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SATURN POWER GENERATION WITH ELECTRODYNAMIC TETHERS IN POLAR ORBIT

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A power generation scheme based on bare electrodynamic tethers (EDT) working in passive mode is investigated for the purpose of supplying power to scientific missions at Saturn. The system employs a spinning EDT on a low-altitude polar orbit which permits to efficiently convert plasmasphere energy into useful power. After optimizing the tether design for power generation we compute the supplied power along the orbit and the impact of the Lorentz force on the orbital elements as function of the tether and orbit characteristics. Although uncertainties in the current ionosphere density modeling strongly affect the performance of the system the peak power density of the EDT appears be greater than conventional power systems.

INTRODUCTION

Among the top priorities of planetary science in the upcoming decade stands the exploration of Saturn's atmosphere, whose analysis will provide key information towards the understanding of our solar system and its formation. It is argued that *a detailed knowledge of the composition of the mixed atmosphere of Saturn as compared to that of Jupiter is fundamental as the next step in constraining models of giant planet formation and the origin of their atmospheres* [1].

Among the different measurement strategies to characterize key features of Saturn atmospheres it has been proposed to employ microwave radiometry (MWR) from a fly-by or orbiting spacecraft combined to multiple high-speed entry probes relaying measurement data to the fly-by or orbiting spacecraft [2]. The power demand, complicated by the need to relay relatively high data rate through an absorber-rich atmosphere, has been listed among the biggest technical challenges for such a mission.

Similarly to the case of Jupiter and to a larger extent power generation at Saturn is greatly complicated by the lack of solar radiation. A reduction factor of almost a hundred is applied when comparing solar radiation at Saturn with the one available in Earth orbit. This forces to rely on heavy and costly RTGs for power generation or, alternatively, to deploy uncomfortably large solar arrays. These facts motivate the interest for non-conventional power generation schemes, among which we find electrodynamic tethers (EDTs) in generation mode regime.

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A recent study by these authors [3] has shown that a spacecraft equipped with relatively short and light bare electrodynamic tethers can be used to convert the energy extracted from Jupiter fast rotating plasmasphere into useful power for a polar orbiting mission like Juno. The article highlights a remarkable property of the in-plane spinning electrodynamic tether: in the process of power generation the EDT has an impacts on the orbit inclination while leaving orbital energy almost unaltered and extracting useful power from the energy of Jupiter's fast rotating plasmasphere. In the same article it is shown that an EDT with total length of 50 km provides peak power exceeding the megawatt level.

While holding a much weaker magnetic field and somewhat lower plasma density Saturn possesses a fast rotating plasmasphere, which motivates an analysis of the performance of EDTs as power systems for science missions.

In this article we investigate the power generation capability of EDT for Saturn missions employing low-altitude (below the D ring) polar orbits with the EDT spinning around an axis normal to the orbital plane. Such arrangement offers the advantage of considerably reduced radiation exposure, simplified data relay and communications with Earth and good coverage of the planet surface.

The structure of the article is the following. First we derive the main constraints for the operation of an EDT in polar orbit around Saturn. Next we compute the power generated by a spinning bare EDT configured for maximum power generation and zero-torque employing a dipole model for Saturn magnetic field and using a simplified ionosphere model. We then assess the variation of orbit inclination produced by the Lorentz force which is constantly directed orthogonally to the orbit plane.

Finally we compare the performance of the EDT with conventional RTGs and discuss the applicability of EDTs as power systems for scince missions around Saturn.

SATURN ENVIRONMENT

Constraints for a polar orbit mission

When considering a polar mission to Saturn some key aspects of Saturn environment have to be taken into account as they constrain the type of orbit that can be chosen.

Saturn rings extend from about 1.11 R_S (inner edge of the D ring) to about 5 R_S (outer edge of the E ring), where R_S is Saturn's equatorial radius. In order to minimize collision hazard with ring material the orbit should avoid crossing the plane of the ring as much as possible and when a plane crossing is inevitable it should take place where the ring material density is lowest. For example during the Cassini orbit insertion the spacecraft crossed the plane between the F and G ring at about 2.6 R_S, a region where the probability of impact is next to zero.

An EDT system at Saturn will need a low-altitude pericenter in order to meet favorable conditions in terms of plasma density and magnetic field strength. A periapsis below the inner edge of the D ring is probably the most reasonable choice. Conversely, safety issues for the mission science instruments and the spacecraft itself will constrain the minimum periapsis radius. A minimum altitude around 2400 km above the 1-bar planetary surface seem reasonable and implies a periapsis radius not smaller than 1.04 R_S.

As for the choice of orbit eccentricity e and argument of periapsis ω, ring collision hazard is a key constraint. Due to Saturn's equatorial bulge (J_2=1.63×10^{-2}) a line of apses precession will increase the location of the inner equatorial plane crossing with the spacecraft gradually approaching the inner edge of the D ring.

For a generic *polar* orbit with initial argument of pericenter ω_0, eccentricity e, pericenter radius r_p the average rate of precession of the line of apses due to the J2 gravitational harmonics can be written as:

$$\frac{d\omega}{dt} = -\frac{3}{4} J_2 r_{eq}^{\;2} \sqrt{\frac{\mu(1-e)^3}{r_p^{\;7}(1+e)^4}} . \tag{1}$$

On the other hand the condition for which the equatorial plane crossing occurs at a critical radius r_C provides the value of the critical argument of pericenter:

$$\omega_c = \pm\cos^{-1}\left[\frac{r_p(1+e)-r_c}{er_c}\right], \tag{2}$$

If we assume that no correction maneuvers are performed to adjust the line of apses (these maneuvers are quite expensive in terms of ΔV) the elapsed time before equatorial crossing at r_c is:

$$\Delta t = \frac{4}{3J_2 R_S^{\;2}} \sqrt{\frac{r_p^{\;7}(1+e)^4}{\mu(1-e)^3}} \left\{ \omega_0 - \cos^{-1}\left[\frac{r_p(1+e)-r_c}{er_c}\right]\right\} \tag{3}$$

For r_C=1.11 R_S and r_p<r_C the function Δt increases monotonically for increasing eccentricity and decreasing periapsis radius. Clearly the best choice of the initial argument of pericenter is to have:

$$\omega_0 = |\omega_c| - \delta\omega , \tag{4}$$

where δω>0 is a small angle.

Assuming r_p=1.04 R_S and based on Eqs. (3,4) a mission lifetime of one year can be achieved with eccentricity greater than 0.91 and starting with ω_0=29 deg. By increasing the eccentricity to 0.942 a two-year mission duration is available.

Clearly, if a circular polar orbit is employed with altitude below the D ring the collision issue disappears. On the other hand the cost in terms of ΔV to reach such an orbit would be extremely high.

Environment Conditions Relevant to EDT Operation

Saturn possesses a magnetic field whose intensity at the equator is $B_S \cong 20$ μT or about 20 times smaller than Jupiter and 1,5 smaller than Earth. Interestingly, unlike any other planet in our solar system, Saturn's magnetic dipole is aligned with the planet rotation axis.

Saturn's plasmasphere corotates with the planet at a rate $\Omega = 1.638\times10^{-4}$ rad/s, i.e. 2.25 rev/day, which is slightly slower than at Jupiter (2.4 rev./day).

The inner plasmasphere is less dense that the Jupiter one, which, in turns, has a much lower density when compared to Earth. Unfortunately though, our current understanding of Saturn complex ionosphere is not good enough to allow predicting the electron density distribution with good accuracy. Saturn's inner plasmasphere is considerably different from Earth's. The presence of the rings and the inner moon Enceladus add to the complexity of plasmasphere dynamics [4]. In addition, unlike Jupiter and similarly to Earth, the influence of solar activity on the inner plasmasphere is substantial and large day/night variations of peak electron density have been observed [5,6].

Radio occultation measurement of electron densities have been carried out during the Poioneer 11, Voyager 1-2 and the Cassini missions. The first three were performed under maximum solar activity while the former near minimum conditions. Pioneer 11, on a low latitude pass (~10 deg) recorded peak densities around 12000 cm^{-3}. Voyager-1, passing at ~73 deg latitude, measured peak densities around 22000 cm^{-3} while Voyeger-2 (~33 deg) reached 16000 cm^{-3}. Along a near-equatorial path, Cassini recorded a density around 6700 cm^{-3} [7]. The altitude corresponding to the peak density for all these missions fall between 1800 and 2500 km with an exponential decrease of density with altitude leading to values between 200 and 900 cm^{-3} at 5000 km altitude.

In addition to the radio occultation measurements a diurnal variation profile of the peak electron density is available from Voyager 1 observations of Saturn electrostatic discharges (SED)[6] and provides a maximum value around 60000 cm^{-3} suggesting that electron densities much higher than the one provided by radio occultation should be expected in the morning region (9^h30^m to 14^h).

As far as the region with radius $r>1.1\ R_S$ Moore and Mendillo [4] predict electron density decreasing until around 100 cm^{-3} at Cassini closest Saturn encounter (1.3 R_S) during low solar activity while Richardson and Jurac [8] predict 30 cm^{-3} at $r=2\ R_S$.

Based on all these data one can construct a very rough density profile which, far from having any scientific relevance per se, can be used for a very preliminary estimation of the EDT performance as a power plant in Saturn orbit. We will adopt the following exponential profile:

$$N_e = N_0 \exp\left[\left(\frac{r_0}{r_{SC}}\right)^m\right] \qquad (5)$$

with:

$$[N_0, r_0, m] = \begin{cases} [5\times 10^5 m^{-3},\ \ 1.5\, r_0,\ \ 6], & R_S + h_0 < r_{sc} < R_S + h_1 \\ [5\times 10^5 m^{-3},\ \ 7.68\, r_0,\ \ 1], & r_{sc} > R_S + h_1 \end{cases} \tag{6}$$

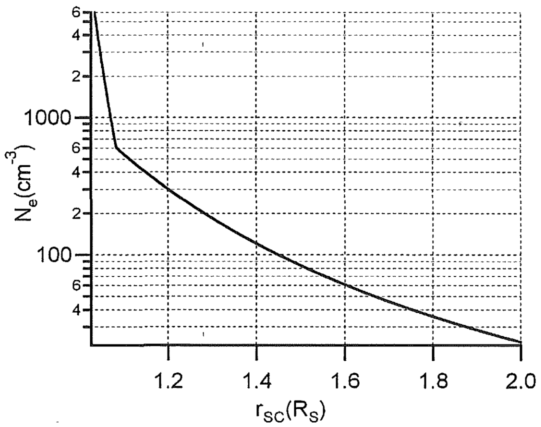

Fig.1 Preliminary ionosphere electron density profile used in the current model

Because the analysis of the EDT performance and orbital dynamics is done analytically it will be easy to readjust the obtained values with a more accurate electron density profile should it be available in the future.

It is possible to see that, given the low plasma density, when compared to Earth but also to Jupiter, EDTs of length up to 40-50 km show negligible ohmic losses even when employing tape section as thin as 0.05 mm.

Finally, the characteristic Debye length of Saturn plasmasphere is known to exceed the one meter level as well as the elctron gyroradius. This means that conductive tapes of 5-10 cm width fall very well into the orbital motion limited (OML) regime for current collection.

POWER GENERATION IN POLAR ORBIT

Similarly to the case treated in Ref. [3] we will consider a spin-stabilized EDT in polar orbit with semimajor axis a, eccentricity e and argument of pericenter ω (Fig.1). The tether rotates around an axis normal to the orbital plane and is designed in such a way that the Lorentz force produces zero net torque, which entails having a central power generating module with two radially deployed partially insulated tether arms [3]. Referring to this design and assuming OML theory with negligible ohmic losses the power generated in the central module is [3]:

$$\dot{W} = kwL^{5/2}N_e\, E_\pi^{3/2}, \tag{7}$$

where w is the tether tape width, L the length of each tether arm, N_e the plasma electron density and E_π is the motional electric field component along the tether spin plane. Finally k is a factor independent of the EDT position along the orbit and which for a rotating two-arm self-balanced EDT optimized for power generation is k ≅4.17×10^{-15} C$^{3/2}$kg$^{1/2}$.

From Ref. [3] and accounting for Eq. (1) the orbital plane component motional electric field E_π and the plasma density variation along the orbit yield:

$$E_\pi(\nu) = \frac{\Omega B_S {R_S}^3 \left|\cos(\omega+\nu)\right| (1+e\cos\nu)^2 \sqrt{1+3\sin^2(\omega+\nu)}}{a^2(1-e^2)^2}, \tag{8}$$

$$N_e(\nu) = N_0 \exp\left\{\left[\frac{r_0(1+e\cos\nu)}{a(1-e^2)}\right]^m\right\}, \tag{9}$$

where ν is the orbit true anomaly.

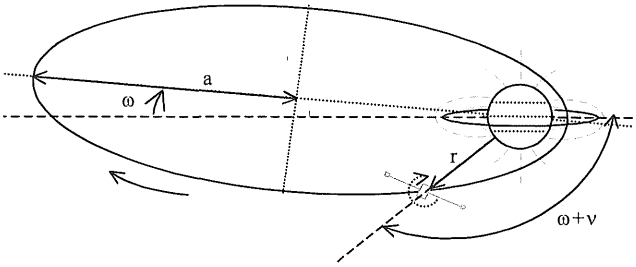

Fig.2. Schematic of a polar orbit EDT around Saturn as referred to in the current analytical model.

Results from Eqs. (7-9) are plotted in Fig (3-4) showing that a system with 25-km tether arm length can produce a peak power from 6 to 8 kW (depending on the argument of periapsis) along both high-eccentricity and circular orbits.

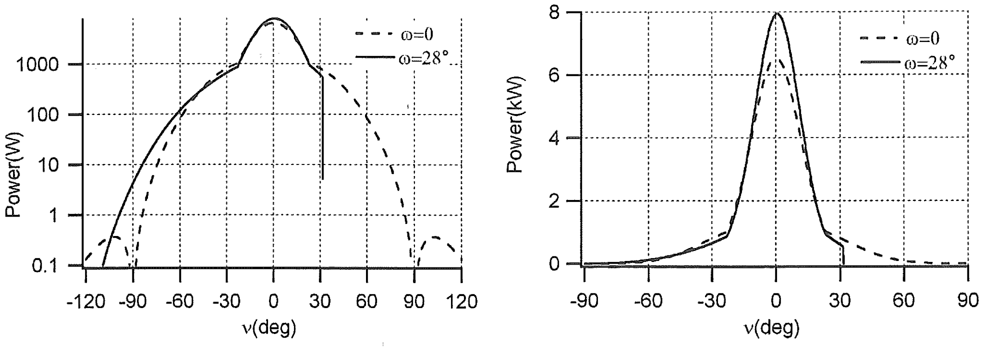

Fig.3. Maximum power (logaritmic and linear scale) generated by a spinning bare EDTs of 25 km arm lengths in polar elliptic orbits with r_p=1.04 r_S, e=0.91 and different values for the argument of pericenter. The tether width is 5 cm. The results do not change appreciably when the orbit eccentricity is increased to 0.95.

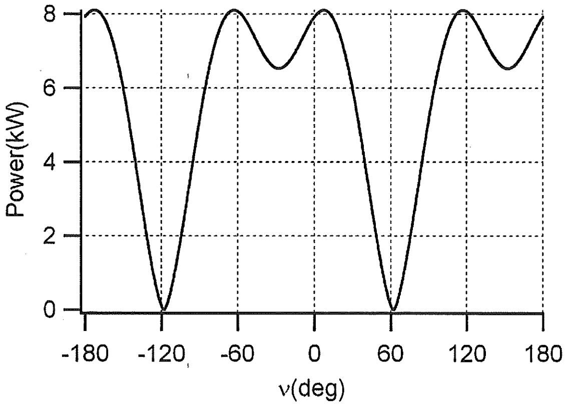

Fig.4. Maximum power generated by a spinning bare EDTs of 25 km arm lengths in polar circular orbit with r_p=1.04 r_S. The tether width is 5 cm.

ORBIT INCLINATION DRIFT

As already pointed out in ref. [3], the power generated on board the EDT comes from plasmasphere energy while the spacecraft orbital energy remains, to first order (i.e. as long as the orbit inclination remains close to 90 degrees), unaffected. On the other hand the interaction between the spacecraft motion and the planet corotating atmosphere causes the inclination to drift in such a way that the orbit tends to become equatorial. The variation of orbital inclination obeys [3]:

$$\frac{di}{d\nu} = \tilde{k}\,\frac{a(1-e^2)}{(1+e\cos\nu)^2}\,\frac{N_e E_\pi^{\ 3/2}}{\mu m_{SC}\Omega}\,. \qquad (10)$$

where m $_{SC}$ is the overall spacecraft mass μ is Saturn's gravitational parameter and $\tilde{k}$ factor independent of the EDT position along the orbit and which for a rotating self-balanced EDT with two partially insulated tether arms optimized for power generation is $\tilde{k}\cong 1.19\times 10^{-14}\ C^{3/2} kg^{1/2}$.

Eq.(5) can be integrated along the orbit to provide the inclination variation per orbit revolution and the average inclination variation per day. The latter is plotted in Fig.(5) considering orbits of different eccentricities and periapsis distances. The inclination drift is minimal.

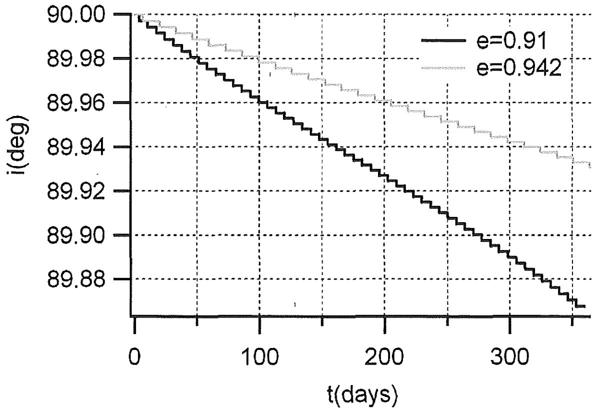

Fig.5 Variation of inclination for a spinning self-balanced insulated EDT of 25-km arm length and a 1-ton overall mass in a polar elliptical orbits with different eccentricities and periapsis radius at 1.04 R$_S$. Tether width and thickness are 5 cm and 0.05 mm, respectively.

Another interesting parameter which can be easily evaluated is the specific energy which can be extracted from the rotating plasmasphere per unit of orbit inclination variation and spacecraft mass:

$$\varepsilon = \frac{1}{m_{SC}}\frac{dW}{di}, \qquad (11)$$

which according to ref [3] has the simple expression:

$$\varepsilon = \eta\Omega\sqrt{\mu a(1-e^2)}, \qquad (12)$$

where the power generation efficiency η reaches about 35% for our power-optimized self-balanced EDT. According to Eq. (12) a 1 t spacecraft equipped with an EDT power generating system could produce at least 500 W average continuos power for a year with about 10 deg of inclination drift. Clearly when high-eccentricity orbits are considered obtaining such value for the average power would imply using tether lengths of many hundreds of km which are not practical. On the other hand the same value of the average power could be achieved for a low circular orbit with reasonable tether length.

COMPARISON WITH OTHER POWER GENERATION METHODS

So far the totality of space missions to Saturn, from Pioneer 11 in 1979 to Cassini-Huygens in 2004, have employed radioisotope thermoelectric generators (RTGs) with power densities up to about 6 W/kg. Given the weak solar flux in Saturn orbit this solar panels are currently not considered as a viable option and future missions will likely be RTG-based.

Unlike RTGs a power generation scheme based on EDTs does not provide constant power throughout the mission. For high-eccentricity orbits most of the power will be concentrated around periapsis (Fig. 3) leaving most of the orbit power-starved. This makes the contribution of the EDT significant for missions whose science operations are concentrated in the vicinity of the planet, as it is the case of an atmosphere science mission. Clearly this limitation disappears if the EDT is used on a low altitude circular orbit.

As a metric of comparison one can consider the peak power density along the orbit (ref.[3]):

$$\delta_{\max} = \frac{kL^{3/2}}{2\rho h_t (1+\sigma)} \max\left(N_e \, E_\pi^{3/2} \middle| \nu = 0..2\pi\right), \qquad (13)$$

where ρ is the tether material density, h_t the tape tether thickness and σ the fraction of tether related hardware mass which for tethers of total length of 50 km can probably be assumed less than unity.

Setting h_t=0.05 mm, σ=0.5, ρ=2700 kg/m^3 (aluminum) and referring to Eqs.(8,9) we obtain peak power densities of 15 W/kg. Tether thickness could possibly be decreased to smaller values by embedding fibers with high specific strength in the conductive tape to supply the structural requirements. On the other too thin a tape could soon experience a drop in efficiency due to the onset of ohmic effects.

When the average delivered power is considered the performance of the EDT falls below the RTG one for high-eccentricity orbits while for low altitude circular orbits EDTs are still the most convenient system.

CONCLUSIONS

The performance of electrodynamic tether systems as power generation means for Saturn polar missions have been evaluated showing that the system can offer power density superior or comparable to RTGs when transiting at low altitude. Consequently, EDTs can be advantageously used in low circular Saturn orbits (below the inner edge of the D ring) as autonomous power generation systems or can be employed in conjunction with RTGs to boost the available power level at low altitude in elliptic orbits.

The impact of the Lorentz force on the orbit inclination is almost negligible for high-eccentricity orbit while still remaining relatively small for circular orbits.

Preliminary values for power produced and power density were derived based on a simplified ionosphere density model. The reader should bear in mind that should a more accurate ionospheric density model become available the results could change considerably.

As expected the performance of a Saturn orbiting EDT is much lower (orders of magnitude) than its Jupiter counterpart.

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