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# An Overview of Electrodynamic Tether Performance in the Jovian System

D. L. Gallagher
NASA Marshall Space Flight Center, Huntsville, Alabama

F. Bagenal
Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado, Boulder, Colorado

J. Moore
SRS Technologies, Huntsville, Alabama

L. Johnson
NASA Marshall Space Flight Center, Huntsville, Alabama

**Abstract**
The Jovian magnetosphere with its strong magnetic field and the rapid rotation of the planet present new opportunities and challenges for the use of electrodynamic tethers. An overview of the basic plasma physics properties of an electrodynamic tether moving through the Jovian magnetosphere is examined. Tether use for both propulsion and power generation are considered. Close to the planet, tether propulsive forces are found to be as high as 50 Newtons and power levels as high as 1 million Watts.

## Introduction

In recent years, tethers have come to offer significant opportunities in many low Earth orbit applications. Conducting and non-conducting tethers are being considered for electrical power and propulsion systems [*Johnson et al.*, 1996]. Conducting or electrodynamic tethers derive their properties as a result of the current flowing through a moving wire in a magnetic field and in the presence of a plasma or conducting medium. Tethers may be useful in any planetary system where there exists a magnetic field and a plasma through which current closure can occur.

But why Jupiter? The first inducement is the large Jovian magnetic field, much larger than that at the Earth. The real motivation, however, is the need for alternative power generation and propulsion techniques for future missions to Jupiter. Due to low solar luminosity, radioactive thermoelectric generators (RTG) have been used for electrical power in all past deep space missions. The finite risk of releasing plutonium into the terrestrial environment may rule out RTGs on future missions. The possibility of using solar panels for electrical power generation has improved in recent years. Even with improvements in this technology, however, extended exposure to high levels of radiation in the Jovian system are expected to rapidly degrade the effectiveness of solar arrays. Extended operations in the Jovian system, or around any planet, also typically require use of an expendable propellant for orbital maneuvering. This may lead to high "wet" spacecraft mass at launch and/or limited lifetime on orbit. It is for these reasons and because of the strong magnetic field and rapid planetary rotation that electromagnetic tethers are being considered for use in the Jovian magnetosphere. The purpose of this report is to determine whether electrodynamic tether usage is feasible from a plasma physics point of view. The engineering feasibility will be addressed elsewhere.

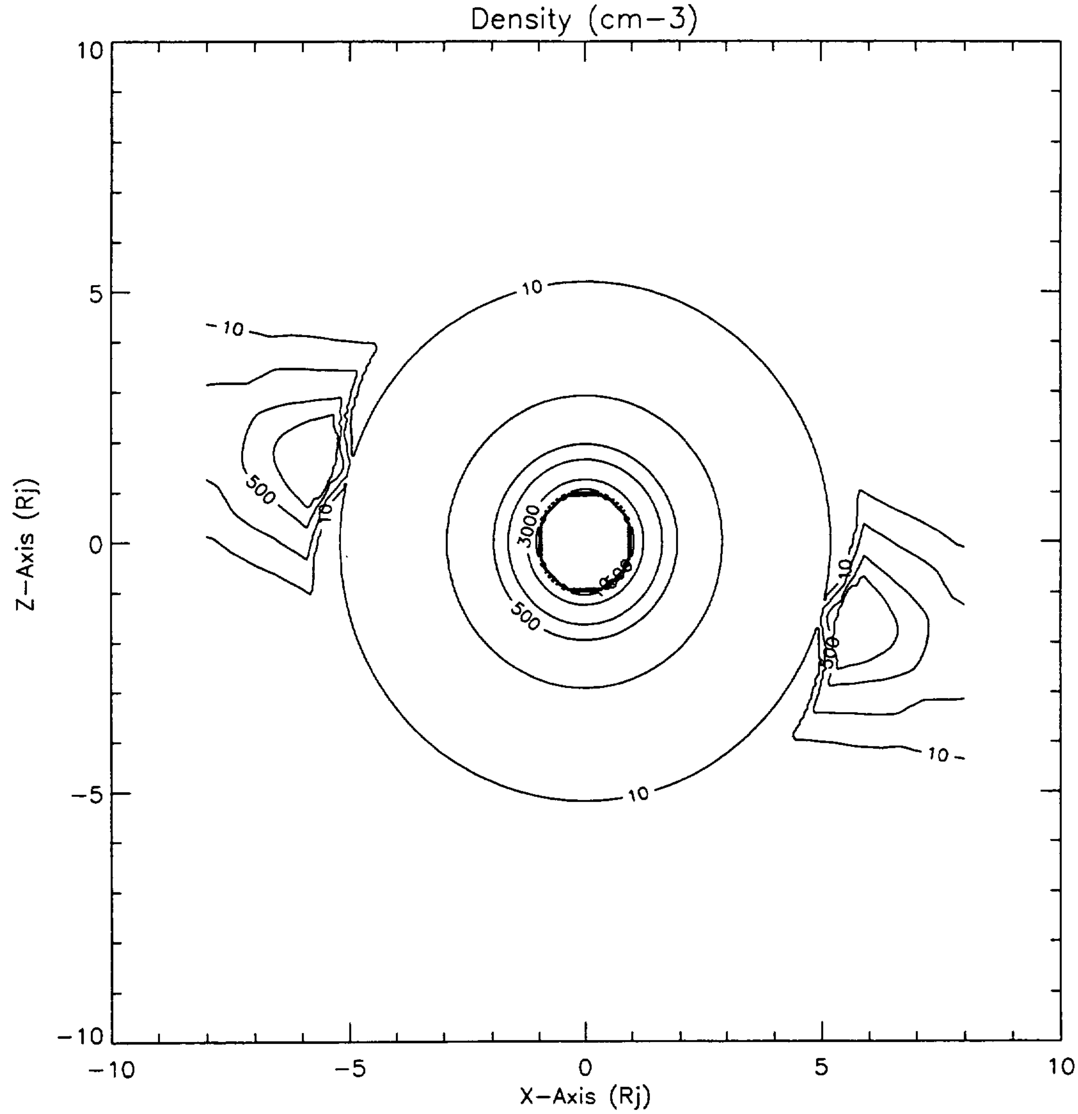
## Tether Physics at Jupiter

This report discusses the initial results of analyzing the performance of an electrodynamic tether in the Jovian planetary system. Tether modeling is based on results from the TSS-1R mission and the theories of *Parker and Murphy* [1967] and *Sanmartin et al.* [1993]. The computed tether performance represent maximum limiting current and resulting power estimates. The Jovian magnetic field model is obtained from *Khurana* [1997], consisting of the GSFC $O_6$ internal field model and an

Euler potential formulation for the external field. The plasma density model is a simplified version of that presented by *Bagenal et al.* [1994] and consists of a spherically symmetric distribution, plus an Io torus. The results also depend on several assumptions. The first is for the electron temperature, which is used to estimate the thermal current to the tether. The electron temperature is taken to be a fixed 10eV. Inside of 5Rj the electron temperature is only a few eV. Outside of this distance it is 10-50eV. That means the estimated current will be somewhat high inside this distance and low, outside this distance. Tether current varies with the square root of the thermal electron temperature, so is not tremendously sensitive to it. A tether length of 10km has been assumed, along with a cylindrical tether of 1mm diameter.

The analysis of electrodynamic tether performance is accomplished in two coordinate systems. One is the System III (1965) coordinate system, which rotates with the Jovian magnetic. Both the magnetic field and density models are defined in this coordinate system. The second is an inertial coordinate system, where the z-axis is along the planetary spin axis. Due to the preliminary nature of this study, no effort has been made to orient the x-axis of this inertial coordinate system toward the first point of Aries or any other inertial reference point. All results are shown graphically in the x-z plane of this work's inertial coordinate system. Each of the displays extend $\pm 8$ $R_J$ along the x and z axes and show constant level contours of various quantities.

The first plot is for total electron density, with constant density contours at 10, 100, 500, 1000, 3000, and 6000 $cm^{-3}$. It is made up of three components: inside the Io torus, the Io torus, and outside the torus. Inside and outside the torus the density falls of exponentially. Inside the torus, the density is derived from linear interpolations of a measured radial profile. The torus falls off exponentially away from the magnetic equator.




Induced tether current will depend upon the speed with which the tether moves through the Jovian magnetic field. That speed will depend on spacecraft motion around the planet ( $\vec{v}_{sc}$ ) and planetary rotation ( $\vec{v}_J$ ). For the purpose of initially exploring tether behavior, the spacecraft motion is assumed to result from a circular orbit at each radial distance and latitude where the calculations are made:

$$\vec{v}_{sc} = \left(\frac{GM_J}{r}\right)^{\frac{1}{2}} \left(-\sin(\theta)\hat{\theta} + \cos(\theta)\hat{\phi}\right) \quad (1)$$

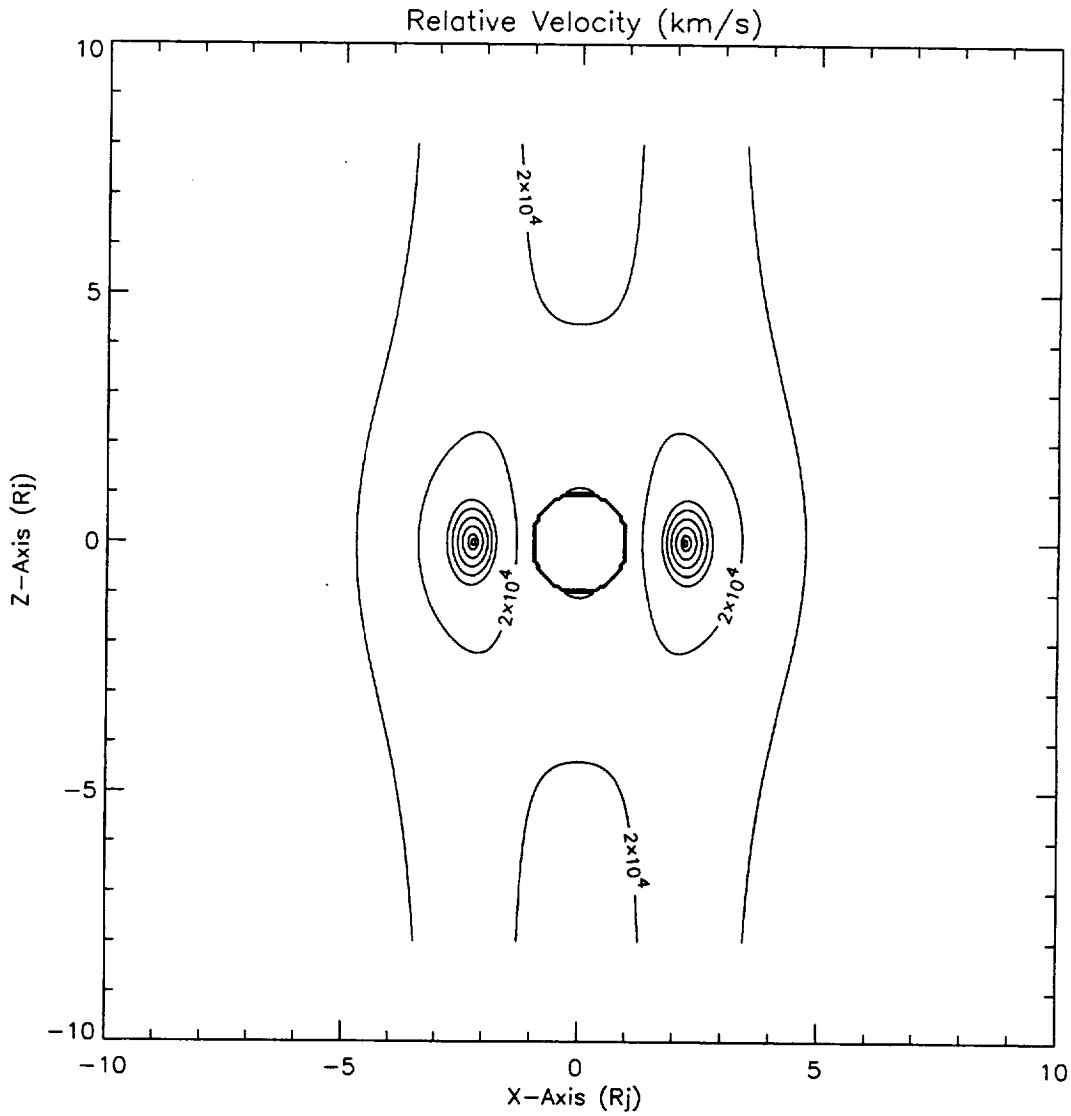
where $\theta$ is the latitude and $\phi$ is the longitude. This velocity is added to the velocity of a stationary location relative to planetary rotation, given by

$$\vec{v}_J = -\,1.7585 \cdot 10^{-4} \cdot r\cos(\theta)\hat{\phi} \ . \quad (2)$$

Jupiter is assumed to rotate with a period of 9 hours 55 minutes 29.70333 seconds. The resulting speed of the spacecraft relative to the planetary magnetic field ( $\vec{v}_{rel}$ ) is plotted next. Constant velocity contours are shown for 1, 2, 4, 6, 8, 10, 20, and 40km/s.

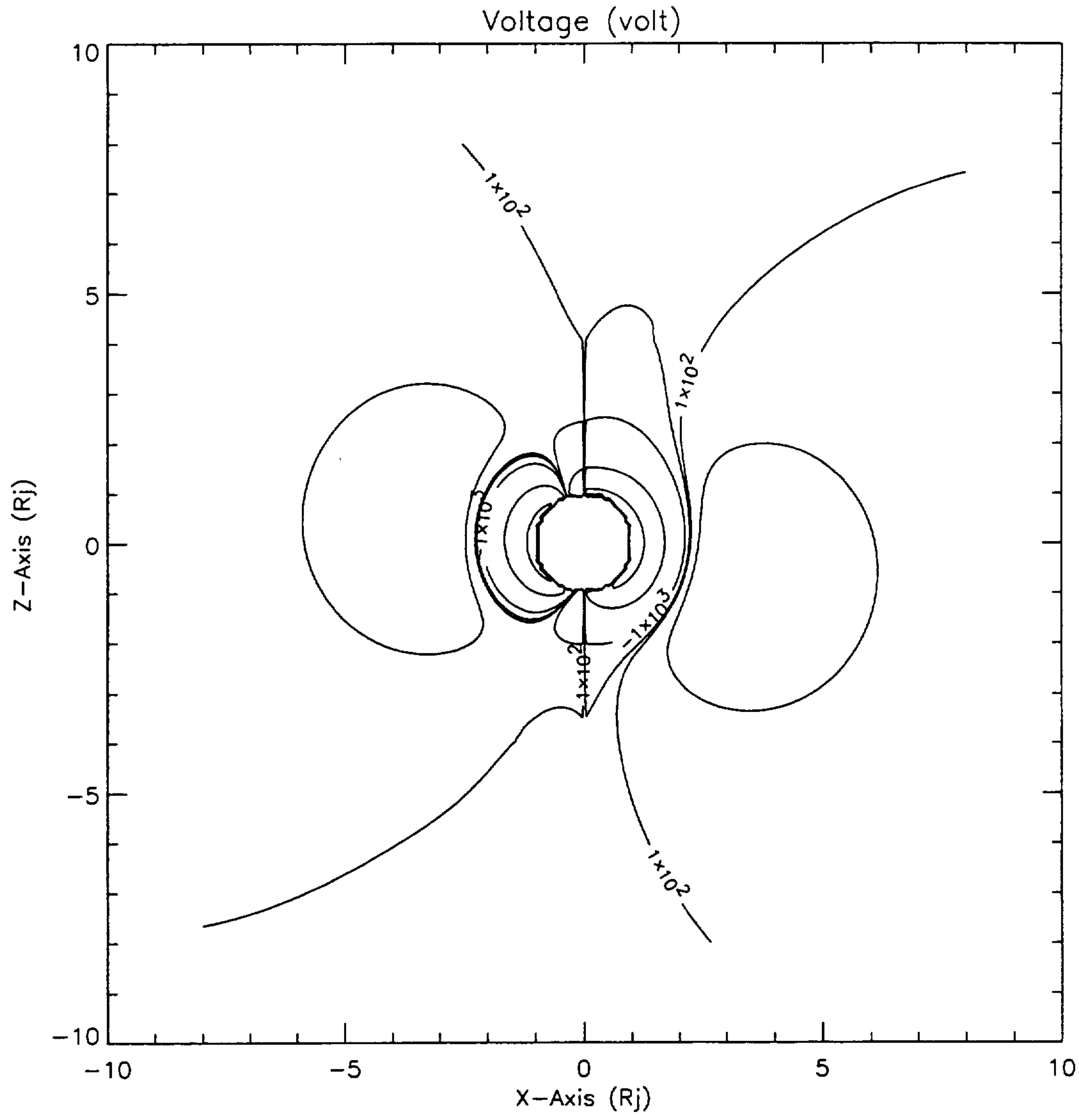
$$\vec{v}_{rel} = \vec{v}_{sc} + \vec{v}_J \quad (3)$$

You can see that for most locations, the planetary rotation dominates the plotted speed, i.e. it increases with increasing distance. Close to the planet, the orbital spacecraft speed begins to dominate over the planetary rotation. At 90 degrees, the planetary motion is not a factor, leaving only the orbital motion to contribute to induced EMF in the tether.




The next plot is for induced EMF in the 10km tether. Contours are shown for -50, -10, -1, -0.1, 0.1, 1, and 10kV values. Induced voltage depends upon the tether length ( $\vec{l}$ ), the velocity relative to the magnetic field ( $\vec{v}_{rel}$ ), and the vector magnetic field ( $\vec{B}$ ).

$$V = \vec{l} \bullet \vec{v}_{rel} \times \vec{B} \qquad (4)$$




Tether current is plotted in next. Here, contours are shown for 0.1, 0.5, 1, 5, 10, and 20 amperes. Based on Parker and Murphy [1967], current into a conductor in a magnetic field is equal to the thermal current ($I_o$) times a factor. The factor is a function of induced voltage (V), the area of the conducting surface (a), and the magnetic field strength (B). The thermal current is a function of the cross-sectional area of the conducting surface and the component of the thermal current density along the magnetic field. Thermal current density ($j_o$) is a function of the density and the mean thermal electron velocity.

$$j_o = \frac{e n_e v_{T_e}}{4} \qquad (5)$$

The component of that along the magnetic field is obtained by taking ¼ of the total thermal current density. The area of the conducting surface is taken to be the area of the tether projected onto a plane transverse to the magnetic field.

$$a = d \cdot l \cdot \sin(\alpha), \tag{6}$$

where $d$ is the diameter of the tether (0.001m), $l$ is the tether length ($10^4$m), and $\alpha$ is the angle between the radial tether and the vector magnetic field. This angle is obtained from

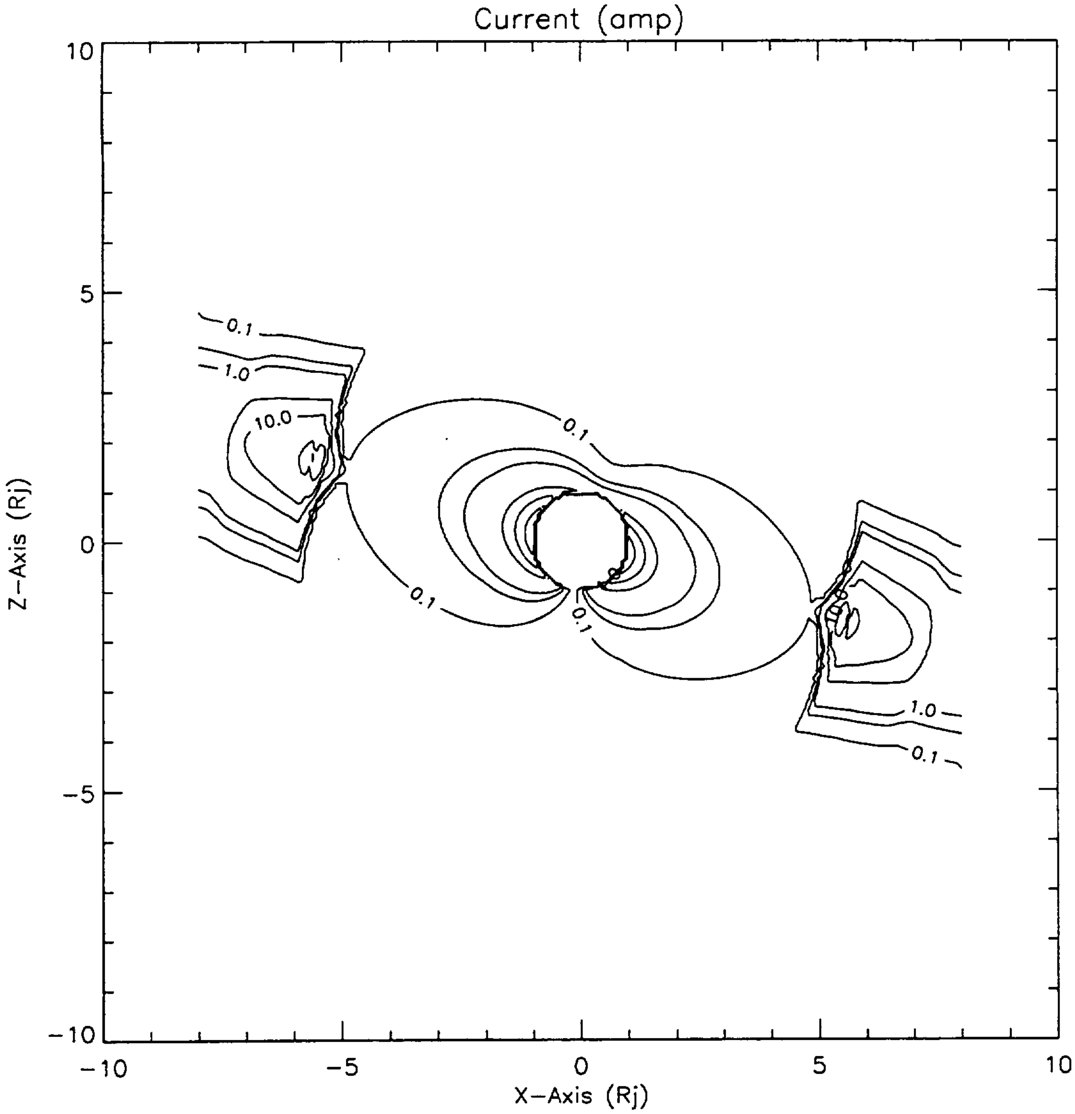
$$\alpha = \cos^{-1}\left(\frac{B_r}{B}\right), \tag{7}$$

where $B_r$ is the radial component of the Jovian magnetic field. The thermal current is multiplied by a factor of 2 to take into account the collection of current from both the parallel and anti-parallel directions along the magnetic field.

$$I_o = 2 \cdot a \cdot j_o \tag{8}$$

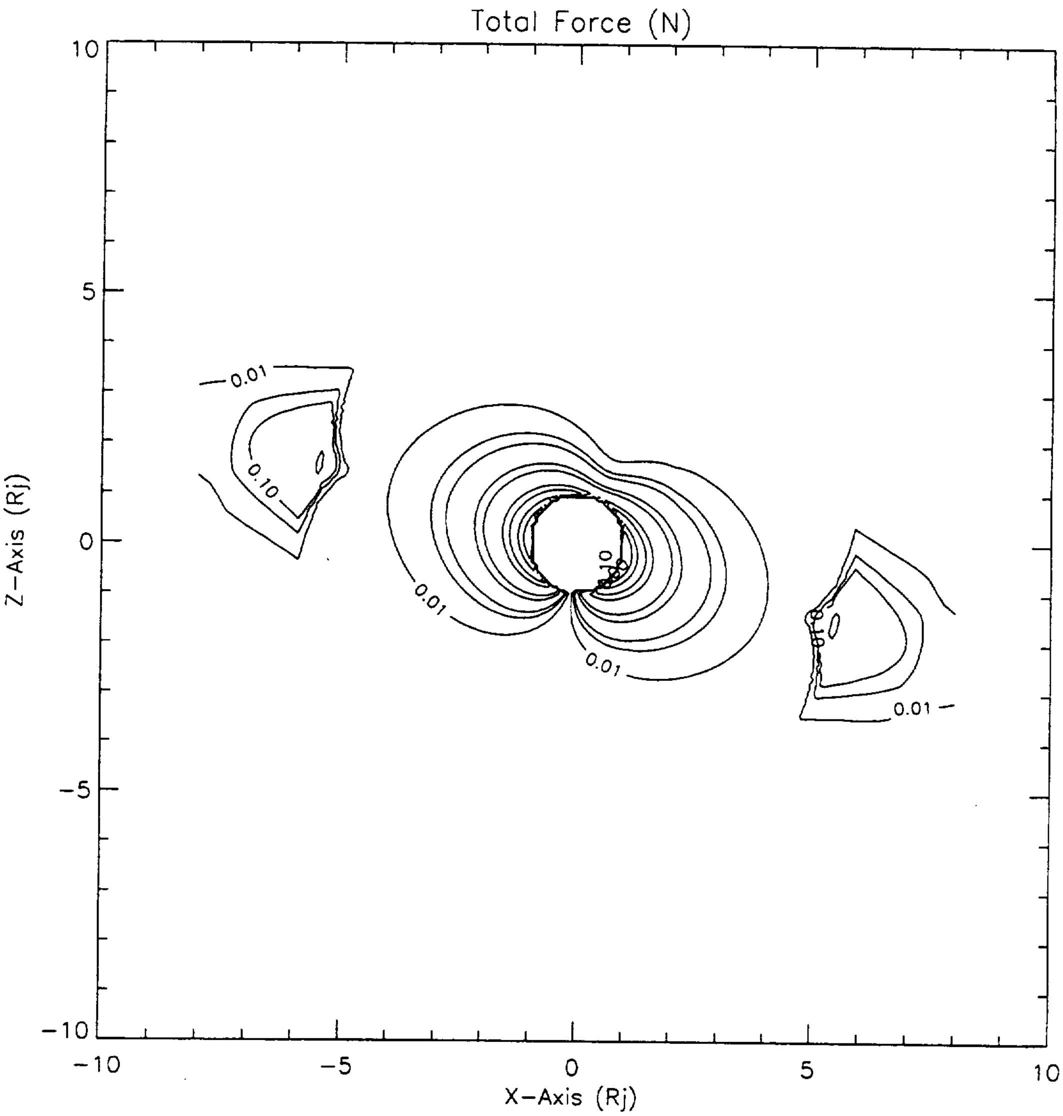
Finally, the current determined following *Parker and Murphy* [1967] is multiplied by factors of 2.5 and 30. The limiting current into a tether was found to be a factor of 2-3 times greater than *Parker and Murphy* [1967] in the TSS and TSS-1R missions, which is the source of the first factor. The second results from the analysis of bare tether performance, which is thought to enhance the current collection by a factor of at least 30 over the spherical end-collector used in the TSS and TSS-1R missions (*Sanmartin et al.*, 1993; *Shiah et al.*, 1997).

$$I = 75 I_o \left(1 + \left[4.56x10^{-3} \frac{V(volts)}{a^2(meters)B^2(gauss)}\right]^{\frac{1}{2}}\right) \tag{9}$$




Next, the force ( $\vec{F}$ ) a current carrying tether would experience is plotted, with contours at 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 25, and 50 Newton. The force is obtained from the tether length ( $l$ ), current ( $\vec{I}$ ), and the magnetic field ( $\vec{B}$ ).

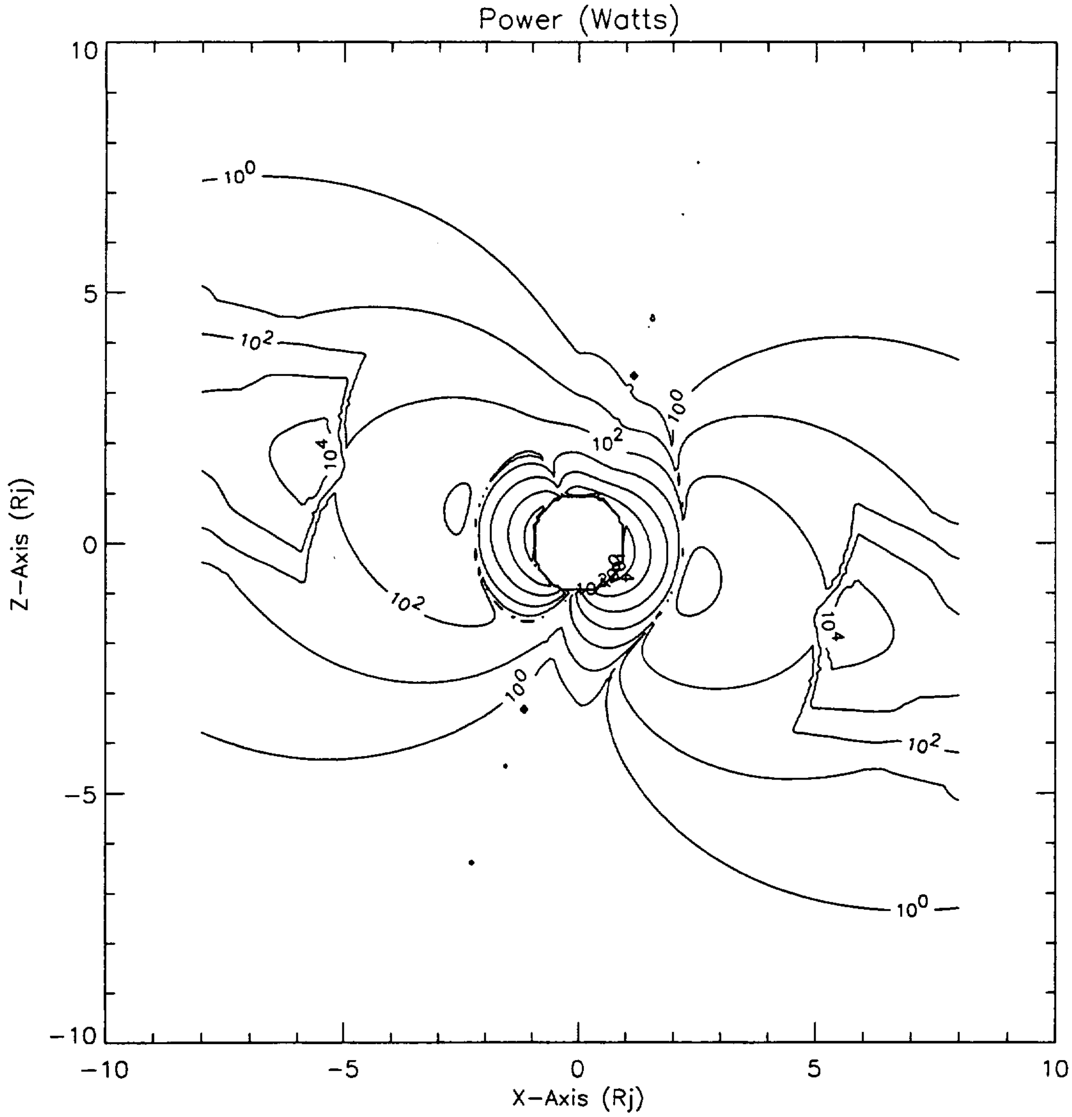
$$\vec{F} = l\vec{I} \times \vec{B} \tag{10}$$




Finally, the power represented in a current carrying tether is shown. Contours are drawn for even decades from 1 W to 10 MW. Power is simply obtained from the product of the induced EMF and the current.

$$P = V \cdot I \tag{11}$$

It can be noted that Europa is at a distance of 9.4Rj and has an orbital period of 3.551 days. That puts Europa beyond these plots, but clearly at low tether functionality, without mitigation by the availability of enhanced ionization (*Ip*, 1996).




**Summary**

Clearly, use of electrodynamic tethers in the Jovian system presents entirely new challenges and opportunities. Near the planet, it appears that induced tether voltages can reach as high as 50,000 volts, currents can become greater than 20 amperes, power levels can reach over a million Watts, and propulsive forces can reach higher than 50 Newton. The answer to our original question is yes. Electrodynamic tethers appear, on the basis of plasma physics, to be feasible for use in the Jovian magnetosphere. They also appear to present significant engineering challenges. High levels of tether current mean that managing a spacecraft system's thermal budget is not simple. The complex geometry of forces that a tether would experience around Jupiter means that sophisticated control of tether current will be required in order to achieve specific mission orbital characteristics. Continued analysis of the use of tethers at Jupiter will require use of a more realistic plasma density model than that used here. A model for electron temperature is also needed. More representative modeling of the Jovian plasma system can then be used in engineering studies to explore development of practical spacecraft systems for use at Jupiter.

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