Plasma Motor Generator (PMG)
Electrodynamic Tether Experiment

NASA Grant NAG9-643

Final Report

For the period 15 September 1992 through 30 September 1995

Principal Investigator
Mario D. Grossi

June 1995

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. James McCoy,
Code SN3, Lyndon B. Johnson Space Flight Center
Houston, Texas 77058

EXECUTIVE SUMMARY

The participation of the Smithsonian Astrophysical Observatory in the Fourth International Conference on Tethers in Space, Washington, DC , 10-14 April 1995 has provided the occasion to present to the tether community an extensive report on the results of the Plasma Motor Generator (PMG) Mission of June 1993.

At the request of NASA-JSC Principal Investigator Dr. James E. McCoy, SAO was given the assignment of re-organizing, under a very short notice, the Session on PMG of April 13, 1995, replacing three papers that has been withdrawn by the Authors with three new papers that SAO solicited, reviewed and edited. SAO was instrumental in making possible for all these three papers to be finished on time for inclusion in the Proceedings of the Conference.

The three papers are as follows :

(a) Electrodynamic Interactions between the PMG tether and the magneto-ionic medium of the Ionosphere,
by M.D.Grossi, J.E.McCoy, R.D. Estes;

(b) Tether-current-voltage characteristics, as determined by the Hollow Cathode Operation Modes,
by R.C. Olsen, Chung-Jen Chang, Chia-Hwa-Chi;

(c) Hawaii-Hilo Ground Observations on the Occasion of the PMG flight of June 23, 1993,
by C. Ottonello, G.Tacconi, S. Pagnani, L. Minna.

Enclosed herewith are copies of the three papers above.

ELECTRODYNAMIC INTERACTIONS BETWEEN THE PMG TETHER AND THE MAGNETO-IONIC MEDIUM OF THE IONOSPHERE

by

Mario D. Grossi (*), James E. McCoy (**), Robert D. Estes (*)

(*) Harvard-Smithsonian CFA, Cambridge, Massachusetts 02138,USA
(**) NASA/Johnson Space Center, Houston, Texas 77058, USA

ABSTRACT

The Plasma Motor Generator (PMG) flight of June 26, 1993 has been the most sophisticated and most succesful mission that has been carried out thus far with an electrodynamic tether.The orbit was a 922 Km x 207 Km ellipse with an inclination of 25.7°. The tether was a 500 meter wire with a resistance of 10 ohm. It achieved ,shortly after release,a gravity-gradient-stabilized configuration. The tether was terminated at the FEP end (Far End Package) and at the NEP end (Near End Package) with plasma contactors, to provide low-resistance path to the ionosphere. The FEP was at a higher altitude with respect to the NEP. The largest electromotive force (emf) that we observed was about 100 Volt, and the largest tether current was 300 milliAmpere. There was a strong difference between the current observed on the dark side of the orbit and the day side's, with a ratio of about 10. Theoretical predictions carried out prior to the flight had pointed out the existance of this day-to-night phenomenon. However, these calculations had overestimated the maximum achievable currents both on the day side and on the night side by about 75%.Electron collection by the FEP (in absence of plasma contactor) had been estimated according to probe theory in an ionosphere with an electron density of about 10^6 el/cc and an electron temperature of 0.14 eV. Both space charge limited and magnetic limited theories predicted currents about ten times smaller than observed, all along the orbital path. There is no question that the use of plasma contactors made it possible to achieve a very large increase in tether current. Concerning the electro-motive force generated by electrodynamic interactions, the theoretical model generated prior to the flight based on the $\overline{V} \times \overline{B} \cdot \overline{L}$ mechanism also overestimated the observed profile of the emf versus time by about 77 %. Other significant results of the PMG flight was the general good agreement between theory and measurements for the plasma resistance during the initial FEP deployment phase and in the post-deployment time, the power profiles for the Generator Mode and for the Motor Mode of the PMG, as well as the profiles of the magnetic drag and of the magnetic thrust. Concerning the issue of circuit closure for the tether current, the PMG evidence shows that ,during deployment, the overlapping plasma clouds at each tether end provided this closure. After a few seconds (at a separation distance FEP-to-NEP of a few meters), circuit closure occurred remotely in the ionosphere (along the lines of force of the geomagnetic field) and the current held a constant value for separation FEP-NEP of 10 to 500 meter. Concerning then the PMG dynamical performance, it was possible to conclude that the FEP and the tether did expand to the full length of 500 meter from the NEP, that the deployment time to full extension was shorter than anticipated, that the deployer functioned with a very low drag impedence, and that the FEP, the tether and the NEP did stabilize and did not lose to the very end of the flight its librated, gravitational gradient attitude.

Concerning the fundamental functioning of the PMG, both the Generator mode and the Motor mode were succesfully demonstrated. Also, a fully probative orbital testing of the functionality of Hollow Cathode Assembly (HCA) plasma contactors has been carried out. These devices most probably will be present in any tether electrodynamics mission of the future.

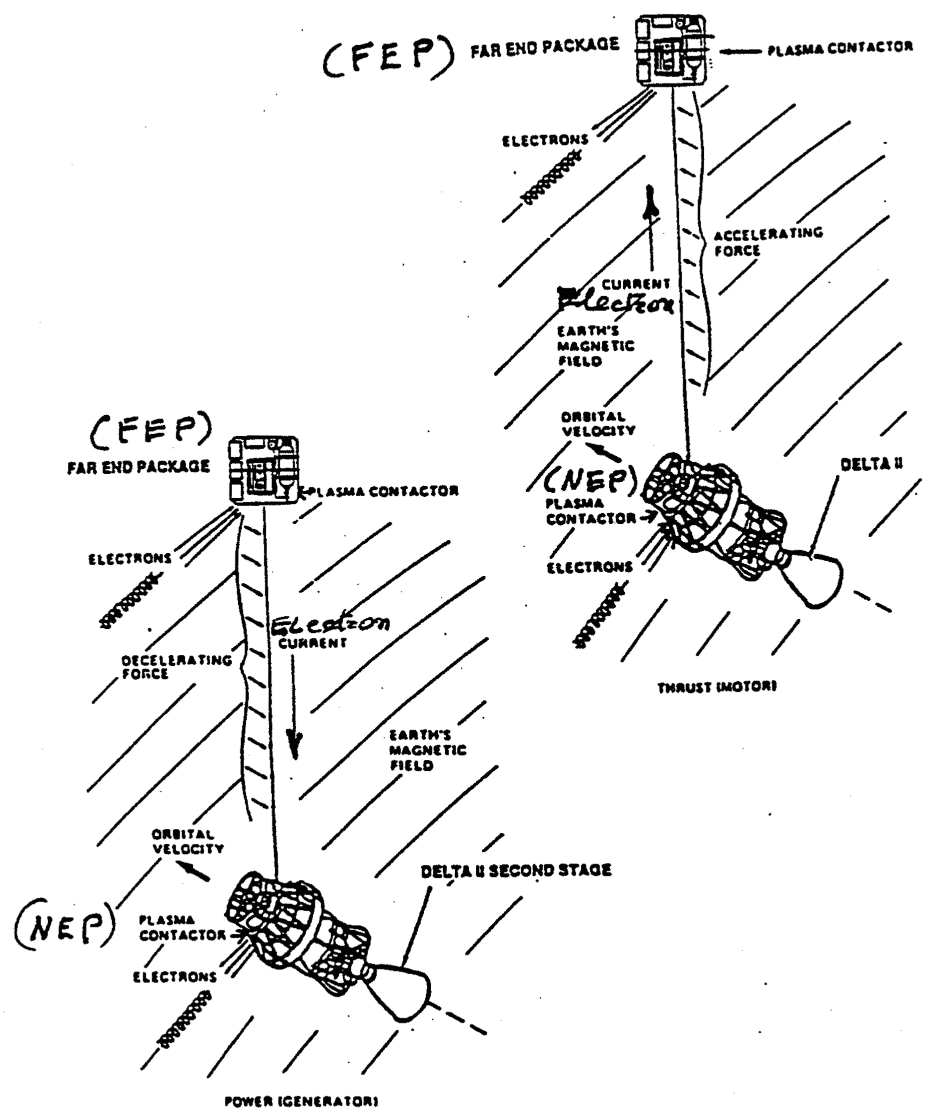


Figure 1. Plasma Motor Generator (PMG)

Electrodynamic Mechanisms and the Two Principal Instrumentation Packages
(Near End Package, or NEP and Far End Package, or FEP)

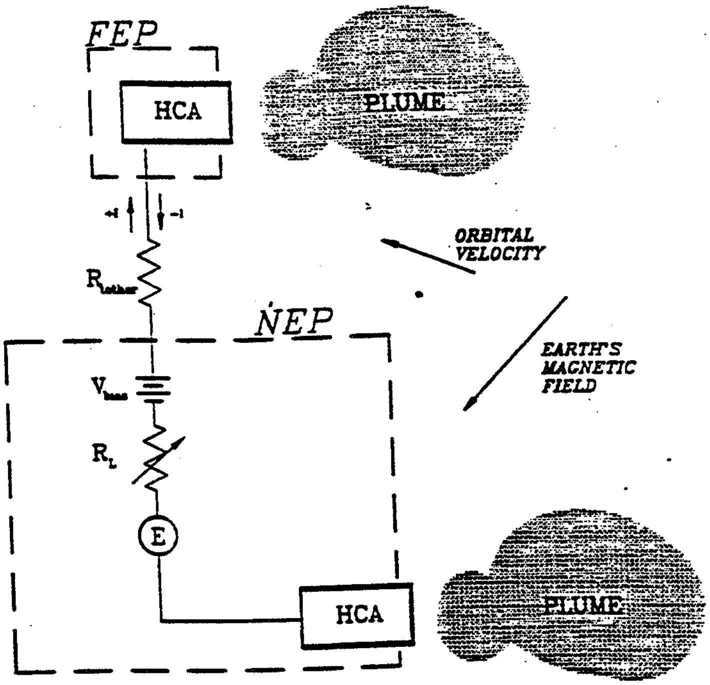


Figure 2.
Circuit diagram of current flow.

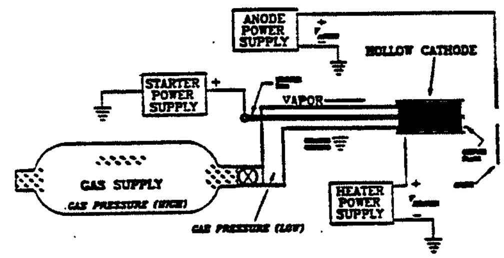


Figure 3
The Hollow Cathode Assembly (HCA) – Functional Scheme.

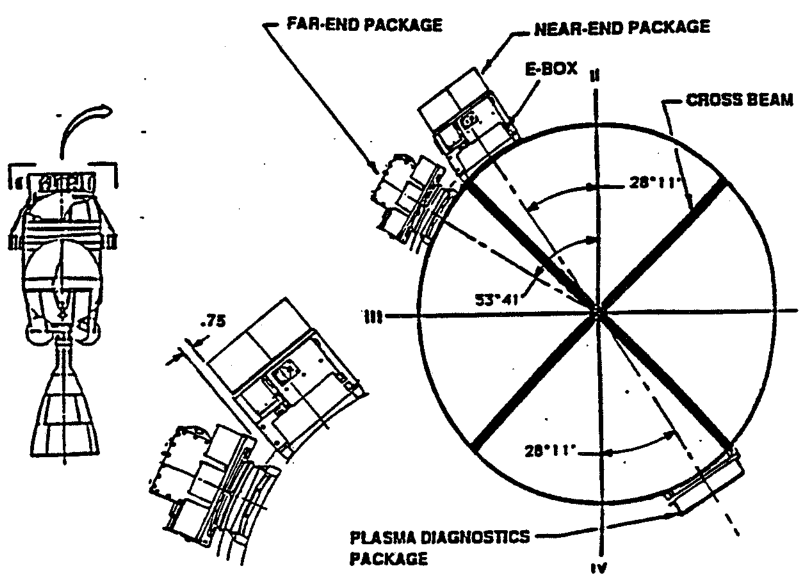


Figure 4
Mounting of FEP, NEP and PDP on the second stage of the DELTA II.

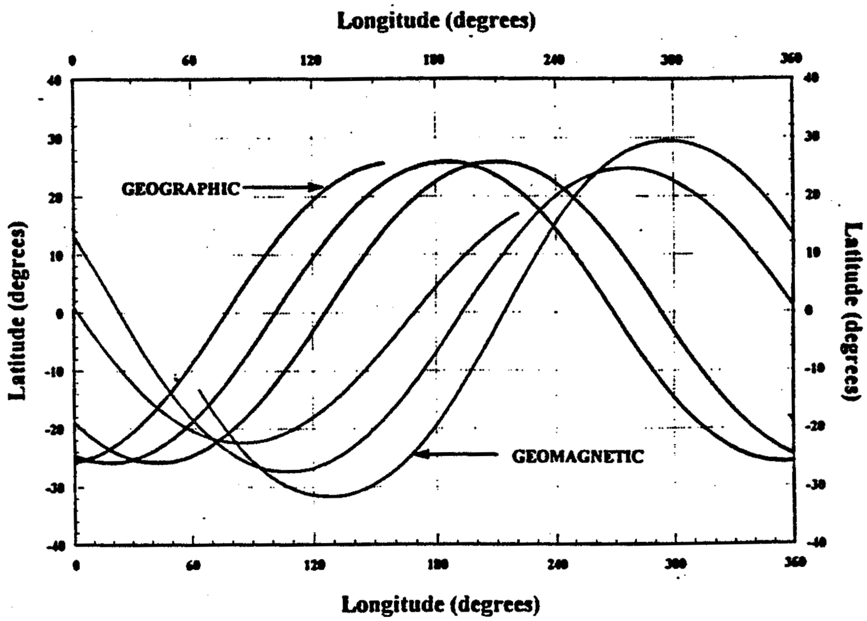


Figure 5.
PMG ground ground tracks for the first 15,000 seconds of Mission Elapsed Time (MET)

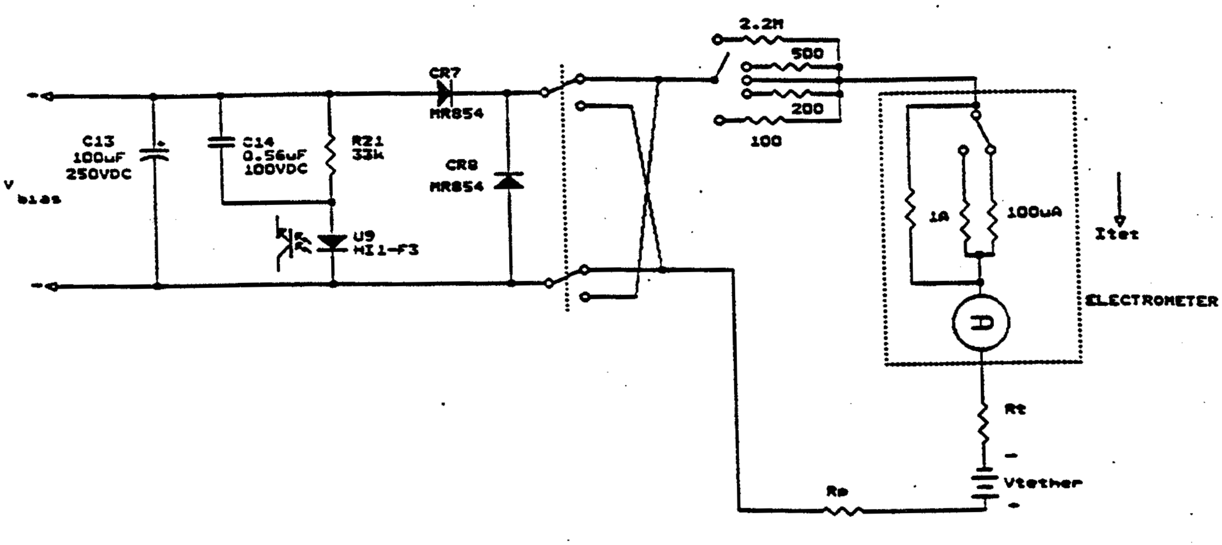


Figure 6. PMG circuit diagram for voltage computation.

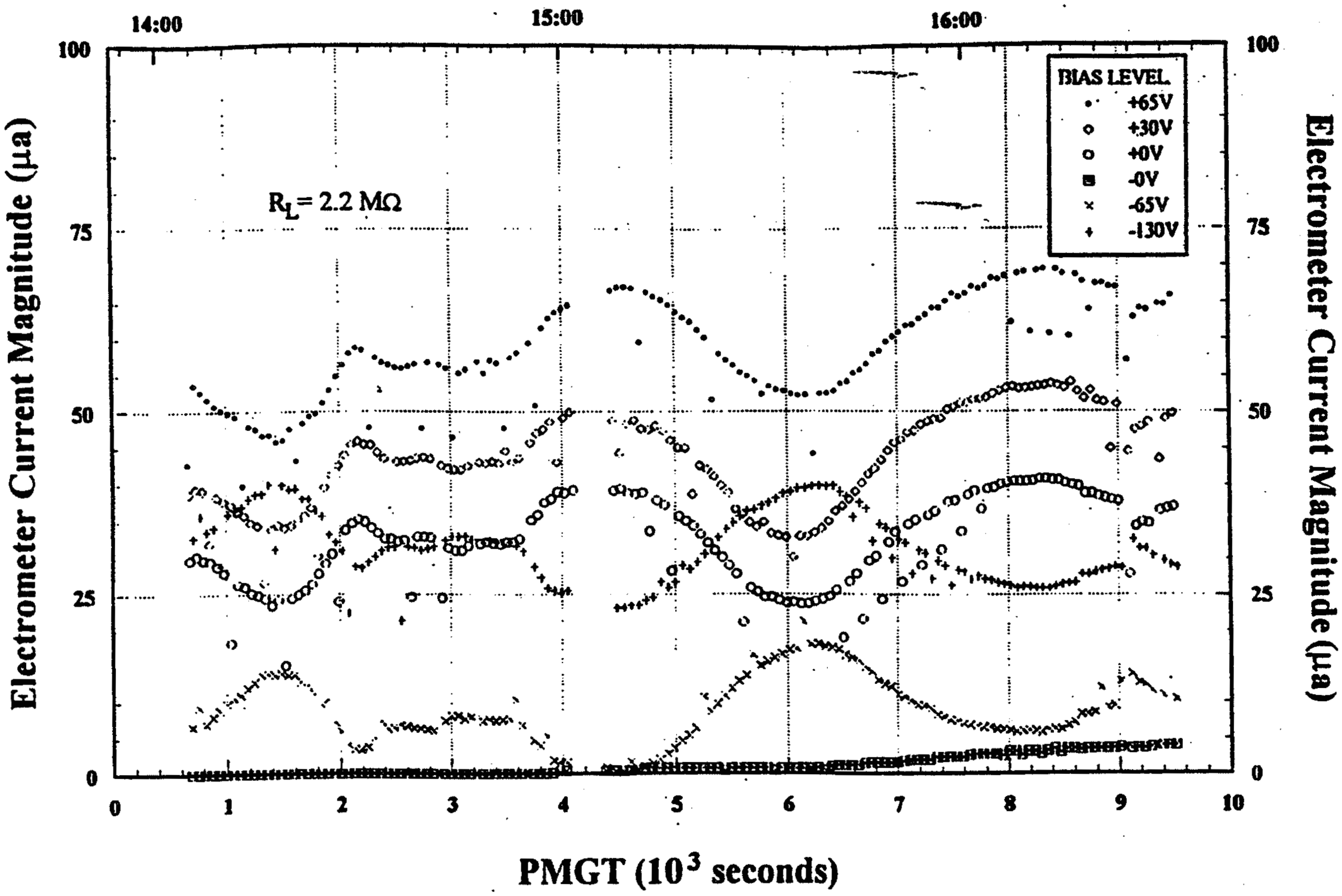


Figure 7. Electrometer current for 2.2 M Ω Load and all bias voltages (linear).

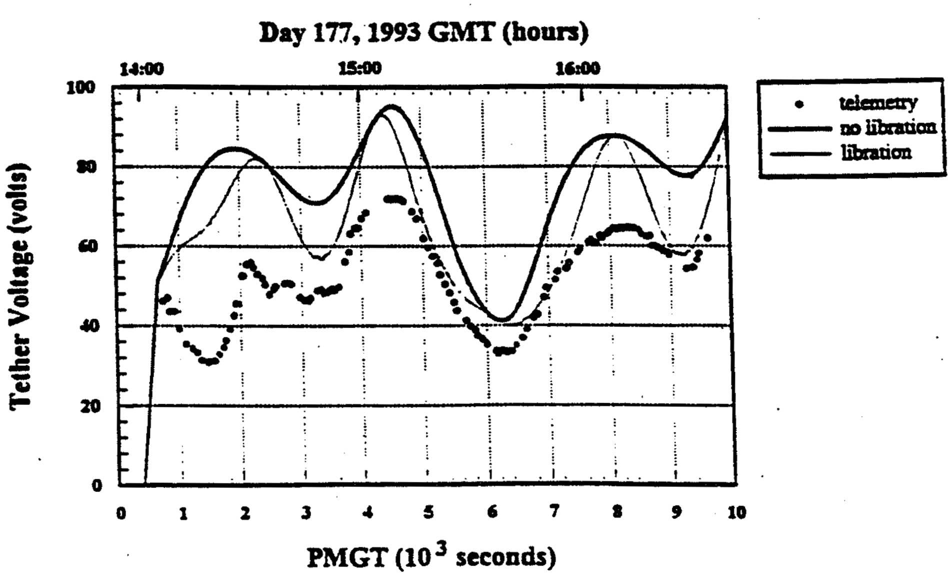


Figure 8. Tether voltage profiles using $\overline{L}\cdot\overline{V}\times\overline{B}$ compared with onboard measurements.

CONCLUSIONS

- The basic properties of power generation and thrust generation by an electrodynamic tether equipped with plasma contactors at each end have been proven by the PMG mission.

- The PMG flight has shown that the electrodynamic effects are strongly dependent upon the sun-lit conditions of the orbit, and almost disappear on the night-side. Most likely, the electron density of the ionosphere, with its day/night dependency, is tha cause of this phenomenon.

- Practical uses of electrodynamic tethers must take into account this variability, that has emerged as a limiting factor of significance. Energy storage, power conditioning, and current stabilization represent possible avenues of search, to make electrodynamic tethers practical and useful.

Tether Current-Voltage Characteristics

As Determined by Hollow Cathode Operation Modes

By R. C. Olsen, Chung-Jen Chang, Chia-Hwa-Chi
Naval Postgraduate School

Current-Voltage characteristics of the Delta-PMG experiment

Based on the hard work of Jim McCoy, et al, at NASA/JSC

Largely based on the thesis:

Electrodynamic behavior of PMG-Delta, Chung-Jen Chang, June 1994

PMG-Delta provided tether potential measurements: 11.

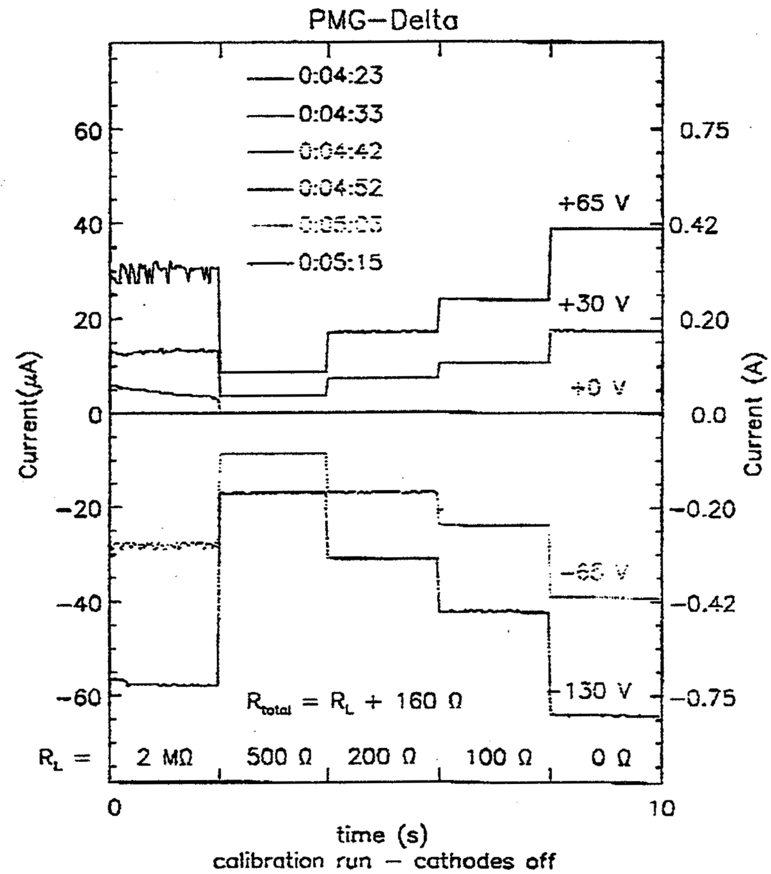
The current through a 2 MΩ resistance was used to determine the tether voltage.

This potential could then be taken as the applied potential for subsequent current measurements at lower resistances, assuming the plasma impedance did not change

The current could be measured with bias potentials from +65 to -130 V.

12.

The first figure (1) shows the calibration mode measurements, prior to the release of the Far-End-Package (FEP). Here, the induced tether voltage is zero - only the bias is observed. This plot illustrates the basic data frame, or cycle, with sweeps of bias voltage and load resistance



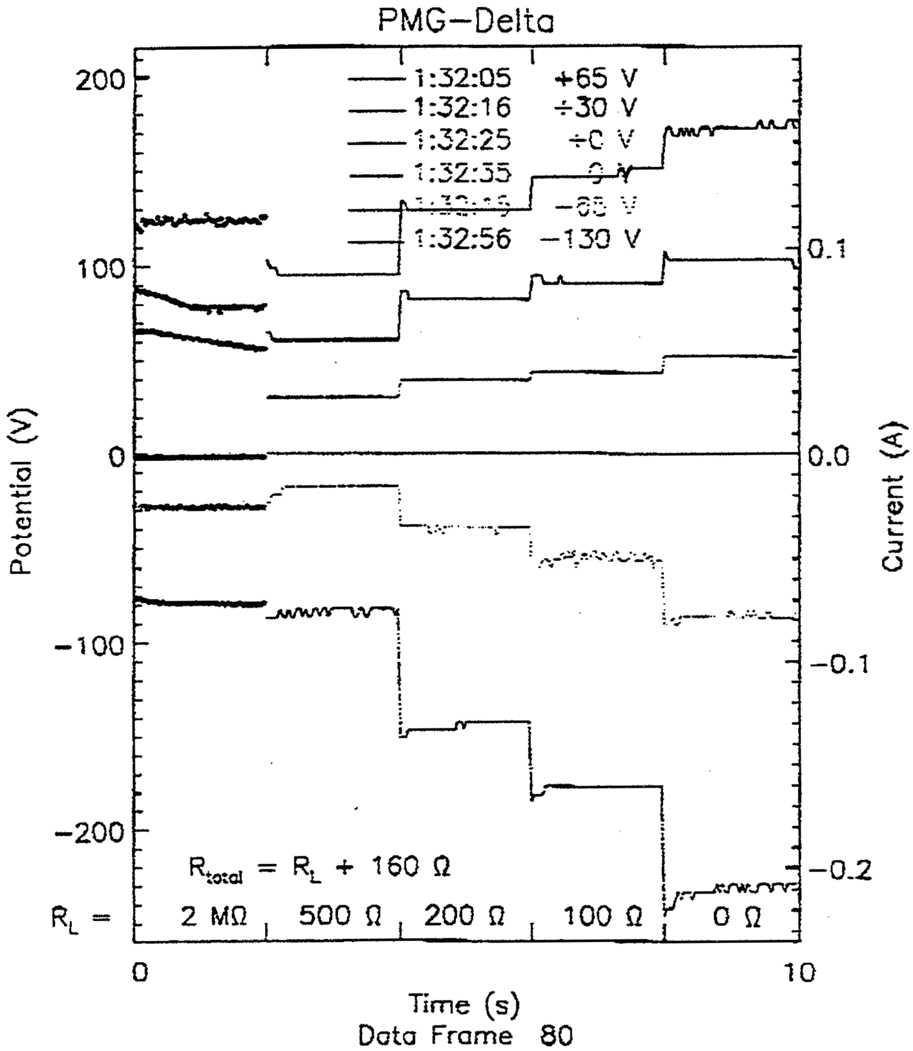
Naval Postgraduate School 21—May—1994 16:59:31.00

(1)

Tether Current-Voltage Characteristics

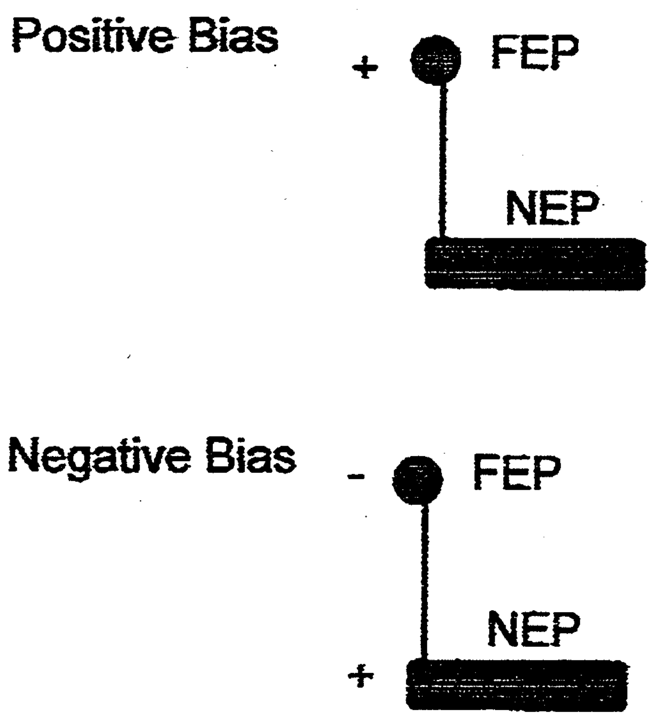
The largest currents were observed in daylight.

The largest VxB induced potentials were in the +60 V range, leading to peak currents of ~+0.15 Amperes. The second figure (2) shows the measurements at ~1.5 hours into the mission. Note that the negative bias producing a net tether voltage of ~-80 V, produced a peak current 0f -0.2 V



Naval Postgraduate School 16—Feb—1994 09:03:43.00

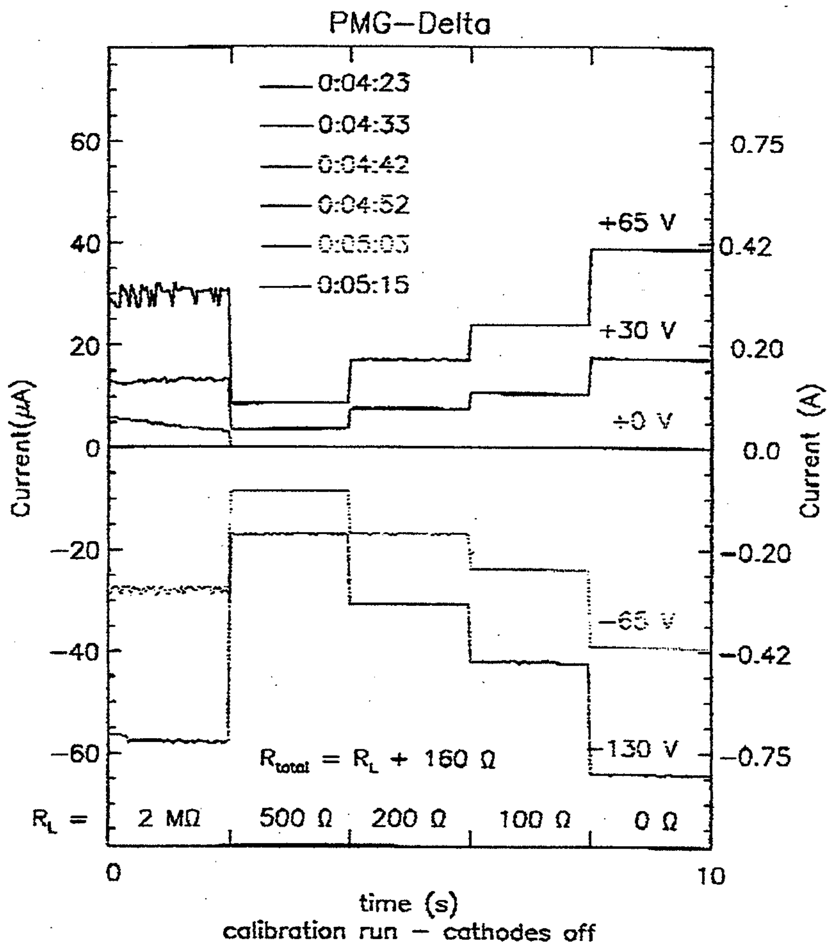
There are effects due to the larger size of the Delta Rocket body



Summarizing the voltage measurements, we find traces which are well explained by calculations of VxB (Figure 3)

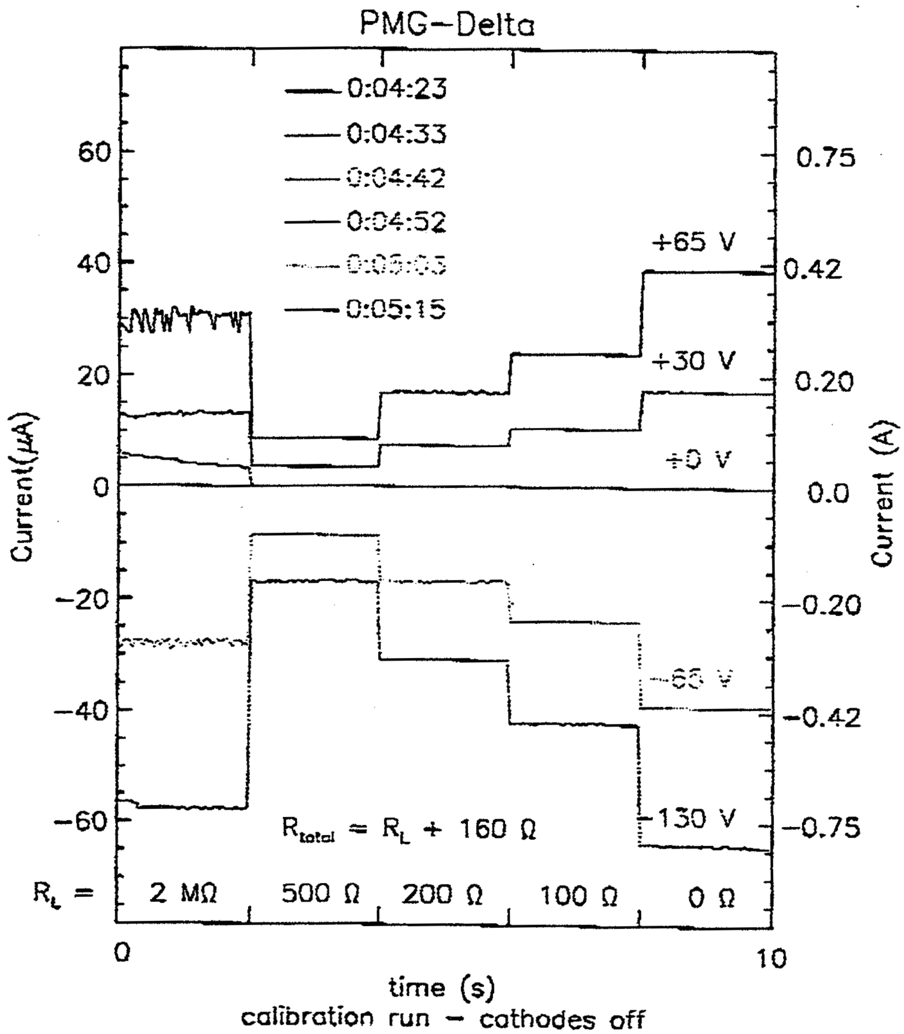
(e.g. Katz et al).

with the exception of the many small spikes. (Note that the apparently wide vertical extent of the measurements at +30 and +0 V bias are due to variations in potential of a capacitor in the bias circuit early in each frame.)



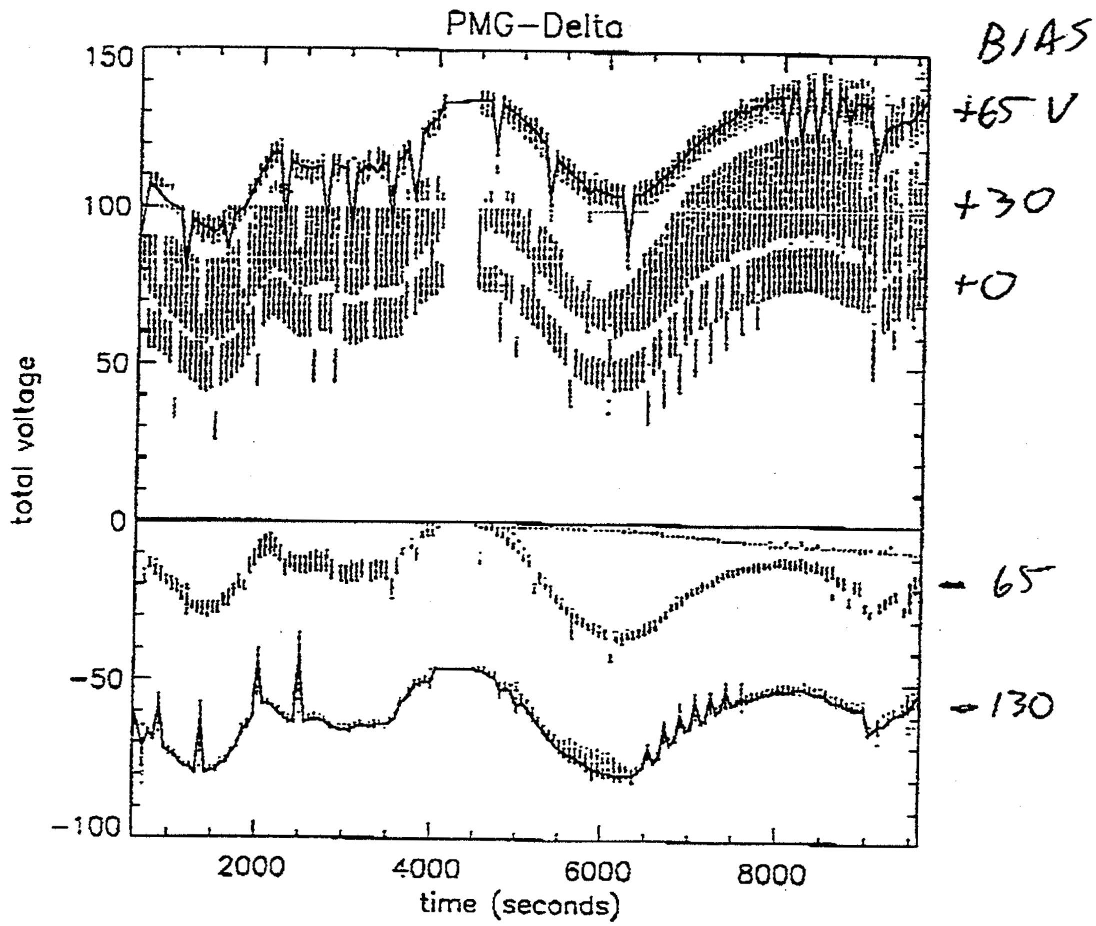
Naval Postgraduate School 21–May–1994 16:59:31.00

(1)



Naval Postgraduate School 21−May−1994 16:59:31.00

2a

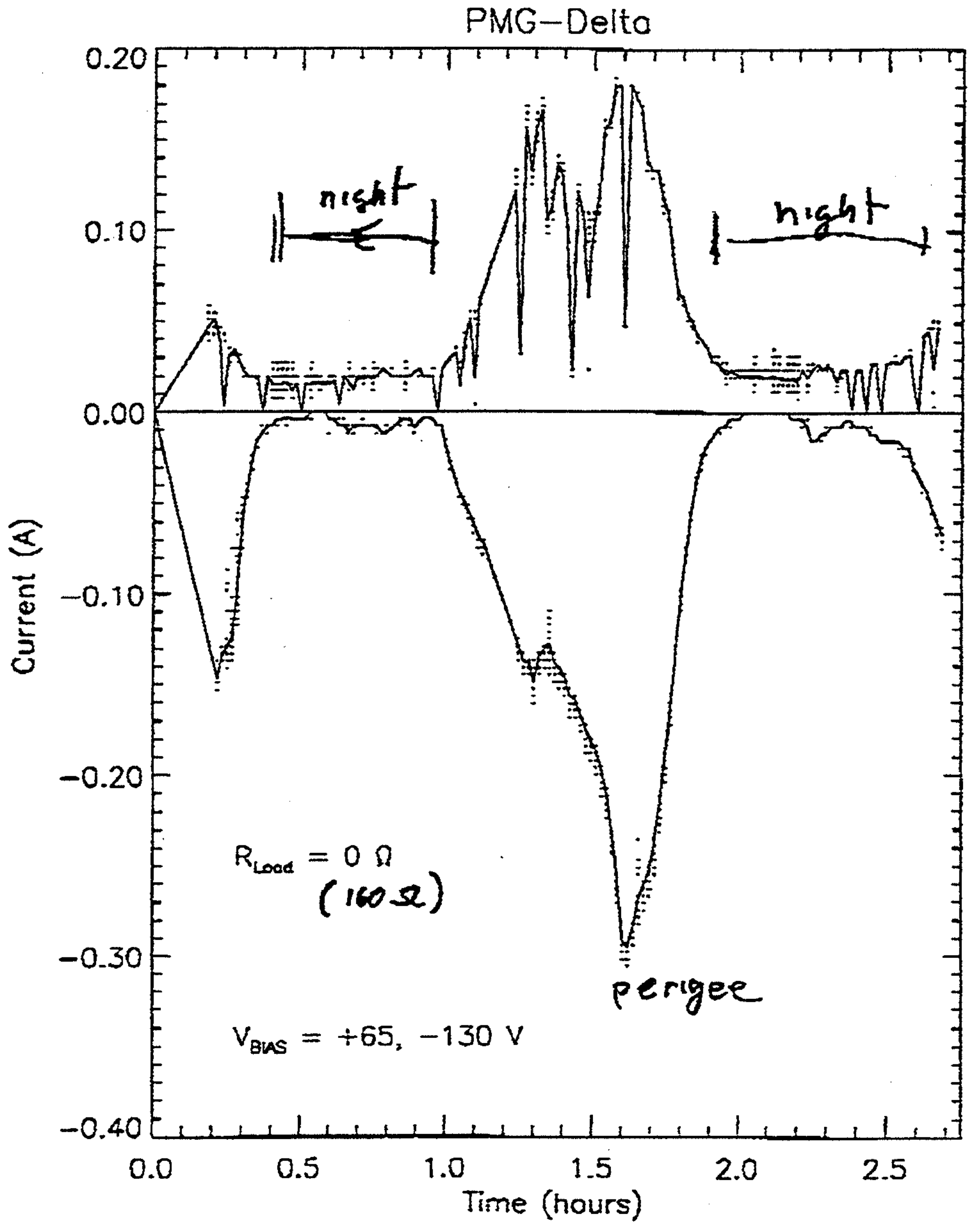


Naval Postgraduate School 11-Sep-1993 19:03:33.00

Current measurements are summarized in the next figure (4).

They do not directly follow the potential curves, because the influence of local time (illumination) and altitude determine the plasma density - which strongly affects the current.

The current collected at -130 V bias is a fairly smooth curve, the +65 V bias data show several drop-outs. This will be addressed below.

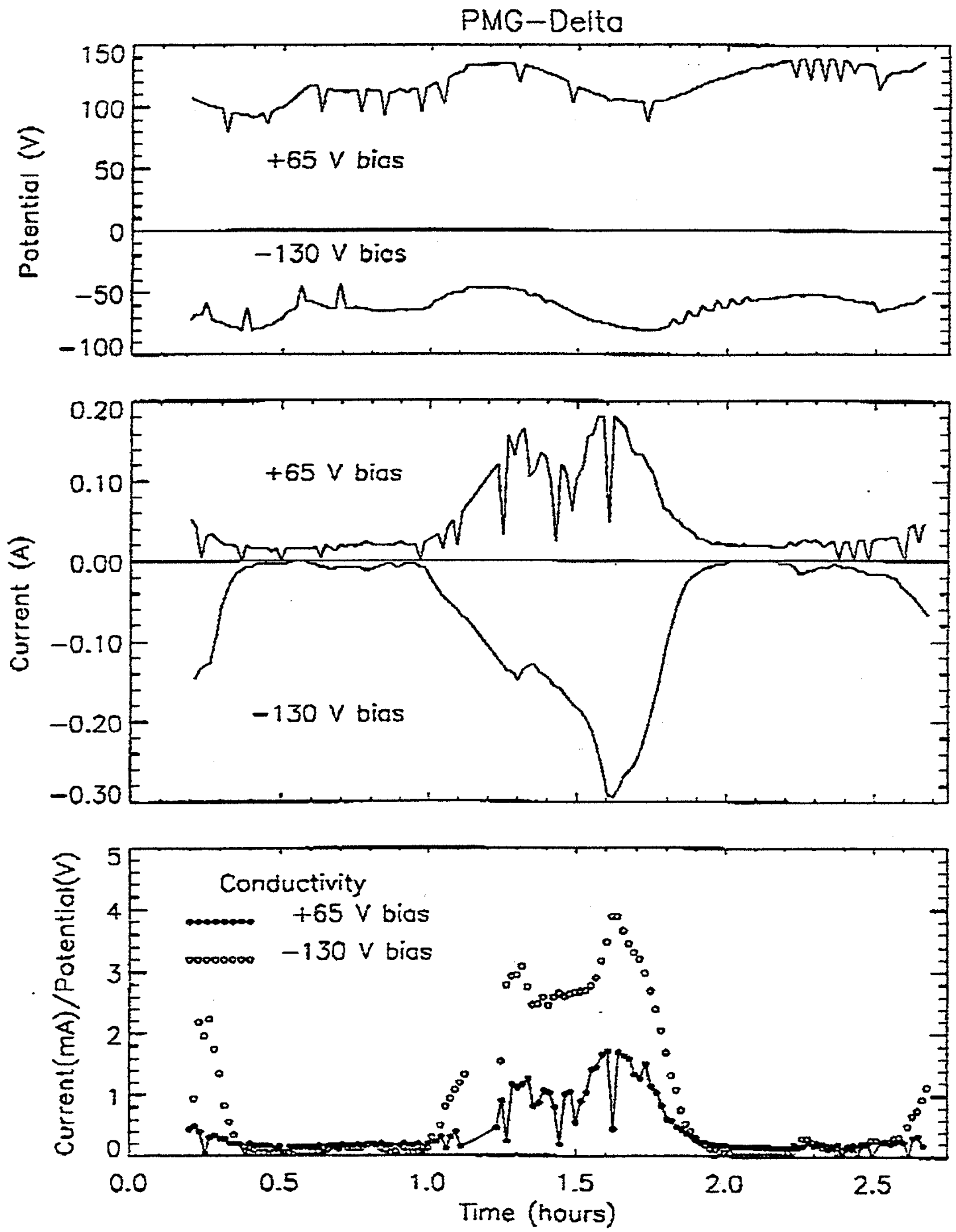


Naval Postgraduate School 5-Dec-1993 17:22:54.00

The conductivity is considered in the next figure (5).

The ratio of the current measured at 160 Ω and the potential measured at 2 MΩ is taken as a measure of the conductivity. Note again that this presupposes no major changes in plasma sheath impedance (voltage drop) with current - not necessarily a good assumption.

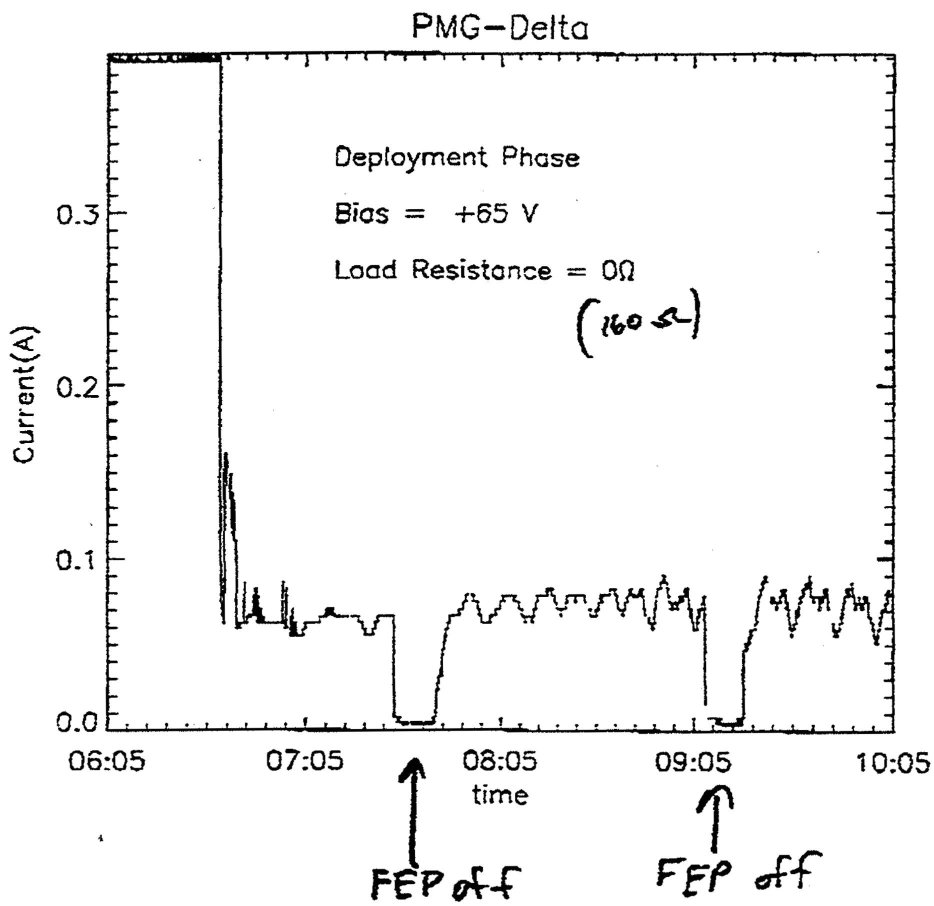
The impedance is low in daylight, at high currents, and rises dramatically in darkness - thousands of Ohms or greater, even with hollow cathodes operating


PMG-Delta
Potential (V)
150
100
50
0
-50
-100
+65 V bias
-130 V bias
Current (A)
0.20
0.10
0.00
-0.10
-0.20
-0.30
+65 V bias
-130 V bias
Current(mA)/Potential(V)
5
4
3
2
1
0
Conductivity
+65 V bias
-130 V bias
0.0
0.5
1.0
1.5
2.0
2.5
Time (hours)

Current Dropouts in the +65 V bias mode correspond to cycling in the FEP hollow cathode (plasma contactor).

The FEP was set on a 90 second cycle of 80 seconds on, 10 seconds off. During the off cycle, relatively small currents flow.

The next figure (6) shows early deployment mode data, where the bias is fixed at +65 V, and the load resistance is at a minimum.

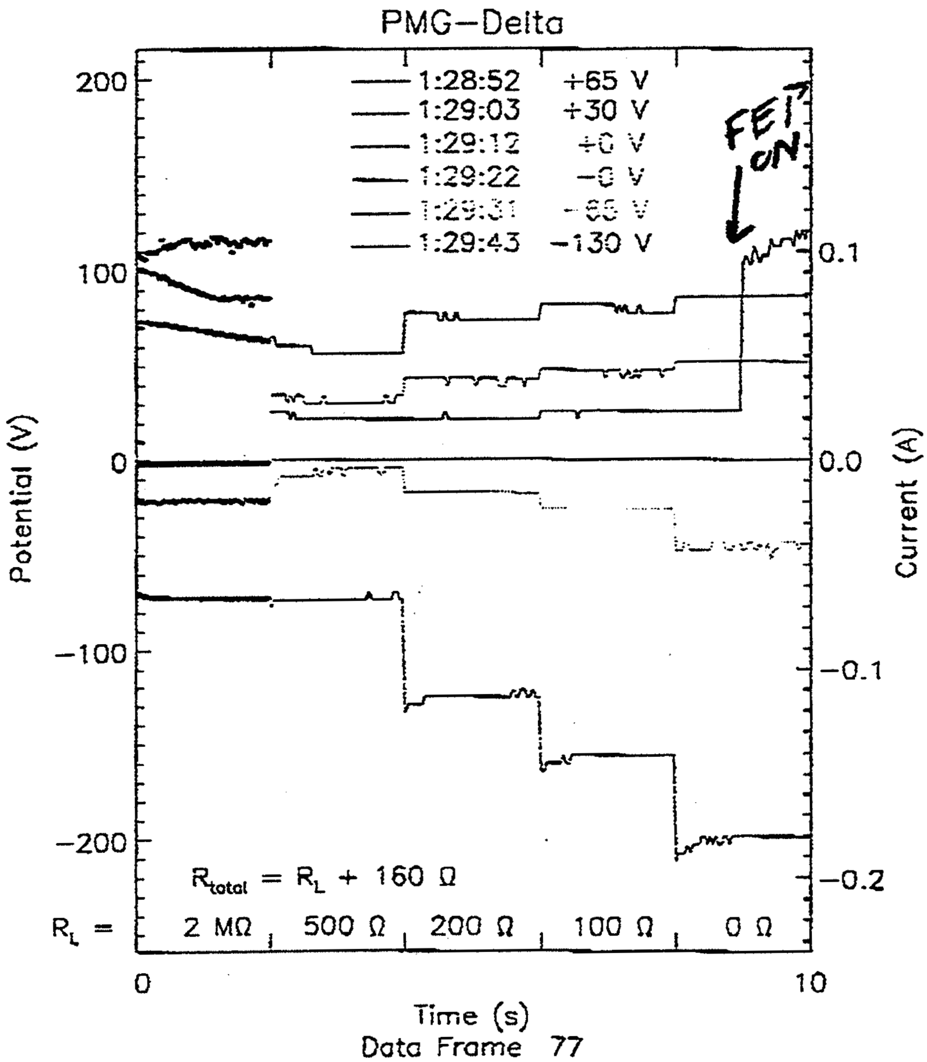


Naval Postgraduate School 13−Jun−1994 12:50:39.00

The same behavior is found throughout the mission.

The next figure (7) shows what happens in a regular data frame, when the FEP cycles on. The current measured at 0 Ω load resistance increases dramatically. Note that this data frame comes shortly prior to the first illustration, coming near perigee, at a time of peak currents.

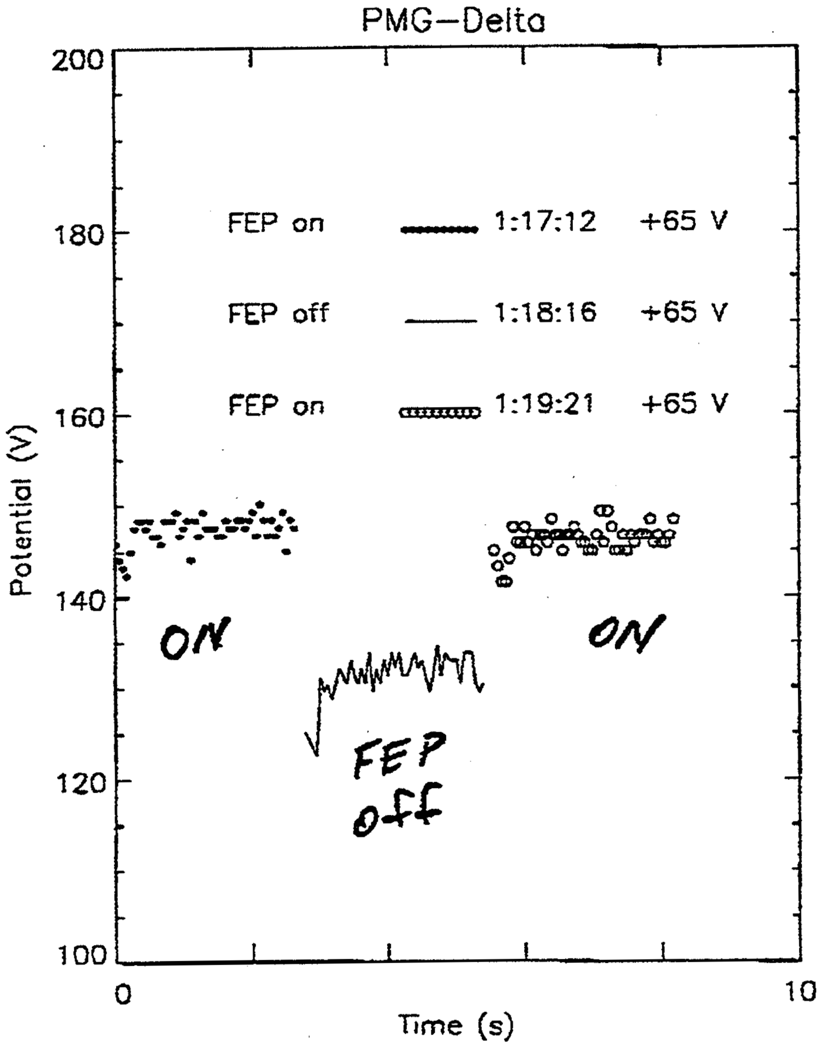
It appears that the FEP has trouble collecting electrons, when the hollow cathode shuts off.



Naval Postgraduate School 5—Dec—1993 16:08:02.00

The tether potential measurement also changes.

Potential measurements at +65 V bias are shown in the next figure (8). Data from three consecutive frames are shown, separated by 64 seconds. In the center frame, the FEP is off, in the adjacent frames, the FEP is on. The decrease implies a plasma impedance of magnitude comparable to the 2 MΩ load resistance - e.g. ~ 1 MΩ.

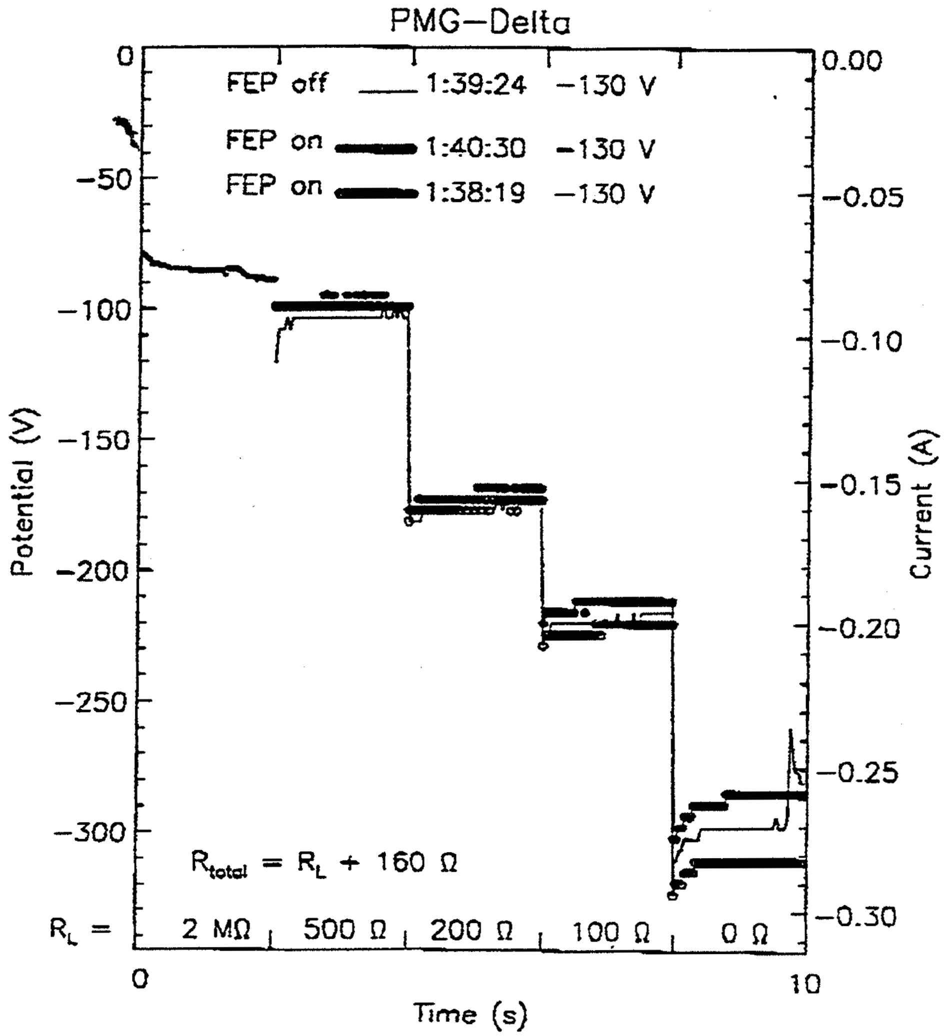


Naval Postgraduate School 25-May-1994 11:33:16.00

Such changes are not found in the -130 V bias data.

The last figure (9) shows data from three consecutive frames, again in the period of peak currents. The thin line is for FEP off data, the two thicker lines are the adjacent intervals during which the FEP cathode is on.

We have the curious result that the FEP can either emit copious electrons in this mode (possible), or it can collect substantial ion currents.


PMG—Delta
FEP off 1:39:24 −130 V
FEP on 1:40:30 −130 V
FEP on 1:38:19 −130 V
Potential (V)
Current (A)
0
−50
−100
−150
−200
−250
−300
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
−0.30
R_total = R_L + 160 Ω
R_L = 2 MΩ | 500 Ω | 200 Ω | 100 Ω | 0 Ω
0
10
Time (s)

Conclusion

The hollow cathodes allow for substantial current collection (emission) at relatively low impedance (a few hundred Ohms at perigee, in sunlight)

There is a larger dependence on ambient plasma density than was expected.

The FEP is unable to collect significant electron currents when the hollow cathode discharge is off - seems to discount effectiveness of so-called 'ignited-mode'. It is not enough to simply emit neutral gas...

HAWAII-HILO GROUND OBSERVATIONS ON THE OCCASION OF THE PMG FLIGHT OF JUNE 23, 1993.

FURTHER SPECTRAL ANALYSIS

Cinthya Ottonello*, Giorgio Tacconi*, Sergio Pagnan** and Luca Minna***

* Dipartimento di Ingegneria Biofisica ed Elettronica-University of Genoa
Via all'Opera Pia 11A, 16145 Genova, Italy.

** Istituto di Automazione Navale- National Research Council of Italy
Torre di Francia-Via De Marini 6, 16149 Genova, Italy.

***Advanced Engineering Technology-Torre A Corte dei Lambruschini-P.zza Borgopila 40
16126 Genova-Italy

ABSTRACT

The analysis of the data collected during PMG flight of June 26, 1993 has been recently extended to cover a time interval during which the PMG was not in orbit, namely the 15 minute interval prior the deployment.

The spectral analysis has shown recorded spectra with line-to-line separation of 0.1 Hz (as observed close to CPA 1), that in such frequency ranges as 48-52 Hz, 164-169 Hz, and 199-201 Hz are not present when the PMG was not in orbit. The current switching of PMG tether occurred at a rate of about one switch every ten seconds. The anomalies noticed in the recorded spectra could be local interferences that occurred by chance at a time close to CPAs. However, it should be noticed that these anomalies are suggestive of the possibility that the observed 0.1 Hz line-to-line separation in the spectrum be the time reversal of the current switching rate.

We will continue the spectral analysis to include the vertical and East-West axis data of our SQUID magnetometer (thus far, only the North-South component has been processed). We wish to remark that our listening had been postulated under the assumption that the tether current, by means of the on-board programming directions, would have acquired periodically an intensity of several Ampere, an occurence that did not materialize due to a switching malfunction in the payload.

DATA ANALYSIS RESULTS

During the Plasma Motor Generator (PMG) flight on June 26, 1993 a ground station, using a Superconducting QUantum Interference Device (SQUID) magnetometer[1,2], was installed at Hilo (Hawaii Islands), to provide experimental evidence of the possibility of revealing signals due to the occurrence of high intensity currents in the tethered satellite.
Measures included about 4 hours of data collected during satellite deployment and about 15 minutes of noise only data. Measures on current Basic Data Frames produced in the tether were also provided by the PMG P.I.[3]. Reconstructed current shape consists of a sequence of frames, extending 60" each. Each frame includes a sequence of states, the state-to-state switching rate is about 10".
In Fig. 1 an example of some single Basic Data Frames is plotted. Each frame should have been ended by a *High-Current* state, that was not obtained due to a payload malfunction (for shape reconstruction it was assumed to be proportional to the last measured current state).

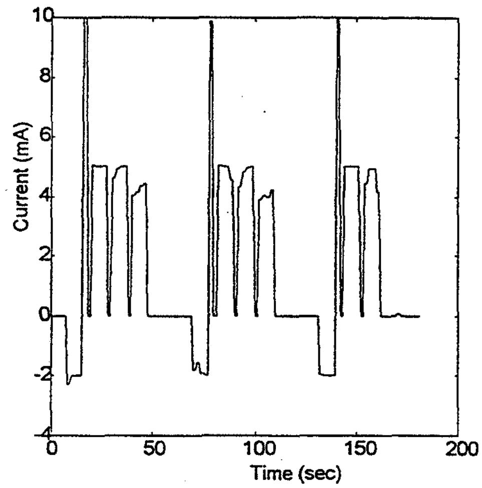


Figure 1: Sequence of Current Basic Data Frames.

Analysis was focused on some records of data containing events of particular interest, that is: the 1st and 2nd Closest Points of Approach (CPAs), that is the time intervals when satellite ground tracks are relatively close to measurement situ (M.E.T. 0:59 and M.E.T. 2:41, respectively); and the time interval when higher current values were observed in the tether.
Assuming that possible signals propagating from orbiting tether down to the Earth's surface would have been perturbations affecting background noise, data analysis was approached by comparing data collected during satellite deployment to noise-only data, measured before tether deployment.
Interesting but unexplained disturbances were observed by examining the changes of data power spectra over time.
The main results of the comparative analysis are briefly described in the following figure comments[4].

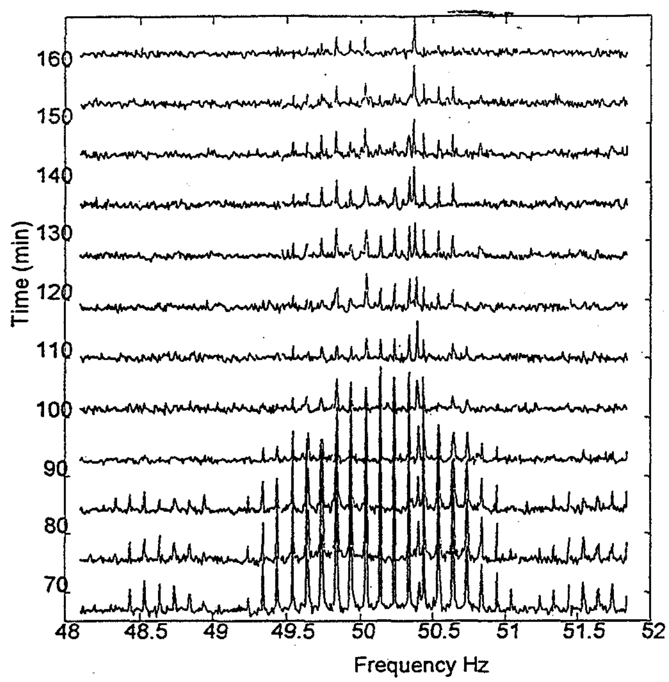


Figure 2: Variation of Power Spectra over Time. SQUID data from M.E.T 1:06 to M.E.T. 2:41.

Figure 2 includes the power spectra of about one and a half hours worth of data, observed in the selected band [48, 52] Hz (associated with the x axis) and in the time interval from M.E.T 1:06 to M.E.T. 2:41 (associated with the y axis).

Each line of the graph corresponds to the spectrum of about eight minutes of signal. The first line and the last lines of the graph are related to the 1st and 2nd CPAs, respectively.

In such frequency range, the power spectra are affected by the presence of impulses, that are suggestive of the occurrence of periodic signals in time domain. It is worth noting that, in the current measures collected aboard satellite, two kinds of periodicity are present : the periodicity of the Basic Data Frames, that is 60" (=1/60 Hz) and the periodicity of the state-to-state current switching, that is 10" (=1/10 Hz). The impulse-to-impulse distance in the observed power spectra is about .1 Hz.

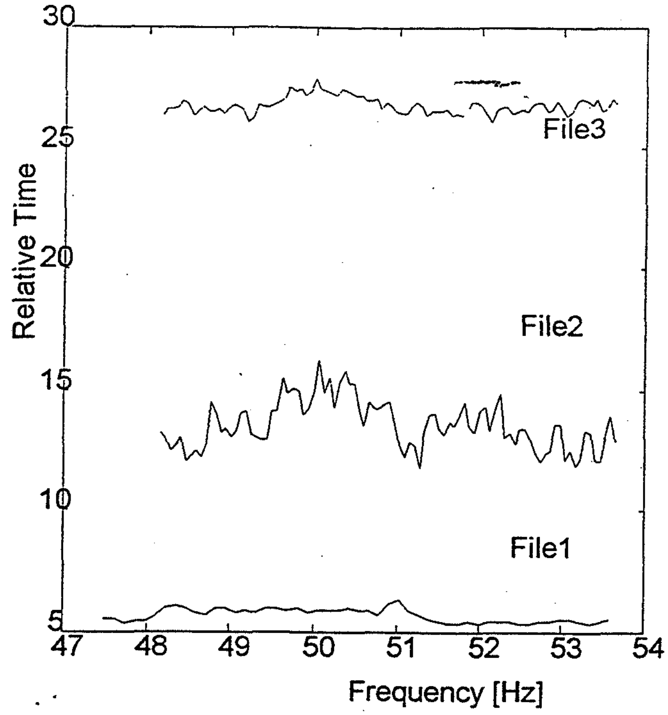


Figure 3: Variation of Power Spectra over Time. SQUID noise-only data.

The same analysis procedure was repeated for noise-only data. In this case, three time records extending for about 5' each, were available. The power spectra of each time record was estimated and the same frequency band of Fig.2 was examined, in order to verify whether the above anomalies were present also before tether deployment. No significative perturbations were observed for noise-only data.

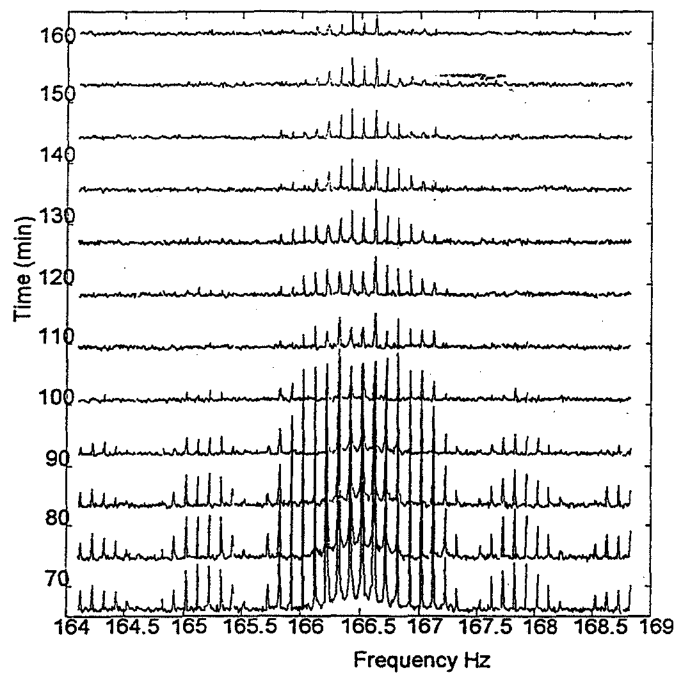


Figure 4: Variation of Power Spectra over Time. SQUID data from M.E.T 1:06 to M.E.T. 2:41.

The above analysis was performed in the frequency range [164,169] Hz. In this case, the spectrum shape may be interpreted as a *sinc-type* envelope, with a main lobe and some sidelobes. Such frequency-domain shape is related to the occurence of square waves in the signal, when observed in time domain.

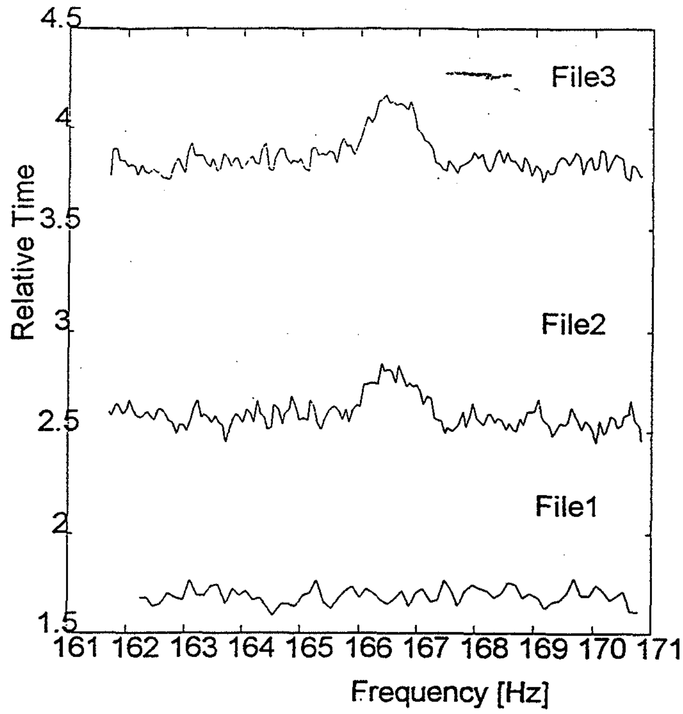


Figure 5: Variation of Power Spectra over Time. SQUID noise-only data.

The comparison with noise-only data spectra do not provide evidence of such phenomenon.

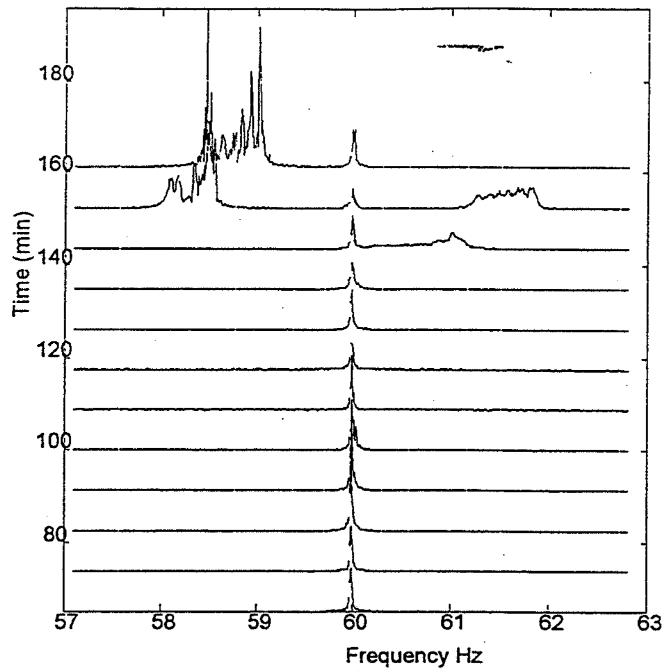


Figure 6: Variation of Power Spectra over Time. SQUID data from M.E.T 1:06 to M.E.T. 2:41.

In the frequency range [57, 62], a narrow-band interference overlapped to background noise was detected. Its power is too large with respect 60 Hz harmonic, to allow a correlation of such narrow-band signal to tether emissions, that are to be expected much weaker than 60 Hz.

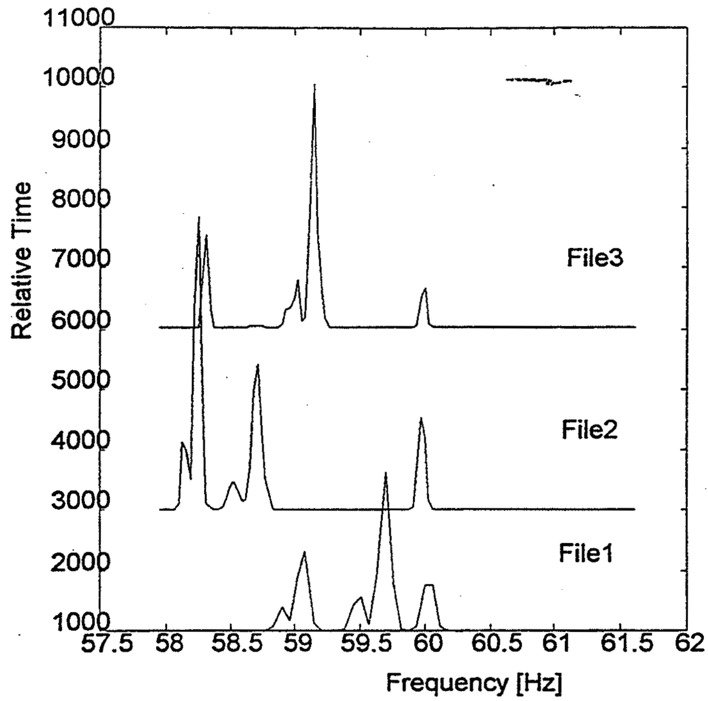


Figure 7: Variation of Power Spectra over Time. SQUID noise-only data.

An interference similar to Fig. 6 is observed in background noise.

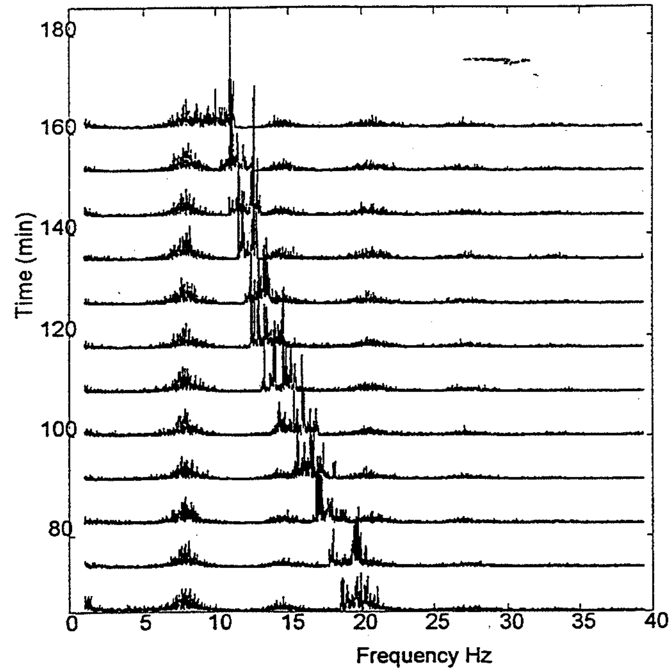


Figure 8: Variation of Power Spectra over Time. SQUID data from M.E.T 1:06 to M.E.T. 2:41.

It shows the power spectra from DC to 40 Hz. Schumann resonances can be clearly recognized; they provide proof of the proper functioning of the instruments. An interference drifting in frequency is present over the all time record analysed.

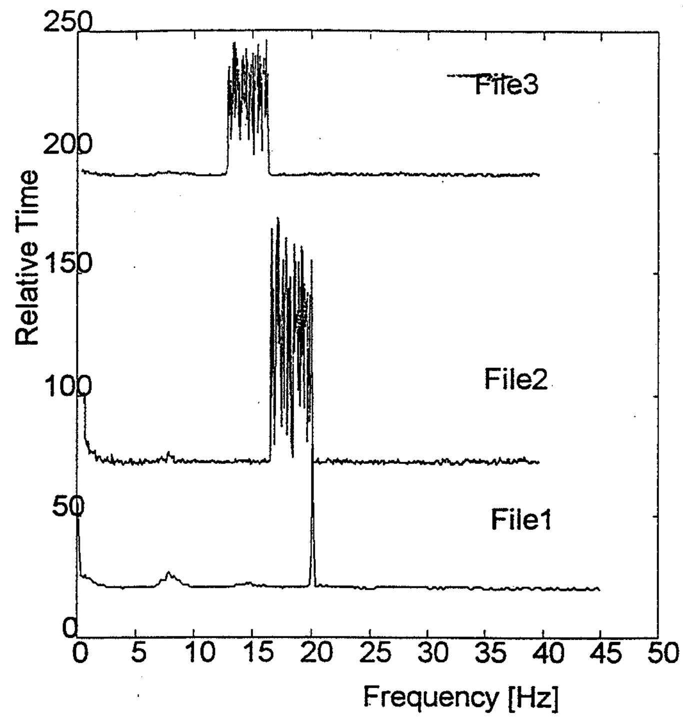


Figure 9: Variation of Power Spectra over Time. SQUID noise-only data.

As concerns the anomaly observed at about 20 Hz, we can definetely confirm that such a disturbance is an interference not related to PMG currents, since the same perturbation was observed in data collected before payload deployment.

CONCLUSIONS

Based on the above results, we are not able to conclude that a clear evidence of ground reception was obtained. However, a possible correlation between the observed spectra .1 Hz line-to-line distance and the 10" current frame switching rate can be deduced.

This analytical approach and its interpretation will be useful as historical reference for similar future experimental attempts.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Mario Grossi for his extremely informative discussion on the work.

REFERENCES

1. Carelli P., Foglietti V., Leoni R., Pullano M."Reliable Low Noise DC-Squid", *IEEE Transactions on Magnetics* vol.25, no.2, pp. 1026-1029, 1989.

2. 2G ENTERPRISES, *Model 581 DC SQUID User's manual and technical reference.*

3. McCoy J.E. and Grossi M.D., "Tether electrodynamics from the Plasma Motor Generator (PMG) mission of June 1993", *Proceedings of Round Table on Tethers*, pp. 260-277, Nordwijk, 1994.

4. L. Minna, C. Ottonello, S. Pagnan, G. Tacconi, "Emissions from TSS1 and PMG tethered satellite systems to the Earth's surface: signal analysis", *ESA International Round Table on Tethers in space*, September 28-30, 1994, Noordwijk, The Netherlands, pp. 373-378.