Plasma turbulence enhanced current collection: Results from the plasma motor generator electrodynamic tether flight

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Abstract. The plasma motor generator (PMG) experiment, launched June 26, 1993, was a tethered system of two identical plasma contactors connected via a 500-m conducting tether. The experiment was designed to demonstrate the ability of plasma contactors to provide a low-impedance connection between a spacecraft and the ionosphere for both the electron emission and collection. The flight data indicate that plasma contactors enhance electron collection and emission by both neutralizing the electron space charge and scattering electrons across the geomagnetic field lines. Up to a 0.3 A steady current flowed along the tether in a circuit completed through the ionosphere. An analytical model for plasma contactor interaction with a background plasma which incorporates electron scattering by plasma waves is compared with the flight data. Good agreement between the model and the data is achieved for an effective scattering frequency equal to one twentieth of the local plasma contactor plasma frequency.

Introduction

The plasma motor generator (PMG) experiment was launched piggyback on the second stage of Delta 221 at 0927 (LT) on June 26, 1993. The primary purpose of the mission was to verify that plasma contactors (PC) provide a low-impedance contact between the spacecraft and the low-Earth orbit (LEO) ionosphere. A plasma contactor is a device that emits a dense, low-temperature plasma cloud through which ions and electrons are emitted and, when biased positively, electrons are collected from the surrounding plasma [McCoy et al., 1993; Williams et al., 1989].

In the PMG system, there were two hollow cathode-based plasma contactors with a differential voltage between them. One remained attached to the Delta 2 as part of the near end package (NEP), and one was deployed at the end of a 500-m conducting tether as part of the far end package (FEP). The plasma contactors were part of a current loop that passed from the ionosphere through the FEP, the tether, the load, the battery, the NEP, and back to the plasma (see Figure 1). One of the plasma contactors acted as a positive current source and the other as a negative current source. The current-voltage curve of the plasma contactors in the changing space environment was determined by measuring the current through the tether as various resistances and voltages were inserted into the circuit.

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Plasma Contactor Theory

Plasma contactors provide a low-impedance conduction path from a space system to the ambient space environment by neutralizing the electron space charge. The plasma contactors on PMG were hollow cathodes operating on Xenon. The hollow cathodes consist of a quarter inch in diameter insert region through which flows an ampere equivalent of Xenon atoms. The insert is a specially treated surface which is a good thermionic emitter of electrons. The electrons flow through a small orifice, where they ionize a fraction of the Xenon gas, to the keeper anode and to space (see Figure 2). The keeper is about +20 V with respect to the cathode insert. The keeper current for these hollow cathodes was measured both in the laboratory and in space to be about 1 A.

In electron emission mode the electrons from the plasma contactor carry the current while the contactor ions neutralize the electron space charge. In the contactor plasma the electron density is approximately equal to the ion density. The higher energy electrons stream through the slowly expanding ion cloud, while the lower energy electrons are trapped within the cloud by the keeper potential. The high electron velocities lead to electron currents much greater than the Xenon ion currents.

Below the electron emission saturation limit the contactor acts as a bipolar emissive probe. Each outgoing ion generated by an electron allows a number of electrons, which is approximately equal to the square root of the ratio of the ion mass to the electron mass, to be emitted [Parks et al., 1993]. When the plasma contactor is collecting electrons from the ionosphere, the contactor ions once again neutralize the electron space charge, in this case the space charge of
ambient electrons. The contactor plasma is extremely turbulent due to current-driven electrostatic instabilities in the orifice region. Incoming electrons are scattered by the contactor plasma and can be collected across the geomagnetic field lines out to an effective radius [Vannaroni et al., 1992; Hastings, 1987].

The plasma contactor scattering frequency has been observed [Vannaroni et al., 1992] to be proportional to the contactor plasma frequency

\[ V_{scat} \propto \alpha \omega_{pe} \]  

where \( \alpha \approx 0.1 \) [Vannaroni et al., 1992; Jongeward et al., 1994]. This scattering frequency of the electrons is also consistent with data which show that the electromagnetic interference (EMI) is proportional to the current fluctuations in the plasma contactor (B. Buchholtz and P. Wilbur, personal communication, 1992).

In order to collect electrons across the geomagnetic field lines, the scattering frequency must be greater than the electron cyclotron frequency [Hastings, 1987].

\[ V_{scat} \gtrsim \omega_{ce} \]  

The electron plasma and cyclotron frequencies are given by, respectively,

\[ \omega_{pe}^2 = 3180n_e \]  
\[ \omega_{ce}^2 = 1.76 \times 10^7|B| \]

where \( n_e \) is the electron density in cubic meters and \( |B| \) is the magnitude of the geomagnetic field in Gauss. Applying (1), (2), (3), and (4), the plasma contactor can collect electrons across magnetic field lines within a volume such that the density near the edge of the collecting volume is

\[ n_e \propto 9.7 \times 10^{10}|B|^2\alpha^2. \]

If we assume the volume is spherical (Particle code simulations show this to be a reasonable assumption), then the effective magnetic collection radius is

\[ r_{mag} = \left( \frac{I_i}{4\pi e^2 n_e \omega_{ce} v_i} \right)^{1/2} \]

where \( I_i \) is the rate at which the plasma contactor emits ions (in amperes) and \( v_i \) is the ion velocity. Calculations were done using the space station environment workbench (EWB) [Jongeward et al., 1989] with a model of the emitted and collected electron currents as a function of the plasma contactor parameters, the applied voltage, and the ionosphere plasma. The contactor current was determined from the characteristics of the contactors used by the experiment (anode potential and the gas flow) and the ambient plasma. The anode potential is the floating potential of the system plus the applied voltage, discussed below.

**PMG Experiment**

After separation of the third stage of the Delta 2 launch vehicle, the second stage was in an orbit with an apogee of 874 km, a perigee of 193 km, and an inclination of 26°. The second stage was positioned so that the FEP was oriented away from the Earth. The FEP was a 0.3 m × 0.3 m × 0.3 m keeler orifice plume keeper

**Figure 2.** Each PMG hollow cathode plasma contactor generates a plume of Xenon ions that neutralize the space charge of current-carrying electrons.
conducting box with a plasma contactor. The NEP, which also had a plasma contactor, remains fixed on the Delta 2. A plasma diagnostics package (PDP), which included two detectors, the small electron electrostatic analyzer (SESA) and the ion mass and energy analyzer (MESA), was fixed to the Delta 2 opposite the NEP. The surface of the Delta 2 included both conducting and insulating materials.

Batteries on board were used to bias the FEP up to +65 V and -130 V with respect to the NEP, in addition to the $v \times B \cdot \ell$ voltage difference induced along the tether. Resistive loads, in series with the tether, were also cycled through during the experiment.

The plasma contactors were identical and they were used to collect or emit electrons under different bias and load conditions, depending on their relative potentials. The current through the tether was the net effect of current flow through both plasma contactor clouds (one collecting and one emitting electron current) to the local ionosphere and the current collected from the ionosphere by the exposed conducting surfaces of the system, mainly on the second stage rocket body. When the electrons are collected at the FEP, the PMG system is in motor mode; otherwise, the electrons are collected by the NEP and the Delta 2 rocket body and the system is in generator mode.

The PMG plasma contactors used a neutral Xenon flow rate of 1 A equivalent. This gas was partially ionized to form a plasma at the keeper ring (which has a radius of 0.05 m) and, based on laboratory measurements and models, consists of about 0.025 A of ~10 eV ions and 1.5 eV electrons with a density of $3 \times 10^{15}$ m$^{-3}$.

**Flight Data**

The differential potential between the NEP and FEP is the sum of the geomagnetic field and the applied voltage. The raw measured voltages and calculated $v \times B \cdot \ell$ potential assuming a 500-m tether are shown in Figure 3.

The calculated ionosphere density for the PMG flight is shown in Figure 4. At 5791 s, PMG mission time, the environment models predict an electron density of $6 \times 10^{11}$ m$^{-3}$ and an electron temperature of 0.14 eV.

Electron collection by the FEP without a plasma contactor can be calculated using probe theory. The comparison of the calculated electron collection based on space charge limited collection and magnetic limited collection gives values of 10 mA and 28 mA, respectively, for 5791 s, PMG mission time. The measured electron collection is 180 mA, and the electron collection computed with the plasma contactor electron scattering model discussed above is 139 mA. Both the space charge limited and the magnetic limited theories predict currents an order of magnitude lower than those observed. Clearly, the plasma contactor increases the amount of current which can be collected from the plasma.

Figure 5 presents currents measured in flight and currents calculated using the model. The lower curves are when, in addition to the $v \times B \cdot \ell$, the FEP was biased to its maximum positive (+65 V) with respect to the NEP. The upper curves are when the FEP was biased to its maximum negative (-130 V) with respect to the NEP. The additional electron current collected by the rocket motors when the delta was positive accounts for the asymmetry between the curves. This effect is included in the model. The agreement with the model was
Figure 6. Comparison between PMG flight data and the turbulent scattering model with \( v_{\text{scat}} = 0.1 \omega_{pe} \), optimized by the choice of \( v_{\text{scat}} = 0.05 \omega_{pe} \). The same comparison, but with \( v_{\text{scat}} = 0.1 \omega_{pe} \), is shown in Figure 6. Note that the calculated currents do not precisely follow the density variations because changes in electron temperature affect the ionosphere electron current density and the magnetic field strength varies along the orbit. The model also ignores geometry and orientation effects and assumes spherical expansion of the contactor plume.

Conclusion

The PMG flight experiment demonstrated the feasibility of using plasma contactors to provide a low-impedance current path between tethered spacecraft and the ionosphere. Such contactor systems improve the performance of electrodynamic tether, plasma motor generator systems. The flight data showed that the contactor plasma aids current collection by neutralizing space charge and scattering electrons across magnetic field lines. Calculations using the analytical models with an effective collision frequency of \( 0.05 \omega_{pe} \) compare well with the data. A quantitative theory for the scattering frequency is yet to be developed.

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References


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