether-generated emf[3].

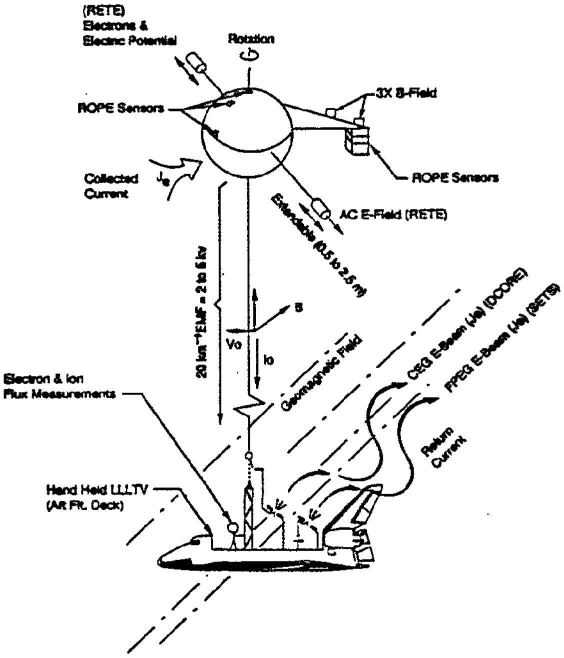

Fig. 1. Functional Schematic of TSS Configuration. (after Fig. 4 in Dobrowolny and Stone, 1994[1])

Data used in this paper in connection with the macroscopic view of current collection will consist primarily of tether current as measured by the satellite core equipment (SCORE) ammeter[3] and satellite potential as determined by the Research on Orbital Plasma Electrodynamics (ROPE) experiment[4] with supporting measurements provided by DCORE, the Research on Electrodynamic Tether Effects (RETE) experiment,[5] and the Shuttle Potential and Return Electron Experiment (SPREE).[6] Data presented to describe the microscopic view of collection are electron differential energy distribution measurements made on the surface of the satellite by Soft Particle Energy Spectrometers (SPES) of the ROPE investigation. Supporting measurements were obtained from TEthered MAGnetic field experiment (TEMAG). Mounting details for the ROPE sensors are given in Fig. 2.

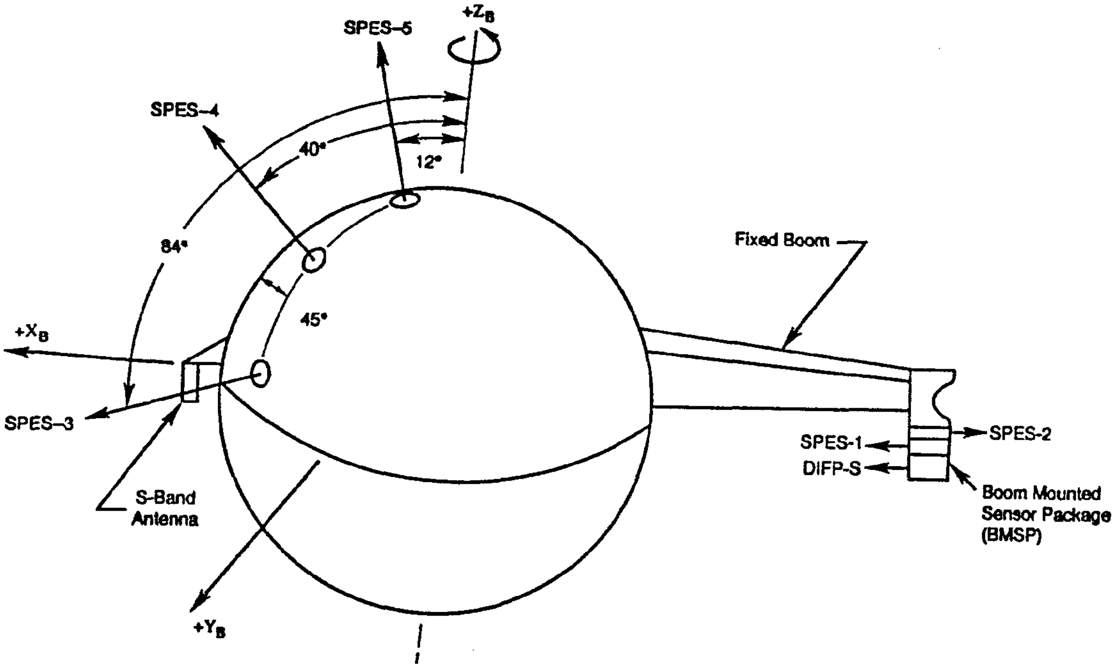

Fig. 2. Mounting Details for ROPE Experiment. Nominal Positions for SPES-3, -4, -5 are Shown. The Satellite Body Coordinate System is Indicated by the X_B, Y_B, Z_B Axes. (after Fig. 2 in Stone et al., 1994[4])

The SPES sensors use a pair of oppositely biased parabolic electrodes to deflect ions and electrons into two separate Channeltron electron multipliers.[7] The particle energy is proportional to the potential difference between the deflection plates (13 eV/volt) and differential number flux is proportional to the measured count rate. The instrument has an energy resolution of $\Delta E/E = 0.15$ and a field-of-view of 2.5° × 10° at FWHM. Simultaneous electron and ion differential spectral measurements are obtained every 2.048 s from a 31-step logarithmic voltage sweep with selectable end-points. For the data shown in this paper, the energy sweep is between 0.7 eV and 1.8 keV. The differential energy distributions of incoming particles are measured at the surface of the satellite at positions of SPES-3, -4, and -5 (see Fig. 2). The ROPE Boom-Mounted Sensor Package (BMSP), located 0.8 m from the surface of the satellite, is actively biased away from satellite potential to within 0.5 V (measured to 2.5 V) of the local plasma floating potential by the ROPE floating supply (FS).[4] This bias voltage can give an estimate of the satellite potential for values less than 500 V, the capacity of the bias supply.

TSS-1

Because of a mechanical error in the deployer system that surfaced during the TSS-1 mission (August 1992), the satellite was deployed to a distance of only 268 m. As a result, the tether-generated emf reached a maximum of 60 V and a proportionately small current was generated. Moreover, because of the near proximity to the Orbiter, the satellite was not allowed to spin or deploy its instrument booms. The science data set from TSS-1 is, therefore, incomplete in spin-phase coverage of the particle distributions around the satellite and the current collected on its surface. In spite of these limitations, however, the mission provided a limited insight into the low-voltage behavior of an electrodynamic tether and its interaction with the ionospheric plasma.

TSS-1R

The reflight of TSS was launched on time at 2:18 CST on February 22, 1996. The pre-deployment checkout of TSS showed that basically all systems were operational. On mission day 2, a payload systems computer was not behaving correctly and consequently satellite deployment was delayed 1 day. Once the deployment began, it was executed in a nominal fashion with very little tether dynamics observed. At a length of 19.7 km, some 5 hours after flyaway, the tether broke within the deployer boom. The satellite then rapidly moved away from the Orbiter, posing no threat to *Columbia* or its crew.

In this paper, data from the TSS-1R mission are presented to illustrate the issues that must be addressed in order to gain a complete picture of the current collection process.

TSS-1R Data

During the time the tether was intact, several scans of the parameter space were obtained; e.g., day/night variations in ambient density, emf values up to 3700 V, tether currents up to 480 mA, and gas release data. The break of the tether prevented the systematic exploration of various configurations in detail, but the data return demonstrated significant current collection capability and power (and the possibility of thrust) generation by orbital tether systems. In the following subsections, the current collection is shown from both a macroscopic and microscopic point of view.

Satellite I-V Relationship (Macroscopic View)

The data presented here were obtained during a particular flight objective called IV24. During part of IV24, the DCORE electron gun assembly (EGA) was used, corresponding to operational mode 2 as mentioned previously in the Science Instrumentation subsection. The EGA was commanded from 12 mA to 500 mA in several steps with a two second step duration and two seconds between steps. Figure 3 presents some of the tether current data obtained from a single EGA sweep performed at 057/01:08:25 during a day IV24. The ambient plasma conditions for this case were: $n = 7 \times 10^5$ cm^{-3}, $T_e = 1500$ K, $B = 0.32$ gauss. The measured currents were normalized by the following:

$$I_0 = 2 \pi a^2 j_0, \qquad (2)$$

$$j_0 = (1/4)\, q\, n\, (8\, kT_e/\pi m_e)^{1/2}, \qquad (3)$$

where a = satellite radius 0.8 m, q = electronic charge, n = plasma density, k = Boltzman's constant, T_e = electron temperature, and m_e = electron mass.

The satellite potential shown in Fig. 3 was estimated from the bias required to drive the ROPE BMSP to the local floating potential. For satellite potentials greater than 500 V, the ROPE FS was saturated and the equation for the TSS circuit was used to solve for satellite potential V. The TSS circuit equation is given by

$$\phi_{\mathrm{emf}} + \phi_{\mathrm{orbiter}} = V + IR + \phi_{\mathrm{ega}}. \qquad (4)$$

Measurements of ϕ_{emf} and ϕ_{ega} were obtained from DCORE. The Orbiter sheath potential, ϕ_{orbiter}, was obtained from SPREE. The tether resistance during the deployed phase was determined to be about 1800 ohms, lower than its value measured at ambient conditions on the ground during preflight checkout. The resistance value was determined by examining several DCORE EGA sweeps and requiring a monotonic, functional (or singled-valued) behavior of the I-V curves at low voltage. Based on properties of copper, the resistance thus implied the temperature of the wire core of the tether to be at a temperature of approximately –5 C.

The standard theoretical prediction of current collected by a positively biased satellite in the ionosphere is given by the Parker-Murphy (P-M) formula[8]:

$$I/I_0 = 1 + [4.56 \times 10^{-3} \cdot V(\text{volts})/a^2(\text{meters})/ B^2(\text{gauss})]^{1/2}. \qquad (5)$$

This model includes magnetic field effects and neglects the ionization of neutral particles. The formula was derived by conserving the canonical angular momentum and energy of the collected electrons. The Parker-Murphy prediction is also shown in Fig. 3.

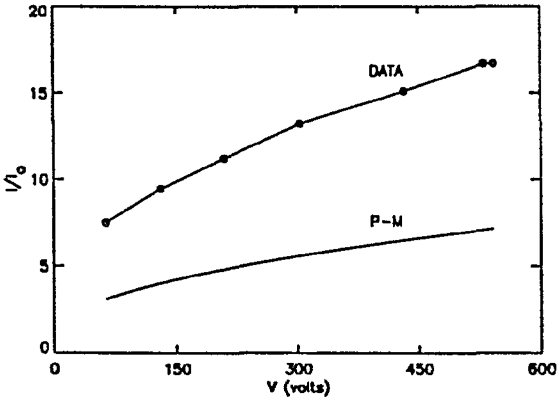

Fig. 3. Satellite Current-Voltage Relationship.

The asymptotic part of the measured current data is a factor of approximately 2.5 larger than the Parker-Murphy prediction. The behavior of the data in this region varies a little slower than $V^{1/2}$, which could be due to uncertainties in ambient plasma density. This case was obtained near the end of the deployment when the emf was about 3000 V. In addition, no satellite thrusters were active at the time of this data. The data demonstrate that current collection in the case of TSS is much more efficient than previously believed.

Previous sounding rocket tether flights have found good agreement between the Parker-Murphy relation and the current collected by a positive biased object.[9] Differences between sounding rockets and the orbital TSS mission are a lower density regime (10^4 cm^{-3} compared to 10^5–10^6 cm^{-3}) and slower speeds (1 km/s compared to 8 km/s) for the sounding rockets. It is clear that Parker-Murphy does not adequately treat the case of an orbiting body. Whether Parker-Murphy can be modified or must be discarded and replaced by something entirely different remains to be seen.

<u>Electron Spectra (Microscopic View)</u>

Electron spectra from the three satellite-mounted SPES sensors from a period when the TSS configuration was held constant are shown in Fig. 4. The 25 kohm resister of the SETS resistor bank was placed in line with the tether for 2 minutes to allow current flow, corresponding to operational mode 1 mentioned previously in the Science Instrumentation subsection. No electron gun and no satellite thrusters were operated during this time. The spin period was approximately 3 minutes, 40 seconds. The line plots in Fig. 4 show the pitch angle of the SPES sensors, the spin phase,

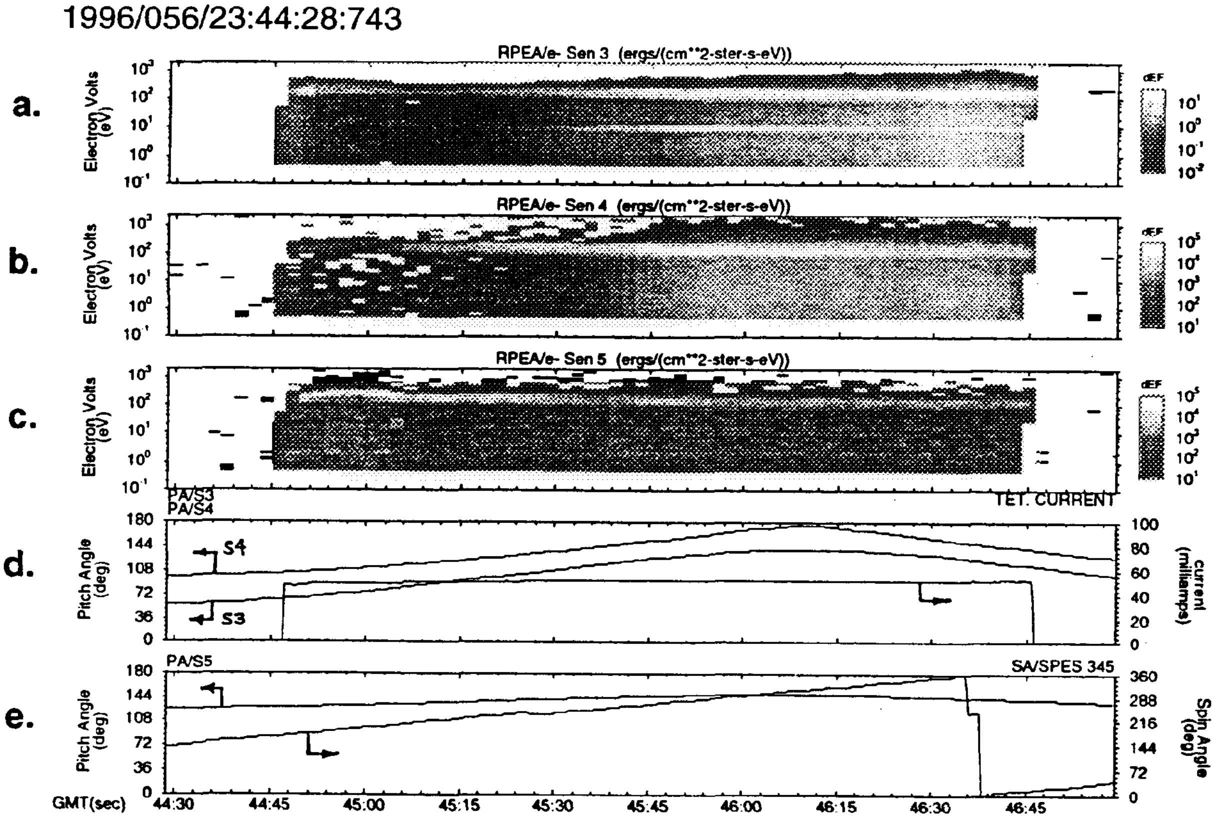

Fig. 4. Electron Data From 1996/056/23:44:30. Spectrogram of Differential Electron Energy Flux From (a) SPES-3, (b) SPES-4, and (c) SPES-5. Line Plots are (d) Pitch Angle of SPES -3, -4 and Tether Current; and (e) Pitch Angle of SPES-5 and Spin Phase of SPES -3,-4,-5.

and the amount and duration of the tether current. As the current begins to flow, SPES -3, -4, and -5 are looking into the wake region and low electron fluxes are observed. As the sensors rotate into the ram direction of the satellite, the electron flux becomes more intense. SPES-3 detects two energized populations: (1) ~8 eV and (2) ~120 eV. The low energy stream is the ionospheric electrons accelerated to the surface by the satellite potential. SPES-4 and -5 do not see this population because of their small geometric factors. The higher, or supra-thermal, energy stream is observed in all three sensors with the intensity highest in SPES-4 when its normal is looking nearly parallel to the magnetic field. However, assessment of other current flow events indicates that this suprathermal population has velocity components both parallel and perpendicular to the magnetic field. When the tether current stops, as noted in panel 4 of Fig. 4, no more electrons are observed by SPES -3, -4 , and -5.

In examining other events where the TSS configuration is held constant for most or all of a spin period, the peak in the electron spectra indicative of spacecraft potential can be followed only up to about 30–40 eV. Above this potential, the ionospheric peak is swamped by a rising background which exhibits an energy^{-2} spectra in phase space density. It is believed that the charging peak is always present; however, at the higher satellite voltages, the background masks this peak. Figure 5 shows an example of this rising background from the event presented in Fig. 4. Figure 5a shows a single SPES-3 sweep from the spin-phase position ~270°, while Figure 5b shows a single sweep from spin phase ~0°. Note how the background increases by an order of magnitude. The energy^{-2} background is indicative of a scattering process. Since the electron-electron collisional pathlengths are so long this suggests wave-particle scattering. Coincident with tether current flow, the AC wave experiment detects disturbances in both the electric and magnetic fields in the frequency range 3 kHz to 100 kHz.

The general features of the electron environment exhibited in this event are repeated during other times that current flows in the tether. The suprathermal electron population exists in the range 100–200 eV. Preliminary analysis has revealed the following characteristics about the suprathermal stream: (1) The population can be seen at times when no tether current is present and the satellite has no appreciable voltage although the intensity is extremely weak at this time. (2) The population intensifies when the satellite potential is greater than the ram energy of O$^+$ (5 eV) and when current flows in the tether. (3) It exhibits a slight spin variation in energy but a significant spin modulation in intensity. (4) The intensity peaks in the ram direction. Connection between the macroscopic measurement of tether current and the microscopic picture of the collection process will require determination of the creation and transport of this suprathermal population.

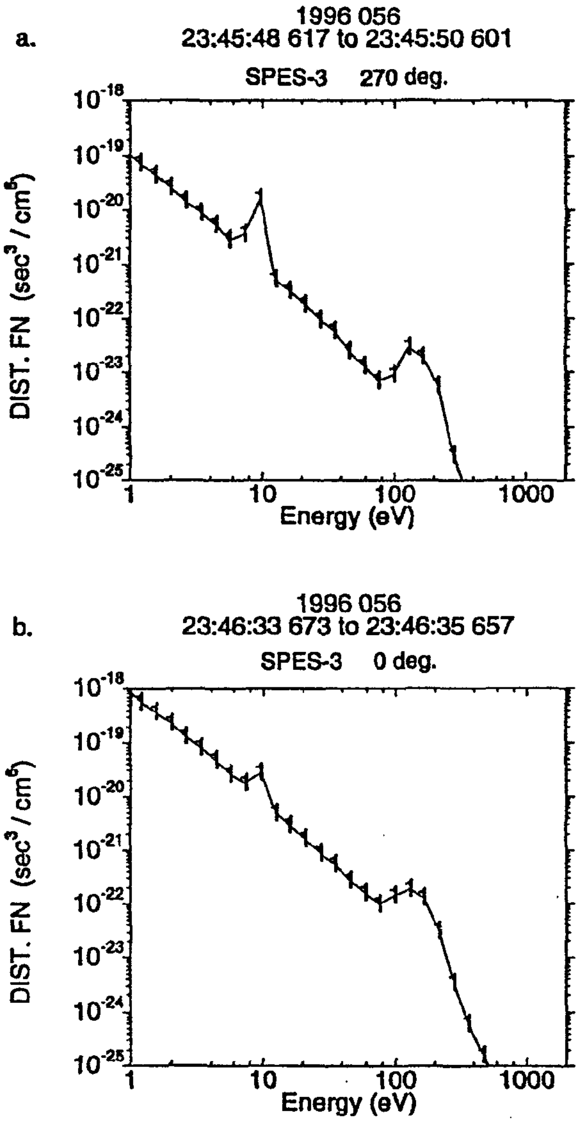

Fig. 5. Phase Space Plot of Single Sweep Data from SPES-3 at (a) Spin Phase ~270° and (b) Spin Phase ~0°.

Summary

The reflight of the TSS allowed the examination of current collection by a positive biased satellite in low Earth orbit. The data collected during the deployment was sufficient to allow the system I-V charateristic to be determined — one of the main goals of the mission.

The current collected by the system is much higher than the standard Parker-Murphy prediction by factors of 2 to 4. Modification of present theories will be required. The collection process appears to be exotic, judging from the high wave activity, spin phase localization of a thermalized background, and the existence of an organized suprathermal electron flow.

The TSS data set, although short of the quantity planned, is quite adequate in the amount and quality to provoke new thinking as to current collection in space plasmas.

Acknowledgments

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References

1. Dobrowolny, M., and N. H. Stone, "A technical overview of TSS-1: The first Tethered Satellite Mission," Nuovo Cimento, 17, 1, 1994.

2. Aguero, V., et al., "The shuttle electrodynamic tether system (SETS) on TSS-1," Nuovo Cimento, 17, 49, 1994.

3. Bonifazi, C., F. Svelto, and J. Sabbagh, "TSS Core Equipment: 1—Electrodynamic package and rationale for system electrodynamic analysis," Nuovo Cimento, 17, 13, 1994.

4. Stone, N. H., K. H. Wright, Jr., J. D. Winningham, J. Baird, and C. Gurgiolo, "A technical description of the TSS-1 ROPE investigation," Nuovo Cimento, 17, 85, 1994.

5. Dowbrowolny M., et al., "The RETE experiment for the TSS-1 mission," Nuovo Cimento, 17, 101, 1994.

6. Oberhardt, M. R., et al., "The shuttle potential and return experiment (SPREE)," Nuovo Cimento, 17, 67, 1994.

7. Winningham, J. D., J. L. Burch, N. Eaker, V. A. Blevins, and R. A. Hoffman, "The low-altitude plasma instrument (LAPI)," Space Sci. Instru., 5, 465, 1981.

8. Parker, L. W., and B. L. Murphy, "Potential buildup on an electron-emitting satellite," J. Geophys. Res., 72, 1631, 1967.

9. Myers, N. B., et al., "A comparison of current voltage relationships of conductors in the Earth's ionosphere with and without electron beam emissions," Geophys. Res. Lett., 16, 365, 1989.