GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 4, PAGES 425-428, FEBRUARY 15, 1998

Current flow through high-voltage sheaths observed by the TEMAG experiment during TSS-1R

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Abstract. During the TSS-1R flight, conditions occurred under which very intense currents flowed through the tether wire system. The effect of these currents during the active phases of operation was clearly seen by the TEMAG sensor assembly located on the short, fixed satellite boom. Magnetic signatures appeared on the field components parallel to the boom and to the spin axis with a strong peak when the boom points closer to the ram direction. While a toroidal current flowing on the ram side of the plasma sheath may explain the main features seen by the TEMAG outboard sensor, further studies are needed for the physical interpretation of the complex electrodynamic interactions of the TSS-ionosphere system.

Introduction

The electrical charging of a body in the Earth's ionosphere, either floating or under the influence of a charge emitting device, has been the subject of many theoretical and observational studies in the past [*Laframboise and Sonmor*, 1993 and references there in]. Naturally induced charging of artificial satellites has been observed to represent significant danger for satellite electronics [*Lai*, 1994] especially near geostationary altitude where high voltages can be attained. The investigation of methods to neutralise these naturally excited voltages, even at low levels, is also very interesting in order to avoid contamination of the low energy plasma space environment which impairs scientific observations [*Pedersen*, 1983]. The potential uses of induced voltages in long tethered systems for power generation [*Nobles*, 1986] have recently received intense interest and led to the analysis of the physical mechanisms involved in the charging of a body in the ionospheric plasma. Theories have generally predicted upper limits for the level at which currents can be drawn from the plasma. Experimentation on such effects, which is nearly impossible in ground based facilities, has been performed in the two TSS missions. During the first flight, TSS-1, launched on July 31, 1992, a maximum deployment of 256 m was reached and induced voltages of a few tens of volts were detected, much in excess of the plasma thermal energy. Detectable but low tether currents were also observed [*Dobrowolny et al.*, 1995]. Extremely high voltages were obtained during the second flight, TSS-1R, when the s/c deployment reached the nearly nominal distance of 19.7 km. The current drawn from the plasma during TSS-1R attained levels high enough to produce perturbations detectable by the boom mounted TEMAG magnetic field experiment. The pulsed tether current technique, developed to investigate magnetic signatures in the plasma sheath structure, allowed the observation of remarkable asymmetries in the distribution of currents around the satellite. The TEMAG observations during two special events are presented.

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Paper number 97GL03045.
0094-8534/98/97GL-03045$05.00

Data analysis

On February 22, 1996, the shuttle STS-75 flight carried the TSS-1R mission into orbit. The tethered satellite was deployed close to the nominal distance of 20 km on February 26th. This allowed several hours of useful observation in the tether voltage and current ranges for which the mission had been designed, until 01:30 UT February 27th, when the tether broke. Figure 1 is a sketch of the satellite, showing the geometry of outboard TEMAG sensor located on the fixed non-conductive carbon fiber boom. Twin triaxial flux-gate magnetometers performed continuous measurements of the magnetic field vector at two fixed positions on the boom, respectively at about 173 and 118 cm from the spin axis. Fields were sampled at rates of 16 and 2 samples/sec, on the outboard and inboard sensors, respectively. A detailed description of the experiment is given elsewhere [*paper in preparation*]. In this short paper we present data from the outboard sensor, which shows very clear and new features, at high temporal resolution. As concerns the data from the inboard sensor, they show, at lower time resolution and closer to the s/c skin, significant similarities and puzzling differences as well, an indication of a complex physical situation in the plasma sheath. An extensive study of *all* available events, also including data from the inboard sensor as well as from particle experiments, is under way. In this paper we concentrate our analysis on two special time intervals, from 1:06:00 to 1:10:00 and 1:18:00 to 1:22:00 when a triple sequence of EGA current pulses of rising intensity up to 480 mA and 380 mA respectively were commanded with an ON/OFF duty cycle of 2 seconds. The geophysical and electrodynamic conditions during the two time intervals were significantly different. The raw data from the outboard TEMAG sensor were first corrected to the satellite attitude reference system (SARF), i.e. the orthogonal rotating satellite

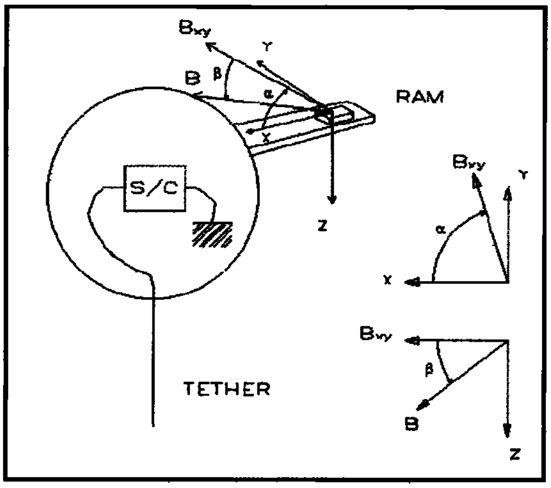

Figure 1. Schematic geometry of the outboard TEMAG sensor on the TSS-1R fixed boom. The rotating SARF reference system for data presentation is indicated. The angle β is the inclination of the B vector to the xy plane; the angle α is the azimuth on the same plane.

reference system as shown in fig. 1, by using pre-flight alignment and sensitivity calibrations and offsets. This process does not alter the character of the data other than in order to make possible the comparison with the model geomagnetic field. For this, the field model IGRF95 (extrapolated to the February 1996 epoch) was adopted to compute the expected field at the instantaneous satellite altitude; the three field components were then converted to the SARF reference system. The time variable rotation matrix was derived from the attitude of the satellite, as given by the Earth's sensors. The observed fields contain a major contribution from the geomagnetic field (of the order of a few tens thousands nT). The x and y components are strongly modulated by the satellite spin, and some residual fluctuations are present on the z component due to the satellite axis precession. The spin period (about 215 sec) was deduced from the described spin modulation. The signal expected from the TSS circuit is superimposed to the geomagnetic field. More precisely, the field perturbation due to the stimulated current steps along the tether is the sum of three contributions: *(a)* the spin axis symmetrical field from the linear current flow along the tether until its attack point inside the s/c, which is only a few tens nT in the y direction for a one Amp current; *(b)* the field from the internal current distribution to the s/c skin, more or less spherically symmetric; *(c)* the field from the current flow toward the sheath and through the ionosphere. It follows that, for any fixed current applied to the system, any dependence upon the spin phase (i.e. spherical asymmetry) of the consequent magnetic field perturbation should be essentially attributed to the last contribution.

Observations

The observed data and the corresponding model data for the two events were extensively compared during the more than 5 hours of deployed tether. The differences on any components never exceeded a few hundred nT, which in terms of misalignment angles imply a very satisfactory uncertainty in orientation of a few tenths of degree or an incorrect extrapolation of the IGRF model field. The result of this comparison gives us, then, full confidence in the observed data. Figure 2 and Figure 3 summarize the observed field perturbations associated with the EGA current pulses sequences for the two time intervals of interest. In the top panel we show the spin phase Φ of the fixed boom (solid line) and the angle α between the xy projection of the B field (dashed line) and the x axis. The bottom panel shows the EGA current pulses sampled by TEMAG on an analog input provided by the CORE experiment (*Bonifazi et al.*, 1994). The other panels show the differences of the measured B_x, B_y, B_z total field components and of the field strength B at the outboard sensor from those given by the model field. Both figures exhibit a very precise temporal relationship between the current steps and the magnetic field pulses. While some 'up and down' of the field components long-term trend reflect the real field discrepancies from the model (plus some residual modulation due to attitude uncertainties), several interesting new remarkable features are noted. A close look at figure 2 shows that the third sequence of current pulses occurred with the boom direction close to the ram direction; the amplitude of the pulses ΔB_x and ΔB_z at maximum current was 2-3 times larger than that seen

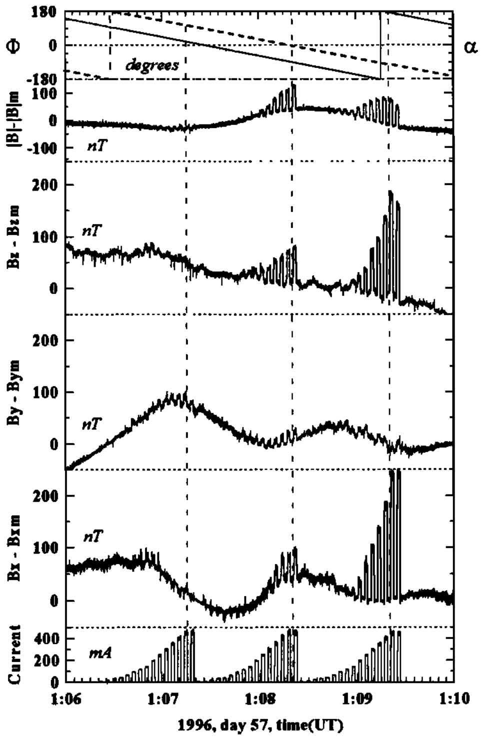

Figure 2. The differences of observed magnetic field components B_x, B_y, B_z and field magnitude B from the IGRF model components B_{xm}, B_{ym}, B_{zm} and magnitude B_m at the outboard sensor between 01:06:00 and 01:10:00 UT, both as seen in the SARF reference system. The lower panel shows the EGA current pulses. In the upper panel the angle Φ is the spin phase of the boom (solid line) with respect to the ram direction (at $\pm 180°$, as from fig 1); the angle α is the phase of the magnetic field in the xy plane (dashed line) with respect to the x axis.

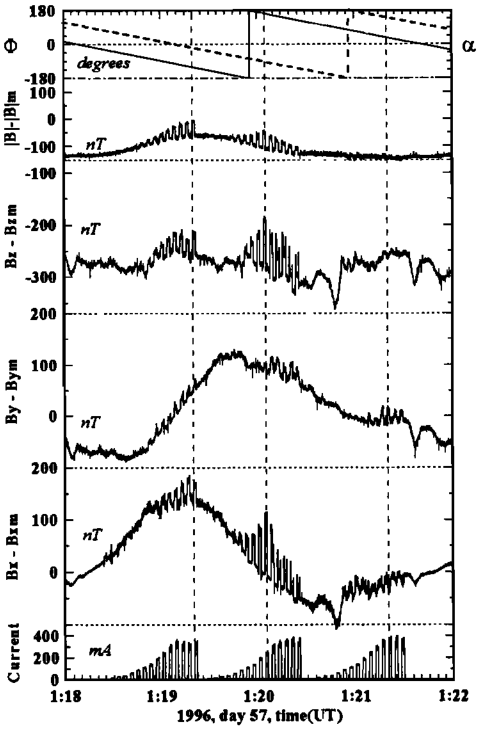

Figure 3. Same as fig. 2 for the time interval 1:18:00 to 1:22:00.

during the second sequence, with the same maximum current level but with the boom pointing about 90 degrees from the ram direction. Last, during the first sequence the boom direction was close to the anti–ram direction and no effect was visible. As concerns the By component, a small magnetic signature ΔB_y is seen only when the current exceeds 150-200 mA, but its amplitude is much lower than that on the other components and does not show any preferential orientation to the ram direction. The amplitude of ΔB_y, more or less identical at any angle Φ, is of the order of 20-30 nT, just the contribution as expected on that axis from the most intense current steps flowing along the tether. In summary, figure 2 shows that:

- i. the most affected field components are B_x and B_z;
- ii. the effect on the B_y component is small;
- iii. while ΔB_x and ΔB_z exhibit an evident dependence of the spin phase angle, no such significant effect is seen on ΔB_y.
- iv. the effect on the field strength B is also spin dependent, although no significant differences are seen between the second and the third current sequence.

Figure 3 adds further important information in that the current sequences during the second event are shifted in time with respect to those of figure 2. Now, the second current sequence extends much beyond the time when the boom turns through the ram direction. The spin phase Φ of the boom corresponding to the maximum effect, i.e. when the ratios $\Delta B_z/i$ and $\Delta B_x/i$ (i is the current intensity) are maximum, is more or less identical to that seen during the first event. The effect decreases beyond that angle, despite the fact that a current maximum occurs again turning past the ram direction. The third sequence of fig. 3 occurs at the same angular position of the first sequence of fig. 2 and even now there is no significant effect on B_x, B_z and B magnitude. Once again, the B_y component shows a small magnetic signature, independent of the spin phase.

Discussion

Highlights of the results shown in figures 2 and 3 are shown in table 1, where the amplitude of the magnetic pulses and some other parameters of interest are shown for the times (indicated by the dashed lines in the two figures) when the boom points toward the ram direction (col. 4 and 6), or is nearly perpendicular (col. 3 and 5), or nearly anti–parallel to it (col. 2 and 7). Generally speaking, combining the results for the two events we can say that the current signatures on the B_x and B_z components appear mostly confined in the hemisphere containing the ram direction with a maximum effect some 10 degrees after crossing it, i.e. in a direction nearly perpendicular to the ambient magnetic field (this last was at 80 and 100 degrees to the ram in the two time intervals). The large amplitude of the magnetic pulses requires that the bulk of the current flows in the sheath not far from the outboard sensor. Having ΔB_x and ΔB_z the same sign implies that this bulk current flows externally to the outboard sensor (otherwise the signs should have been opposite). A physical situation may arise then, to some extent resembling that of a nearly parallel shock upstream of the satellite. The

Table 1.

Time (UT)	01:07:15	01:08:20	01:09:20	01:19:20	01:20:05	01:21:20
ΔB_x(nT)	noise	60	250	50	120	25
ΔB_y(nT)	20–30	20–30	20–30	20–30	20–30	20–30
ΔB_z(nT)	noise	70	210	50	100	noise
Current(mA)	480	480	450	350	250	380
Boom direction	anti–ram	normal to ram	ram	normal to ram	ram	anti–ram

Highlights of the events shown in figures 2 and 3. The ram direction corresponds to $\Phi = \pm 180°$. The angle α of the xy projection of the vector field to the ram direction was about 80 and 100 degrees in the two events. The field pointed below the horizonthal plane by a nearly constant angle β (between 38 and 42 degrees). The ionospheric electron density and satellite potential were [*Thompson et al.*, 1997] 810^5 and $310^5 cm^{-3}$ and 600 and 1000 volts, respectively.

ratios $\Delta B_z/\Delta B_x$ at the time of maximum effect (at 01:09:20 and 01:20:05 respectively) is nearly identical for the two events; but the ratio of the two ΔB_z pulses, and that of the two ΔB_x pulses as well, in the two events is about a factor of 2 higher than expected from the ratio 1.2 between the current levels (*Thompson et al.*, 1997). This feature may find an explanation in the significantly larger ionospheric electron densities during the first event with higher current densities around the satellite because of higher conductivity. As concerns the y component, the signature expected from a current flowing along the geomagnetic field would show stronger ΔB_y components than observed, roughly of the same order of ΔB_z and ΔB_x. The amplitude and the lack of azimuthal effects of the small pulses ΔB_y are indeed more or less just what we expect from the distant current flowing in the tether. It is very remarkable then, that the closer current in the plasma sheath produces no significant effect on y, while really strong effects are seen only on x and z axes. Azimuthal effects have also been found by other experiments, although under ambient conditions very different from those existing during the events we discussed above. Gurgiolo et al. [1997] have found an apparent anisotropy in azimuth for suprathermal electrons in low voltage satellite conditions. They talk in terms of some similarity to the terrestrial bow shock produced by the incident solar wind. In similar low voltage conditions, Ma and Schunk [1997] have shown in a simulation that the bulk of current flows along the geomagnetic field. Singh and Leung [1997] find that at satellite voltages slightly larger than that corresponding to ion ram energy the magnetic field–aligned current predicted by the Parker and Murphy model tend to rotate toward the ram direction. There is no simple explanation to predict how these results can be extrapolated to the high voltage regime existing during our events. Any current flowing along the geomagnetic field line, as from the Parker–Murphy model, should produce significant perturbations (modulated by the spin phase) on all the field components, including B_y, in contrast with our findings. The observed lack of large pulses on By during the EGA current sequences, implies that, at least at high voltages, the closure path of ionospheric currents inside and outside of the plasma sheath must flow in such a way to produce irrelevant ΔB_y effects. At present preliminary stage, we are then led to hypothesize the existence of a sort of toroidal stepped arch current, in the forward plasma sheath hemisphere centered on the ram direction, essentially parallel to the instantaneous y–axis and perpendicular to the spin. A global physical interpretation requires a combined analysis of magnetic field and particle observations. A study extended to several other similar events (although characterized by lower current levels) and also taking into account the inboard sensor data is presently in progress.

Acknowledgments. This work was financially supported by the Italian Space Agency and by German DARA. Support by NASA/GSFC is also acknowledged.

References

Bonifazi, C., F. Svelto, and J. Sabbagh, TSS Core Equipment, *Nuovo Cimento*, 17C, 13, 1994.

Dobrowolny, M., U. Guidoni, E. Melchioni, G. Vannaroni, and J. P. Lebreton, Current - voltage characteristics of the TSS-1 satellite, *J. Geophys. Res*, *100*, 23953, 1995.

Gurgiolo C., J. D. Winningham, K. Wright and N. Stone, TSS-1R: Suprathermal Electron Distriibution Observed in Low Voltage Satellite Configurations, *Geophys. Res. Lett.*, this issue pag., 1997.

Laframboise, J. G., and L. J. Sonmor, Current collection by probes and electrodes in space magnetoplasmas: a review, *J. Geophys. Res.*, 98, 337, 1993.

Lai, S. T., An improved Langmuir probe formula for modeling satellite interactions with near–geostationary environment, *J. Geophys. Res.*, 99, 459, 1994.

Ma, T. Z., and R. W. Schunk, 3-D Time-Dependent Simulation of the Tethered Satellite–Ionosphere Interaction, *Geophys. Res. Lett.*, this issue pag., 1997.

Nobles, W., Electrodynamic Tethers for energy conversion, *AAS 86-280*, Int. Conf., 1986.

Pedersen, A., Introduction, *S/c Plasma Interactions, ESA SP-198*, VII, 1983.

Singh, N., and W. C. Leung, Three dimensional Simulation of Plasma Processes Occurring Near the Tethered Satellite: 1. Current Collection and Applicability of the Parker-Murphy Model, *Geophys. Res. Lett.*, this issue pag., 1997.

Thompson, D. C., C. Bonifazi, B. E. Gilchrist, S. D. Williams, W. J. Raitt, J. P. Lebreton, G. Vannaroni and W. J. Burke, The Current-Voltage Characteristics of a Large Probe in Low Earth Orbit: TSS1-R Results, *Geophys. Res. Lett.*, this issue pag., 1997.

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(Received February 15, 1997; revised October 3, 1997; accepted October 13, 1997.)