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Shuttle charging by tether controlled electron beam

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Abstract. During the reflight of the tethered satellite system, the electron generator assembly (EGA) emitted steady electron beams six times with the satellite deployed between 6.2 and 16.1 km. Maximum beam energies and currents were 1.65 keV and 0.4 A, respectively. Data presented here show that: (1) emissions create local electron clouds that can charge the shuttle, (2) ionization of thruster gas by beam electrons in the sheath did not reduce the shuttle potential, (3) the EGA utilizes more than half the induced potential, and (4) ionospheric density gradients and magnetic field orientations affect the circuit's potential distribution.

Introduction

The Tethered Satellite System (TSS) [*Dobrowolny and Stone*, 1994] consisted of an instrumented, conducting satellite deployed upward from the shuttle by an electrically conducting tether. Orbital motion across the Earth's magnetic field generated the electromotive force to drive circuit currents. TSS supported three circuit configurations with: (1) one of four resistors connecting the tether to shuttle ground, (2) the fast pulsed electron generator (FPEG) emitting an electron beam, and (3) the tether operating as the electron generator assembly's (EGA) cathode to emit electron beams.

This paper describes ionospheric plasma responses to extended, EGA beam emissions during the deployed phase of the Tethered Satellite System Reflight (TSS 1R). Data are viewed from the perspective of induced ion and electron environments detected by the Shuttle Potential and Return Electron Experiment (SPREE) in the payload bay. We first briefly describe the SPREE, EGA and TSS 1R circuit during EGA operations, then present electron and ion spectral data acquired during six prolonged EGA firings. Detailed analyses are given for two events. The final section discusses coupling of the TSS 1R circuit to the ionosphere.

Instrumentation and the TSS 1R Circuit

The TSS science payload is described in a special issue of *Il Nuovo Cimento* [1994]. Presented here are measurements of: (1) energetic electron and ion fluxes by SPREE [*Oberhardt et al.*, 1994], (2) currents in the tether by a satellite ammeter [*Bonifazi et al.*, 1994], (3) potential differences between the tether and shuttle ground by a voltmeter in the payload bay [*Agüero et al.*, 1994], and (4) electron densities by a Langmuir probe (LP) on the satellite [*Dobrowolny et al.*, 1994].

The SPREE consists of two triquadraspherical electrostatic analyzers (ESAs) mounted on rotary tables. Fluxes of electrons and ions were measured in 32 logarithmically spaced energy channels ranging from 9.8 eV to 10 keV. Particles entered the apertures through angular fans ~100° by 8.5°, divided into ten zones. Zone 0 looked in the shuttle-horizontal direction and zone 9 looked toward shuttle zenith. Full spectra were compiled simultaneously from all 10 zones and 32 energy steps at a rate of 1 or 8 s^{-1}. Sensor rotation allowed sampling of the 2π sr upper hemisphere every 30 s.

The EGA consisted of two diodes with the tether attached to the cathodes and the shuttle ground to the anodes [*Bonifazi et al.*, 1994]. Current-limited, heater filaments provided the electron clouds from which the beams were extracted. Only one EGA operated at a time and fired directly out of the payload bay. Density measurements were obtained when the LP, ~15 cm from the satellite's surface, was outside its wake.

Figure 1 is a simplified diagram of the TSS 1R circuit for EGA firings. The satellite at the tether's high potential end collected ionospheric electrons, allowing current to flow through the tether. With the EGA operating, an electron beam nearly equal to the tether in current was emitted into the ionosphere. Preflight testing showed that leakage currents to the anode were negligible. The energy of emitted electrons equaled the potential difference applied between the cathode and anode and was measured by the voltmeter. In this configuration, the shuttle ground was isolated from the circuit and the shuttle potential, Φ_S, floated with respect to the ambient plasma. If the trajectories of energetic, EGA-generated electrons returned to the shuttle, Φ_S as-

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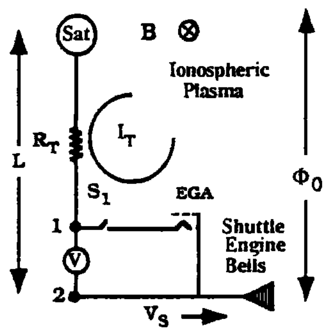

Figure 1. TSS circuit during EGA operations.

sumed the negative values required to attract an equal number of cold ions from the ionosphere to its grounded conducting surfaces. When the circuit was open the statellite and shuttle were very near their local plasma potentials, and the voltmeter essentially measured the entire motionally induced potential, $\Phi_0 = (\mathbf{V_S} \times \mathbf{B}) \cdot \mathbf{L}$, where $\mathbf{V_S}$ is the shuttle velocity, $\mathbf{B}$ the magnetic field, and $\mathbf{L}$ a vector along the tether.

Observations

Data in Table 1 describe the six prolonged EGA beam emissions of the TSS 1R deployment which occurred in two predefined sequences. The first two events lasted 56 s and the last four 224 s. Table 1 lists the universal time, UT, on February 26 or 27, 1996, when each firing began, local time, LT, tether length, L, (kilometers), tether current, I_T (milliamps), shuttle potential, Φ_S, open-circuit potential, Φ_0, potential applied to the EGA, $V_{1,2}$, potential drop along the tether, $R_T I_T$, satellite potential, Φ_{Sa}, plasma density, n_e (cm^{-3}), and beam pitch angle, α_B. Cited values of Φ_0 and I_T were taken near the beginning and end of each beam emission. Potentials are given in volts. Values of Φ_{Sa} were estimated using Ohm's law,

$$\Phi_0 = V_{1,2} + R_T I_T + \Phi_{Sa} - \Phi_S \qquad (1)$$

The tether resistance $R_T \approx 1.8$ kΩ [*Chang et al.*, 1997]. The EGA perveance, estimated from simultaneously measured values of $V_{1,2}$ and I_T was very close to its preflight specification of 6.4 μP.

The data in Table 1 demonstrate three points: (1) The shuttle was in sunlight for five of the emissions; event 4 occurred as the shuttle crossed the dusk terminator. (2) Except for event 4, values of $V_{1,2}$ and I_T remained narrowly confined during individual EGA emissions. (3) Values of α_B indicate that the beam had strong field-aligned components in three events and should have escaped the shuttle. During the two 56 s and the last 224 s emission, beam electrons were emitted almost perpendicular to $\mathbf{B}$. A large fraction of them should have returned to the shuttle [*Hardy et al.*, 1995]. The most strongly negative shuttle potentials occurred during the $\alpha_B \approx 90°$ emissions.

Plate 1 gives the directional differential fluxes of electrons (top plot) and ions (lower plot) measured by SPREE during the four 224 s firings. Plate 1A shows that SPREE detected intense fluxes of electrons with nearly thermal shapes. Flux modulations in this spectrogram reflect gradients in the densities of electron guiding centers sampled as SPREE rotated. The maximum electron fluxes, $\sim 5 \times 10^{11}$ cm^{-2} sr^{-1} s^{-1}, were detected as SPREE faced shuttle-forward. The local densities of superthermal electrons were $>10^3$ cm^{-3}. Ion fluxes were confined to the lowest energy channel of SPREE, indicating that $\Phi_S > -10$ V. During subsequent events, electron fluxes were detected at lower energies even though the emitted beams were more energetic and carried larger currents.

Data in Plate 1B suggest that the shuttle passed through a transition region. At the beginning of the event, electron spectra were similar to those of Plate 1A. Thereafter, electron fluxes decreased and ion fluxes rose. The progression of the ion spectral peak indicates that the shuttle charged to increasingly negative potentials. Figure 2 presents detailed measurements from this 4 min interval. Figure 2a shows values of $V_{1,2}$ (open circles) and I_T (closed circles). The dashed line represents the total potential induced in the circuit estimated by a linear extrapolation between measurements of Φ_0 taken just before and after the EGA fired. Note that tether length increased, the shuttle's speed was constant, and the magnetic field decreased. In fact, all three quantities Φ_0, $V_{1,2}$, and I_T decreased with time. Figure 2b plots the tether potential drop $R_T I_T$, Φ_S, and Φ_{Sa} determined from (1) and the SPREE data as a function of UT. Φ_{Sa} values estimated from Ohm's law substantially agree with measurements made on the satellite [*Stone et al.*, 1994].

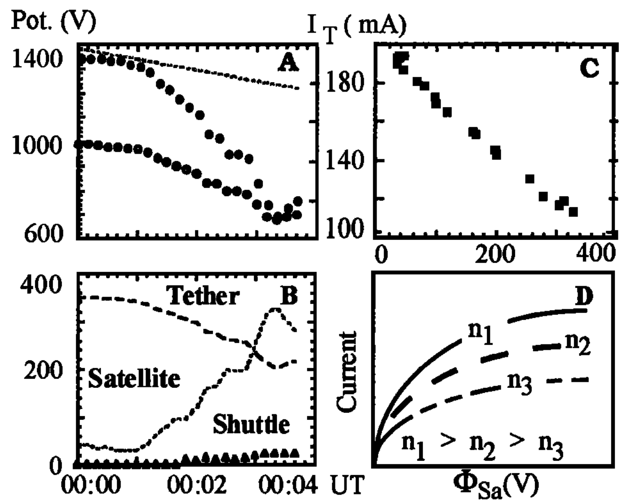

Figure 2. Measurements acquired during the EGA firing at 2359:58 UT. Data in the left and upper right plots are explained in the text. The lower right plot qualitatively represents magnetically limited current-voltage characteristics of the satellite in three electron ambient plasma density environments.

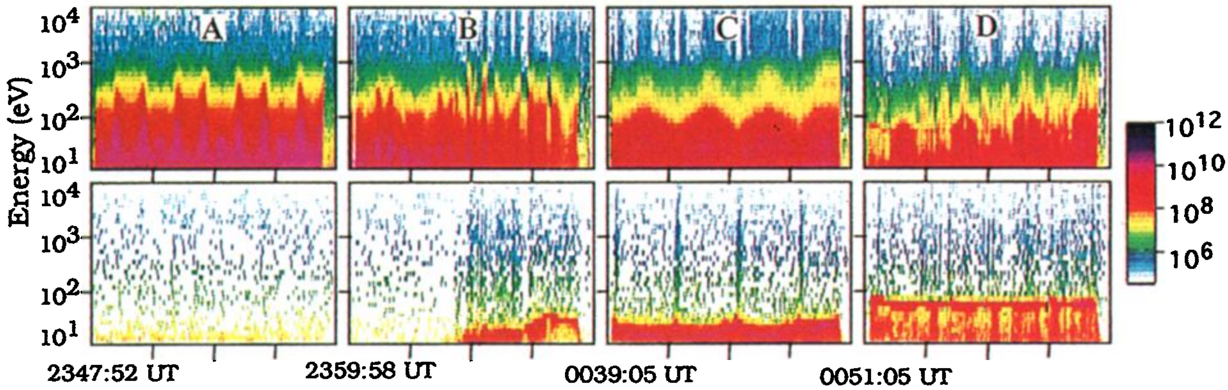

Plate 1. SPREE differential electron (top) and ion (bottom) fluxes for the four 224 s EGA firings. Plots A, B, C, and D correspond to events 3, 4, 5,and 6 in Table 1. The initial UT is given, with tick marks at one minute separations.

Figure 2c shows that during the shuttle charging transition I_T decreased as Φ_{Sa} rose. Under steady density conditions a magnetically limited current-voltage relationship maintains [*Stone and Bonifazi*, 1997]. Langmuir probe measurements on the satellite indicate that plasma density fell from $\sim 1.3 \times 10^6$ cm^{-3} at 2358 UT to $\sim 1.8 \times 10^5$ cm^{-3} at 0004 UT. Reliable density measurements could be made only when the probe faced the satellite ram direction and beam systems were inactive. Figure 2d offers a schematic of the current-voltage characteristics for positively charged satellites with three different, but constant, external ionospheric densities [*Stone and Bonifazi*, 1997]. The arrow indicates that if plasma density fell rapidly, the I_T versus Φ_{Sa} shown in Figure 2c is qualitatively intelligible.

Ion spectra acquired during the two 56 s EGA firings (Plate 2) resemble those in Plate 1D except that after an initial transient, Φ_S remained steady at ~-90 V. This highest level of shuttle charging during EGA firings was achieved at relatively short tether lengths and low tether currents (Table 1). At ~2317:23 UT two aft vernier thrusters fired and Φ_S rapidly changed from -90 to -120 V, then returned to its pre-firing value. During the ~6 s interval between the thruster firing and EGA turn off, SPREE detected intense ion fluxes in all energy channels up to 90 eV. This indicates that secondary ionization was generated inside the potential sheath around the shuttle. Intermediate energies reflect potential differences between the shuttle and the birth locations of new ions. The two thrusters which caused the enhanced shuttle potential and sheath ionization are directed downward and splash gas off the shuttle wings. During TSS 1, firings of these thrusters consistently increased potential differences between the shuttle and the ionospheric plasma [*Machuzak et al.*, 1996]. On TSS 1R, with resistors in the circuit, SPREE detected similar increases in the magnitude of Φ_S during firings of these thrusters [*Gentile et al.*, 1997], but no significant ion fluxes appeared at energies below the charging peak. It was thus concluded that incoming ions with energies $\leq\sim$600 eV produced little new ionization in crossing the sheath. At the time of the thruster firing, the EGA was emitting an electron current of 130 mA at an energy of 795 eV (Table 1). These electrons traverse the shuttle's sheath with kinetic energies sufficient to ionize a measurable fraction of neutrals in the near-shuttle plume. Since Φ_S became more negative, neutrals in the plume were more effective at inhibiting ambient ions from reaching the shuttle's conducting surfaces than beam electrons were in increasing sheath ionization.

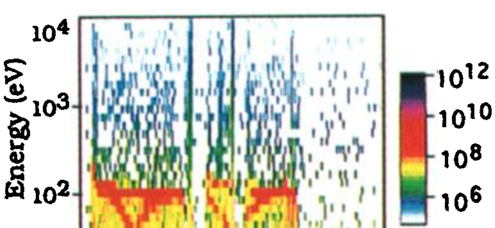

Plate 2. SPREE differential ion fluxes for the two 56 s EGA firings, events 1 and 2 of Table 1. The initial UT is given, with tick marks at one minute separations.

Discussion

The discussion of Figure 1 argues that during EGA firings the shuttle was isolated from the TSS 1R circuit and Φ_S floated with respect to the ionospheric plasma. To intercept equal fluxes of ions and more mobile electrons, spacecraft in the ionosphere normally float at a few tenths of a volt negative. Φ_S readings of several tens of volts require the local presence of dense superthermal electrons. Only electrons with energies sufficient to overcome the Φ_S barrier reach shuttle conducting surfaces. Floating values of Φ_S depend on the ambient plasma density, the energy/density of the superthermal electron population and the magnetic field direction. Data in Plate 1B and Figure 2 clearly demonstrate the role of the background plasma density.

Control by the magnetic field is seen empirically. The

Table 1. TSS Circuit Parameters during EGA Firings

No.	UT	LT	L	I_T	Φ_S	Φ_0	$V_{1,2}$	$R_T\ I_T$	Φ_{Sa}	n_e	α_B
1	2315:21	07:15	6.2	105/120	−90	1300/1315	675/720	189/216	346/289	2.5×10^5	76°
2	2316:30	07:20	6.3	115/130	−90	1315/1330	730/795	207/234	368/291	2.5×10^5	79°
3	2347:52	16:20	8.8	180/196	−10	1510/1545	940/975	324/352	236/208	4.8×10^5	135°
4	2359:58	19:40	9.9	193/120	−25	1386/1224	990/701	347/216	40/282	1.3×10^6	129°
5	0039:07	06:30	14.5	97/160	−25	2600/3034	620/840	174/288	1718/1881	1.0×10^4	48°
6	0051:09	08:45	16.1	407/446	−70	3525/3545	1590/1650	733/802	1177/1068	5.5×10^5	90°

largest values of $|\Phi_S|$ occurred when α_B was ~90°. In all three cases the magnetic field was mostly in the shuttle-horizontal plane, pointing aft of the right wing. As beam electrons emerged from the EGA they experienced magnetic forces that turned them back toward the shuttle, aft of the TSS payload. In the other three EGA firings the beam was more magnetically aligned and could escape the shuttle easily. Although electron fluxes reaching SPREE were intense, their energies were substantially below that of the beam ($V_{1,2}$). Thus, most of the electrons reaching SPREE were heated ambients and secondaries created in collisions with neutrals. When the beam was magnetically bent in the shuttle-aft direction, the access of warm electrons, and perhaps even beam electrons, to current-collecting surfaces was increased, driving Φ_S more negative.

During the six events, the EGAs emitted sustained electron beams with energies and currents up to 1650 eV and 400 mA. The efficiency of the TSS 1R circuit can be assessed by examining the distribution of potentials in Table 1. The entire potential from orbital motion, Φ_0, is distributed throughout the circuit according to Ohm's law. On average, more than half of the potential ($V_{1,2}/\Phi_0$) was available for electron beam firings. About 30% of the potential (Φ_{Sa}/Φ_0) was required to support the extraction of electrons from the ionosphere by the satellite; ~17% was dissipated in the tether ($R_T I_T/\Phi_0$). Thus, only a small fraction (Φ_S/Φ_0) could be allocated to the shuttle's sheath.

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