Tether-mission design for multiple flybys of moon Europa

Juan R. Sanmartín*, Mario Charro*, Gonzalo Sanchez-Arriaga**, Antonio Sanchez-Torres*
*Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio / Universidad Politécnica de Madrid
**Departamemto de Bioingeniería e Ingeniería Aeroespacial / Universidad Carlos III de Madrid

Mission concept. Electrodynamic tape-tethers are shown to allow a cheap, light, fast mission to Jupiter for multiple flybys of moon *Europa* and close exploration of the Jovian interior. As regards flybys, this mission is similar to the *Clipper* mission presently considered by NASA, the basic difference (periapsis location) arising from mission-challenge metrics.

Clipper minimizes damaging radiation-dose by avoiding the Jupiter neighborhood and its very harsh environment; periapsis would be at Europa, apoapsis as far as moon *Callisto*. As in all past outer-planet missions, Clipper faces, however, critical power and propulsion needs.

In turn, tethers can provide both propulsion and power, but need reach near the planet to find higher plasma density and magnetic field, leading to high induced tether current, and Lorentz drag and power.[1] The bottom line might be a strong radiation dose under the very intense Radiation Belts of Jupiter.[2, 3]

Mission design must limit dose. Perijove r_p would be near Jupiter, and apojove about moon *Ganymede*, for an 1:1 resonance with Europa to keep dose down: Setting apojove at Europa, for convenient parallel flybys, would require two perijove passes per flyby; it would restrict r_p choice too. Further, the *Ganymede* apojove, resulting in high eccentricity, about 0.86, is also less requiring on tether operations.

But design must also deal with electrons the tether attracts and captures, more energetic for longer tethers, which Lorentz drag needs because of the low Jovian plasma density. This may result in strong tether heating, and electrons (intended to be collected) reaching the tape with *range* in aluminum exceeding thickness.[4]

The S/C would need no gravity assists, reaching Jupiter in a *Hohmann* transfer, at velocity 5.64 km/s in a relative equatorial, hyperbolic orbit of eccentricity $e_h \approx 1.02$. Values of $|\Delta e|$ from capture in the perijove pass are always a small fraction of unity; calculations here will consider capture orbit as parabolic.

Divine-Garrett models are used for plasma density and radiation flux. Also used is a no-tilt, no-offset dipole model of the Jovian magnetic field, which is thus perpendicular to both S/C and co-rotating plasma velocities. Further, due to the low Jovian gravity-gradient, tether spinning is necessary to keep it straight, *hollow cathode* plasma contactors placed at both ends taking active turns at being cathodic.

Mission design. Efficiency of tether capture of the incoming S/C is gauged by the ratio M_{SC}/m_t at desired $|\Delta e|$. With HC voltage-drop and ohmic effects (as regularly at Jupiter) negligible, Ref.1 gave

$$\frac{|\Delta e|}{e_h - 1} \times \frac{M_{SC}}{m_t} \approx 0.15 \times \left(\frac{L}{50km}\right)^{3/2} \frac{0.05mm}{h} \times \Sigma(\tilde r_M) \qquad (1)$$

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

Here $r_M = a_s\sqrt{2a_s/r_p}$ is radius where drag vanishes in a parabolic orbit of perijove r_p (with $a_s \approx 2.24R_J$ the stationary-circular-orbit radius), plasma density following the classical *Divine-Garrett* model,

$$\frac{N_e}{N_s}(\tilde r, \tilde r_M) = \exp\left(\frac{2.72\,\tilde r_M^{\,2/3}}{\tilde r} - 3.43\right). \qquad (3)$$

Σ increases with $\tilde r_M = \sqrt{2}\,(a_s/r_p)^{3/2} \approx 4.74\,(R_J/r_p)^{3/2}$; capture efficiency is thus higher the lower perijove radius r_p. It is also clearly higher the greater tape-tether length L and smaller thickness h.

Too long a tape, however, will result in attracted electrons hitting it at values of energy ε with *range* (*penetration depth*) $\delta_e(\varepsilon)$ larger than thickness h if too low, and/or perijove too close to Jupiter.[4] (No design criterion involves tape width w, scaling with M_{SC} over a broad range; *Debye* length is of order 1m)

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

$$\varepsilon = eE_m(L-s), \qquad E_m(r,\varphi) = v'(r)\,B(r)\cos\varphi$$

where $\boldsymbol{E_m}$ is the motional electric field, $\boldsymbol{v}'$ S/C velocity relative to the co-rotating plasma, r radius at a generic point in the drag arc $r_p \le r \le r_M$, and φ instantaneous angle between spinning tether and $\boldsymbol{E_m}$.

Maximum energy corresponds to values $s = 0$, $\varphi = 0$, $r = r_p$, $\Rightarrow$ $\varepsilon_{\max}(r_p, L) = e\,E_{mp0}(r_p)\,L$, (4)

$E_{mp0} = v'_p B_p$, $B_p = B_s(a_s/r_p)^3$,

$$v'_p = \sqrt{2\mu_J/r_p} - \Omega_J r_p = \sqrt{2\mu_J/r_p} \times \left[1-(r_p/2^{1/3}a_s)^{3/2}\right]$$

$$E_{mp0} = E_*\,(a_s/r_p)^{7/2}\left[1-(r_p/2^{1/3}a_s)^{3/2}\right] \equiv E_*\,(\tilde{r}_M - 1)\,(\tilde{r}_M/2^{7/8})^{4/3} \qquad (5)$$

$$E_* \equiv (2\mu_J/a_s)^{1/2}B_s \approx 0.38\ \mathrm{G} \times 39.8\ \mathrm{km/s} \approx 1.51\times10^3\ \mathrm{V/km} \qquad (6)$$

For a simplest design we suggest the lowest acceptable thickness h at given L and r_p values would be

$$h \;=\; \delta_e\,[\varepsilon_{\text{max}}(\,r_p,\,L\,)] \;\equiv\; \delta_e\,[eE_{\text{mp0}}(r_p)\,L] \tag{7}$$

Note that Eq.(1) involved integrations over

1) full range $0 < s < L$ determining tether current, 2) full range of angles $-\pi/2 < \varphi < \pi/2$,

3) twice from r_p to r_M (over full drag arc), with range $\delta_e\,(\varepsilon) \;<\; h$ throughout that triple integration whereas $\delta_e\,(\varepsilon) \;=\; h$ holds at just one limit point in the 3D integration domain.

Using Eqs. (4)-(6), Eq. (1) can now be rewritten as

$$\frac{|\Delta e|}{e_h - 1} \times \frac{M_{SC}}{m_t} \;\approx\; 0.15 \times \Sigma(\tilde{r}_M) \times \left(\frac{\varepsilon_{\max}}{eE_{mp0} \times 50km}\right)^{3/2} \frac{0.05mm}{\delta_e(\varepsilon_{\max})}$$

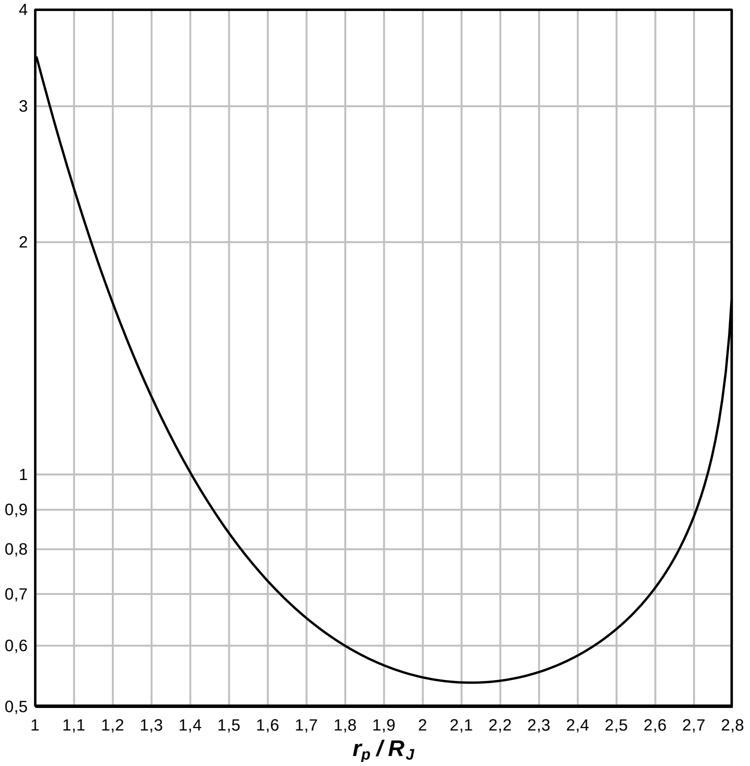
$$= 0.15 \times \frac{\Sigma(\tilde{r}_M)}{\tilde{r}_M^2\left(\tilde{r}_M - 1\right)^{3/2}} \times \frac{(\varepsilon_{\max}/\varepsilon^*)^{3/2}}{\delta_e(\varepsilon_{\max})\,/\,0.05mm}\;, \tag{8}$$

involving just two (r_M, ε_{max}) ratios, with $\varepsilon^* \;\approx\; 0.151 \times 0.5 \,/\, 2^{7/6}$ MeV $\approx$ 0.0336 MeV. (9)

For a desired value of ratio $|\Delta e|/0.02 > 1$, the captured mass ratio is largest for some *optimum* values of r_M (or, equivalently, r_p) and $\varepsilon_{\max}$ making the ratios involving them in Eq.(8) as large as convenient. For choices of $\varepsilon_{\max}^{\mathrm{opt}}$ and r_p^{opt} there follow $h_{design} = \delta_e(\varepsilon_{\max}^{\mathrm{opt}})$, $L_{design} = \varepsilon_{\max}^{\mathrm{opt}} / eE_{mp0}(r_p^{opt})$. Finally, Eq.(8) yields the mass ratio; tether width w follows a choice of M_{SC}.

Note that moving from $r_p = 1.4\ R_J$ (one case considered in Ref. 1) to $r_p \approx R_J$ in the Figure, increases efficiency by half an order of magnitude. A value $r_p = 1.005\ R_J$, say, would correspond to about 350 km altitude above Jupiter. We take 3.5 as value of the r_M ratio in (8), here just writing $r_p \approx R_J$.

We now have $eE_{mp0}(r_p^{opt}) \approx 0.020$ MeV / km. Also, the right-hand-side of Eq. (8) is just 0.525 times the value of the $\varepsilon_{\max}$ ratio. As regards that ratio, it increases (but moderately) with decreasing $\varepsilon_{\max}$, from some minimum around 0.3 MeV.



The r_M *ratio in Eq.*(8) *versus perijove ratio*

For $\varepsilon_{max} = 0.1$ MeV, Fig. 6.4 of Ref.5, from the GEANT Montecarlo code, gives $\delta_e(\varepsilon_{max}) =$ 2 mils ≈ 0.051 mm, leading to an ε_{max} ratio of 5.03, a RHS of (8) of 2.64, and lengths $L = 5$ km, $h = 0.051$ mm.

For $\varepsilon_{max} = 0.04$ MeV, we find $\delta_e(\varepsilon_{max}) =$ 0.4 mils ≈ 0.010 mm, $L = 2$ km, $h = 0.010$ mm, ε_{max} ratio of 6.49, RHS of (8) of 3.41. The above *range*-δ_e values are somewhat below values from model ESTAR (Ref. 6). A larger ε_{max} ratio could lead to too thin tapes, requiring reinforcing with *Zylon* to prevent tearing.

Radiation dose and heating. As general result, capture can be achieved with a ratio $M_{SC}/m_t \sim 3$. 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, requiring a sequence of 8 perijove passes (with Δe about - 0.02) to reach $e = 0.86$.

A last decrement previous to a first resonant orbit must, however, be reached in two convenient steps by switching current off appropriately over part of the drag arc, to allow for a first flyby of Europa; switching current off afterward over the entire resonance orbit would allow repeated flybys.

Dose per orbit for eccentricity over 0.5, say, proves also near-independent of perijove radius if near Jupiter, the number of perijove passes thus being a metric for total dose.[2,3] The dose per orbit is about 0.1 Mrad for

200 *mils* of Aluminum shielding. Dose is also near independent of longitude, proving the simple dipole model in the inner magnetosphere accurate. The GIRE radiation model was used throughout calculations.

Over 20 flybys would then make a total of 30 perijove passes, leading to 30 × 0.1 Mrad, or 3.0 Mrad cumulative dose under 200 mils shielding (as compared with 2.9 Mrad for 100 mils shielding of the *Jupiter Europa Orbiter* in the originally planned *EJSM* mission). As with *Clipper*, 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 (Ref. 1). Maximum temperature occurs at values $s = 0$, $\varphi = 0$, $r = r_p$, exhibiting a dependence

$$T_{\max} \propto L^{3/8} (\tilde{r}_M - 1)^{3/8} \tilde{r}_M^{\,1/2} \tag{10}$$

At the short tether length $L = 2$ km, and $r_p \approx R_J$, there results a modest 477 K maximum temperature.

Measurements around perijove. In addition to Europa flyby measurements, multiple perijove passes so close to Jupiter would allow high resolution determination of Jovian gravity and magnetic fields, and bulk abundance of water. Also, the orbiting tether itself could be an active instrument. During each flyby, with hollow cathodes off, the tether will be electrically floating; ions will be attracted over most of the tether, resulting in a continuous beam of energetic secondary-emission electrons, energy and flux increasing with distance from anodic tether-end. This will allow for artificial auroral effects to probe the Jovian ionosphere.

Conclusions

For some range of tether tape width w, and spacecraft mass $M_{SC} \sim 100 - 200$ kg, say, light/fast/cheap missions to Jupiter, for close exploration of its interior and multiple flybys of Europa, are possible using tethers. About 1/3 of total mass M_{SC} is tether mass. No wet mass is needed, and no gravity assists, the S/C reaching Jupiter in a direct Hohmann transfer. Mission-design keeps collected-electron *range* below tape thickness throughout. This is achieved by using short, thin tapes ($L \sim 3$ km, $h \sim 0.02$ mm, say) while setting the perijove for capture and apojove lowering extremely close to Jupiter (hundreds of kilometers above the planet). This results in very light tether and S/C, and moderate tether heating. Accumulated dose is controled by the number of Europa flybys, about 20.

References

1 J.R.Sanmartin, M.Charro, E.C.Lorenzini, H.B.Garrett, C.Bombardelli, C.Bramanti, *Electrodynamic Tether at Jupiter- I: Capture Operation and Constraints*, IEEE Trans. Plasma Science **36,** 2450-58 (2008)

2 J.R.Sanmartin, M.Charro, E.C.Lorenzini, H.B.Garrett, C.Bombardelli, C.Bramanti, *Electrodynamic Tether at Jupiter- II: Fast Moon Tour after Capture*, IEEE Trans. Plasma Science **37**, 620-626 (2009).

3 M.Charro, J.R.Sanmartin, C.Bombardelli, A.Sanchez-Torres, E.C.Lorenzini, H.B.Garrett, R.W.Evans, *A proposed two-stage two-tether scientific mission at Jupiter*, IEEE Trans. Plasma Science **40**, 274-281 (2012).

4 G.Sanchez-Arriaga, J.R.Sanmartin, *Relativistic current collection by a cylindrical Langmuir probe*, Physics of Plasmas **19**, p063506 8pp (2012)

5 D.Hastings, H.Garrett, *Space Environment Interactions*, Cambridge University Press, 1996

6 *ESTAR, Stopping power and Range Tables for Electrons*, National Institute of Standards and Technology, 2010.