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Analysis of Tether-Mission Concept for Multiple Flybys of Moon Europa

Juan R. Sanmartín* and Mario Charro†

Universidad Politécnica de Madrid, 28040 Madrid, Spain

Henry B. Garrett‡

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
and

Gonzalo Sánchez-Arriaga§ and Antonio Sánchez-Torres¶

Universidad Carlos III de Madrid, 28911 Leganés, Spain

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All four giant planets, far from the Earth and sun and having deep gravitational wells, present propulsion and power mission issues, but they also have an ambient plasma and magnetic field that allows for a common mission concept. Electrodynastic tethers can provide propellantless drag for planetary capture and operation down the gravitational well, and they can generate power to use along with or be stored for inverting tether current. The design for an alternative to NASA's proposed Europa mission is presented here. The operation requires the spacecraft to pass repeatedly near Jupiter, for greater plasma density and magnetic field, raising a radiation-dose issue that past analyses did take into account; tape tethers tens of kilometers long and tens of micrometers thick, for greater operation efficiency, are considered. This might result, however, in attracted electrons reaching the tape with a penetration range that exceeds tape thickness, thereby escaping collection. The mission design requires keeping the range below thickness throughout, resulting in an orbit perijove only hundreds of kilometers above Jupiter and tapes a few kilometers long. A somewhat similar mission design might apply to other giant outer planets.

Nomenclature

a_s	=	Jovian stationary-circular-orbit radius, m
B	=	Jovian magnetic field modulus, T
E_m	=	motional electric field, V/m
e_c	=	orbit eccentricity after capture
e_h	=	incoming orbit eccentricity
h	=	tape tether thickness, m
I_{av}	=	electric current averaged over tether length, A
L	=	tether length
M_{SC}	=	spacecraft mass, kg
m_e	=	electron mass
m_t	=	tether mass
N_e	=	ambient electron density, $1/m^3$
R_J	=	Jupiter's equatorial radius, km
\mathbf{r}	=	spacecraft position vector
s	=	tether length from the anodic end
T_{max}	=	maximum tether temperature, K
U	=	spacecraft orbital energy
\mathbf{v}	=	spacecraft velocity vector, m/s
\mathbf{v}_{pl}	=	corotating plasma velocity
v_∞	=	incoming orbit velocity, km/s
\mathbf{v}'	=	relative velocity, $\mathbf{v} - \mathbf{v}_{pl}$
W_c	=	magnetic drag work, J

w	=	tether width
δ_e	=	penetration depth
ϵ_{max}	=	maximum energy of electrons reaching the tether, eV
μ_J	=	Jupiter's gravitational parameter, km^3/s^2
ρ_t	=	tether density, kg/m^3
ϕ	=	angle between E_m and the spinning tether, rad
Ω_J	=	Jupiter's spin, rad/s

Subscripts

h	=	hyperbolic
p	=	perijove
s	=	stationary-circular orbit

I. Introduction

THE need for reducing the costs of space missions has long been a pressing one, but space missions to the outer planets of the solar system, which are of high interest for planetary science, are especially affected by this constraint [1]. Innovative and probably nonconventional ideas are needed. In this respect, designing and flying robotic space probes to Uranus and Neptune with common space platforms (two copies) were proposed recently. These two planets are termed ice giants, which are different from the gas giants, Jupiter and Saturn; missions could fly in the late 2020s or early 2030s. Looking at scaled-back concepts to be developed at less cost, and identifying potential concepts across a spectrum of price points, have been considered critical [2].

Missions to all four giant outer planets face common issues. They are far from the Earth and Sun, and they present deep gravitational wells, setting both power and propulsion issues. Since solar power might not be effective, they might rely on radioisotope thermal generators, as was recently used by the Curiosity mission to Mars [3]. These devices, however, are weak/heavy power sources, and they use plutonium 238, which would require funding additional production of space-grade plutonium. The scarce available power on board, with electric propulsion limited, and the deep gravitational wells involved in capturing and maneuvering when not just single-flyby missions, make the use of Radioisotope Thermoelectric Generators a poor solution.

Early in this century, and as part of NASA's Project Prometheus (conceived to use nuclear fission for power in space and, indirectly,

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*Emeritus Professor, Department of Applied Physics, School of Aerospace Engineering, Plaza Cardenal Cisneros 3.

†Adjunct Professor, Department of Applied Physics, School of Aerospace Engineering, Plaza Cardenal Cisneros 3.

‡Principal Scientist, Reliability Engineering and Mission Environmental Assurance Office, 4800 Oak Grove Drive. Associate Fellow AIAA.

§Ramón y Cajal Research Fellow, Department of Bioengineering and Aerospace Engineering, Avenida de la Universidad 30.

¶Juan de la Cierva Research Fellow, Department of Bioengineering and Aerospace Engineering, Avenida de la Universidad 30.

$$v'^2 = v^2(r) + \Omega_J^2 r^2 - 2\Omega_J r_p v_p \quad (4)$$

Calculating W_c involves three integrations: first, to find the instantaneous tether current averaged over its length, from the anodic ($s = 0$) to the cathodic ($s = L$) end, I_{av} . With HC voltage-drop and ohmic effects (particularly true at Jupiter) negligible, we have the tether bias relative to the local ambient plasma: $\Delta V \approx E_m(L - s)$. This readily leads to [7]

$$I_{av} = \frac{2}{5} \frac{2wL}{\pi} e N_e \sqrt{\frac{2eE_m L}{m_e}} \quad (5)$$

where w and $N_e(r)$ are the tape width and ambient plasma density, respectively.

Second, integrating the magnetic drag power [7],

$$\dot{W}_c = \vec{v} \cdot \vec{F}_{\text{magn}} = \vec{v} \cdot (L \vec{I}_{av} \wedge \vec{B}) \quad (6)$$

over the spin angle φ at every position in the orbit of capture, and then integrating over the drag arc in the orbit, twice from the perijove r_p to a radius $r_M = a_s \sqrt{2a_s/r_p}$ where drag vanishes with vanishing relative-velocity component along the orbit [6],

$$W_c = 2 \int_{r_p}^{r_M} \frac{dr}{dr/dt} \langle \dot{W}_c \rangle_\varphi \quad (7)$$

where dr/dt is taken from the Barker's equation giving time t from the perijove pass as a function of true anomaly for a parabolic orbit [6] and its conic equation.

Equation (2) then yields, using $\tilde{r}_M \equiv r_M/r_p \approx 4.74(R_J/r_p)^{3/2}$ [6,7],

$$\begin{aligned} \frac{e_h - e_c}{e_h - 1} \frac{M_{SC}}{m_t} &= 0.80 \frac{m_e N_s a_s \sqrt{v_s} (LeB_s/m_e)^{3/2}}{\rho_t h v_\infty^2} \Sigma(\tilde{r}_M) \\ &\approx 0.15 \left(\frac{L}{50 \text{ km}} \right)^{3/2} \frac{0.05 \text{ mm}}{h} \times \Sigma(\tilde{r}_M) \end{aligned} \quad (8)$$

$$\Sigma(\tilde{r}_M) = \int_1^{\tilde{r}_M} \frac{\tilde{r}_M^2 d\tilde{r} / 2^{5/4} \tilde{r}^{17/4}}{(\tilde{r}_M^2 + \tilde{r}^3 - 2\tilde{r}_M \tilde{r})^{1/4}} \frac{\tilde{r}_M - \tilde{r}}{\sqrt{\tilde{r} - 1}} \frac{N_e}{N_s}(\tilde{r}, \tilde{r}_M), \quad (\tilde{r} \approx r/r_p) \quad (9)$$

In Eq. (8), we used aluminum for tether density and the classical Divine–Garrett model of plasma density [11]:

$$\frac{N_e}{N_s}(\tilde{r}, \tilde{r}_M) = \exp\left(\frac{2.72 \tilde{r}_M^{2/3}}{\tilde{r}} - 3.43\right) \quad (10)$$

The preceding characteristic values are $v_s \approx 39.8 \text{ km/s}$, $N_s \approx 1.44 \times 10^2 \text{ cm}^{-3}$, and $B_s \approx 0.38 \text{ G}$.

Eccentricity would decrease in successive perijove passes. A total eccentricity decrement $\Delta e_T \approx -0.16$ is required to reach the Ganymede apojove at $e = 0.86$ from $e_h \approx 1.02$. The eccentricity decrement per perijove pass proves nearly independent of both radius r_p and e value before each pass (for $e > 0.5$, suppose); the dose per orbit proves similarly near independent of eccentricity and perijove radius if near Jupiter, with the number of perijove passes thus being a metric for the total dose [8].

The dose is also nearly independent of longitude, proving the simple dipole model in the inner magnetosphere accurate; the Galileo Interim Radiation Electron radiation model is used throughout calculations [12]. The calculations here deal with prograde S/C orbits throughout; retrograde orbits would lead to a moderate decrease in total dose and a moderate increase in maximum temperature [8].

IV. Mission Design

The efficiency of tether capture of the incoming S/C is gauged by the ratio M_{SC}/m_t at desired $|\Delta e|$. Σ increases in Eq. (9) with $\tilde{r}_M \approx 4.74(R_J/r_p)^{3/2}$; the efficiency is thus higher the lower is perijove radius r_p . It is also clearly higher when the tape is longer and thinner. Too long a tape, however, will result in attracted electrons hitting it at values of energy ε with the range (penetration depth) $\delta_e(\varepsilon)$ larger than the thickness h if too low and/or the perijove too close to Jupiter [10]. No design criterion involves tape width w , which scales with M_{SC} over a broad range; the Debye length is on the order of meters.

The energy of electrons reaching the tether at a point distant s from the anodic end is

$$\varepsilon = eE_m(r, \varphi) \times (L - s) \quad (11)$$

The maximum energy then corresponds to values $s = 0$, $\varphi = 0$, $r = r_p$,

$$\Rightarrow \varepsilon_{\text{max}}(r_p, L) = eE_{mp0}(r_p)L, \quad E_{mp0} = v_p' B_p \quad (12)$$

with $v_p' = v_p - \Omega_J r_p$, from Eq. (4), reflecting on the fact that relative velocity is tangent to the orbit at perijove. Using the dipole law for $B(r)$ and $\Omega_J a_s = v_s/\sqrt{2}$, we may finally write

$$E_{mp0} = v_s B_s \times (\tilde{r}_M - 1)(\tilde{r}_M/2^{7/8})^{4/3} \quad (13)$$

For a very simple design that keeps the penetration range nowhere exceeding tape thickness, the lowest acceptable thickness h at given L and r_p values would be

$$h = \delta_e[\varepsilon_{\text{max}}(r_p, L)] \equiv \delta_e[eE_{mp0}(r_p)L]. \quad (14)$$

Since δ_e (now a functional of r_p, L) increases with increasing electron energy, we would have the range $\delta_e(\varepsilon) < h$ throughout that triple (s, φ, r) integration, whereas $\delta_e(\varepsilon) = h$ would hold at just one limit point in the three-dimensional integration domain.

Using Eqs. (12–14), Eq. (8), giving the captured mass-ratio for a desired $|\Delta e|$, can now be rewritten as

$$\begin{aligned} \frac{|\Delta e|}{e_h - 1} \times \frac{M_{SC}}{m_t} &\approx 0.15 \times \Sigma(\tilde{r}_M) \times \left(\frac{\varepsilon_{\text{max}}}{eE_{mp0} \times 50 \text{ km}} \right)^{3/2} \frac{0.05 \text{ mm}}{\delta_e(\varepsilon_{\text{max}})} \\ &= 1.22 \times Y(\tilde{r}_M) \times \frac{(\varepsilon_{\text{max}}/\text{MeV})^{3/2}}{\delta_e(\varepsilon_{\text{max}})/\text{mm}}, \quad Y \equiv \frac{\Sigma(\tilde{r}_M)}{\tilde{r}_M^2 (\tilde{r}_M - 1)^{3/2}} \end{aligned} \quad (15)$$

involving just two ($r_M, \varepsilon_{\text{max}}$) ratios. For a desired value of ratio $|\Delta e|/0.018 > 1$, the captured mass ratio is largest for some optimum values of r_M (or, equivalently, r_p) and ε_{max} , making the ratios involving them in Eq. (15) as large as convenient. For optimum choices of ε_{max} and r_p , there follow $h_{\text{design}} = \delta_e(\varepsilon_{\text{max}}^{\text{opt}})$ and $L_{\text{design}} = \varepsilon_{\text{max}}^{\text{opt}}/eE_{mp0}(r_p^{\text{opt}})$. Finally, Eq. (15) yields the mass ratio; the tether width w will follow a choice of M_{SC} .

Note that moving from $r_p = a_s$, suppose, to r_p/R_J (i.e., $\tilde{r}_M = 4.74$) in Fig. 2 for the ratio $Y[(r_p/R_J)]$ increases efficiency by over a factor of six. A value of $r_p = 1.005R_J$, suppose, would correspond to about $s \approx 350 \text{ km}$ altitude H above Jupiter. We take 3.5 as the value of the r_M ratio in Eq. (15) by here just writing $r_p \approx R_J$. We now have $eE_{mp0}(r_p^{\text{opt}}) \approx 0.020 \text{ MeV/km}$. Also, Eq. (15) now reads

$$\frac{|\Delta e|}{e_h - 1} \times \frac{M_{SC}}{m_t} \approx 4.27 \times \frac{(\varepsilon_{\text{max}}/\text{MeV})^{3/2}}{\delta_e(\varepsilon_{\text{max}})/\text{mm}} \quad (16)$$

As regards the ε_{max} ratio, it increases (though moderately) with decreasing ε_{max} (δ_e varying roughly as $\varepsilon_{\text{max}}^{3/2}$) from some minimum around 0.3 MeV . For $\varepsilon_{\text{max}} = 0.1, 0.065$, and 0.04 MeV , figure 6.4 of [13], from the GEANT Monte Carlo code, gives $\delta_e(\varepsilon_{\text{max}}) = 2, 0.9$, and 0.4 mils (or $h \approx 0.051, 0.023$, and 0.010 mm), respectively. The corresponding values on the right-hand side of Eq. (16) are 2.65, 3.08, and 3.42, or $M_{SC}/m_t \sim 3$ for $|\Delta e| \approx 0.02$.

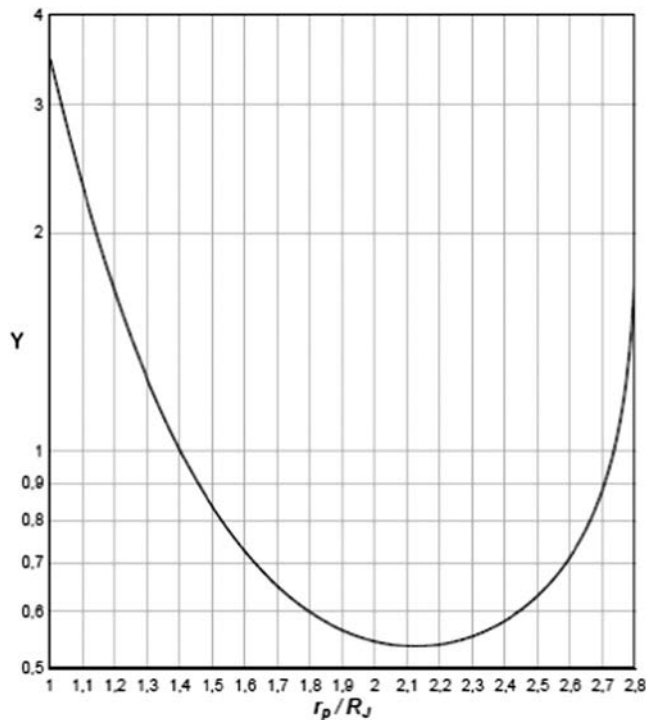


Fig. 2 Representation of the function $Y(r_M/r_p)$, introduced in Eq. (15), basically determining the captured mass ratio; use is made of the relation $r_M/r_p \approx 4.74(R_J/r_p)^{3/2}$.

Values of length L for the preceding ϵ_{\max} values of 0.1, 0.065, and 0.04 MeV, are $L = 5$, 3.25, and 2 km, respectively. Note that the capture efficiency, as gauged by the mass ratio in Eq. (16), increases with decreasing length and thickness. A too thin tape, however, might require some coating to reinforce it against tearing.

V. Discussion

Tether capture is characterized by a ratio $M_{SC}/m_t \sim 3$, with the mission requiring a sequence of about eight perijove passes (with $|\Delta e| \sim 0.02$) to reach $e = 0.86$. Before a first resonant orbit, however, operation requires two convenient steps by switching the current off over part of the drag arc to allow for a first flyby of Europa; switching the current off afterward over the entire resonance orbit would allow repeated flybys. The dose per orbit may reach near 0.1 Mrad for 200 mils (about 5 mm) of aluminum shielding [8]. Over 20 flybys would then make a total of 30 perijove passes, leading to 30×0.1 Mrad, or a 3.0 Mrad cumulative dose under 200 mils of shielding. Individual payload electronics could need their own shielding; also, some nesting radiation protection might be required.

Tether heating from electron collection is a local and (typically conservative) quasi-steady process [6], basically balancing heating and thermal radiation. Maximum temperature occurs at $s = 0$, $\varphi = 0$, and $r = r_p$, exhibiting a dependence [6]

$$\text{emissivity} \times T_{\max}^4 \propto L^{3/2} \times \text{a function of } \tilde{r}_M. \quad (17)$$

Table 1 Summary of relevant mission design parameters

Orbital parameters		Tether and S/C parameters		Jupiter parameters	
Parameter	Value	Parameter	Value	Parameter	Value
v_∞	5.64 km/s	M_{SC}	200 kg	R_J	71,492 km
H_p	350 km	m_t	65 kg	μ_J	$1.267 \times 10^{17} \text{ m}^3 \text{ s}^{-2}$
e_h	1.02	L	2 km	Ω_J	$1.76 \times 10^{-4} \text{ rad/s}^{-1}$
e at flybys	0.86	h	12 μm	B_s	0.38 G
Perijove passes before flybys	9	w	100 cm	N_s	$1.44 \times 10^2 \text{ cm}^{-3}$

Using a rough-surface Al tape with a very thin oxidized layer (still allowing the highly energetic electrons that reach the tape to get through to its conductive interior), thermal emissivity might lie well above the 0.04 value of fully conductive polished-surface aluminum [14]. For values of 0.4 emissivity, $r_p \approx R_J$ and lengths $L = 2$, 3.25, and 5 km, there result 567, 680, and 799 K maximum temperatures, respectively. The $L = 2$ km value ($T_{\max} = 294$ C) suggests the convenience of keeping the length at the lowest range end and ϵ_{\max} definitely below 0.1 MeV.

As opposed to the NASA Europa mission concept, the tether-mission concept would also allow exploration of the Jovian interior. Multiple perijove passes so close to Jupiter would allow high-resolution determination of Jovian gravity and magnetic fields, as well as bulk abundance of water. Independently, in situ detection of charged grains might advance well beyond remote-imaging ring studies, allowing measurements of dust charge, mass, and chemical composition; the typical size is centered at about 1 μm . The grain-tether interaction makes for a complex dusty-plasma problem, involving grain dynamics and charge evolution [8,15].

Also, the orbiting tether could itself be an active instrument. With hollow cathodes off during each flyby, the tether will be electrically floating [8], attracting ions over most of its length. This results in a continuous beam of energetic secondary-emission electrons, with their energy and flux increasing with distance from the anodic tether end, allowing for auroral effects to probe the Jovian ionosphere [16]. Some characteristic mission values are given in the Table 1.

VI. Conclusions

For a broad range of tether tape width w and a total spacecraft mass of $M_{SC} \sim 200$ kg, suppose, light/fast missions to Jupiter for close exploration of its interior and its immediate neighborhood, as well as multiple flybys of Europa, are possible using tethers. About one-third of total mass would be tether mass. Neither wet mass nor gravity assists are needed, with the S/C reaching Jupiter in a relatively short, direct Hohmann transfer. Mission design depends critically on keeping the collected-electron range below tape thickness throughout. This is achieved by setting the perijove for capture and apojove-lowering very close to Jupiter (hundreds of kilometers above it) while using short, thin tapes ($L \sim 2$ km, $h \sim 0.012$ mm, suppose), resulting in a very light tether and S/C, as well as moderate tether heating. The accumulated dose is suppose-controlled by the number of Europa flybys, which is about 20 here. The large Debye length in the Jovian ambient plasma allows use of tapes with w of about 1 m.

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G. G. Spanjers
Associate Editor