GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 4, PAGES 433-436, FEBRUARY 15, 1998

Negative shuttle charging during TSS 1R

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Abstract. We studied 21 intervals during the TSS 1R deployment with a 15 Ω or 25 kΩ resistor connecting the tether to shuttle ground. Ion spectral peaks detected by the Shuttle Potential and Return Electron Experiment indicate that the shuttle consistently charged negatively with respect to the local plasma. With the 15 Ω shunt in the circuit, shuttle potential, Φ_S, decreased from -17 to -245 V as tether length, L, increased to 2.6 km. Current in the circuit depended strongly on ionospheric density. With the 25 kΩ resistor in place, $\Phi_S \approx -300$ V in the low density, nightside ionosphere with $L = 5.1$ km. Near local noon $\Phi_S \approx -80$ V with $L = 17.2$ km. The shuttle charged to ∼-600 V during two dawn terminator crossings, one with and one without thruster firings. As on TSS 1, firings of two aft vernier thrusters significantly increased $|\Phi_S|$. In the case without thruster firings, simultaneous variations of Φ_S, tether current, and the inferred satellite potential are consistent with strong azimuthal and vertical ionospheric density gradients. These are the first known direct measurements of strong negative shuttle charging.

Introduction

Although severe negative charging is common at geostationary altitudes [*De Forest*, 1972], it seldom occurs in the ionosphere [*Gussenhoven et al.*, 1985]. The shuttle charged negatively to a few tens of volts on the first Tethered Satellite System mission (TSS 1) [*Machuzak et al.*, 1996]. This paper describes 21 negative shuttle charging events during the TSS reflight (TSS 1R) from 2130 UT on February 25 to 0106 UT on February 26, 1996 when an electrically conducting satellite was deployed upward from and connected to the shuttle by a conducting tether [*Stone and Bonifazi*, 1997]. Tether length, L, ranged from 180 m to >17.2 km. A 15 Ω shunt or 25 kΩ resistor electrically connected the tether to shuttle ground and no electron beams were emitted.

Figure 1 represents the TSS 1R circuit for negative shuttle charging. The shuttle flew with velocity $\mathbf{V}_S \approx$ 7.7 km s^{-1} with engine bells-to-ram to facilitate ion current collection. The satellite, on the high potential end of the tether, collected electrons from the ionosphere. A satellite ammeter [*Bonifazi et al.*, 1994] measured tether current, I_T. At the shuttle end of the circuit were the resistor, R_S, voltmeter, V, and switch S_1 [*Agüero et al.*, 1994]. With S_1 open, no current flowed in the tether and potential sheaths could not form about the shuttle or satellite. Thus, $V_{1,2}$ measured total induced potential $\Phi_0 = (-\mathbf{V}_S \times \mathbf{B}) \cdot \mathbf{L}$. When S_1 closed, the voltmeter measured the potential drop across R_S. We present measurements of the potential sheath, Φ_S, that developed about the shuttle with S_1 closed and $R_S = 15$ Ω or 25 kΩ. Our analysis tool is Ohm's law,

$$\Phi_0 = (\mathbf{V}_S \times \mathbf{B}) \cdot \mathbf{L} = \Phi_{Sa} + (R_T + R_S)I_T - \Phi_S \quad (1)$$

where Φ_{Sa} is satellite potential and $R_T = 1.8$ kΩ is estimated tether resistance [*Chang et al., 1997*].

Negative shuttle potentials with respect to the ambient plasma were determined from characteristic peaks in ion spectra detected by the Shuttle Potential and Return Electron Experiment (SPREE) in the payload bay. SPREE consists of two nested triquadraspherical electrostatic analyzers (ESAs) which measured ion and electron fluxes from 9.8 eV to 10 keV in 32 logarithmically-spaced energy channels [*Oberhardt et al.*, 1994]. The ESAs detect particles in an angular fan ∼100° by 8.5° in 10 zones viewing from shuttle horizontal to shuttle

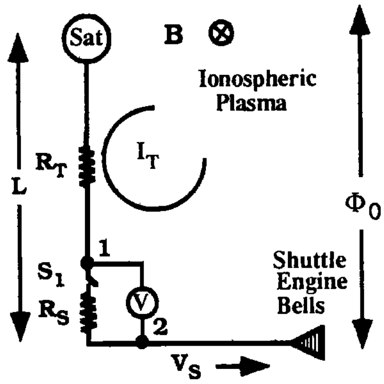

Figure 1. The TSS 1R circuit with tether deployed and no electron beam emissions.

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Paper number 97GL03001.
0094-8534/98/97GL-03001$05.00

zenith. Full spectra were compiled simultaneously from all 10 zones and 32 energy steps at a rate of 1 or 8 s^{-1}.

SPREE data from TSS 1 negative charging events with $R_S = 15\ \Omega$ and $L = 268$ m show that firings by two aft vernier thrusters, L5D and R5D, markedly decreased I_T and increased $|\Phi_S|$ [*Machuzak et al.*, 1996]. The thrusters injected enough gas near the shuttle engines to increase sheath impedance by collisionally hindering ambient ions from reaching conducting shuttle surfaces. TSS 1R experiments were designed to determine if collisional breakdown would occur in strong sheaths and allow the shuttle potential to relax. *Agüero et al.* [1997] describe a numerical model for ram and thermal ion currents to exposed shuttle conducting surfaces. Within the ±20% uncertainty of the plasma density data, the model adequately explains shuttle current collection on TSS 1 and nominal charging experiments of TSS 1R.

Observations

During TSS 1R, the 15 Ω shunt was used only with $L < 3$ km producing nine negative charging events, none of which show significant potential changes related to thruster firings. The 25 kΩ resistor was used at all tether lengths, but significant negative shuttle potentials were recorded only with $L > 2$ km.

Negative shuttle charging with 15 Ω shunt

Figure 2 presents data from four TSS 1R sensors for the nine 43-s events with the 15 Ω shunt in the circuit plotted as a function of universal time, UT, shuttle local time, LT, and tether length, L, in meters. From the top, Figure 2 plots measurements of: (a) motional emf, Φ_0, by the voltmeter [*Agüero et al.*, 1994] just after the circuit opened, (b) shuttle potential, Φ_S, inferred from SPREE ion spectra, (c) tether current, I_T, by the satellite ammeter [*Bonifazi et al.*, 1994], and (d) electron density, n_e, by a Langmuir probe (LP) on the satellite [*Dobrowolny et al.*, 1994]. Data were taken early in the deployment as L increased steadily from 186 m to 2.6 km. The first event occurred at the dawn terminator. The next six were in sunlight, the eighth at dusk, and the last at night. Φ_0 rose steadily from 24 V to 225 V. SPREE data show that Φ_S fell from ~-17 V to -115 V at $L = 1.5$ km, then increased slightly to ~-90 V at dusk. The lowest potential with the shunt, -245 V at 2232:00 UT, coincided with a steep electron density gradient. I_T reached a maximum of 60 mA at $L = 2.0$ km while

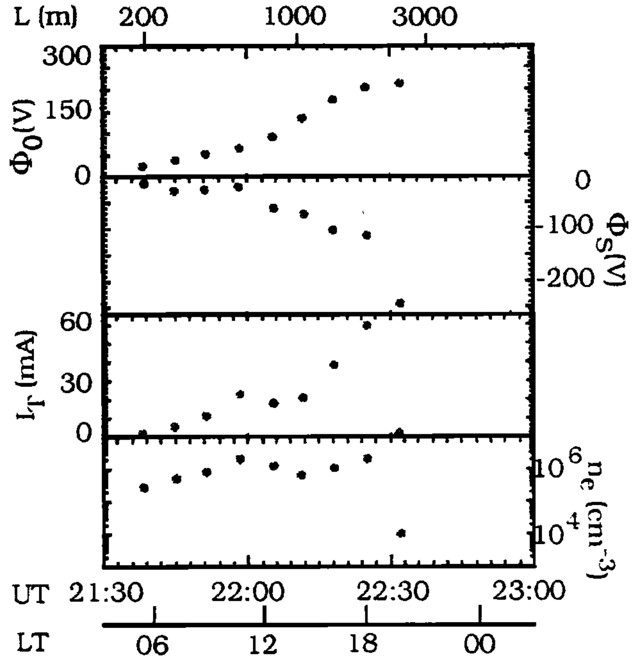

Figure 2. TSS 1R measurements for 2238:00 – 2232:00 UT on February 25, 1996 with the 15 Ω shunt in the circuit.

Table 1. TSS 1R Negative Charging Events with the 25 kΩ Resistor

Event	Day/UT	L	Φ_S	I_T	Φ_0	LT	n_e	Thruster Time	Thrusters
1	56/2231:16	2505	-157	1	229	19:31	1.0×10^4		
2	56/2245:20	3735	-65	6	255	23:05	2.0×10^5		
3a	56/2247:02	3900	-75	6	270	23:35	2.0×10^5	2247:09	R5R,R5D,F5L,L5D
3b	56/2247:30	3947	-145	3	270	23:40	2.0×10^5	2247:26-47:32	L5D,R5D
4a	56/2252:03	4407	-110	8	367	01:04	1.8×10^5	2251:24-51:35	F5L,F5R
4b	56/2252:54	4493	-196	5	367	01:18	1.8×10^5	2252:09-52:41	L5L,L5D,R5D
5	56/2253:44	4579	-157	9	426	01:34			
6a	56/2258:45	5089	-306	13	662	03:03	8.0×10^4		
6b	56/2259:17	5140	-245	16	662	03:11	8.0×10^4	2259:39-59:45	L5D,R5D
7	56/2300:45	5272	-196	20	740	03:36	1.0×10^4	2301:29-01:35	L5D,R5D
8a	56/2305:28	5584	-596	15	976	04:53		2305:20-05:27	L5D,R5D
8b	56/2306:15	5627	-196	23	976	05:06		2306:20	R5D+8
9a	56/2307:12	5682	-157	28	1029	05:19	1.2×10^5	2307:22,07:26	L5D+14
9b								2307:32-07:39	L5D,R5D
10	56/2344:49	8265	-90	49	1445	15:17	8.0×10^5		
11a	57/0035:59	13714	-596	49	2199	04:52			
11b	57/0037:00	13849	-101	58	2199	05:09			
12	57/0103:07	17235	-81	118	3258	11:43	2.0×10^6	0104:49	F1L,F5L,F1U,F4D

plasma density was still high. The last current reading, ~2 mA at 2232:00 UT, closely followed the first negative charging event with the 25 kΩ resistor, when I_T fell from 60 mA to 1 mA.

Negative shuttle charging with 25 kΩ resistor

Table 1 lists 12 events with the 25 kΩ resistor in the circuit by Julian day/UT, tether length in meters, shuttle potential in volts, tether current in milliamps, motional potential in volts, shuttle local time, electron density, times and names of thrusters fired prior to or during events. Two readings, a and b, are given for events 3, 4, 6, 8, 9, and 11 in which changing environmental conditions significantly affected circuit parameters. The duration of 25 kΩ resistor insertions varied: (1) for event 1, it was 12 s; (2) events 2 – 8, it was in for 12 s, removed for 2 s, then reinserted for 43 s; and (3) events 9 – 12, it was in for 120 s. After 56/2250 UT, the satellite was spinning at a rate of 0.25 rpm. Electron densities are not available for 57/0033-0045 UT when the LP was off or in the satellite wake.

Data in Table 1 show that: (1) Multiple thrusters fired prior to or during 7 events; none were associated with the other 5. (2) Ten events were at night or near the dawn terminator, only 2 in sunlight. (3) Φ_0 increased steadily to 3258 V at $L \approx 17.2$ km. (4) I_T rose to a maximum of 118 mA in event 12. For events 3, 4, and 8, I_T was slightly lower than preceding values. (5) L5D and/or R5D fired prior to or during these same events as Φ_S decreased by -70 V, -80 V and -400 V, respectively. (6) The lowest Φ_S, -596 V, was measured twice, both at dawn terminator crossings. Event 8, occurred at 2305:28 UT with $L \approx 5.6$ km after a 7 s thruster firing. Event 11 began at 57/0035:59 UT with $L \approx 13.7$ km and no thrusters firing.

We next examine thruster firing effects. Plate 1A is a SPREE energy-vs-time spectrogram of directional differential ion fluxes for events 4 and 5 with $L \approx 4.5$ km. Traces below the plot mark thruster firings and resistor insertions. When the resistor was first placed in the circuit at 2253:03 UT, $\Phi_S \approx$ -110 V and $I_T \approx$ 8 mA. At 2252:09 UT, thrusters fired, Φ_S instantly fell to -196 V and I_T to 5 mA. The circuit opened for 2 s, causing a brief relaxation of Φ_S. When the resistor was reinserted, Φ_S returned to its previous level. Thrusters fired until 2252:41 UT. L5D and R5D, which significantly affect Φ_S [*Machuzak et al.*, 1996], were among those activated. With all thrusters off, Φ_S returned to -110 V and remained there until resistor removal. Event 5 began at 2253:44 UT with $\Phi_S \approx$ -157 V initially. No other thrusters fired. When the circuit opened briefly, Φ_S relaxed, then returned to the previous level while the circuit remained closed. I_T was steady at ~9 mA, close to the values before thrusters fired.

Plate 1B shows SPREE ion spectra for event 11 at 57/0035:59 UT as the shuttle approached the dawn terminator with $L \approx 13.7$ km. The shuttle initially charged to -596 V, for ~30 s, then Φ_S rapidly increased to -100 V. In the transition, I_T rose from 49 mA to 58 mA. No thruster firings or other gas releases occurred either during or several minutes prior to this event. There are, unfortunately, no plasma density data for this time. It appears, however, that only an abrupt environmental change could produce such a rapid increase in Φ_S. The presence of a steep plasma density gradient as the shuttle crossed the dawn terminator appears to be the most likely cause.

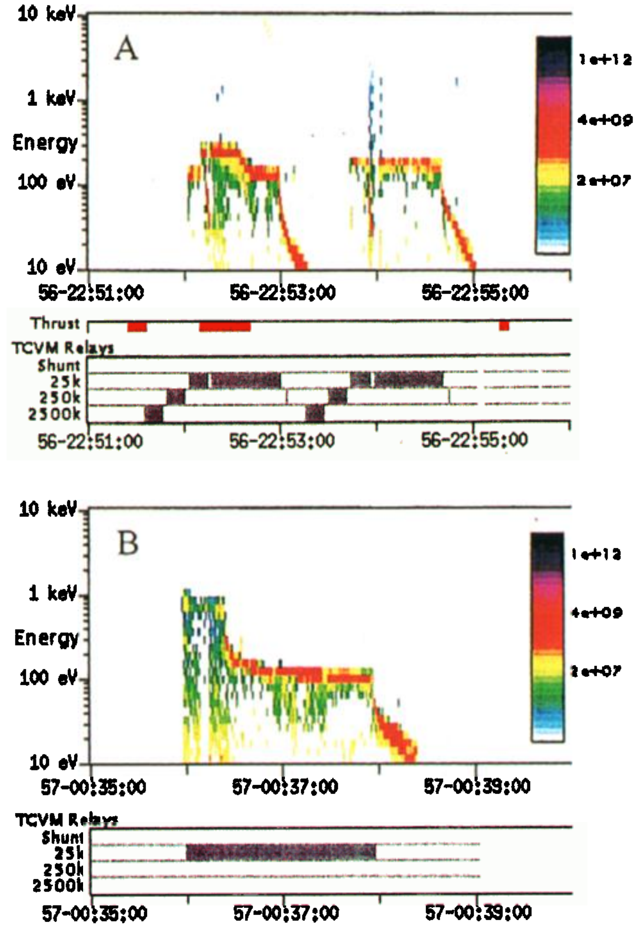

Plate 1. SPREE directional differential ion fluxes for (A) 2251:00 – 2256:00 UT on February 25, 1996 and (B) 0035:00 – 0040:00 UT on February 26, 1996. Traces below the plots indicate thruster firings and resistor insertions.

Summary and Discussion

SPREE data for the TSS 1R deployment show that when the 15 Ω (at $L < 3$ km) or the 25 kΩ (at $L >$ 2 km) resistor was in the circuit, the shuttle charged negatively with respect to the ambient plasma. With $L < 300$ m and the 15 Ω resistor in place, the shuttle charged to a few tens of volts, as on TSS 1 [*Machuzak et al.*, 1996]. With the tether extended to greater distances, $|\Phi_S|$ was significantly higher, providing the first direct measurements of negative shuttle charging to several hundred volts. When aft vernier thrusters L5D and/or R5D fired with resistors in the circuit, I_T either decreased (and Φ_S became more negative) or remained unchanged, confirming TSS 1 results. L5D and R5D fire downward splashing gas off the shuttle wings which then moves upstream. Collisions between this neutral gas and ambient oxygen ions degrade efficiency of ion current collection by shuttle conducting surfaces. We next consider thruster firing effects on shuttle-ionosphere interactions. *Agüero et al.* [1997] discuss shuttle current collection dynamics with no thruster firings.

The negatively charged SCATHA satellite relaxed to low values when neutral gas was introduced into the sheath [*Cohen et al.*, 1982]. *Machuzak et al.*, [1996] expected similar effects on TSS 1R. For this to happen, oxygen ions accelerating though the sheath would undergo ionizing collisions with plume neutrals and ignite a spontaneous discharge. Data presented here clearly show that this did not happen. No evidence of sheath ion creation appeared in any SPREE measurement with only a resistor in the circuit and the shuttle charged negatively. Sheath ionization occurred during electron beam emissions when the shuttle was charged negatively and thrusters fired. Beam electrons were responsible for the new ions. However, even with new ions created in the sheath, Φ_S did not relax.

Not all rapid variations in Φ_S and I_T were thruster firing effects. Minimum shuttle potentials of ~-600 V were recorded twice, both near the dawn terminator, one with and one without thruster firings. Both times Φ_S and I_T were affected by azimuthal density gradients during terminator crossings.

TSS 1R currents in Figure 2 and Table 1 can be used to calculate the Ohmic potential drop along the tether. Combined with voltage $V_{1,2}$ across R_S, this yields an estimate of Φ_{Sa} which suggests that during all 15 Ω and 25 kΩ events out to $L = 5.6$ km, the satellite remained near plasma potential. This was also true for dayside events 10 and 12 at $L = 8.3$ and 17.2 km, respectively. Solutions to (1) indicate that $\Phi_{Sa} \approx 195$ V and 72 V during terminator crossings 8b and 9a. Of special interest is the terminator crossing of event 11. As Φ_S changed from -596 V to -101 V (Plate 1B), Φ_{Sa} rose from 220 V to 505 V and I_T from 49 mA to 58 mA. Thus, at the shuttle altitude, conducting surfaces collected ~18% more ion current with their attractive potential reduced by a factor of 6. This is intelligible only if the shuttle passed through increasing ionospheric densities near the dawn terminator. At 13.8 km above the shuttle, Φ_{Sa} had to increase by a factor of 2.3 to attract ~18% more electrons. This partition of potential in the TSS 1R circuit suggests that the density increase at the shuttle did not occur at the satellite altitude. The existence of both vertical and azimuthal ionospheric density gradients is required to explain TSS 1R measurements during this dawn terminator crossing.

Acknowledgments. This work was supported by the U.S. Air Force Office of Scientific Research task 2311PL04 and Air Force contract F19628-96-K-0030 with Boston College. The authors thank N. Bonito, C. Roth, and E. Courtney of RADEX, Inc., who designed and maintained the SPREE software.

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(Received January 13, 1997; revised September 25, 1997; accepted October 14, 1997.)