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Shuttle charging by fixed energy beam emissions

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Abstract. We present environmental responses observed by the Shuttle Potential and Return Electron Experiment during 13 prolonged electron beam emissions from the Fast Pulsed Electron Generator (FPEG) during the TSS 1R deployment. As the tether lengthened from 0.18 to 2.5 km, FPEG fired nine times at a nominal current of 100 mA at 1 keV. The motional potential induced across the system increased from 24 to 225 V. With a 15 Ω resistor connecting the tether to shuttle ground, current was higher and the degree of negative shuttle charging lower when FPEG was off than when it was on. While most FPEG firings left the shuttle uncharged, two created significant potentials: one to +70 V in a nighttime, equatorial plasma depletion and one to -60 V, with the tether ~15 km.

Introduction

During the Tethered Satellite System reflight (TSS 1R) a conducting satellite was deployed above the shuttle Columbia by an electrically conducting tether. Orbital motion across the Earth's magnetic field generated an electromotive force to drive currents [*Dobrowolny and Stone*, 1994]. Current flow between the shuttle and local plasma was achieved through passive ion collection at conducting shuttle surfaces [*Agüero et al.*, 1997; *Gentile et al.*, 1997] or by electron beam emissions by two independent instruments. The first was the electron generator assembly (EGA), a diode emitter whose cathode was connected to the tether and anode to shuttle ground [*Bonifazi et al.*, 1994]. The EGA operated over a wide range of beam currents, I, and energies specified by $I = 6.4 \times 10^{-4} V^{\frac{3}{2}}$, where V is the voltage between the tether end and shuttle ground. The second, the Fast Pulsed Electron Generator (FPEG), emitted electrons at a fixed energy and current of 1 keV and 100 mA.

This paper presents ionospheric plasma responses to extended FPEG emissions detected in the payload bay by the Shuttle Potential and Return Electron Experiment (SPREE). We briefly describe SPREE, FPEG and the TSS 1R circuit during FPEG operations, then present SPREE spectral data for 13 FPEG firings. Two events illustrate positive and negative shuttle charging. The last section discusses the shuttle's electrical coupling to the ionosphere during FPEG emissions.

Instrumentation and the TSS 1R Circuit

The TSS payload is described in a special issue of *Il Nuovo Cimento* [1994]. We use measurements of: (1) electron and ion fluxes by SPREE [*Oberhardt et al.*, 1994], (2) tether current, I_T, by the satellite ammeter [*Bonifazi et al.*, 1994], (3) potentials between the tether and shuttle by a voltmeter in the payload bay [*Agüero et al.*, 1994], and (4) electron densities, n_e, by a Langmuir probe (LP) on the satellite [*Dobrowolny et al.*, 1994].

SPREE has two triquadraspherical electrostatic analyzers mounted on rotary tables. Electrons and ions from 9.8 eV – 10 keV were sampled in 32 logarithmically spaced steps. Particles entered the apertures through angular fans ~100° by 8.5° in 10 zones looking from shuttle-horizontal to shuttle-zenith. Full energy spectra were compiled simultaneously at rates of 1 or 8 s^{-1}. The full 2π sr upper hemisphere was sampled in 30 s.

FPEG was designed to emit a nominal current of 100 mA in dc or pulsed (≤30 kHz) modes. Electrons were ejected with an energy of 1 keV through a 1 cm^2 aperture aimed 23° above the shuttle's right wing. In sequence, one of four resistors, R_S, of 2.5 MΩ, 250 kΩ, 25 kΩ, or 15 Ω, could be inserted between the tether and shuttle ground [*Agüero et al.*, 1994].

Figure 1 represents the TSS 1R circuit for FPEG operations. Columbia flew engine bells-to-ram to facilitate ion current collection. The satellite, deployed upward to a distance, L, on the high potential end of the tether, collected ionospheric electrons. The circuit included a voltmeter and two switches. With S_1 open and FPEG off, no current flowed and no sheaths formed about the shuttle or satellite. Thus, $V_{1,2}$ was a measure of the induced potential $\Phi_0 = (-\mathbf{V}_S \times \mathbf{B}) \cdot \mathbf{L}$, where $\mathbf{V}_S$ and $\mathbf{B}$ are shuttle velocity and magnetic field. With S_1 closed,

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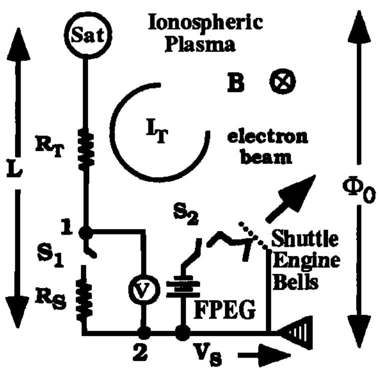

Figure 1. TSS 1R circuit during FPEG operations.

$V_{1,2} = R_S I_T$. FPEG operated with S_1 either open or closed. SPREE data were taken with both S_1 and S_2 closed and R_S = 15 Ω or 25 kΩ. *Gentile et al.* [1997] describe cases with the same resistors and FPEG off.

Observations

The first experiment occurred early in the deployment. As shown in the top plot of Figure 2, it had 4 circuit configurations, each 100 s. (1) The circuit was passive (S_1 and S_2 open) and $V_{1,2} = \Phi_0$. (2) FPEG turned on, (S_1 open, S_2 closed). (3) FPEG continued firing and resistors were inserted from high to low impedance into the circuit (S_1, S_2 closed). (4) FPEG turned off and resistors were reinserted in sequence (S_1 closed, S_2 open). Table 1 summarizes firings with the 15 Ω resistor. The columns list: (1) event number, (2) universal time, UT, of resistor insertion on February 25, 1996, (3) tether length, L, (km), (4) open-circuit potential, Φ_0, (volts), (5) tether current, I_T, (mA) with FPEG on, (6) tether current, I'_T, measured ~1 min later with R_S = 15 Ω but FPEG off, (7) shuttle local time, LT, and (8) electron density, n_e(cm^{-3}).

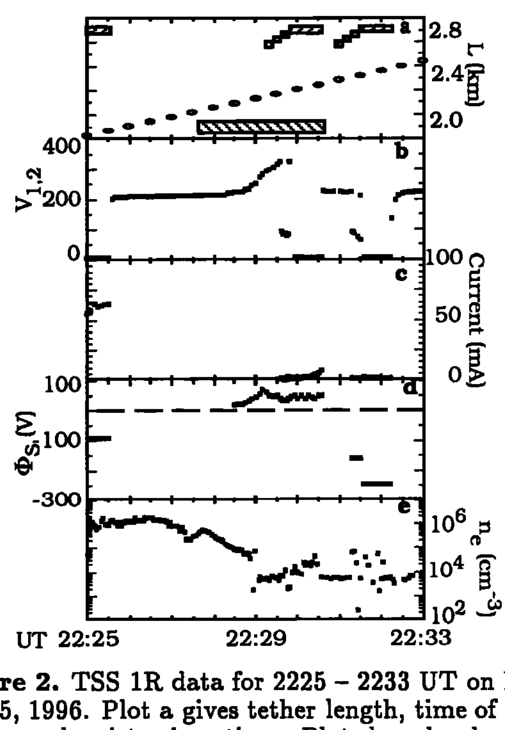

Figure 2. TSS 1R data for 2225 – 2233 UT on February 25, 1996. Plot a gives tether length, time of FPEG firings, and resistor insertions. Plots b and c show voltmeter and ammeter readings, respectively. Plot d contains shuttle potentials inferred from SPREE spectra. Plot e indicates electron density.

Data in Table 1 and SPREE spectra (not shown) support several conclusions: (1) SPREE detected electron fluxes >10^{11} cm^{-2} s^{-1} throughout the first FPEG emission. Spectra decreased monotonically with energy to several hundred eV. No ion fluxes were detected, indicating low levels of shuttle charging. (2) SPREE detected no fluxes above photoelectron background during events 3–8. Similar appearance/disappearance cycles for superthermal electrons occurred during FPEG firings after the tether break and are not tether related. Trajectory anaysis shows that beam electrons impacted insulating shuttle surfaces at these times. (3) Ion fluxes, detected only in event 8, indicate that the shuttle charged to -15 V. (4) The shuttle charged positively during event 9 as it passed through an equatorial plasma depletion. (5) With R_S = 15 Ω, $I_T > I'_T$ and the shuttle charged more negatively when FPEG was off than when it was on (*Gentile et al.* [1997]).

Plate 1A is an energy-vs-time color spectrogram of directional differential fluxes (cm^{-2} s^{-1} sr^{-1} eV^{-1}) of electrons (top) and ions (middle) reaching SPREE during event 9. The bottom plot shows R_S insertions. When FPEG turned on at 2227:36 UT, electron fluxes first rose then fell. From 2218:15 UT until FPEG turned off, intense electron fluxes were detected. Persistent peaks appear in electron spectra after 2228:30 UT showing that the shuttle charged positively with respect to the local plasma. The charging-peak energy rose to >70 eV, fell to 32 eV, then stabilized near 50 eV.

Figure 2 is an overview of TSS 1R data for 2225 – 2233 UT. Figure 2a plots L, increasing from ~2 to 2.7 km, and times of FPEG firing and resistor insertions. Figure 2b records voltmeter readings. With the 15 Ω resistor inserted, the tether was essentially short circuited to shuttle ground and the voltmeter measured very low potentials. With the 25 kΩ resistor in place,

Table 1. FPEG Firing Events of Experiment 1

No.	UT	L	Φ_0	I_T	I'_T	LT	n_e
1	2136:35	0.18	24	10	2	05:18	1.5×10^5
2	2143:03	0.24	38	16	6	07:06	2.1×10^5
3	2149:53	0.35	50	27	11	08:30	8.0×10^5
4	2156:25	0.54	65	29	24	10:30	2.0×10^6
5	2203:05	0.69	83	39	19	12:12	3.0×10^6
6	2209:47	0.98	122	52	21	14:00	1.0×10^6
7	2216:00	1.43	165	76	36	15:42	9.0×10^5
8	2223:08	2.19	203	93	55	17:42	2.0×10^6
9	2229:50	2.39	443	6	2	19:30	6.0×10^4

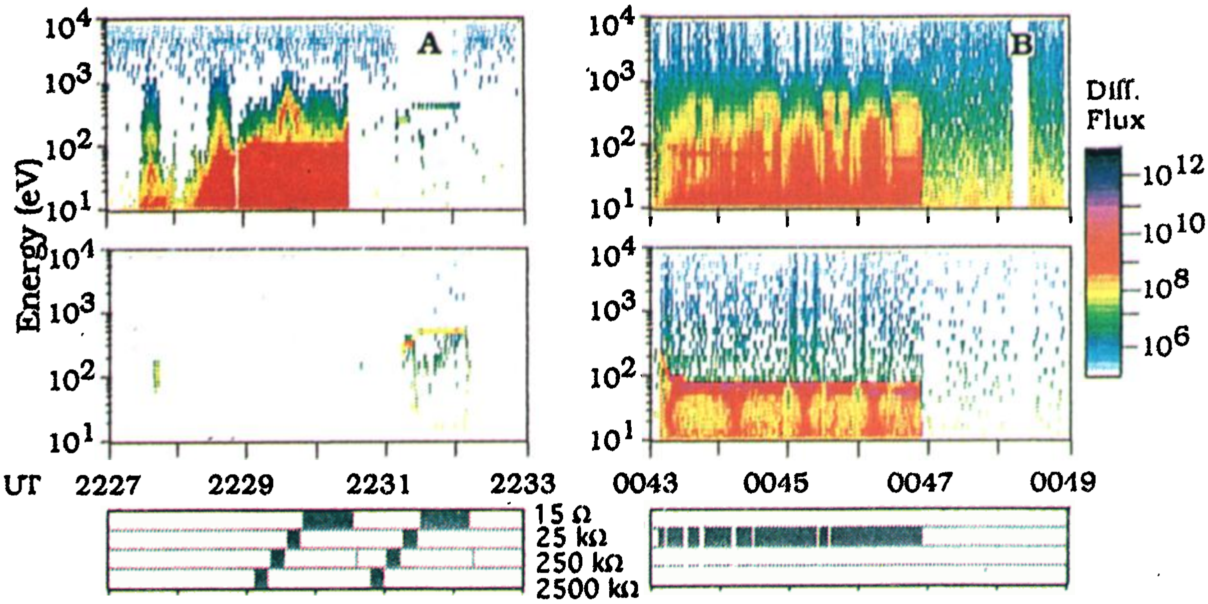

Plate 1. Energy-vs-time spectrograms of SPREE electron and ion fluxes (A) 2227 – 2233 UT on February 25, 1996, and (B) 0043 – 0049 UT on February 26, 1996.

potentials fell from 90 to 83 V (after 2229:36 UT) and from 93 to 65 V (after 2231:18 UT). When the circuit was open or high-impedance resistors were in place, $V_{1,2}$ rose slowly from ~200 V to 225 V at 2228:30 UT, then rapidly to 325 V. During this rapid transition, the magnetic field and shuttle attitude changed only slightly, thus Φ_0 should have increased slowly. After the 15 Ω resistor was removed and FPEG turned off, $V_{1,2}$ was nearly constant at 225 V. Figure 2c shows a remarkable decrease in I_T between the first (22:25 UT) and second/third 15 Ω resistor insertions. Figure 2d records shuttle potential variations inferred from SPREE data and Figure 2e gives electron density at the satellite. As a whole the data show that the positive shuttle charging during the FPEG firing was not strongly dependent on whether any resistor was in the circuit but did coincide with: (1) a rapid density decrease from $\sim 10^5$ cm^{-3} to $< 10^4$ cm^{-3} and (2) an increase in $V_{1,2}$ from 225 to 325 V. Finally, while Φ_S of -90 V was sufficient to draw ion current of ~60 mA with $n_e \approx 10^6$ cm^{-3} (2225 UT), -245 V was required to draw ~2 mA (Table 1) with $n_e \approx 10^4$ cm^{-3} (2232 UT).

Experiment 2 included two 12 min sequences, each with a different resistor, which were run twice. For each sequence, the circuit was initially passive for 4 min (S_1, S_2 open), the EGA fired for 4 min [*Burke et al.*, 1997], then FPEG fired for 4 min (S_1, S_2 closed). R_S was 25 kΩ or 250 kΩ during the FPEG cycles. Data from the FPEG firings are given in Table 2 in a format similar to that of Table 1. The last column lists R_S. SPREE detected intense electron fluxes during all 4 events. I_T was nearly constant except during event 3 when it rose steadily from 95 to 120 mA. No shuttle charging was evident with R_S = 250 kΩ. In event 1, SPREE detected no ion fluxes and electron spectra peaked at ~15 eV indicating positive shuttle charging. The only strong negative shuttle charging occurred during the second 25 kΩ insertion near the dawn terminator. The LP was off as emission began, but measured a plasma density of $\sim 10^6$ cm^{-3} immediately after FPEG turned off. Plate 1B shows SPREE electron and ion fluxes for this event. A clear ion charging peak is seen at ~60 eV with periodic ion fluxes for all energies 10 – 60 eV at 1 min intervals when SPREE looked toward FPEG. A similar effect was observed during EGA emission at 0051 UT when SPREE faced the EGA beam (Plate 1D of *Burke et al.*, [1997]). Ions with intermediate energies were created within the sheath in collisions between beam electrons and neutrals.

Summary and Discussion

The data demonstrate that FPEG emissions did affect the TSS 1R circuit, and under different circumstances left the shuttle charged positively or negatively. More subtle effects were also present. With R_S = 15

Table 2. FPEG Firing Events of Experiment 2

No.	UT	L	R_T	Φ_0	Φ_S	I_T	LT	n_e
1	2351:55	8.89	25 kΩ	1547	+15	55	17:18	1.2×10^6
2	0003:55	9.93	250 kΩ	1223		2	20:06	5.0×10^5
3	0043:05	14.6	25 kΩ	3060	−60	95 - 120	06:35	1.0×10^6
4	0055:05	16.2	250 kΩ	3560		10	09:30	1.5×10^6

Ω, more current flowed through the tether. Also, the shuttle charged less negatively when FPEG was on than when it was off. These observations are related through requirements of Ohm's and Kirchoff's laws. Ohm's law determines how Φ_0 is distributed between the sheath potentials of the satellite Φ_{Sa} and shuttle Φ_S and resistive potential drops $I_T(R_S + R_T)$. Kirchoff's law demands current continuity at any node. Thus, if the satellite collects electron current I_T and FPEG emits an electon current of 100 mA, then an electron current (100 - I_T) must return to the shuttle from the ionosphere. *Hardy et al.* [1995] showed that FPEG emissions produce warm electron populations near the shuttle consisting of beam particles, collision-generated secondaries and heated ambient electrons. Return currents (100 - I_T) determine the level of shuttle charging. During experiment 1 the return current from the dayside ionosphere was such that -15 V $< \Phi_S <$ 10 V. Since Φ_S was more negative with $R_S = 15$ Ω and FPEG off, a larger fraction of Φ_0 was available for Φ_{Sa} than when FPEG was on. The higher values of Φ_{Sa} allowed the satellite to collect more ionospheric electrons [*Stone and Bonifazi*, 1997].

During event 9, the satellite extracted only 6 mA of current from the low-density, nightside ionosphere. To provide an electron return current of 94 mA to the shuttle required that Φ_S reach >70 V. There remains an unresolved difference between the SPREE and voltmeter data. From Ohm's Law, $V_{1,2} = \Phi_0 + \Phi_S$. Throughout this event the induced potential Φ_0 should have remained nearly constant. Figure 2b shows that although $V_{1,2}$ and Φ_S followed similar upward trends, SPREE spectra indicate that Φ_S rose by ~70 V, while the voltmeter reading increased ~100 V. A 30 eV difference is within the energy-resolution capability of SPREE.

The shuttle charged negatively twice with FPEG emitting. (1) During event 8 of experiment 1, Φ_S was -15 V, but no electron fluxes reached SPREE. I_T remained steady at 93 mA. If FPEG emitted at 100 mA, there is a 7 mA deficit that must be made up of electrons with energies outside the sheath >15 eV. The flux of these electrons to shuttle conducting surfaces must exceed the accelerated ion ram current by 7 mA. (2) With $R_S = 25$ kΩ and FPEG emitting (event 3 of experiment 2), the shuttle charged to -60 V. During the 4 min firing I_T systematically rose from 95 to 120 mA. If FPEG emissions were nominal, the return current (100 - I_T) changed from a 5 mA surplus of electrons with energies >60 eV to a 15 mA surplus of ions. The reason for this is unclear. Based on FPEG current drifts observed during preflight tests, it appears likely that the emitted current drifted from its nominal value so that the tether and FPEG currents were approximately equal. In this case, the measured value of Φ_S is the floating potential required to attract as many ions from the ionosphere as beam-heated electrons reached conducting shuttle surfaces.

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