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Enhanced electrodynamic tether currents due to electron emission from a neutral gas discharge: Results from the TSS–1R mission

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Abstract. During the reflight of the first electrodynamic Tethered Satellite System (TSS–1R) mission, the unplanned separation of the tether at the Orbiter end resulted in the highest tether current during the mission. In the moments just prior to the tether separation with 19.7 km of tether deployed and a generated electromotive force (EMF) of 3482 V, currents reaching approximately 0.97 A were shunted through the tether to the Orbiter electrical ground, which was in contact with the ionosphere primarily through its main engine surfaces. This current level was nearly twice as large as observed during any nominal operating period. As the failure point of the tether entered into the ambient plasma, the current increased to 1.1 A and maintained this level even after the break for approximately 75 s. The principal surprise in these results was that the broken end of the tether, with only a few short strands of copper wire, could support higher currents than the much larger Orbiter conducting surface areas. Analysis of possible current enhancement mechanisms revealed that only a gas–enhanced electrical discharge, providing an electron emission source, was plausible. Ground plasma chamber tests confirmed this analysis. The TSS–1R results thus represent the highest electron current emission from a neutral plasma source yet demonstrated in a space plasma. This is of interest for current collection processes in general and plasma contactor development in particular.

1. Introduction

The reflight of the joint Italian–U.S. Tethered Satellite System (TSS–1R) had as a goal the exploration of physical processes and fundamental limits associated with driving large currents through the ionosphere using a long electrodynamically–tethered double–probe [*Dobrowolny and Melchioni*, 1993; *Banks*, 1989]. A schematic depiction of the conducting tether system is shown in Figure 1 just before and after tether break, where an electromotive force (EMF) is generated by the motion ($\mathbf{v}_0$) of the conductor (length $\mathbf{L}$) across the magnetic field ($\mathbf{B}$) as given by $\varphi_{\text{emf}} = \mathbf{v}_0 \times \mathbf{B} \cdot \mathbf{L}$. The ability to drive currents through such a system, for a given tether EMF, depends critically on contact efficiency with the ionospheric plasma at each tether end. This in turn depends on the ability to draw/emit charge to/from highly charged surfaces which may depend on space charge, magnetic confinement, and plasma turbulence effects. Current collection processes in a space plasma were recently reviewed by *Laframboise and Sonmor* [1993] and specific issues for an electrodynamic tether were reviewed by *Dobrowolny* [1987]. Early TSS–1R results have, in fact, shown that the tether currents for nominal operations were several times larger than previously predicted when compared to magnetically–confined stationary current–collection models [*Thompson et al.*, 1997]. However, even more impressive was the observation that the largest tether current level achieved for the entire mission (1.1 A) came only *after* the tether inadvertently separated from the Orbiter at its lower end leaving a few short copper wire strands in contact with the space plasma [*Szalai*, 1996].

In the following sections, we summarize relevant aspects of TSS–1R observations at the time of the tether break. We identify a plausible explanation and discuss laboratory plasma chamber experiments used to verify the explanation.

2. TSS–1R Observations at Tether Break

A full description of the TSS mission goals and experimental systems (including those used for measurements in this paper) can be found in *Dobrowolny and Stone* [1994] and companion papers. Here, we note that the TSS–1R system operated flawlessly for 5.5 hours prior to the tether break. The satellite reached near full deployment, achieving 19.7 out of a planned 20.7 km, and the induced EMF at the time was measured at −3482 V. At 057/01:29:16 GMT, just before tether separation, the Orbiter was located near the equator west of Indonesia at an altitude of 297 km, about a half hour before local sunset. The measured plasma parameters measured by the Research on Electrodynamic Tether Effects (RETE) experiment were $n_e \approx 10^{12}$ m^{-3} and $T_e \approx$ 1100–1200 K.

Approximately 9 s prior to the tether break and while

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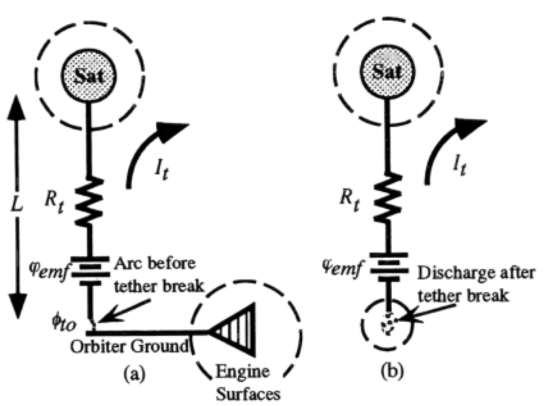

Figure 1. Simplified drawing of an electrodynamic tether (a) just prior to and (b) after tether break. Electrical contact with the space plasma is made at each end of the long tether through effective sheath impedances (dotted lines).

in an open–circuit configuration, multiple arc–like discharges between tether and Orbiter electrical ground were detected by voltage and current instruments connected to the tether. Post–flight analysis revealed that a single failure point was involved as it moved through deployer tether control boxes under multi–layer insulation blankets [*Szalai*, 1996]. During these discharges, the tether current I_t, reached 0.97 A (see Figure 2) at a discharge voltage of approximately 82 V. The discharge voltage was measured by the same voltmeter which nominally measures open–circuit EMF. In this configuration, return currents to the ionosphere at the Orbiter end involved ion current collection to, and possibly to some degree secondary electron emission from, various Orbiter conducting surfaces such as the main engine nozzles, which could provide some 16 m^2 of sheath–enhanceable ram–ion current collection area [*Agüero*, 1996; *Agüero et al.*, 1997]. The Orbiter potential was measured at approximately -596 ± 75 V by the Shuttle Potential and Return Electron Experiment (SPREE) which *Agüero et al.* [1997] explains is lower than existing models predict. The satellite's current collection response was also higher than predicted by pre–mission models as discussed by *Thompson et al.* [1997]. Once the arc point exited the deployer satellite cradle and became exposed to the background plasma, tether current increased to a value of 1.1 A (057/01:29:21 GMT in Figure 2) and the measured Orbiter potential was reduced to its floating plasma potential. More remarkably, however, is that for some 75 s *after* the tether broke and was well away from the Orbiter vicinity, essentially the same 1.1–A current level continued to conduct through the tether attached to the satellite based on current readings made at the satellite end of the tether.

The TSS tether consisted of ten strands of 34 AWG (0.16 mm, dia.) copper wires wrapped around a Nomex core with a 0.305–mm thick FEP Teflon outer insulating jacket under layers of Kevlar 29 and braided Nomex. The overall tether diameter was 2.54 mm [*Szalai*, 1996].

3. Ionospheric Current Contact

The key question which must be addressed is how could a few short copper wires, biased negatively with respect to the local plasma (see Figure 1), provide even better current contact with the ionosphere than the sizable ion collection areas of the Orbiter? For the electrodynamic tether circuits of Figure 1 and assuming negligible potential drop in the ionosphere, the tether circuit loop potentials sum to

$$\varphi_{\text{emf}} = \varphi_{\text{sat}} + I_t R_t + \varphi_{to} - \varphi_L, \tag{1}$$

where R_t is the tether resistance for the 19.7–km section remaining with the satellite, φ_{to} is the measured potential between the tether and the Orbiter, φ_{sat} is the satellite potential with respect to the local plasma, and φ_L is either the Orbiter potential just prior to the tether break as measured by SPREE or the estimated potential of the exposed wire strands after the break.

Prior to the tether break, with the 0.97–A current flowing through the tether to Orbiter electrical ground, all but the satellite potential is known in Equation 1 which is thus calculated to be approximately $\varphi_{\text{sat}} \sim$ 1220 V. Here, the tether resistance, R_t, was reduced from its estimated total value of 1800 Ω prior to the break [*Thompson et al.*, 1997] by the loss of the 2 km of tether remaining on the reel after the break ($\sim$ 0.083 Ω/m) giving a value of 1635 Ω. After the break, $\varphi_{to} \sim 0$. Further, *Thompson et al.* [1997] have concluded that at sufficiently high satellite potentials, the change in collected current with potential can be described by a φ^{β} dependency ($\beta = 0.52 \pm 0.03$) which is very close to $\beta = 0.5$ predicted for magnetically confined stationary plasmas by *Parker and Murphy* [1967]. If we assume the *Thompson et al.* [1997] value for β seen shortly before tether break ($\beta = 0.55$), the predicted change in satellite potential in going from 0.97 A to 1.1 A after the break yields a value of $\varphi_{\text{sat}} \sim$ 1585 V. Thus, using Equation 1, φ_L can be estimated to be approximately -100 V.

Current continuity requires that the integrated current flux through any surface surrounding the wire end be equal to the tether current, I_t. (Figure 3) Thus,

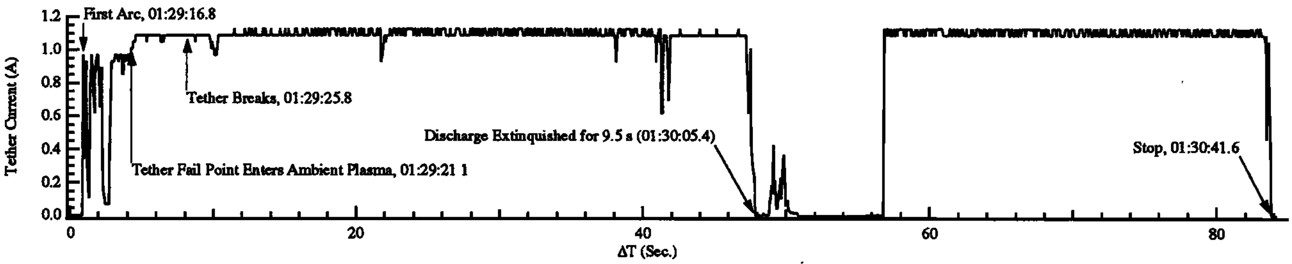

Figure 2. Measurements of tether current as measured at the satellite shortly before and after tether break which shows that currents continued to flow at high levels for some 75 s after the break.

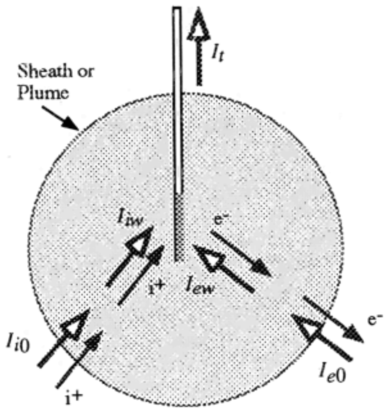

Figure 3. Current continuity requires that total current comprised of ion and electron sources at the wire of the tether end and at the outer sheath boundary with the ionosphere must equal the tether current.

at the exposed wire surface we can consider both incoming ions, I_{iw}, and possibly outgoing electrons, I_{ew}. Similarly, this same total current must ultimately connect with the ambient ionosphere at some distance and be the sum of incoming external ion current, I_{i0}, and ejected electron current, I_{e0}, due to various processes discussed below. Therefore, current continuity requires

$$I_t = I_{ew} + I_{iw} = I_{e0} + I_{i0}. \tag{2}$$

It is possible to eliminate both ion collection from the ionosphere, I_{i0}, and electron emission from the wire, I_{ew}, as significant contributors to current flow. Orbital motion limited (OML) estimates for current collection [*Laframboise and Parker*, 1973; *Dobrowolny*, 1987] show that the required potentials to attract adequate ion current to the wire end was well beyond even the available tether EMF. For electron emission currents from the copper wire we have considered: (a) secondary emission due to high–energy ion impingement; (b) thermionic emission due to wire heating; and, (c) field emission due to high electric fields at the wire tips. Kinetic and potential secondary electron emission yield rates due to ion collisions with the surface of copper and other metals have values less than one (~0.1–0.3) in the energy range under consideration here [*Lakits et al.*, 1990] thus providing only a small enhancement. Maximum possible thermionic emission currents from copper can be estimated from the Richardson–Dushman emission equation for a clean metal surface [*Jenkins and Trodden*, 1965]. Even at the wire melting temperature (1356 K), electron emission currents from the wire would have been many orders of magnitude less than observed. Finally, analysis of the expected electric field levels around the wire tips indicate that threshold levels ($\sim 10^7$ V/cm) for significant emissions were not easily achieved nor would they have been expected to be significant [*Jenkins and Trodden*, 1965]. Therefore, we have narrowed the continuity requirements of Equation 2 on physical grounds to read

$$I_t = I_{iw} = I_{e0}. \tag{3}$$

Gas ionization in the vicinity of the tether end using secondary electron emission as a seed source, however, could provide a dense, slowly–moving cloud of ions around the conductors and a source of more rapidly–moving electrons to be ejected into the ambient ionosphere. A likely source of ionizable gas, recognized shortly after the mission, was trapped air inside the insulating FEP Teflon sheath in gaps between the wire conductors and Nomex strands [*Szalai*, 1996]. This trapped air would be very nearly at a pressure of 1 atmosphere and any small void or "pin hole" would provide a small jet of ionizable gas. Further, *Wilbur et al.* [1996] have suggested that an ablative process involving the Teflon and Nomex dielectric materials could have also provided gas for ionization.

We have estimated the trapped air gas flow rate from the tether end by assuming a small opening and large pressure gradient to the vacuum of space. Under these conditions the gas exit velocity can be assumed to be approximately the gas sound speed, $c = \sqrt{\gamma RT}$, where γ is the ratio of specific heats, R is the gas constant for air, and T is the gas temperature. Since the location of the tether break had just come off the tether reel, we can assume a temperature close to that of the reel system ($\sim +10°$C) resulting in an estimate for the gas exit speed of $c \sim 340$ m/s. Assuming the pressure inside the tether is roughly constant, the gas mass flow rate, $\dot{m}$, can be approximated as $\dot{m} = \rho c A$, where ρ is the mass density of air inside the tether and A is the area of the opening. We have conservatively estimated the opening of the broken tether as being equivalent to a small rectangle which just surrounds two parallel wire strands since gaps of this size were common in the tether wire wrapping (see photos in *Szalai* [1996]). This provides a mass flow estimate of $\dot{m} = 5.3 \times 10^{20}$ molecules/s which would only need be about 1% singly ionized to provide enough current carriers to support the 1.1 A measured in the tether.

That an ionization gas discharge was almost certainly present can be explained several ways. The mean free path, λ, for ionizing collisions as a function of radial distance, R, from the end of the tether can be estimated by calculating the expansion of the gas density, n_n. Here we assume the gas expands at the sound speed, c, into a solid–angle half–space, yielding a density estimate of

$$n_n = \frac{5.3 \times 10^{20}}{2\pi c R^2} (\mathrm{m}^{-3}). \tag{4}$$

By assuming a constant collision cross–section of $\sigma = 3 \times 10^{20}$ m^2 [*Banks and Kockarts*, 1973], an ionization mean free path, $\lambda = 1/(n_n \sigma)$, is calculated which ranges from 0.13 mm at a 1–mm distance to 3.3 mm at 5 mm and 13 mm at 1 cm. If we assume that the lower tether end potential (~ -100 V) was uniformly dropped across a 1–cm length, the resulting electric field would require an electron to fall through at least a distance of approximately 1.5 mm to acquire the necessary ionization energy (~ 15 eV). This would suggest that ionization could not occur closer than about 2 mm and would extend out to some distance less than about 1 cm. Similarly, *Brown* [1959] indicates that ionization efficiency is optimized for electric field to pressure ratios (E/P) in the range of 10^4 to 10^5 V/m/mm$_{\mathrm{Hg}}$. By assuming that the gas is in thermal equilibrium, the required radial distances which satisfy the E/P constraints can be estimated to lie between 2.5 and 8.5 mm which is in close agreement with our previous estimates.

4. Discussion

To verify the above analysis, tests were conducted in a 6-m × 9-m plasma chamber by applying high voltage potential to small conducting probes immersed in a Neon plasma to simulate aspects of the tether end contact as shown in Figure 3 [*Gilchrist et al.*, 1996]. Some probe samples allowed independent control of an N_2 gas flow which was selected since it is the dominant constituent of air trapped in the tether.

With N_2 gas emission, a high current electrical discharge could be initiated with its onset voltage threshold being a function of gas flow rate. For example, at a flow rate of 4.8×10^{20} particles per second, which is near the flow rate predicted for the end of the tether, a negative potential of approximately 2200 V was required to initiate a discharge. After the onset of the discharge and the power supply providing maximum current ($\sim$ 800 mA), the potential between the probe and chamber wall dropped to between 150 and 200 V negative.

In the analysis of Section 3, we found that it was necessary to consider some kind of electron emission process to explain the current levels and a neutral-gas electrical discharge was the only plausible explanation. The ground plasma chamber tests were found to be in general agreement with this analysis and the laboratory current-voltage response compared favorably with in-flight observations at the initial neutral gas flow rates predicted from the end of the separated tether. The suggestion by *Wilbur et al.* [1996] that an ablative process may have been present would have provided an additional source of gas for ionization. The extinguishing of the discharge observed starting at 57/01:30:15 GMT in Figure 2 followed by a restart is not surprising as it was also seen at times in the laboratory tests.

The underlying physics of hollow cathode plasma contactors in electron emission mode has fundamental similarities with the neutral-gas electrical discharge described here [*Williams and Wilbur*, 1992; *Parks et al.*, 1993]. We believe the TSS-1R results described here are applicable and represent the highest electron current emission from a neutral plasma source yet demonstrated in a space plasma. This is of interest for current collection processes in general and plasma contactor development in particular. Additional tests would be required to determine if the tether end could have supported even more current if additional EMF was available.

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