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Electrodynamic Aspects of the First Tethered Satellite Mission

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The tethered satellite system (TSS) project was developed, starting from 1984, as a unique system to make active experiments in space plasmas. This paper aims at providing a thorough description of the basic electrodynamic aspects of a TSS orbiting in the ionosphere. As will be seen, a wide variety of plasma physics phenomena are associated with the interaction of a conducting tether with the ionospheric plasma and, as a consequence, numerous basic science objectives can be addressed with a TSS system. Besides reviewing the various electrodynamic phenomena and our present knowledge on them, we provide also a description of the scientific payload and the nominal science objectives of the first tethered satellite project (TSS-1). A brief account, as well as a first evaluation, are also given of the mission itself, which was flown with the shuttle Atlantis launched on July 31, 1992.

1. Introduction

The idea of having long conducting tethers in Earth's orbit was proposed as early as 1973 [*Grossi*, 1973], with the purpose of generating and communicating to the Earth ULF waves. In 1974, G. Colombo gave a quantitative treatment of the dynamics of a system consisting of a satellite tethered from the shuttle and orbiting at different separation distances [*Colombo et al.*, 1974]. Shortly after, several studies [*Dobrowolny et al.*, 1976, 1979; *Williamson and Banks*, 1976; *Dobrowolny*, 1978] first indicated the great scientific interest of a system based on a conducting tether (so called electrodynamic tether). At the same time, a coordinated study by a committee of numerous scientists established the scientific rationale for a program based on long tethers deployed from the shuttle orbiter [*Banks*, 1980].

A real space project (the first tethered satellite system (TSS-1)), started only in 1984, in the form of a joint venture between NASA and the Italian National Space Agency. The mission (see Figure 1), flown in August 1992 with the shuttle flight STS-46, consisted in deploying a 500-kg subsatellite tethered to the space shuttle. During the TSS-1 mission, the shuttle *Atlantis* was revolving around the Earth with a quasi circular prograde orbit with 28° of inclination, at an altitude of about 300 km. The subsatellite was 1.6 m in diameter with a conducting surface. The tether wire (conductive) was insulated from the ionospheric plasma with a dielectric coating. The payload included also electron sources on the shuttle for active control of the current flowing in the tether. The TSS subsatellite was deployed radially upward from the orbiter cargo bay.

The basic features of electrodynamic tethers have indeed been addressed in several publications [*Banks*, 1980; *Arnold and Dobrowolny*, 1980; *Banks et al.*, 1981] including reviews on the subject [*Dobrowolny*, 1987; *Banks*, 1989]. In particular, early studies on tether electrodynamics and a preliminary description of the mission TSS-1 were addressed by *Dobrowolny* [1987].

In this review we plan to recall the most recent studies and considerations related to tether electrodynamics and, consequently, assess our present state of knowledge on processes associated with the interaction of conducting tethers with space plasmas. At the same time, we will give a thorough description of the payload of TSS-1 and of the nominal TSS-1 mission.

The plan of the review is the following. We will start in section 2, with a basic physical description of processes associated with the motion of conducting tethers in orbit (or, in general, the motion of large conducting bodies in a magnetoplasma). It will be found that our knowledge of electrodynamic tether interactions is very approximate and that our ability to model these theoretically or simulate them in the laboratory is limited, so that the results of the measurements associated with TSS-1 will be crucial in clarifying our ideas.

In section 3 we touch on a possible important application of electrodynamic tethers which is that of generating power and/or propulsion in space. Section 4 describes in some detail the TSS-1 project. We start with the electrical configurations of the system and recall some recent work on modeling of the tether circuit in the ionosphere. We then review the science objectives of the nominal mission and, in particular, those which had the highest priority. A brief description of the payload is given and its capabilities to address the science objectives of the mission are discussed. Section 5 gives an overview of what happened in the first TSS-1 flight and what type of electrodynamic measurements were performed.

2. Basic Physical Description of Electrodynamics of Conducting Tethers in Orbit

All the electrodynamic interactions of a conducting tether with the ambient plasma medium are due to the fact that, because of the system motion across magnetic field lines, a polarization electric field is set up along the tether length. For an observer moving with the tether system this is given by

$$\mathbf{E} = +\mathbf{V}_0 \times \mathbf{B} \qquad (1)$$

$\mathbf{V}_0$ being the velocity of the tethered system with respect to the Earth's (comoving) ionosphere and $\mathbf{B}$ the Earth's magnetic field. A corresponding potential difference (which is the open circuit voltage) is then applied by the tether, during its motion, across magnetic flux tubes in the ionosphere, and, by means of current in the tether, space charge is in fact transported across widely separated flux tubes.

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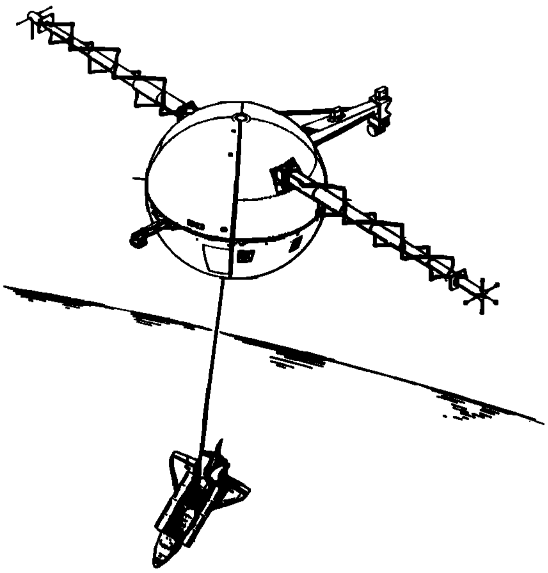

Fig. 1. Artist view of the TSS-1 mission.

Taking a tether length L = 20 km, as in the nominal TSS-1 mission, V_0 = 8 km/s (typical orbital speed of the shuttle at tether operations altitude) and the average magnetic field intensity (B = 0.3 G) we obtain a maximum potential difference between the system terminations

$$\Delta\Phi = 4.8 \text{ kV} \quad (2)$$

when the tether's motion is perpendicular to **B**. In fact, for a 28° inclination prograde orbit and taking the magnetic field geometry into account, this voltage varies along the tether orbit (roughly between 3 and 5 kV).

It is this voltage that causes the system to induce a variety of plasma processes. Indeed, a number of plasma physics questions are raised by electrodynamic tethers such as, for example, the properties of current collection and injection from highly charged and rapidly moving electrodes in a magnetoplasma; the electrical contact with the plasma medium; current propagation and closure out of the source and, connected with this, wave emissions from a dc and/or pulsed current source.

As already mentioned, a number of publications addressing the scientific interest of electrodynamic tethers have appeared in the literature. As a consequence, we will only outline here what are the essential elements of the interaction of a conducting tether with the ionosphere and then proceed to a review of the more recent studies.

The system we are referring to is (like TSS-1) a conducting insulated tether which electrically contacts the ionosphere at its two terminations (the TSS satellite and the orbiter for TSS-1).

Figure 2 gives a qualitative picture of the interaction of such a system with the ionosphere. As a consequence of the electromotive field (1) (and for an eastward orbit), the upper termination of the system (the satellite in the case of TSS-1) will be positively charged with respect to the ionosphere, while the lower termination (the orbiter for TSS-1) will be charged negative. Both terminations are in general surrounded by a space charge sheath, i.e., a region where the plasma is nonneutral, which constitutes the transition between the charged body and the ionosphere. These space charge regions constitute what we can call the local interaction of the tethered system with the ionosphere.

Referring in particular to a TSS-1 system, the orbiter is supposed to be kept close to plasma potential (as will be indicated in the following) in which case we have a high-voltage sheath only around the satellite.

The positive electrode, i.e., the satellite, collects electrons and the negative one, in a completely passive situation, would collect ions. In practice, on TSS-1, electron guns on the orbiter were sending back into the ionosphere the charges collected at the upper end. In either situation a current flows along the tether.

A plausible path for this current in the ionosphere, which is the one that was suggested in the early work on electrodynamic tethers [*Williamson and Banks*, 1976; *Dobrowolny et al.*, 1979] is, as indicated in Figure 2, along the magnetic flux tubes intercepted by the terminations of the system, since the electrical conductivity transverse to B lines is negligible at shuttle altitudes.

The current system in the ionosphere, caused by the tether motion, represents what we can call the global perturbation induced in the ionosphere by the system.

Figure 2 shows only the current leaving the tether at one termination and entering the tether at the other termination and, on purpose, does not indicate any path of closure of the current system. It is in fact meant to represent the view from an observer sitting on the tether at a given instant of time. From this reference point, at any given time, the tether injects a current pulse into the magnetic flux tubes intercepted by its two terminations at that time. Later in this paper we will discuss at length the present ideas about the current system induced in the ionosphere by the moving tether system.

The qualitative picture just given, although lacking of details, allows us to put forward a simplified equivalent circuit of the tethered satellite system (see Figure 3) which is a useful illustration of the complexity of such a system. Again, the point of view is that of an observer on the moving tether at any given time.

In Figure 3, Z_{sat} and Z_{orb} represent the impedances associated with two regions of space charge in general associated with both the satellite and the orbiter. They

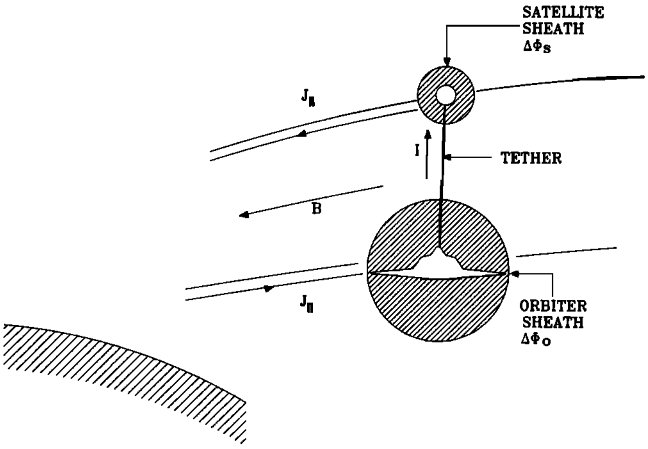

Fig. 2. Qualitative picture of the interaction of TSS-1 with the ionosphere.

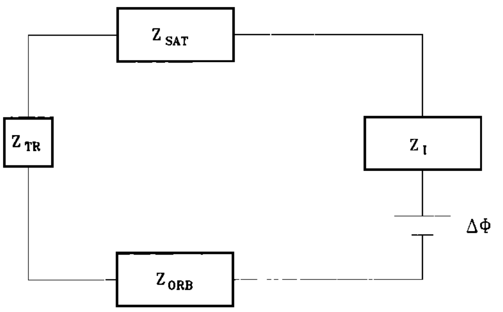

Fig. 3. Circuit equivalent of the electrodynamic tether.

therefore represent what we have called the local interaction of the tethered system with the ionosphere. Notice that these impedances are non-ohmic and are expected to depend nonlinearly from the current. Z_{tr} is the impedance of the ionosphere to the continuation of tether current, whatever is the path of the induced current system in the ionosphere and therefore represents the global part of the interaction. Finally, Z_I is the internal tether impedance.

It is clear that the problems of local and global interactions with the ionosphere are coupled together. This is what in fact makes a complete theoretical description of such a system quite unfeasible. On the other hand, there are ideas (and studies have been done) on the two separate problems of local and global interactions. The first problem is that of charged particle collection at TSS from the surrounding medium and the possible limitations to the current that the system can draw due to plasma sheath effects. When dealing with this problem, any global interaction of TSS with the ionosphere, is neglected. Vice versa, there are studies on the global current system induced in the ionosphere and the radiation of waves associated with the tether's motion where, on the contrary, plasma sheath effects are neglected. Finally, some recent simulation experiments in the laboratory [*Stenzel and Urrutia*, 1986, 1990] include both global and local interactions and their coupling.

2.1. *Local Interactions*

As seen in (2), the potentials induced by the tether's motion are far above the thermal energy of the ionospheric electrons ($KT_e \sim 0.1/0.2$ eV). It follows that the tethered satellite can be brought to a highly charged state ($e\Phi_S/KT_e \gg 1$), and the problem of local interaction is that of collection of charges from a highly charged body (electrons for the positive satellite).

Here we should stress, first of all, that, to our knowledge, a complete theoretical treatment of charged particle collection by a highly charged electrode, in the presence of magnetic field and accounting for the motion of the body, does not exist yet. Indeed, even for a quiescent sheath, i.e., disregarding collective plasma phenomena, we do not have a self-consistent solution.

A recent review of the work of current collection in a magnetoplasma has been given by *Laframboise and Somor* [1990]. Figure 4, taken from a paper by *Linson* [1969], can still be used as a summary of our knowledge on current-voltage characteristics. In Figure 4,

$$I_0 = 4\pi R^2 n e v_{\text{the}}$$

denotes the thermal current collected by a sphere of radius R with $v_{\text{the}} = (KT_e/m_e)^{1/2}$ the thermal velocity of the ionosphere electrons. A typical value for the thermal current density is given by $J_0 = nev_{\text{the}} \simeq 10$ mA/m^2. The curve behaving asymptotically as $\Phi^{1/2}$ corresponds to the upper limit of charge collection, in presence of a magnetic field, derived by *Parker and Murphy* [1967]. More precisely, from that model,

$$\frac{I}{I_0} = \frac{1}{2}\left(1 + 2\sqrt{\frac{2\Phi}{\Phi_0}}\right) \tag{3}$$

where

$$\frac{e\Phi_0}{KT_e} = \left(\frac{R}{a_e}\right)^2 \tag{4}$$

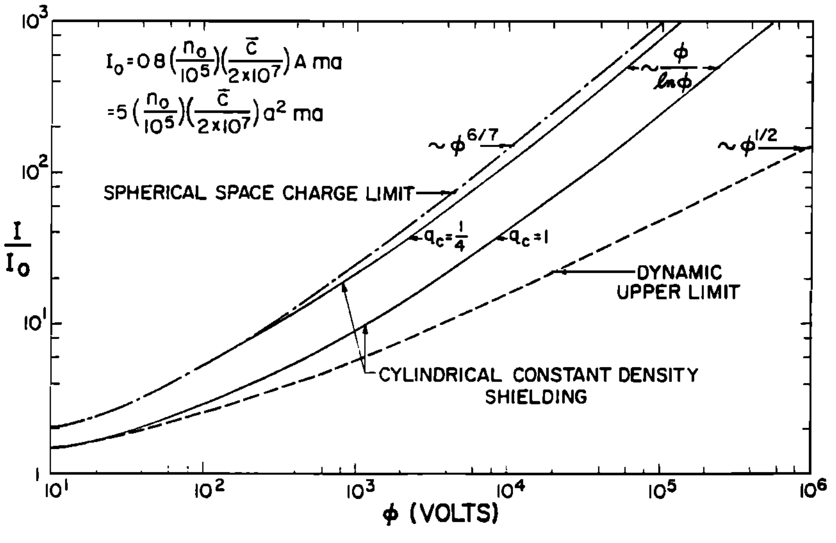

Fig. 4. Current-voltage characteristics of a charged body from different theoretical models [from *Linson*, 1969].

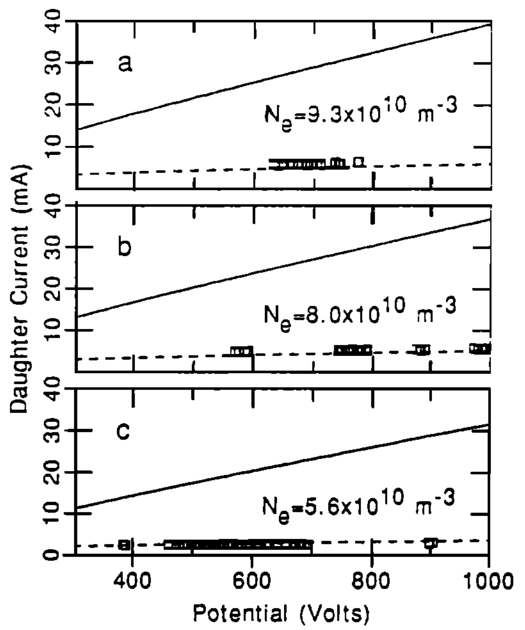

Fig. 5. Current-voltage characteristics of the daughter vehicle in the CHARGE 2 experiment [from *Myers and Raitt*, 1989].

Φ_0 being therefore the potential at which an electron should be accelerated to have a gyroradius equal to the radius R of the collecting body (a_e is the thermal Larmor radius). The curve behaving asymptotically as $\Phi^{6/7}$ corresponds to the spherical space charge theory in absence of magnetic field [*Alpert et al.*, 1965]. It is easily anticipated that the presence of a magnetic field will alter substantially the sheath geometry with respect to the $B = 0$ case. The sheath will become elongated along the magnetic field direction and much shorter in the transverse direction [*Linson*, 1982]. The length scale in the direction perpendicular to **B** will correspond to the Larmor radius of an electron with energy $e\Phi$ (Φ being the collector potential).

However, even in the framework of a quiescent sheath model (and without velocity flow), things are not so simple. A feature that renders impossible any further quantitative treatment (and in fact causes enormous difficulties also to numerical simulations) is the presence of a population of electrons trapped in the sheath, which rotate around the body with the $\mathbf{E} \times \mathbf{B}$ drift (**E** being the sheath self-consistent field). *Linson* [1969] argued that these electron rotations would cause the electron cyclotron instability, and, as a consequence, electrons could be scattered and collected by the body also across magnetic field lines. In this case the Parker and Murphy limit would be overtaken and, as indicated in the intermediate curves of Figure 4, we would have characteristic current-voltage curves intermediate between the Parker and Murphy and the spherical space charge limit. The parameter q_c denoting such intermediate curves in Figure 4 represents the critical value for the ratio $q = \omega_{pe}^2/\omega_{ce}^2$ between the squared electron plasma and cyclotron frequencies such that, for $q > q_c$, the electron cloud would become turbulent.

Recently, it has been pointed out by *Papadopoulos and Drobot* [1990] that we may have higher currents than those shown in Figure 4, also because of ionization produced by the electrons trapped in the sheath region. Papadopoulos and Drobot give the following formula for the current (which is obtained from order of magnitude considerations and refers to a magnetic field $B = 0.3$ G)

$$I = 20\left(\frac{\Phi}{10^3}\right)^{13/4}\left(\frac{N}{10^{12}}\right)\left(\frac{10^5}{n_0}\right)^{1/2} \tag{5}$$

where I is in ampere, Φ is in keV, the neutral density N, and the electron density n_0 are in cm^{-3}. It turns out that, to have currents higher than the Parker and Murphy limit, we should have a neutral density far in excess of that present in the ionosphere at the shuttle altitudes. This may occur, during a mission of the type TSS-1, when the satellite thrusters are operated, so that it should be possible to verify the enhanced ionization and corresponding current increase during such a mission.

Several additional observations are in order. The first is that the theories briefly discussed above do not take into account the body's hypersonic motion nor the additional asymmetry which should appear between wake and ram region. A second observation is that other instabilities, besides the electron cyclotron waves invoked by Linson, could occur such as, for example, the lower hybrid instability or the electron two stream instability. It would be certainly difficult, if not impossible, to account for those theoretically, but, certainly, these questions can be elucidated by local measurements around the tethered satellite of TSS-1.

Collection of charges by a polarized body has been actually measured in the CHARGE 2 space experiment [*Myers and Raitt*, 1989]. CHARGE 2 was a sounding rocket flight with two tethered payloads: a mother payload, containing an electron gun, and a daughter payload deployed at a maximum distance of 426 m from the mother (across magnetic field). A voltage bias up to 450 V, was applied to the tether from the mother to the daughter payload. Figure 5 shows measurements of current collection from the daughter vehicle, at different ionospheric electron densities. The values of the daughter potential were derived by adding the voltage bias applied to the tether to the mother potential (obtained through floating probe measurements) and subtracting the voltage drop across the 4 kΩ tether resistance. A good agreement is found between the measured points and the Parker and Murphy model (the dashed line in the plot), while the current remains always below the spherical space charge limit (the solid line in the plots).

There are, however, also indications, from laboratory experiments [*Stenzel and Urrutia*, 1990], that the situation might be more complex than depicted so far and, in particular, that a stationary sheath (or stationary current collection) is indeed not reached.

Let us refer here to the simplest case where a strong voltage pulse ($\Phi = 100$ V) is applied to three plane electrodes of different areas. Figure 6 gives the measured collector current versus time for an identical pulse (100 V of amplitude, 50 ns of duration) and shows indeed a characteristic nonstationary behavior. Accurate diagnostic measurements in the surrounding plasma indicate clearly the causes of the observed behavior. Figure 7 gives the radial plasma density profile (perpendicular to the magnetic field direction) versus time, after switch on of the voltage, for the largest collector. We see that the initially uniform density profile develops a deep density depletion inside the current channel. The initial overshoot of the current (see Figure 6) is due to the fact that the plasma ions do not evacuate instantaneously; their presence reduces the space charge and allow the higher current to be collected (higher than the space charge limit). This fact was indeed already pointed out by *Chen* [1965] in dealing with the behavior of probes in pulsed discharges. Looking at the temporal development in Figure 7, we see that the plasma is, first, expelled to the sides with supersonical velocity, then diffuses back, to be reexpelled quasi-periodically. When ions are expelled (across B), electrons are attracted into the current channel and absorbed at the collector. Charge neutrality is found to be maintained to a high degree; thus the expulsion of ions causes a loss in collected electrons and hence the current drops following the first (and subsequent) overshoots. The temporal width of the overshoots is

$$\tau_1 \sim r_c\left(\frac{m_i}{2e\Phi}\right)^{1/2}$$

where m_i is the ion mass, r_c is the collector radius, and Φ the collector potential. On the other hand, the separation time between subsequent overshoots is

$$\tau_2 \sim r_c\left(\frac{m_i}{2KT_e}\right)^{1/2}$$

For the TSS-1 satellite, with Φ = 1 kV and oxigen ions, we would find $\tau_1 \sim 10\ \mu s$, $\tau_2 \sim 6.6$ s.

On the other hand, the satellite transit time is $\tau \sim 2r_c/V_0 \sim 20$ ms. Hence $\tau_2 \gg \tau$. As a consequence one would say that, in the case of TSS-1, for most of the transient time τ across the magnetic flux tube, one should be in the low current state (corresponding to full ion depletion from the ion current channel) and no oscillatory behavior for the current (apart from the first overshoot), should be seen.

Finally, let us recall that, in the same laboratory experiments [*Stenzel and Urrutia*, 1990], strong-density fluctuations in a broad-frequency range, starting at the ion acoustic frequency, were measured near the collector. These fluctuations, which are excited by the ion and electron counterstreaming currents, are a further indication that, as already anticipated, the perturbed region around the collector of a tethered system is bound to be a turbulent region.

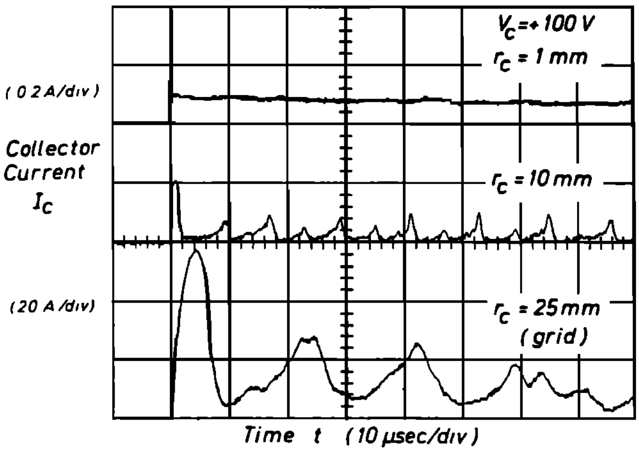

Fig. 6. Collector currents for three electrodes biased by the same step voltage (100 V), Δt = 50 ns [from *Stenzel and Urrutia*, 1990].

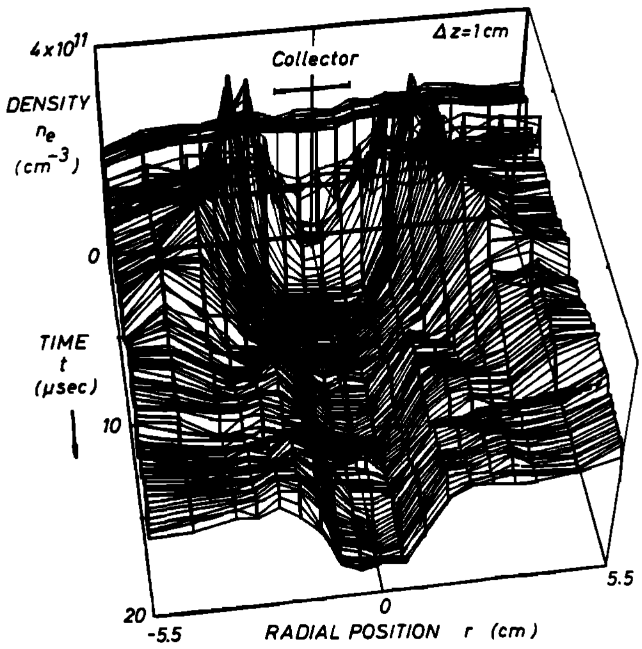

Fig. 7. Radial electron density profile versus time after switch on of a voltage Φ = 100 V [from *Stenzel and Urrutia*, 1990].

In conclusion, we should stress that the sheath structure around a highly charged body moving in a magnetoplasma and the processes occurring there, are largely unexplored. Such sheath studies are a first priority science objective in the TSS-1 mission, as will be seen, and we expect a major increase in our understanding from local plasma and wave measurements around the TSS satellite.

2.2. *Global Perturbation Induced by a Tethered Satellite System*

As mentioned already, at a given instant of time, the two terminations of the tethered system apply potential pulses of opposite polarization to the magnetic flux tubes they intercept. A transfer of charge consequently takes place between the plasma and the two terminations of the system. This perturbation generates waves out of the system. It is these waves which transport away the space charge set up between the end flux tubes. This picture for the global interaction of a large conducting body moving with respect to a magnetoplasma was first indicated by *Drell et al.* [1965]. The superposition of the waves generated, at successive times, on different flux tubes, forms two wings of opposite charge polarization left behind by the two termination of the tether system (see Figure 8).

The duration of the voltage pulse applied by a given conductor to the magnetic flux tube intercepted is given, in order of magnitude, by

$$\tau = D/V_0 \tag{6}$$

D being the conductor dimension in the direction of motion. More precisely, the dimension D should include also the extent of the sheath surrounding the conductor in the direction of motion. Drell, Foley and Ruderman were referring to large dimensions such that

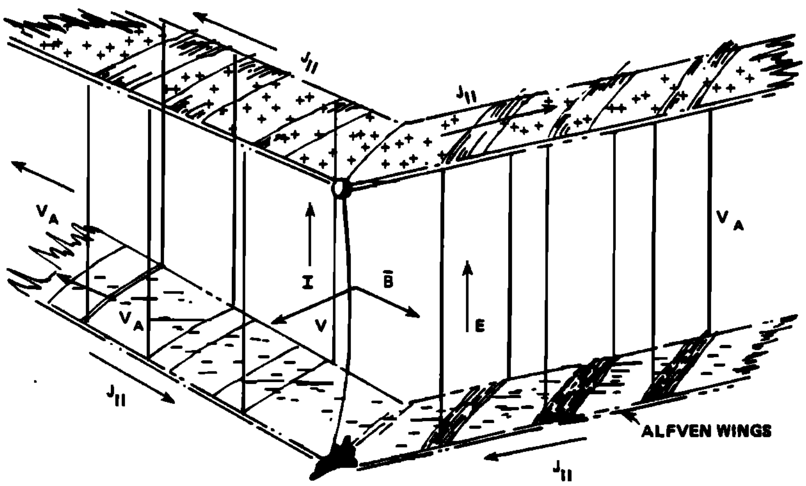

Fig. 8. Alfvén wings attached to the TSS-1 system [from *Banks*, 1980].

$$f = \frac{1}{\tau} < f_{ci}$$

f_{ci} being the ion cyclotron frequency. For the ionospheric plasma ($f_{ci} \sim 30$ Hz) this implies $D > 50$ m. In this case, in the cold plasma approximation, the waves propagating away from the system are Alfvén and fast-mode waves. However, as the Alfvenic Mach number $M_A = V_0/V_A \ll 1$, the fast-mode waves decay spherically away from the source, and it is only Alfvén waves that propagate unattenuated. The angle of the Alfvén wings with respect to **B** lines is given by

$$\theta_A = \arctan\left(\frac{V_0}{V_A}\right)$$

and a typical value at the altitude of TSS-1 is $\theta_A \sim 1.7°$.

For Alfvén waves one derives [*Neubauer*, 1980]

$$J_{\|} = \sum\nolimits_A \nabla \cdot \underline{E}$$

with $\Sigma_A \sim 1/\mu_0 V_A$ a conductance due to Alfvén waves. This shows clearly that the continuation of the tether current in the ionosphere is related to the transport of the space charge set up between the two terminations of the system.

In the case of TSS-1, taking for D the satellite diameter, we obtain

$$f \sim 5 \text{ kHz}$$

Hence the electrodynamic tether in principle generates waves from ELF to VLF. However, the fact that the typical frequency $f \sim 1/\tau$ is in the VLF range suggests a preferential generation of waves in this range (i.e., whistler waves).

These considerations indicate that, contrary to what is quoted in early publications on the current path induced by TSS-1 in the ionosphere [*Williamson and Banks*, 1976; *Dobrowolny et al.*, 1979; *Banks*, 1980], closure of the current system through the E layer of the ionosphere is not the only possibility.

The wave generation, the subsequent propagation in the ionosphere and possible detection at ground are one of the points of general interest of TSS-1. Two of the selected experiments for TSS-1 were in fact dedicated to detect low-frequency waves at ground so as to ascertain the capability of the system as a low-frequency wave generator.

Whatever the waves generated, it must be kept in mind that the terminations of the system are in contact with the magnetic flux tubes intercepted only for the time τ. What happens to the perturbation generated after that does not affect the forces and currents in the conductor.

Numerous theoretical works have addressed the problem of computing the wave power radiated by the tether system or, in an equivalent way, the impedance of the transmission lines associated with the tether [*Belcastro et al.*, 1982; *Rasmussen et al.*, 1985; *Dobrowolny and Veltri*, 1986; *Barnett and Olbert*, 1986; *Hastings and Whang*, 1987; *Estes*, 1988; *Wright and Schwartz*, 1990; *Donohue et al.*, 1991; *Stein and Neubauer*, 1992]. All of these works refer to a linear approximation and an infinite homogeneous collisionless magnetoplasma. A solution of the nonlinear MHD equations was done by [*Neubauer*, 1980]. Propagation of the waves into the real (nonhomogeneous and finite) ionospheric medium has not been addressed so far except for some considerations [*Dobrowolny et al.*, 1979; *Neubauer*, 1980] relevant to Alfvén waves and their possible reflection at density gradients (the E layer for the Earth's ionosphere). For a review of the papers quoted above, we refer to the work of *Donohue et al.* [1991], which is the most recent contribution to the subject and contains calculations, both for Alfvén and whistler waves, taking also into account a sheath structure around the two terminations of the system. Summarizing the results, the tether radiation in Alfvén waves has associated a radiation resistance which depends on ionospheric conditions and is typically very small, of the order of 1 Ω or less. There is, however, a higher-frequency band for radiation and, more precisely, a band of lower hybrid whistler radiation, from the TSS-1 satellite, where the radiation impedances would be higher, of the order of tens of ohms.

Therefore it appears that more power is radiated in whistler waves that in Alfvén waves. As we will see in more detail, recent simulation experiments in the laboratory [*Stenzel and Urrutia*, 1989] are consistent with the above theoretical findings in that whistler radiation (and not Alfvén waves)

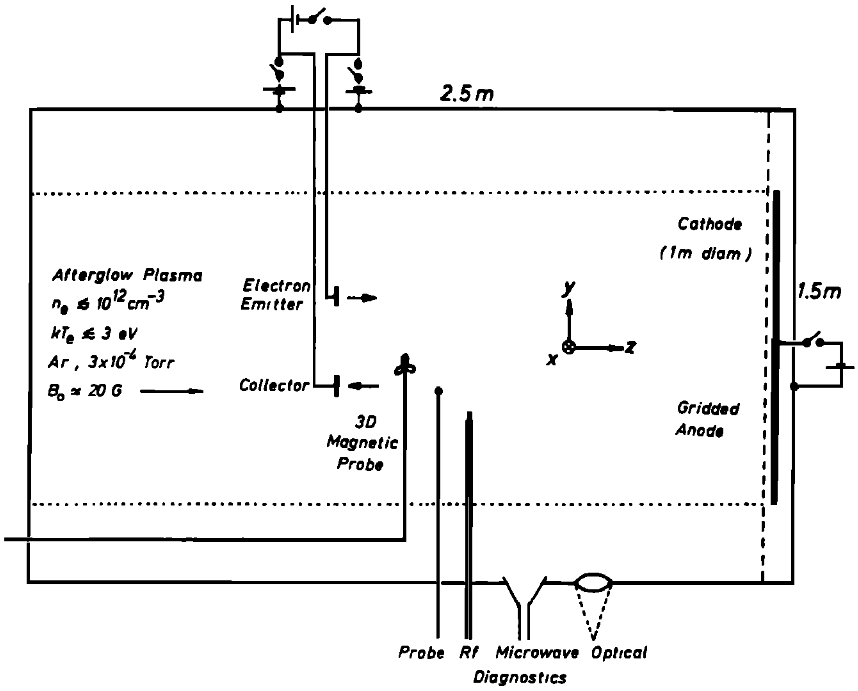

Fig. 9. Schematic arrangement of laboratory modeling of tethers [from *Stenzel and Urrutia*, 1990].

are measured for a simulated electrodynamic tether. Referring to TSS-1, and in the context of the equivalent circuit of Figure 3, if the radiation resistance for whistler waves is only a few tens of ohms, this impedance would be negligible (both with respect to the tether internal resistance, $Z_i = 2.2$ kΩ and the sheath impedance) and, as a consequence, from the point of view of tether current-voltage characteristics, the effect of the global ionospheric perturbation should not be of significance.

Experimental results on plasma wave radiation from a simulated tether system have been obtained in a vacuum chamber with an afterglow plasma [*Urrutia and Stenzel*, 1990; *Stenzel and Urrutia*, 1990]. Figure 9 indicates the experimental set up. To simulate a tether system in space, the authors have inserted in the plasma an electron emitter and an electron collector well separated across B_0 ($r \sim 15$ cm with an electron Larmor radius of ~1 cm). To simulate the tether system, (where current pulses of opposite polarity are injected along the flux tubes intercepted by the system terminations), pulsed voltages were applied between the electrodes of the experiment. Figure 10 gives the results obtained, from magnetic measurements in the chamber, as to the propagation of cross field plasma currents induced by a single current pulse through a tether. More precisely, these are contours, in the $x = 0$ plane, of the current density J_x, taken at different times (from 0.1 to 0.9 μs) after the application of the pulse through the tether (pulse duration was 0.2 μs). We recall that z is the direction of the background magnetic field and y is along the tether. It is seen that, in response to the turn on of the tether current, an opposing plasma current is induced (solid lines). The turn off of the tether current induces a current of opposite sign (dashed lines). Furthermore, the dispersion relation properties of whistler waves can be desumed from the phase fronts of Figure 10.

To simulate a continuous tether motion, the authors use the following approach. The continuous motion of an electrode is broken up into individual displacements Δx (Δx being the electrode size) and the dc current of the real conductor in motion is broken up into a sequence of adjacent current pulses (of duration $\Delta t = \Delta x / V_0$). After measuring the magnetic perturbation corresponding to each step (and current pulse), all the measured field contributions are linearly superimposed.

Results are shown in Figure 11, which shows the projection of magnetic lines into the $V_0 - B$ plane and the corresponding current density profile $J_x(y, z)$. It is seen that the simulated moving current generates a comoving whistler wing. Out of these measurements, the authors draw the picture of current density lines expected from a moving tether shown in Figure 12. Each termination of the tether will launch a whistler wing with nested current helices. The wedge of the whistler may shunt some current between the wings. The current in the wings spreads with the ray cone of oblique whistlers (angle $\theta_w \leq 19°$ for $\omega \ll \omega_{ce}$). For a 20-km tether the ray cones of the two wings (emanating from the two tether terminations) begin to intersect at a distance of ~30 km. At this distance the opposing currents merge and distinct current channels cannot be identified any more.

Therefore, according to these experiments, the tether radiation occurs in low-frequency whistler waves. According to the authors, Alfvén waves are not excited when the switching time is faster than the ion cyclotron period. It is not clear whether this absence of Alfvén wave excitation apply to in orbit tethered systems as well. On the other hand, the experimental finding of a whistler wing associated with current in a moving tether is consistent with the theoretical finding that the radiation resistance in the whistler range is much higher than for Alfvén waves. It is suggested by the authors of the above experiments that the comoving whistler wedge structure generated along the entire tether length

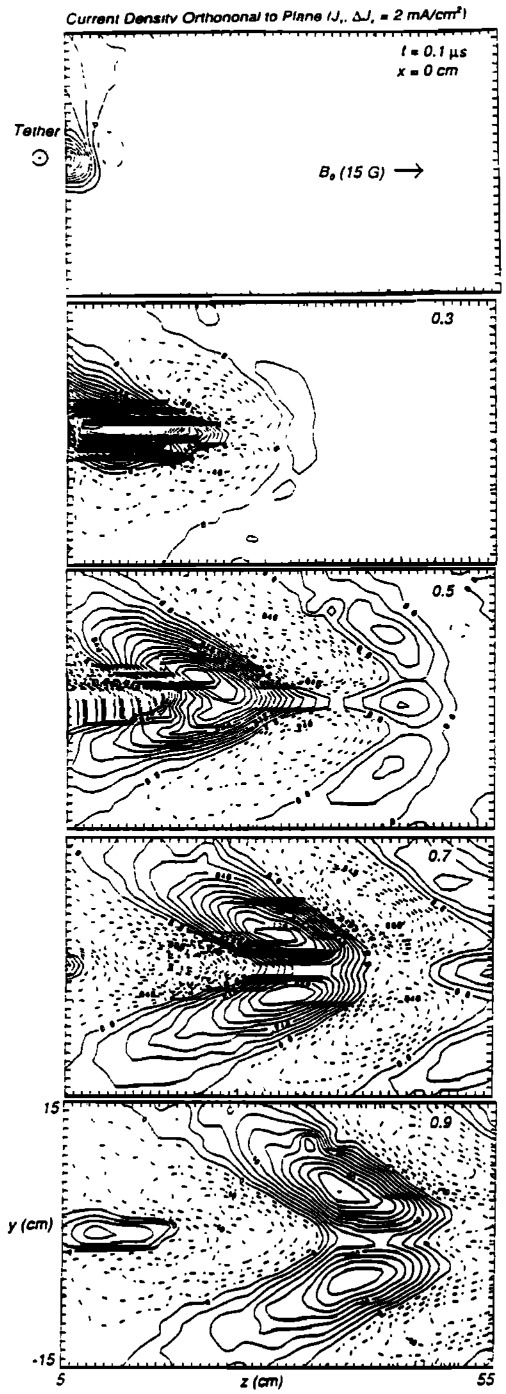

Fig. 10. Propagation of crossed field plasma currents induced by a single current pulse through a tether [from *Stenzel and Urrutia*, 1991].

could possibly produce a whistler tone detectable at the ground when the tether passes by.

In a TSS-1 type mission we are not able to measure waves at a distance from the tether in space as, for this, one would need a free flying platform. However, the comparison of tether current measurements in TSS-1 with the predictions of an electrical model, like that of Figure 3, should give an indirect information as to the magnitude of the radiation impedance.

3. GENERATION OF POWER AND/OR PROPULSION WITH ELECTRODYNAMIC TETHERS

One of the most interesting applications of the use of conducting tethers in space is that of power generation in orbit. This stems from the basic electrodynamic concepts, illustrated in section 2. The application of power generation is indeed quite natural: the moving tether draws a current from the ionosphere and this current can be used in a load to provide electrical power.

In the following we shall assume that the tether is perfectly rigid. For an introductory discussion on the dynamic effects induced by a current flowing into a tether, see *Arnold* [1987].

The drag force associated with a current I flowing into a tether of length L is

$$\mathbf{F} = (\mathbf{I} \times \mathbf{B})L \tag{7}$$

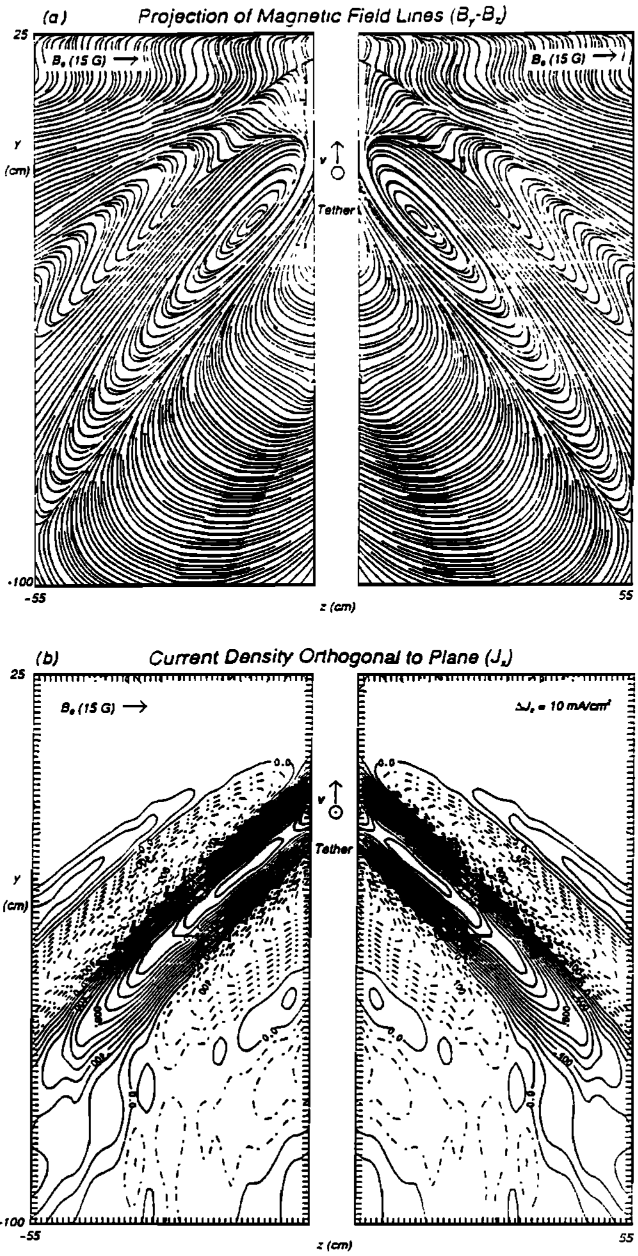

Fig. 11. Whistler wedge excited by an insulated tether carrying a dc current and moving across B_0 [from *Stenzel and Urrutia*, 1991].

where I is the vectorial tether current. Therefore, as electrical power is obtained at the expense of the kinetic energy of the tethered system, the orbit will be degraded during this generation and should then be maintained to a nominal value by other means.

Conversely, if a power supply with a voltage greater than $(\mathbf{V} \times \mathbf{B}) \cdot \mathbf{L}$ is used to "buck" the induced emf, the current in the tether will be reversed and the above force will turn into acceleration, with a net propulsion effect.

For the application of power (and/or propulsion) generation to be of practical interest, for example in connection with a space station, the power generated must be of the order of several kilowatts. To obtain such powers, both the value of the induced emf and the value of the current in the tether are obviously important. As we have seen, a 20-km-long tether can have open circuit voltages ranging from 1.5 to 4.5 kV. If the tether internal resistance is low enough, very large short circuit currents could be induced. However, there are plasma density constraints that limit the current and, more specifically, the amount of current to be drawn depends on the impedance between the two tether conducting terminations and the plasma. In any case, for significant power generation, currents of the order of several amperes should be obtainable in the tether.

There are then two main problems which must be addressed. The first is to ascertain that, given the possibility of drawing enough current in the tether, this way of power generation and/or propulsion is convenient with respect to other more conventional ways of producing energy.

The second problem, which is more of a physical nature, is that of finding ways to obtain large currents in a tether system.

Several studies [*Grossi et al.*, 1982; *McCoy*, 1987; *Nobles*, 1987; *Martinez-Sanchez and Hastings*, 1987], more of an engineering nature, have addressed the first problem with the conclusion that, for stations which are in orbit for a long time (more than 1 year), like the space station, it is indeed convenient to use tethers for power generation. For example, it has been derived [*McCoy*, 1987] that tether systems have a 0.3 $\mathrm{kg/kW^{-1}\ h^{-1}}$ advantage over fuel cells for production of on orbit power. It must be added that, in such studies, several assumptions are made, and, in particular, it is assumed that the high voltage of a tether system can easily be converted to the needs of onboard power supplies.

Possible identified applications of the concept of power generation though electrodynamic tethers are drag compensation, orbit altitude changes, orbital energy storage for solar arrays, and changes of orbital inclination (as can be found in the above quoted studies). These are essentially definition studies of tether systems with a given power capability and address various technological aspects of these systems by essentially supposing that a given amount of current can be drawn.

The capability of drawing large currents is, however, by no means obvious. For the application of power generation, one needs of course to use tethers of low internal resistance (for example, an aluminum cable of a few millimiters in diameter and a 20-km length, has an impedance of the order of 10–50 Ω), but this is a necessary but not sufficient condition. Coming back to the tether equivalent circuit of Figure 3, we see in fact we have to deal also with the contact impedances of the two terminations with the ionosphere (and, in addition, also the impedance of the ionospheric circuit of current closure, it it is not too low).

In the case of TSS-1, in order to increase the current that the electrodynamic tether would draw in a completely passive situation, electron guns are used on the orbiter side. Then the maximum current capability is determined by the maximum current of the electron gun, but, as we will show later, addressing TSS-1 in more detail, it is not at all granted that this maximum current is reached and, in fact, even in the case of TSS-1, is likely not to be reached because of the sheath impedance around the satellite or, equivalently, the insufficient amount of charges which (especially at night time) the ionosphere can supply. Notice that the impedance of the ionospheric current closure should also be taken into consideration but, on the basis of the discussion in section 2, we consider that to be negligible in comparison with the sheath resistance around the two tether terminations.

The problem of obtaining large currents in a tether system is then that of improving the electrical contact between the two tether terminations and the ionosphere. If this is done, the two tether terminations will be at potentials close to that of the surrounding plasma and, as a consequence, a sizable fraction of the $(\mathbf{V} \times \mathbf{B}) \cdot \mathbf{L}$ emf voltage will appear across the tether, including possibly any interposed useful load.

An obvious way to obtain large currents is that of using large collecting electrodes on both ends of the system. However, in passive TSS systems this would imply extremely large collecting areas on the ion collecting side (as an example, to collect ~10 A, a sphere of radius ~50 m would be necessary). An alternative is that of having a large electrode at the electron collecting end (radius ~10 m for a 10-A current) and a correspondingly powerful electron gun on the other termination. Also, this does not appear convenient, one of the reasons being that the electron gun itself (to operate at such high currents) would consume substantial power.

It appears that the most promising way to obtain large currents requires the use of plasma sources, of the hollow cathode type [*McCoy*, 1987], at the two tether terminations. Figure 13 shows the current-voltage characteristics of an hollow cathode and indicates, first of all, that this device can be operated at both polarities (as it should be for the application to a tether system) and, second, that, in both cases, it is fundamentally a low impedance device. Sizable currents can be obtained, as can be seen from Figure 13, which is a vacuum characterization of the plasma source.

Because of the above features, substantial work, both theoretical and in laboratory plasma chambers, has been addressed to these plasma sources and, in particular, to their interaction with an ambient plasma.

Theoretical models [*Wei and Wilbur*, 1986; *Hastings et al.*, 1987; *Hastings*, 1987; *Davis et al.*, 1988; *Iess and Dobrowolny*, 1989; *Gerver et al.*, 1990; *Katz and Davis*, 1990; *Dobrowolny and Melchioni*, 1992; *Ahedo and Sanmartín*, 1992] have shown that this interaction is mainly characterized by the appearance of a double layer, at some distance from the source. Figure 14 shows a typical potential profile obtained theoretically [*Dobrowolny and Melchioni*, 1992] as well as the space charge profile. Most of the potential, at which the source is polarized with respect to the ambient, drops at this layer. The position of the layer is a function of the ratio between the density of the plasma produced by the cathode and the ambient plasma density, the layer occurring

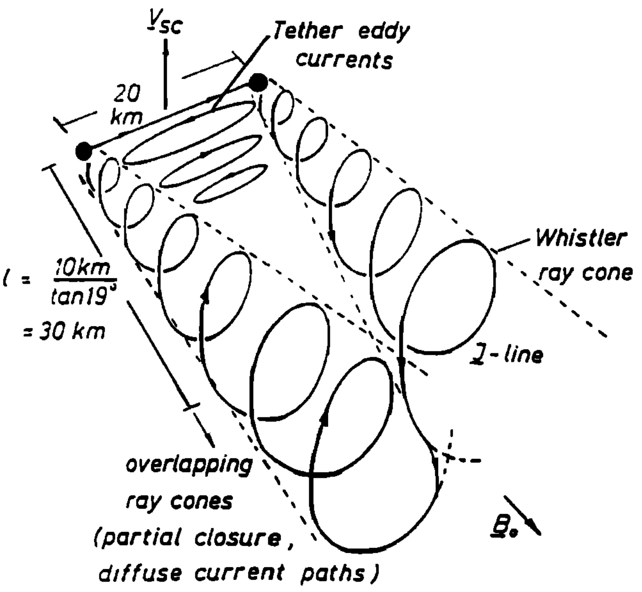

Fig. 12. Possible current system of a moving electrodynamic tether with dc currents [from *Stenzel and Urrutia*, 1991].

further away from the source when this ratio increases. In practice, the position of the double layer defines an effective surface for collection of ambient charges whose size can be very high in comparison with the dimension of the source.

In laboratory chambers [*Williams et al.*, 1987; *Vannaroni et al.*, 1989, 1992], two hollow cathodes have been used, at opposite sides of the chamber, one as a plasma contactor properly and the other to produce an ambient plasma. For the case of zero magnetic field, results in agreement with those of a consistent theoretical model have been obtained [*Melchioni and Dobrowolny*, 1992; *Vannaroni et al.*, 1992].

The effect of the magnetic field on the current-voltage characteristics of the source, in the presence of an ambient plasma, has also been investigated [*Vannaroni et al.*, 1990]. Figure 15 compares current-voltage characteristics of a low current hollow cathode, in presence of an ambient plasma, for various values of a magnetic field perpendicular to the chamber axis, including also the case of zero field. Quite contrary to theoretical considerations [*Gerver et al.*, 1990], no large difference in the characteristics seem to be introduced by the magnetic field. This should be related to turbulence characterizing the interaction region, as has been in detail shown (for the case $B = 0$) by *Vannaroni et al.* [1992].

Extrapolation of plasma chamber data to space conditions, cannot however be done entirely for a variety of reasons such as wall effects, the fact that the neutral gas pressure which can be obtained is higher than in the ionosphere and the fact that laboratory plasmas are in general not isothermal. In particular, no high voltages (of the order of kilovolts), as those associated with long conducting tethers, can be reached in the laboratory. Therefore some direct space experimentation of hollow cathodes as plasma contactors at the terminations of a tether system, is of extreme importance to assess the feasibility of power generation through electrodynamic tethers.

Finally, the TSS-1 project, at least in the way it was planned, was going to address some aspects related to power generation. First of all, the behavior of high-voltage sheaths at the satellite and the response of the ionosphere to the system when it attempts to draw currents larger than the thermal currents, are clearly topics of relevance for understanding the feasibility of power generation. In the second place, although no hollow cathodes were present on TSS-1, in case of a nominal deployment, and therefore a motional emf of several kilovolts, it was anticipated that the high voltage, in conjunction with thrusters operations (both on the satellite and on the orbiter) would have created extra-ionizations so that current at the maximum capability of the TSS EGA gun could be reached.

4. THE MISSION TSS-1

We will provide a fairly complete description of the TSS-1 project and what should have been the nominal TSS-1 mission. We will not go into any detailed description of the TSS-1 flight of August 1992 except for a short account in section 5. A review of this flight, and what has been accomplished there, should soon appear as a result of the collective work of the TSS-1 Investigator Working Group (IWG).

4.1. *General Description*

The TSS-1 configuration [*Penzo and Amman*, 1989] is based on three elements: the deployer, the satellite, and the tether itself.

The deployer is a structure, placed on the shuttle orbiter, hosting the satellite, a reel for the tether, and the mechanisms for controlling deployment and retrieval. In addition, it contains several instruments that will be described later.

The tether had a conducting core and several insulating layers, with an overall diameter of 2 mm. The electrical resistance of the 20-km tether was 2.2 kΩ. The deployer, the tether control mechanism, and the tether itself were developed by Martin Marietta in the United States.

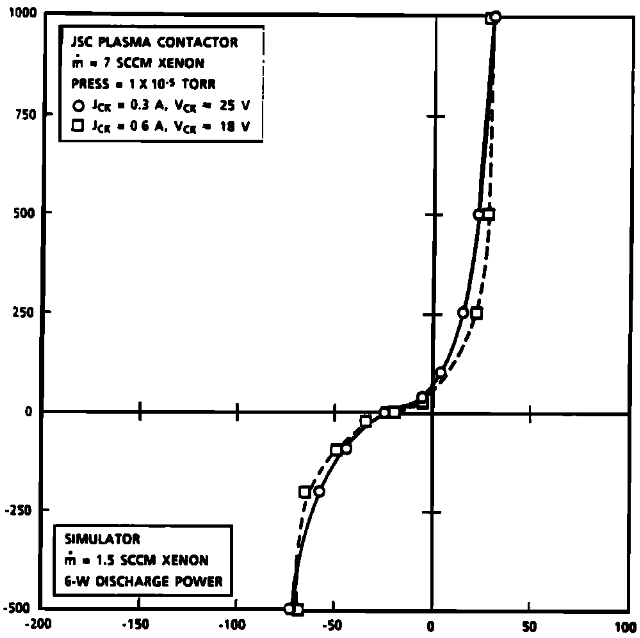

Fig. 13. Typical current-voltage characteristics of an hollow cathode [from *McCoy*, 1987].

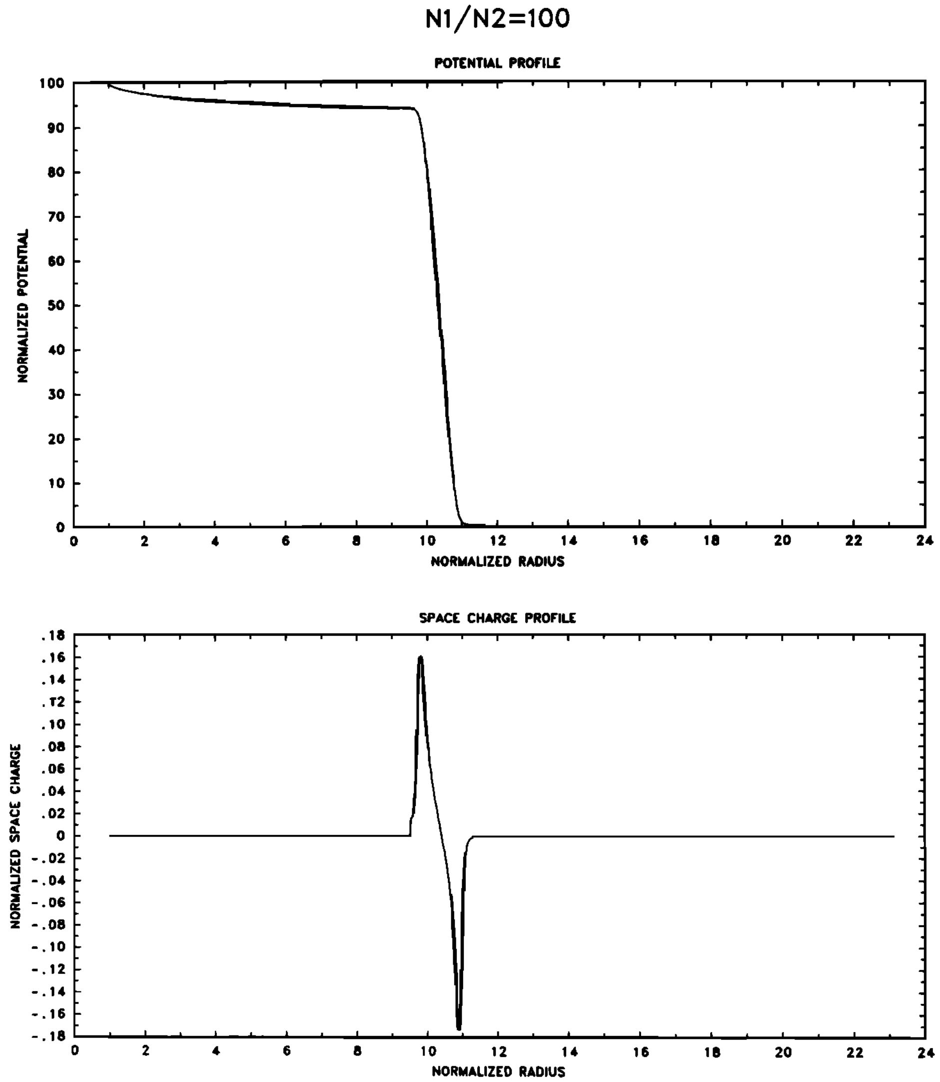

Fig. 14. Potential and space charge profile around a spherical plasma source immersed in an ambient collisionless nonmagnetized plasma and polarized at a positive potential. Potential is normalized to kT_e and radius to the source radius. N_1/N_2 is the ratio between source and ambient plasma densities [from *Dobrowolny and Melchioni*, 1992].

The satellite, developed by Alenia in Italy, was designed on the concept of successive use for several consecutive missions. Consequently, it had a modular structure, with a service module and a propulsion module, which could be common to several missions, and a payload module whose content would obviously change for different missions.

The satellite was initially mounted on top of a deployable boom, extending 12 m above the orbiter at the beginning of the TSS-1 mission. The satellite was released from this distance and initially helped though the use of "in-line" thrusters on the satellite. Further away from the orbiter, starting from ~1 km, the gravity gradient force is sufficiently high so that deployment could have continued without the use of thrusters.

The satellite (see Figure 16) had additional thrusters (yaw thrusters) allowing spinning, at a controlled rate, around the tether axis. The nominal rate was to be 0.25 rpm during deployment and 0.7 rpm when on station. As seen in Figure 16, the satellite had a fixed boom (1 m long), housing some instrumentation, and two deployable and retrieval booms (DRBs) above the equatorial plane. The DRBs could be extended as high as 2.5 m from the satellite surface and were also carrying instrumentation, as will be described later.

Figure 17 shows the nominal mission profile. The planned deployment was to 20 km where a stop of ~10 hours was to occur (called on station 1). After that, retrieval would have started with a new stop, of ~3 hours, at 2.5 km (on station 2), followed by a last portion of retrieval ending with satellite recapture in the orbiter cargo bay. The total mission duration, from beginning of deployment to satellite docking, was supposed to be of 36 hour.

From the point of view of electrodynamics and plasma science, it is also clear that the period "on Station 1" was of major interest as, at that maximum deployment distance, the electric potential due to the motion is maximum. This implies (see section 4.2) that, on the one hand, a substantial potential difference is available to operate the electron gun assembly (EGA) and, on the other, the satellite itself can become highly charged. These are also the conditions when we expect maximum current to flow in the tether. Further-

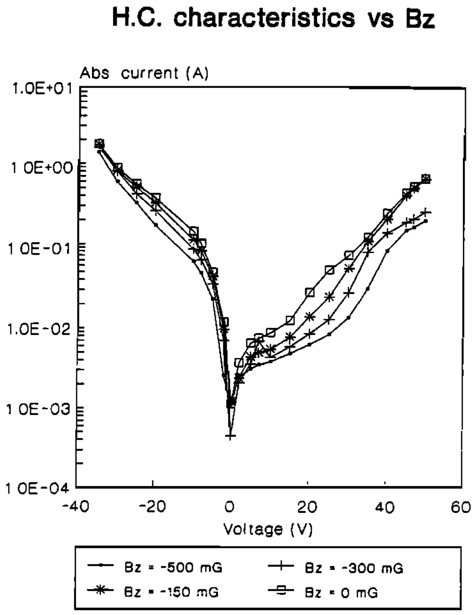

Fig. 15. Current-voltage characteristics of an hollow cathode for different values of the transverse magnetic field [from *Vannaroni et al.*, 1990].

more, in that phase the satellite was supposed to be spinning and the DRBs extended at various radial distances (and then retrieved) so that measurements were supposed to be taken both as a function of azimuth and of distance from the satellite surface.

4.2. *Electrical Configurations*

Figure 18 addresses the basic electrical configurations of TSS-1. This diagram, which refers to instrumentation on the orbiter, has its two main elements, in two electron guns, called EGA and fast pulsed electron gun (FPEG).

EGA is an electron gun capable of giving 0.7 A at 5 kV, whose main feature is that of having the cathode connected to the tether, whereas the anode is grounded to the orbiter [*Bonifazi et al.*, 1987]. In this way the gun is powered by the tether electromotive force. This type of connection was undoubtedly the basic electrical configuration of TSS-1 from the point of view of electrodynamic science. With EGA, one had the additional possibility of requiring a certain current value, which was reached and maintained through a feedback loop on the temperature of the filament emitting electrons. When this is actually achieved, the satellite voltage with respect to the ionosphere is also controlled. By varying the gun current, (and when the required values can be actually obtained) one obtains in fact the current-voltage characteristics of the satellite and of the entire tether system as well.

Notice, however, that this capability of current control may not always be possible. In particular, when requiring high currents from the EGA gun, the ionosphere at the satellite end, may not be able to supply the required amount of electrons to sustain the commanded current. This is especially true at night time, when the electron density is minimum.

The limitation of the current control capability during the TSS-1 mission is illustrated in Figure 19, which shows the results of a simulation of the tether circuit. Here we have used a circuit which includes the EGA, the resistance of the

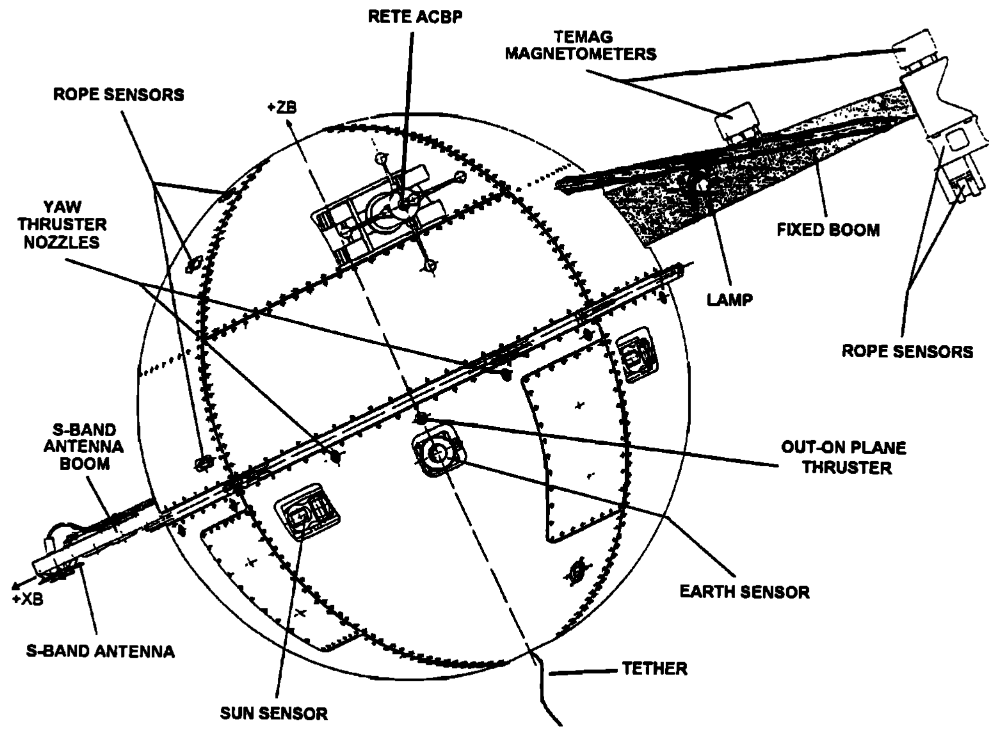

Fig. 16. Drawing of the TSS-1 satellite.

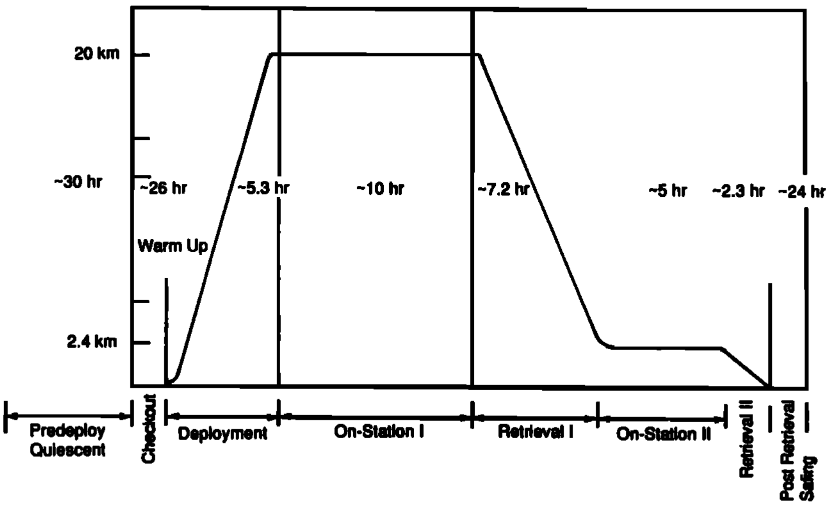

Fig. 17. Nominal profile of the TSS-1 mission.

tether and a sheath resistance, on the satellite side, which comes from the assumption of a spherical space charge collection (the resistance of the paint, which is about 2 Ω, is negligible in comparison with the tether one). The resistance of the external ionospheric circuit has been neglected (see the discussion of section 2.2). The plots refer to one orbit, using the International Reference Ionosphere with average solar flux conditions. An eccentric dipole model was used for the Earth's magnetic field [*Fraser-Smith*, 1987]. Starting from the bottom, the first panel gives the variation of the electron density during one orbit, related to variations in latitude and passage from day to night (the numbers plotted are densities in cm^{-3} normalized to 10^6). The second panel shows the current which would be obtained during the orbit, by supposing the EGA to be set up to give the maximum current of 0.7 A. As it is seen, the current is substantially less and, in fact, never exceeds 0.5 A in this model. This means that the control capability built in the EGA system could actually fail at high currents (it will, however, work for smaller currents). The third panel contains the variation of the tether electromotive force (for a tether length of 20 km). Finally, the last two panels give the voltage of the satellite with respect to the ionosphere (which is, at most, 1.5 kV, at night time) and the voltage which sets up across the EGA gun (always around 1 kV).

In conclusion, on the basis of these simulations, we should expect that currents up to the maximum capability of the EGA gun should not be reached. It is realized however, that this might not be true, when the satellite thrusters are operating if anomalous ionization phenomena will occur. Then a higher electron supply is available to the satellite and higher currents (perhaps up to the maximum EGA capability) could be reached.

Coming back to Figure 18, the second electron gun FPEG, which is part of the experiment shuttle electrodynamics

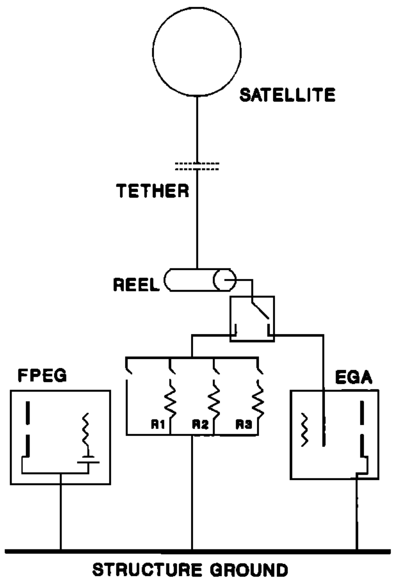

Fig. 18. Basic electrical configurations of TSS-1 (FPEG, fast pulsed electron generator; EGA, electron gun assembly).

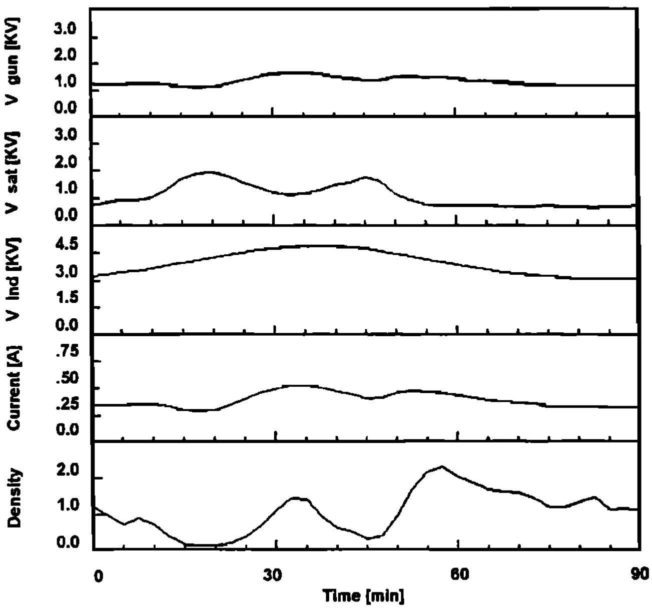

Fig. 19. Results of numerical simulations of an electrodynamic tether circuit (see text for explanations).

TABLE 1. TSS-1 Science Investigations

Acronym	Title	Principal Investigator	Organization
CORE	core equipment	C. Bonifazi	Agenzia Spaziale Italiana, Rome
SPREE	shuttle potential and return electorn experiment	D. Hardy	Air Force Geophysics Laboratory, Bedford, Mass.
SETS	space electrodynamic tether system	P. Banks	Stanford, Calif.
ROPE	research on orbital plasma electrodynamics	N. Stone	Marshall Space Flight Center, Huntsville, Ala.
RETE	research on electrodynamic tether effects	M. Dobrowolny	Consiglio Nazionale delle Ricerche, Frascati, Italy
TEMAG	magnetic field experiment for TSS missions	F. Mariani	University of Rome
EMET	investigation of em emissions by the electrodynamic tether	R. Estes	Smithsonian Astrophysical Observatory, Cambridge, Mass.
TEID	theoretical and experimental investigation on TSS dynamics	S. Bergamaschi	University of Padova, Padova, Italy
IMDN	investigation and measurement of dynamic noise	D. Gullahorn	Smithsonian Astrophysical Observatory, Cambridge, Mass.
TMST	theory and modelling in support of tether	A. Drobot	Science Application International Corporation, McLean, Virginia
OESEE	observations at the Earth's surface of em emission by TSS	G. Tacconi	University of Genova, Genova, Italy
TOP	tether optical phenomena	S. Mende	Lockheed

tether system (SETS) (see section 4.4), is a pulsed electron gun with its own power supply and therefore independent from the tether electromotive force. A second important electrical configuration was then one where the tether was connected (through a variable resistor) to the orbiter ground and the FPEG operating and ejecting an electron beam in the ionosphere. The maximum current capability of FPEG is 100 mA.

It must be stressed that the two configurations (with either the EGA or the FPEG inserted into the circuit) are basically different. The FPEG gives first of all the possibility of performing electron beam experiments in the ionospheric plasma. However, when the tether is grounded to the orbiter, it also induces some current in the tether in a way which depends on the interaction of the beam with the surrounding plasma and the return currents to the shuttle. In addition, when both electron guns are operating, the current emission from FPEG allows one to avoid orbiter charging related to leakage currents from the EGA gun.

Most of the TSS-1 nominal mission was configured, from an operational point of view, as a sequence of cycles where either one or the other of the above electrical configurations (each with several variations) were adopted.

4.3. *Science Objectives*

We have already said that the general science objective of TSS-1, from the point of view of electrodynamics, was that of understanding both the local and the global interaction of an electrodynamic tether with the ionosphere. Many important and subtle plasma physics problems are hidden in these interactions. The following is a list of more specific science objectives: (1) current characteristics of electrodynamic tether; (2) characterization of a high voltage plasma sheath; (3) tether spontaneous electromagnetic emissions; (4) wave generation by time varying tether operations; (5) plasma expansion phenomena; (6) critical velocity ionization phenomena; and (7) dynamic noise in tethered satellite systems.

We add some short comments to the list. By characterization of a high-voltage sheath, we mean investigating instabilities and consequent waves in the space charge region surrounding the satellite, their role in determining current collection, the possible onset of anomalous ionization etc. By tether spontaneous emissions we refer to the global current system induced in the ambient plasma by the moving tether in an hypothetical stationary situation. On the other hand, by pulsing the FPEG electron gun or closing or opening the tether switch, we induce time varying phenomena as VLF wave generation and collapse or formation of a plasma sheath.

A large wake is probably characterizing the satellite environment. Wave and particle phenomena associated with expansion of the outside plasma into this evacuated cavity, as predicted by theory [*Samir et al.*, 1983], can therefore be investigated.

Critical velocity ionization [*Newell*, 1985] may also occur in connection with the emission of thruster gas from the satellite and its interaction with the ambient plasma.

Finally, dynamic investigations are of basic importance to ascertain the capabilities of tethered systems to provide measurements, from low altitudes, of gravity gradient or Earth's magnetic field anomalies.

4.4. *TSS-1 Experiments*

Table 1 lists the investigations selected for TSS-1 with the corresponding Principal Investigators (PIs). Two investigations refer to tether dynamics (PIs Gullahorn and Bergamaschi). A third one (PI Drobot) refers to theoretical electrodynamic studies. The remaining investigations all involve instrumentation which is on the orbiter, on the satellite, and within ground-based facilities.

Referring to the electrodynamic investigation, this has been concerned with both analytical studies and numerical simulations (with particle in cells codes) of the phenomena and structure of the sheath around a charged body in a magnetized flowing plasma. One important result, out of these studies, is the fact that, owing to the satellite motion, the portion of the flux tube intercepted by the satellite sheath may not have time to be completely depleted of ions. As a consequence, a steady state sheath may not be reached and, in such nonstationary situation, currents to the satellite

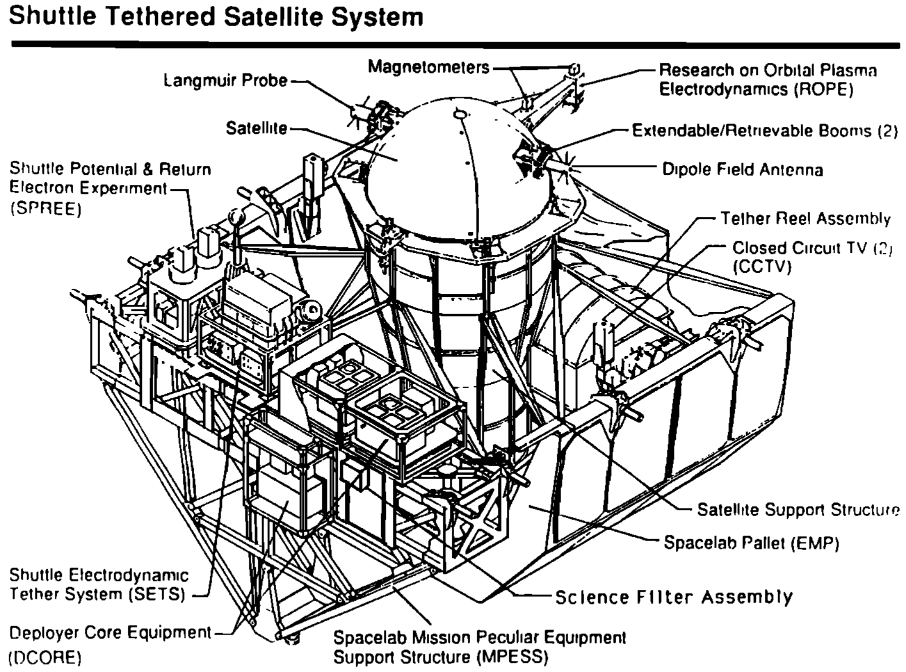

Fig. 20. Orbiter payload configuration during TSS-1 mission.

higher than those foreseen through stationary sheath models could be obtained. These results have been discussed in the TSS-1 IWGs but, to our knowledge, have not yet appeared in the literature. Presentations have, however, being given in a recent American Geophysical Union meeting [*Drobot et al.*, 1992] including also a theory of whistler wave emissions from the tether [*Chang et al.*, 1992].

4.4.1. *Experiments on board the satellite.* The experiment research on orbital plasma electrodynamics, provided by N. Stone of NASA Marshall Space Flight Center, measured charged particles, both on the surface of the satellite and also on the 1-m satellite fixed boom. Ion and electron fluxes to the satellite were measured by three sensors soft particle energy spectrometer (SPES) mounted at three locations on the satellite surface. Two of these sensors were also located at the tip of the fixed boom, one looking toward and the other away from the satellite. The sensors SPES give energy distributions of both ions and electrons in the energy range 10 eV to 10 keV. A different instrument, the differential ion flux probe, was also mounted on the fixed boom, as can be seen in Figure 16. This measures the current, flow direction, energy, and temperature of ions, either flowing around the satellite or created in the satellite sheath.

The tether magnetic field experiment, provided by F. Mariani, of Rome University (Italy), had two flux gate magnetometers mounted at the midpoint and at the end of the satellite boom (see Figure 16) [*Candidi and Dobrowolny*, 1987]. These give the magnetic field vector 15 times per second with a resolution of ± 1 nT and therefore provide information about the current induced by the system's motion, as well as the magnetic field generated by current in the tether.

The experiment research on electrodynamic tether effects (RETE), provided by M. Dobrowolny of Consiglio Nazionale delle Ricerche, Italy, had its sensors on two cylindrical canisters attached to the two deployable booms. One of the canisters, the ac boom package, was containing electric dipoles, on three axes, and search coil antennas (on two axes). These allowed measurements of electric and magnetic fluctuations in the frequency range 160 Hz to 12 MHz, which include all relevant characteristic frequencies of the ionospheric plasma. A second canister, the dc boom package, on the other boom, was devoted to dc measurements. It contained three Langmuir probes. Two of these were used as a dipole to obtain wave form electric fields from 0 to 175 Hz. The third was operated as a Langmuir probe properly to determine local potential, local electron density and temperature. In a nominal mission, with the DRBs moving, the RETE measurements were supposed to be taken at different radial distances from the satellite skin (and at different azimuths due to the satellite rotation), so as to clarify the structure of the space charge region around the satellite and the possible wave phenomena occurring there.

Finally, the satellite mounted Core equipment [*Bonifazi*, 1987], provided by the Italian Space Agency, included a triaxial accelerometer to investigate satellite dynamical characteristics and an ammeter to measure the tether current.

4.4.2. *Experiments on board the orbiter.* Figure 20 is a drawing of the TSS-1 pallet on the orbiter showing also the scientific payload mounted there.

The shuttle electrodynamics tether system (SETS) experiment, provided by P. Banks, of Stanford University, consisted of an electron gun, FPEG, a spherical retarding potential analyzer (SRPA), a charge and current probe (CCP), a spherical Langmuir probe (SLP), and a triaxial flux gate magnetometer (AMAG). The FPEG, which we have already mentioned, was emitting 100-mA electron beam with energy 1 keV. It was pulse modulated with on-off times ranging from 600 ns to 105 s. The SRPA measured the ion current density, energy and temperature. The CCP measured the return current to the orbiter, and the SLP measured the local space potential and the local electron density and temperature. Finally, the AMAG magnetometer mapped magnetic lines in the Cargo Bay, so that the FPEG beam could be aimed with precision for several experiments.

Besides SETS, which was the only selected experiment on the orbiter, there were other pieces of equipment which had more the character of essential facilities and whose need was decided by the TSS IWG after the initial selection of proposals. One of these was the EGA electron gun, which we have already described and which, together with some tether insulation switches, was completing the CORE instrumentation, provided by the Italian Space Agency.

The shuttle potential and return electron experiment, provided by M. Oberhardt, of the Air Force Geophysics Lab, was designed to determine the potential of the Space Shuttle Orbiter with respect to the ambient plasma, in the various electrical configurations possible and with the various current values used.

Finally, the tether optical emission experiment, provided by S. Mende (Lockheed Corporation), used the hand held camera system on board the orbiter, replacing the film which is normally used with a charged-coupled device. This new camera, with visual, spectrographic, and interferometric measurements, gave information on tether dynamics, optical effects within the satellite sheath as well as generated by the interaction with the plasma of the electron beams from the orbiter.

4.4.3. *Ground-based experiments.* Two experiments, called observation of on Earth surface electromagnetic emissions (OESEE) and investigation of em emissions by the electrodynamic tether (EMET) provided by G. Tacconi (University of Genova, Italy) and B. Estes (SAO), respectively, were dedicated to the possible detection at ground of the electromagnetic disturbance associated with the TSS motion. Ground detection is in principle possible if the waves generated by the TSS motion are partially transmitted through the ionospheric layers [*Booker et al.*, 1970]. A quantitative evaluation of the problem of propagation of TSS signals has been started [*Grossi*, 1982; *Estes*, 1989]. In an attempt to measure the signature of TSS emission from the ground, it is most favorable to have a station over which TSS is flying. Accordingly, during the nominal mission, the foreseen observation sites were Mona Island (in the Caribbeans), Arecibo and a station in Australia, for the EMET investigation, and the Canary Island and a station in Kenia for the OESEE investigation. Both magnetometers and ELF receivers were used at these stations with the capability of surveying a frequency range from dc to about 3 kHz.

5. CONCLUSIONS

TSS-1 must be considered as a new space system in which the technological and scientific aspects are strongly linked together. In the mission, which took place in the space shuttle Atlantis in August 1992, several problems on the deployer mechanisms caused, in the end, the satellite to be deployed only 257 m from the shuttle orbiter. When, after many attempts, the satellite was unlocked from this position, there was general uncertainty as to the problems faced. As a consequence, there was significant concern that further attempts to deploy might, on the one hand, not lead to sufficient distance to fulfill primary electrodynamic objectives but, on the other hand, could probably result in a loss of the satellite. This led to a unanimous consensus among the science and engineering teams to start a satellite retrieval which was then successfully accomplished. In all, the satellite stayed ~20 hours at the maximum distance with all the experiments (both on the satellite and on the orbiter) operating during most of the mission duration.

A main goal of TSS-1, although of an engineering nature, was obviously that of proving the dynamics of the system. More specifically, the stated operational goals of the TSS-1 mission were to deploy to a minimum of 10 km and achieve a stable on station configuration for a sufficient time to permit the prime science and technology objectives to be reached, and then retrieve the satellite. The successful accomplishment of these goals was certainly of significance for the future use of tethered satellite systems both for science and for many applications which have been envisaged for such systems [*Penzo and Amman*, 1989].

The deployment obtained was clearly insufficient for the above goals. However, there were ~20 hours of stable deployment in the near vicinity of the shuttle and the operations at such distances, which were supposed to be critical for the mission, were fully tested with complete control of the tether and satellite dynamics. This experience will certainly be of great significance to the future use of long tethers in space because they showed the TSS to be safe, stable and easy to control.

Apart from the dynamic goals, TSS-1 was supposed to constitute an unique active experiment in the ionospheric plasma, the most interesting phenomena being related, as it has been amply discussed in the paper, to the high $(\mathbf{V} \times \mathbf{B}) \cdot \mathbf{L}$ voltages associated with the long tether.

The primary scientific objectives of the mission were indeed: (1) the demonstration of electrical power generation and the characterization of the system current-voltage response, in particular at high voltages; (2) the characterization of the satellite sheath and the mechanisms of current collection and current closure in the ionosphere.

With the maximum deployed tether length of 257 m, the $(\mathbf{V} \times \mathbf{B}) \cdot \mathbf{L}$ maximum voltage was ~50 V, far below the high-voltage range corresponding to the primary objectives above. No substantial current was reached on the tether. More precisely, the current was ~20 mA with the tether connected to the orbiter ground, while the insertion of the EGA gun in the circuit pushed the current level down to 2 mA simply because the gun was designed to provide more substantial current only at much higher voltages.

Therefore, it must be clearly stated that the primary objectives of the mission were not reached. There were, however, some other science objectives, considered secondary in that not directly related to having long tether deployment, but not for that scientifically less interesting. Examples include the investigation of electron beam dynamics (through the use of FPEG), orbiter charging characteristics and shuttle glow. These type of objectives were successfully accomplished. In fact, the type of experiments which were conducted were somewhat similar to those on the CHARGE 2 rocket with the difference, however, of a much longer measurement time and of a rather complete diagnostic instrumentation working both on the orbiter and on the satellite side. Results from such interesting experiments will soon be presented in meetings and in the literature.

In conclusion, the capability of deploying at some distance from the orbiter and then retrieving a satellite was demonstrated. As, on the other hand, all the instrumentation aboard TSS-1 proved to work perfectly, it is strongly hoped that a quick reflight of the system can be programmed to accomplish, at longer tether lengths, those primary objectives which was not possible to address in the mission just flown.

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