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The TSS-1R mission: Overview and scientific context

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1. Mission Background

The Tethered Satellite System (TSS) program is a binational collaboration between NASA and the Italian Space Agency (ASI) with NASA providing the Shuttle-based deployer and tether and ASI providing a satellite especially designed for tethered deployment. Twelve science investigations (see Table 1) were supported by NASA, ASI, or the Air Force Philips Laboratory. The goals of the TSS-1R mission, which was the second flight of the TSS hardware, were to provide unique opportunities to explore (1) certain space plasma-electrodynamic processes—particularly those involved in the generation of ionospheric currents, and (2) the orbital mechanics of a gravity-gradient stabilized system of two satellites linked by a long conducting tether.

TSS-1R was launched February 22, 1996 on STS-75 into a 300-km, circular orbit at 28.5° inclination. Satellite flyaway occurred at MET 3/00:27 and a unique data set was obtained over the next 5 hours as the tether was deployed to a length of 19,695 m. At MET 3/05:11, during a day pass, the tether suddenly broke near the top of the deployer boom. The break resulted from a flaw in the tether insulation which allowed the ignition of a strong electrical discharge that melted the tether. The operations that had begun at satellite flyaway, however, allowed significant science to be accomplished.

2. Instrumentation and Measurements

The TSS converted mechanical energy into electrical energy in a classical demonstration of Faraday's law. The configuration was such that the satellite received a positive bias and collected electrons from the ionosphere, which conducted through the tether to the orbiter where the circuit could be closed back to the ionosphere (see Fig. 1). There were four basic electrical configurations at the orbiter: (1) Open circuit with no current flow—in which case the full tether-generated emf existed across the open switch; (2) Passive current closure—in which current was controlled by adding a load resistance in series with the tether, and closure was through the collection of positive ions by conducting surfaces on the negatively charged orbiter; (3) Addition of SETS experiment's Fast-Pulse Electron Gun (FPEG) to the above circuit to discharge the orbiter; and (4) Use of the ASI Core electron gun—in which case tether current flowed directly to the gun cathode (the orbiter was not part of the electrical circuit) and was emitted back in to the ionosphere. An electrical schematic is shown in Figure 3 of Dobrowolny and Stone [1994].

The TSS was instrumented to control the tether current (as described above) and diagnose the environmental space plasma properties under highly nonequilibrium conditions. The investigations, shown in Table 1, provided the required ensemble of instruments which were mounted on either the orbiter or the satellite. Ground-based RF measurements were also made, and ionosound data, combined with several models, were used to predict the ambient ionospheric conditions [*Szuszczewicz et al.*, 1997]. A functional schematic of the TSS and its instrumentation is given in Figure 1. A detailed description of the instrumentation, which also flew on the TSS-1 mission, is provided in a special TSS-1 issue of *Il Nuovo Cimento* [1994]. The interdependence of the TSS investigations resulted in an integrated approach to the science, with all the instrumentation and hardware being operated as a single experiment.

The data set obtained from TSS-1R, in one sense, falls far short of premission expectations. There was no opportunity to execute the detailed experiments that had evolved over several years of planning (operations were primarily limited to calibration); therefore, the data set lacks a systematic approach and does not provide complete information. In another sense, however, the TSS-1R data set includes more than could have been hoped for under the circumstances. In fact, the tether break itself provided an especially intriguing and potentially valuable event in which large currents (>1 A) at high satellite potentials (>1 kV) began flowing ~10 s prior to the break and continued for ~90 s *after* separation [*Gilchrist et al.*, 1997]. The data obtained during deployment are also unique in that they have uncovered new and unexpected physical processes discussed below. Though limited, the data set is of high quality and includes 13 major operational sequences, covers a significant portion of the planned ranges of the tether current and voltage, and includes a variety of ionospheric conditions. Figure 2 provides the conditions under which data were obtained for the various operational sequences used in the papers that follow.

3. Scientific Context

The most fundamental scientific result from the mission to date is that the various theoretical current collection models developed over the past 70 years [e.g., *Langmuir and Blodgett*, 1923, 1924; *Beard and Johnson*, 1961; *Parker and Murphy*, 1967] do not include the full range of processes by which an electrically biased, mesosonic satellite (supersonic with respect to the ion sound speed but subsonic with respect to that of the electrons) interacts with its environmental space plasma. The predicted relation between satellite potential and

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Table 1. TSS-1R Science Investigations

PI/Institution		Investigation/Primary Function
Orbiter-Mounted		
C. Bonifazi/ASI	DCORE	(e-guns, tether current control, I and V measurements)
B.E. Gilchrist/University of Michigan	SETS	(e-guns, tether current control; I, V, and plasma meas.)
D.A. Hardy/USAF Phillips Lab	SPREE	(ion and electron distributions and orbiter potential)
S. Mende/Lockheed (Now at U C. Berkeley)	TOP	(low light-level TV)
Satellite-Mounted		
M. Dobrowolny/CNR/IFIS (Now at ASI)	RETE	(ac and dc electric fields, ambient electrons, sat. pot.)
F. Mariani/Second University of Rome	TEMAG	(ac and dc magnetic fields)
N.H. Stone/NASA/MSFC	ROPE	(ion and electron distributions, satellite potential)
Ground-Based/Theoretical		
S. Bergamaschi/Padua University	TEID	(theoretical: tether dynamics)
A. Drobot/SAIC	TMST	(theoretical: plasma-electrodynamic models)
R.E. Estes/SAO	EMET	(ground-based measurements: em waves)
G. Gullahorn/SAO	IMDN	(theoretical: tether dynamics)
G. Tacconi/University of Genoa	OESEE	(ground-based measurements: em waves)

charge collection (the current-voltage characteristic) is, correspondingly, incorrect. Second, a variety of specific physical effects, including the creation of suprathermal charged particle populations, plasma waves, and magnetic perturbations were observed. These effects may be related to the unexpected nature of the current-voltage relationship. Third, a sharp transition in the interaction process was found to occur at the relatively low spacecraft potential of +5 V—the ram energy of the dominant atomic oxygen ions. The reflection of ionospheric ions by the satellite when its potential exceeded the ion ram energy was expected. However, a transition in the basic physical processes involved was a complete surprise.

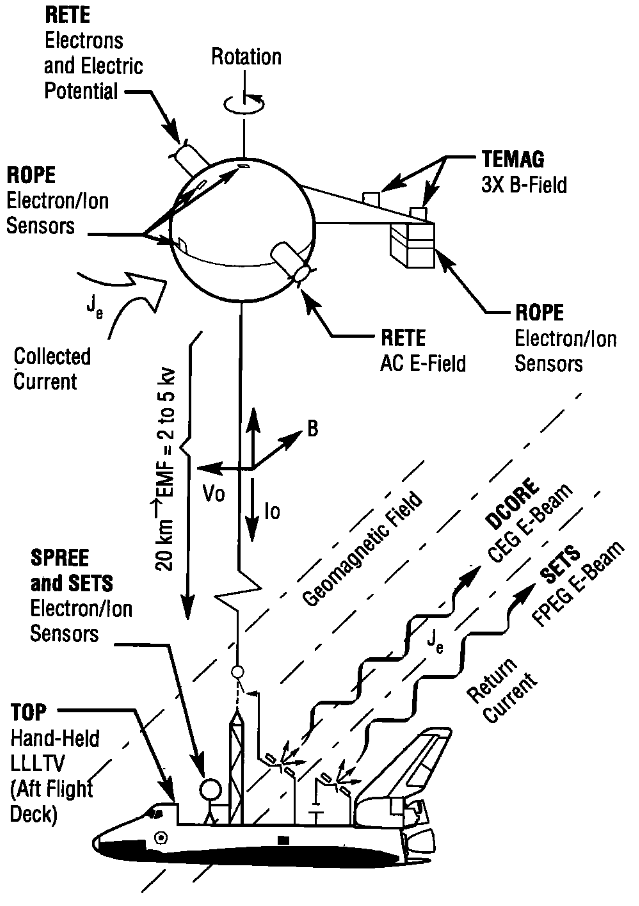

Figure 1. A functional schematic of the TSS-1R instrumentation and hardware.

The disagreement observed between the measured TSS-1R current-voltage characteristic and the predictions of the theoretical models may provide for the most significant improvement to our understanding of the physics of current collection in space since the Langmuir-Blodgett model was introduced in 1923 to explain how an electrostatic probe collects current from an unmagnetized, stationary laboratory plasma [*Papadopoulos*, 1996]. The Langmuir-Blodgett theory was modified by Parker and Murphy in 1967 to account for the fact that the ionospheric plasma has an imbedded magnetic field which reduces cross-field charge mobility—limiting current

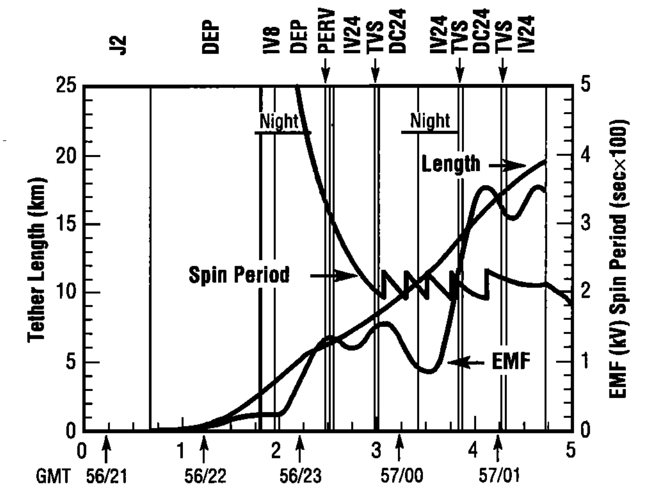

Figure 2. Conditions under which the TSS-1R data set was obtained. Occurrence of various science operating cycles listed across the top are denoted by vertical lines. (The definitions of these sequences are given in *Dobrowolny and Stone*, [1994].) Two night passes are shown by horizontal bars near the top. Time from flyaway is given across the bottom. Satellite spin (due to torque from the tether) was controlled at 0.25 rpm (period of ~200 s). Satellite flyaway occurred at GMT 56/20:46 (MET 3/00:27).

collection approximately to a magnetic flux tube. (A review of the theory is given in *Laframboise and Sonmor*, 1993.) The magnetically limited model seemed to explain observations made from several relatively slow-moving sounding rocket experiments and was accepted as authoritative for the past 30 years—until the TSS-1R mission. Immediately, even during the 5 hours of data acquisition, it became obvious that serious differences existed between theoretical models and the measured results. For example, Figure 3 shows that the attractive potential required on the satellite to collect a given current is typically an order of magnitude less than that predicted by the Parker-Murphy model [*Thompson et al.*, 1997]. This shows that current collection is far more efficient than predicted and suggests the requirement for rather rigid adherence of electrons to magnetic field lines assumed in the magnetically limited models may be too severe.

The sharp transition observed in the satellite particle and field environment at a potential of +5 V seems to suggest an abrupt modification of the physical processes. Below +5 V, mostly accelerated ionospheric thermal electrons were observed. However, when the satellite potential transcended the +5 V level, a sudden onset of suprathermal (~200 eV) electrons, plasma waves, magnetic perturbations, and turbulence in the satellite sheath were observed [see *Winningham et al.*, 1997; *Iess et al.*, 1997; *Mariani et al.*, 1997; and *Wright et al.*, 1997, respectively]. The suprathermal flux intensity grew rapidly with increasing satellite potential and quickly swamped the ionospheric thermals [*Winningham et al.*, 1997]. In addition, relatively energetic ions were observed outflowing from the satellite's sheath. The ram energy of ionospheric atomic oxygen ions is ~5 eV, so that the critical voltage for the transition is the level at which oxygen ions would be reflected or strongly deflected out of the sheath. It appears possible that the outflowing ions, or possibly the expulsion of ions from the plasma sheath, may provide the free energy required to drive the energization of the suprathermal electrons.

In addition to shedding new light on the basic current-voltage relationship, the present TSS-1R data set, as discussed in the papers that follow, may also provide glimpses of important space plasma processes that occur naturally near Earth and throughout the solar system. For example:

(1) The reflection of ions by the potential barrier around the positively biased satellite created counterstreaming ion beams that, in turn, generated a spectrum of lower hybrid waves. Similar processes are seen in ionospheric double layers, at the magnetopause and at the Earth's bow shock, all of which involve the basic physics of how charged particle beams couple to and dissipate energy in plasmas [*Kindel and Kennel*, 1971].

(2) The modulation of electron beams during TSS-1R operations [*Gough et al.*, 1997] may be related to the cyclotron resonant maser effect. This effect is thought to be involved in the production of auroral kilometric radiation [*Wu et al.*, 1989].

(3) There is strong evidence of pickup ion processes at the TSS satellite. Such processes are commonly associated with solar wind interactions with planets and comets [*Intriligator et al.*, 1996].

(4) The characteristics of a high voltage, negatively charged spacecraft and its effects on the ionospheric plasma are important because this study (made possible for the first time by TSS-1R) can lead to improved techniques for biasing antennas in space to enhance their coupling to the magnetospheric plasma—which has direct applications to the measurement of dc electric fields [*Gentile et al.*, 1997].

Satellite-ionospheric interactions under controlled conditions unique to the TSS-1R can also be used to study the collisionless expansion of plasma into the void region of the satellite's wake [*Stone et al.*, 1988]. This process has many potential applications in space and was suggested as a mechanism for closure of the wake of the Moon in the solar wind plasma by *Samir et al.* [1983]. Recent measurements from the WIND mission appear to confirm this closure process [*Ogilvie et al.*, 1996].

Electrodynamic tethers can also enable a number of other unique experiments in which specific scientific cause and effect mechanisms can be studied. For example, tethers can be used as long antennas to emit ULF (Alfvén lower hybrid) waves which, if our present understanding is correct, will induce pitch-angle scattering and the precipitation of electrons trapped in the radiation belts [*Kennel and Petschek*, 1966].

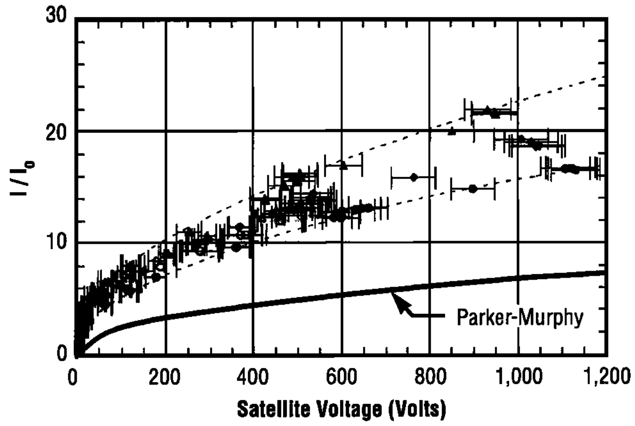

Figure 3. The TSS-1R current-voltage characteristics, obtained from the six Core electron gun controlled sweeps of the third IV24 cycle (beginning at 4:20 in Fig. 2), compared to the characteristic predicted by the Parker-Murphy model.

4. Summary

Although our understanding of the TSS-1R data set is incomplete at this point, it is apparent that (1) a sharp transition in the physics of the interaction between the TSS and the ionosphere occurs, when the satellite potential exceeds +5 V, in which electron flux to the satellite changes from being primarily accelerated ionospheric thermals to being dominated by a new suprathermal electron population; and (2) the current-voltage characteristic, possibly as a result of the above transition, is in disagreement with the Parker-Murphy model, which requires an order-of-magnitude higher satellite potential to collect a given current. Current extraction from the ionosphere was surprisingly efficient—to the extent, in fact, that the TSS never pushed the ionospheric plasma's limits of conductivity. This result is extremely encouraging for scientific and technological applications of electrodynamic tethers, such as the generation and study of current systems, electromagnetic waves, or plasma disturbances in the ionosphere, the generation of electrical power or electrodynamic thrust, and the use of tethers as VLF/ULF antennas. The complex of effects observed at the satellite are shown schematically in Figure 4.

The TSS-1R observations show that there is much concerning space plasma physics that we still do not understand—even the rather basic process of current collection that was assumed to be well in hand. The papers that follow will (1) provide an

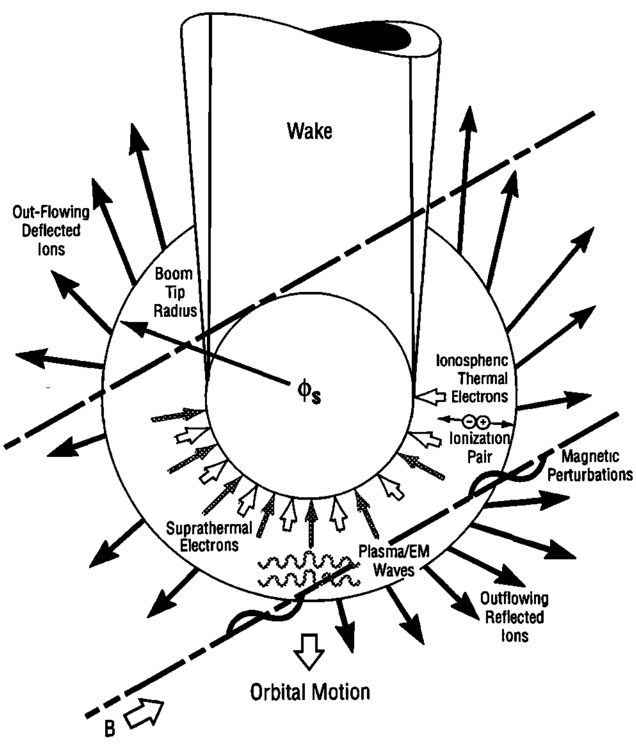

Figure 4. A composite schematic of the complex array of physical effects and characteristics observed in the near environment of the TSS satellite.

in-depth treatment of the TSS current-voltage characteristic and the measured aspects of the associated physical processes, including the transition observed at a satellite potential of +5 V; and (2) analyze orbiter potential and return currents during tether operations. An attempt to provide a theoretical framework that relates the complex of observations will be presented in a second special GRL issue on TSS-1R results. Results obtained from the investigation of tether dynamics will be presented elsewhere. As the physics contained in the TSS-1R observations become more clear, this mission may well serve to elucidate plasma-electrodynamic processes commonly found to operate in the Earth's near space environment.

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