GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 4, PAGES 421-424, FEBRUARY 15, 1998

Plasma waves in the sheath of the TSS-1R satellite

L. Iess,[1,2] C. Harvey,[3] G. Vannaroni,[2] J.P. Lebreton,[4] M. Dobrowolny,[5]
R. Manning,[3] P. Cerulli-Irelli,[2] A. Onelli,[2] F. De Venuto.[2]

Abstract. The current flow in the Tethered Satellite System (TSS) induces a strong excitation of electric and magnetic fluctuations in the potential sheath surrounding the subsatellite. The wave sensors of the experiment RETE (Research on Electrodynamic Tether Effects) have measured power spectra of electromagnetic fields from 180 Hz to 12 MHz, providing information on the physical processes taking place around highly charged bodies in the ionosphere and, in particular, the role of wave-particle interactions and anomalous collisionality. We report on the observations during three events of almost steady current flow at 50, 190 and 55 mA, taking place at positive satellite potentials of about 9, 200 and 2 V. The largest power spectral density occurs at frequencies between 2 and 4 kHz, close to the lower hybrid frequency, where electric field fluctuations up to 12 V/m have been observed. In this frequency band the fields are electrostatic and radially polarized, with a marked ram-wake signature.

Introduction

The interaction of charged bodies with the ionospheric environment has raised a great interest since the beginning of the space exploration. Recently, the flight of orbiting, conductive tethers and the prospect of potential applications of these systems for power generation in space has given further relevance and interest to this topic. Theoretical models of current-voltage (I-V) characteristics have been proposed under different hypotheses (lack of collisional and ionization processes, isotropic or magnetically limited flow) [*Beard and Johnson*, 1961; *Beard*, 1966; *Alpert et al.*, 1965; *Parker and Murphy*, 1967; *Linson*, 1982], but none of them is likely to encompass the complexity of a highly non-linear problem in the presence of three-dimensional asymmetry caused by the magnetic field and the motion of the body at orbital speeds.

An element neglected in the theoretical models developed so far is the role of anomalous collisions in the charge collection process. In general large currents in the plasma due to strong electric fields trigger instabilities in the flow. These produce particle scattering which increases the plasma resistivity, modifies the sheath radius, reduces the channelling effect of the magnetic field and increases the ionization rate of neutral atoms [*Linson*, 1982]. Moreover, the onset of lower hybrid waves could trigger critical ionization phenomena, if favourable conditions are met (for example, during thruster operations). All these effects, if really occurring, are surely important in developing a consistent picture of the charge collection processes in the ionosphere and point to the relevance of plasma wave measurements.

One of the primary scientific objectives of the Tethered Satellite System flown in February 1996 (known as TSS-1R) was the study of the electrical response of a large, polarized conductor and its interaction with the ionospheric environment [*Dobrowolny and Stone*, 1994]. The scientific instrumentation at both ends of the tether (Space Shuttle and subsatellite,) together with the controlled current flow provided by electron guns have supplied a wealth of information in spite of the early failure of the mission. In general the I-V characteristics of the system indicate that the current collected by the satellite is larger than predicted by models with magnetically limited flow [*Vannaroni et al.*, Tether Satellite Reflight, Part II]. This is an indication that particle heating and anomalous collisionality may play a significant role in the charge collection process.

The components of fluctuating electric and magnetic field vectors in the satellite sheath are measured by the Wave Receiver Analyzer (WRA) of the experiment RETE, in a frequency band ranging from 180 Hz to 12 MHz (for an exhaustive description of the experiment, see *Dobrowolny et al.* [1994]). The sensors are mounted at the tip of a boom at a distance of about 40 cm from the satellite skin. An identical, symmetric boom housed the plasma diagnostic package of the experiment RETE.

Analysis

Due to the relatively long measurement cycle at low frequencies (9.2 s in the band 0.18-0.8 kHz) and the large ram-wake modulation at the spin period of about 4 min, the interpretation of the data is easier in periods of steady current flow and satellite potential. The latter is a function not only of the tether current and induced voltage, but also of the density and temperature of the ionospheric plasma. Our analysis is based on three events taking place from 056/23:44:40 to 056/23:55:40 GMT. A survey of the wave activity during the three events is shown in fig.1, which presents the measurements of the electric sensors in all frequency bands. The events are identified by the current plotted in the bottom panel (red line). The orientation of the canister with respect to the ram-wake line can be read from the data of the ion sensor (blue line), mounted on the other canister of the experiment RETE, on the oppo-

[1]Dipartimento Aerospaziale, Università di Roma "La Sapienza", Roma, Italy

[2]Istituto di Fisica dello Spazio Interplanetario, CNR, Frascati, Italy

[3]Observatoire de Meudon, Meudon, France

[4]Space Science Dept., ESA-ESTEC, Noordwjik, The Netherlands

[5]Agenzia Spaziale Italiana, Roma, Italy

Paper number 97GL03101.
0094-8534/98/97GL-03101$05.00

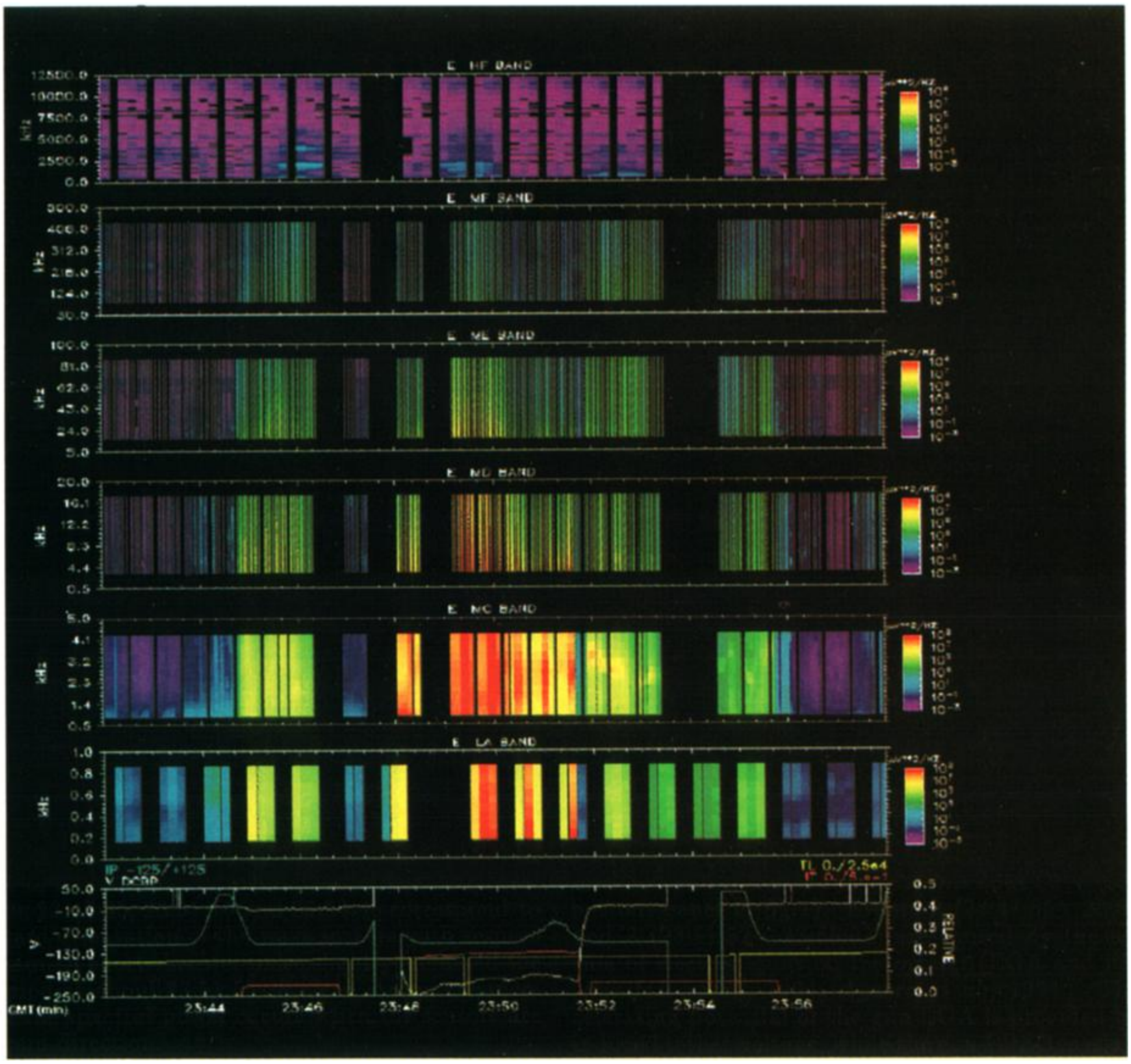

Figure 1. Spectrograms of electric signals (in $\mu V^2/Hz$) measured by the experiment RETE between 056/23:42:00 and 056/23:57:00 GMT (1996), when the TSS-1R satellite was polarized and current was flowing in the tether. From top panel, frequency ranges are: 450-12000 kHz, 90-450 kHz, 20-90 kHz, 4.5-20 kHz, 0.8-4.5 kHz, 0.2-0.8 kHz. The intensity color bar spans the levels $10^{-3} - 10^{9}$. The canister potential with respect to the satellite (equal with excellent approximation to the potential drop across the sheath) can be read in the bottom panel (white line), in the range -250/+50 V. Tether current (red), ion probe current (blue) and tether length (yellow) are plotted in the same panel with relative scales ranging from, respectively, 0/500 mA, -125/+125 nA, 0/25 km. Peak readings of the ion probe, mounted on the opposite side of the satellite, indicate that the wave sensors are in the wake. The peak amplitude is strongly dependent on the satellite potential. Some data gaps due to telemetry glitches are present in the figure.

site side of the satellite. The peaks of the ion current at 23:44:20, 23:47:45, 23:51:10 and 23:54:45 correspond to a rearward orientation of the wave sensors with respect to the ram. A short thruster pulse slightly increased the spin period at about 23:51:55. A clear, strong enhancement of the spectral power occurs when the sensors are in the ram direction.

During event 1 (23:44:24 - 23:46:44) the tether was connected to the orbiter ground through a 25 kΩ shunt resistor. The 50 mA current was essentially provided by the ions collected by the orbiter engines. The satellite potential with respect to the plasma, measured by the instruments RETE and ROPE, was about 9 V (see the bottom panel in fig.1). Events 2 (23:47:55 - 23:51:40) and 3 (23:51:52 - 23:55:02) are caused by the activation of electron guns on the orbiter (EGA and FPEG) [*Bonifazi et al.*, 1994; *Aguero et al.*, 1994.] The accelerating potential of the gun EGA is provided by the induced tether voltage, while the gun FPEG is equipped with an independent high voltage power supply. During event 2, generated by the gun EGA, the ambient plasma density was rising, causing a current increase from 180 to 200 mA and a satellite potential decrease from 250 to 200 V over a time span of about 4 min.

In event 3 the gun FPEG provided a very stable current (56-57 mA,) with a very small satellite potential (between 2 and 3 V).

The frequency decomposition of the fields can be read more accurately from fig.2, which shows the largest power spectra measured by the E_y-sensor during the three events. For comparison, we show also a typical spectrum acquired at zero current. The maximum spectral power is reached in all cases in the band 2-3.5 kHz, close to the lower hybrid frequency ($\approx 5 - 6$ kHz) and the reciprocal of the transit time of the satellite across a magnetic field line (≈ 5 kHz). Not surprisingly, the spectrum attains its largest value ($5\,10^9$ $\mu V^2/Hz$) during event 2, at 23:50:10, when the current was intense and the canister was facing the ram direction. Indeed, measurements of the current density in the sheath have shown a strong azimuthal anisotropy [*Vannaroni et al.,* Tether Satellite Reflight, Part II].

The spectra fall off very rapidly after 10-20 kHz, approximately following a power law f^{-k} with spectral index $3 < k < 4$. up to $f = 1$ MHz, where they become roughly white and independent of the tether current. It is remarkable that, for almost equal current level (event 1 and 3), the shape of the spectra changes significantly. Event 3 occurs when the satellite potential is low enough to allow ion collection (i.e. below 5 eV, the ion energy in the moving frame of reference), while during event 1 ambient ions are reflected away from the sheath. At low satellite potential the spectrum exhibits a wide range of excited frequencies, up to about 100 kHz, but always with a pronounced peak between 2 and 3 kHz. The very low excitation levels at high frequencies indicate that phenomena involving very short time scales do not significantly affect the particle dynamics in the sheath.

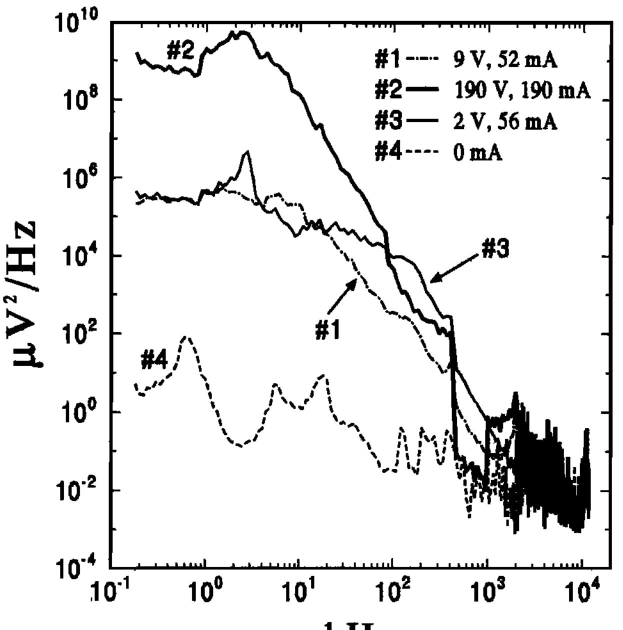

Figure 2. Largest power spectra (in $\mu V^2/Hz$) measured by the radial (y) sensor during each of the three charging events: (1) 9 V, 52 mA; (2) 190 V, 190 mA; (3) 2 V, 56 mA. A spectrum with the satellite at floating potential (dashed line) is included for comparison.

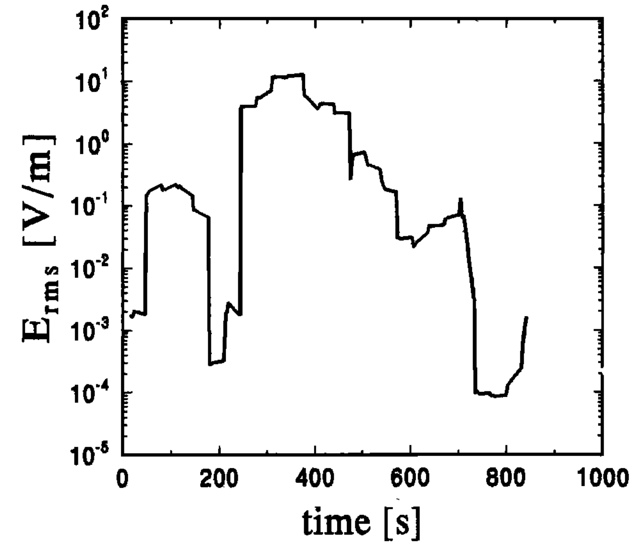

Figure 3. RMS value of electric fields (in V/m) vs. time (in seconds past 23:44:00 GMT,) in the frequency band 0.8-4.5 kHz.

On the other hand, LF waves could be far more effective in producing particle scattering. Indeed, electric fields up to 12 V/m rms are measured during event 2 in the band 0.8-4.1 kHz (see fig.3). The corresponding level of energy fluctuations is about 4 eV, much larger than the thermal energy. Collisions due to wave-particle interactions may therefore produce scattering across magnetic field lines. If these fields, as it is likely, are present in the presheath (an issue which cannot be however ascertained by our experiment), this process plays a significant role in the charge collection. Consistently, a remarkable particle heating is to be expected. Oscillating fields are probably irrelevant within the sheath, where the electric field of the satellite dominates the particle dynamics.

The predominantly electrostatic character of the fluctuations is read from the large value (between $3\,10^3$ and $1\,10^4$ Ω) of the wave impedence, computed from the measured ratio of orthogonal electric and magnetic components. For comparison, in the frequency range under consideration the only relevant electromagnetic mode (whistler) has a wave impedence of a few ohms. This implies the alignement between the wave-vector $\mathbf{k}$ and the electric fields of the wave $\mathbf{E}$. As the rejection of electric signals from the magnetic sensors may not be good, the above figures have to be assumed as lower bounds. The wave impedence decreases at higher frequencies, reaching minum values of a few tens of ohms at 100 kHz.

When current is flowing, the radial sensor (E_y) measures in general fields up to an order of magnitude larger than the E_x and E_z. This indicates with good confidence that the polarization of the LF waves is consistent with a radially oriented, electrostatic electric field, with wave-vector $\mathbf{k}||\mathbf{E}$.

The dominating radial orientation of the fluctuating fields can be read in fig.4, which shows the scalar product $\hat{\mathbf{s}}\cdot\hat{\mathbf{E}}$ between the unit vectors oriented along the ram ($\hat{\mathbf{s}}$) and the wave electric field ($\hat{\mathbf{E}}$). As expected, this quantity follows the cosine of the satellite phase angle (line b). In the bottom panel, line (c) shows the cosine

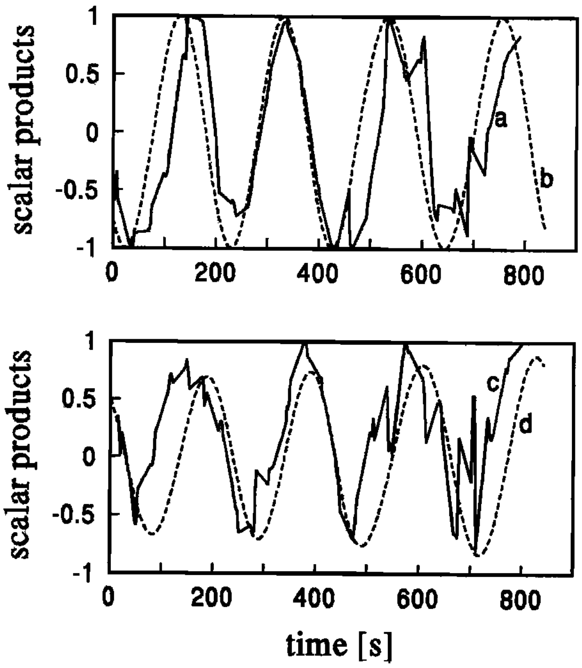

Figure 4. Top panel: plot of the scalar products $\hat{\mathbf{s}} \cdot \hat{\mathbf{E}}$ (a) and $\hat{\mathbf{s}} \cdot \hat{\mathbf{y}}$ (b). $\hat{\mathbf{s}}$, $\hat{\mathbf{E}}$ and $\hat{\mathbf{y}}$ are respectively the unit vectors along ram, electric field and y-sensor. Bottom panel: scalar products $\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}$ (c) and $\hat{\mathbf{y}} \cdot \hat{\mathbf{B}}$ (d). $\hat{\mathbf{B}}$ is the unit vector along the geomagnetic field. Time is in seconds past 23:44:00 GMT.

of the angle between **E** and the local geomagnetic field **B**. In the time span under consideration, the magnetic field was oriented at an elevation of about 45° above the satellite equatorial plane and roughly orthogonal (104°) to the ram direction. Again, one finds a clear modulation with the spin phase angle (line d). It is remarkable that the maximum field excitation during event 2 occurs approximately when $\mathbf{E} \cdot \mathbf{B} = 0$, suggesting the onset of lower hybrid waves. At the same time, however, this condition occurs when the canister is in the ram direction, where larger excitations are expected anyway, due to the larger current density and the presence of reflected ions [*Vannaroni et al.*, Tether Satellite Reflight, Part II]. Therefore this experimental result is also compatible with current-driven instabilities associated with the mainly radial flow of the electrons in the sheath.

Conclusions

The large, random electrostatic fields (up to 12 V/m) measured by the instrument RETE in the sheath of the satellite TSS-1R show that wave-particle interactions and the associated anomalous collisions may significantly affect ithe electron collection of tethered systems. Moreover, a substantial particle heating is likely to occur. We suggest that these two factors may cause the violation of magnetically limited charge collection models developed so far. At the present stage of the analysis it is not possible to identify the origin of the measured fields, which fall in the lower hybrid band.

Acknowledgments. The work of Italian authors has been funded in part by ASI (Agenzia Spaziale Italiana). L. Iess wishes to thank IFSI-CNR for supporting this research.

References

Aguero, V., P.M. Banks, B. Gilchrist, I. Linscott, W.J. Raitt, D. Thompson, V. Tolat, A.B. White, S. Williams, and P.J. Williamson, The shuttle electrodynamic tether system (SETS) on TSS-1, *Nuovo Cimento C17*, 49, 1994.

Alpert, Y. L., A.V. Gurevich, and L.P. Pitaewskii, *Space Physics with Artificial Satellites*, p.186, Consult. Bur., New York, 1965.

Beard, D.B., and F.S. Johnson, Ionospheric Limitations on Attainable Satellite Potentials, J. Geophys. Res., *66*, 4113, 1961.

Beard, D.B., Correction to Paper by D.B. Beard and F.S. Johnson "Ionospheric Limitations on Attainable Satellite Potentials", J. Geophys. Res., *71*, 4707, 1966.

Bonifazi, C., F. Svelto, and J. Sabbagh, TSS Core Equipment. I.- Electrodynamic Package and Rationale for System Electrodynamic Analysis, *Nuovo Cimento 17C*, 13, 1994.

Dobrowolny, M., and N.H. Stone, A Technical Overview of the TSS-1: the First Tethered-Satellite System Mission, *Nuovo Cimento 17C*, 1, 1994.

Dobrowolny, M., E. Melchioni, U. Guidoni, L. Iess, M. Maggi, R. Orfei, Y. De Conchy, C.C. Harvey, R.M. Manning, F. Wouters, J.P. Lebreton, S. Ekolm, and A. Butler, The RETE experiment for the TSS-1 mission, *Nuovo Cimento 17C*, 101, 1994.

Linson, L.M., Charge neutralization as studied experimentally and theoretically, in *Artificial Particle Beams in Space Plasma Studies*, edited by B. Grandal, p. 573, Plenum, New York, 1982.

Parker, L.W., and B.L. Murphy, Potential buildup on an electron-emitting ionospheric satellite, J. Geophys. Res., *72*, 1631, 1967.

Vannaroni, G., M. Dobrowolny, J.P. Lebreton, E. Melchioni, F. De Venuto, C.C. Harvey, L. Iess, U. Guidoni, C. Bonifazi, and F. Mariani, Current-voltage characteristics of the TSS-1R satellite: comparison with isotropic and anisotropic models, Geophys. Res. Lett., , Tether Satellite Reflight, Part II.

L. Iess, Dipartimento Aerospaziale, Università di Roma "La Sapienza", via Eudossiana 18, 00184 Rome, Italy. e-mail: iess@nero.ing.uniroma1.it

P. Cerulli-Irelli, F. De Venuto, A. Onelli, G. Vannaroni IFSI-CNR, C.P. 27, 00044 Frascati, Italy

C.C. Harvey and R. Manning, Observatoire de Paris-Meudon, 92195 Meudon, France

J.P. Lebreton Space Science Department, ESA-ESTEC, 2200 AG Noordwijk, The Netherlands

M. Dobrowolny, ASI, viale Regina Margherita 202, 00198 Roma, Italy

(Received February 4, 1997; revised October 9, 1997; accepted October 17, 1997.)