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TRADE-OFF STUDY ON DEORBITING S/C IN NEAR-POLAR ORBIT

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Abstract

Usual long, flexible, ED tethers kept vertical by the gravity gradient might be less efficient for deorbiting S/C in near-polar orbits than conventional (Hall, Ion) electrical thrusters. A trade-off study on this application is here presented for tethers kept horizontal and perpendicular to the orbital plane. A tether thus oriented must be rigid and short for structural reasons, requiring a non-convex cross section and a power supply as in the case of electrical thrusters. Very recent developments on bare-tether collection theory allow predicting the current collected by an arbitrary cross section. For the horizontal tether, structural considerations on length play the role of ohmic effects in vertical tethers, in determining the optimal contribution of tether mass to the overall deorbiting system. For a given deorbiting-mission impulse, tether-system mass is minimal at some optimal length that increases weakly with the impulse. The horizontal-tether system may beat both the vertical tether and the electrical thruster as regards mass requirements for a narrow length range centered at about 100 m, allowing, however, for a broad mission-impulse range.

Introduction

Guidelines and regulations on limiting space debris will require deorbiting a LEO S/C at the end of its operational life. Deorbiting involves prolonged drag -drag fluctuations being irrelevant- and is therefore a particularly suitable application of electrodynamic (ED) tethers, which depend on ambient conditions. The *specific impulse* of ED-tethers is proportional to tether length [and to its cathodic Plasma Contactor (PC) efficiency]. With state-of-the-art PC's, 10 km long tethers have specific impulse two orders of magnitude greater than Hall or Ion propulsors.[1] Also, they need no power supply, orbit decay being a thermodynamic irreversibility that makes for Joule heating out of orbital energy.

An ED bare tether (BT) acts as its own anode, collecting electrons over a positively-biased segment left uninsulated; a PC at the cathodic end ejects electrons.[2] In 1992 ESA recommended testing the BT concept in the Columbus Precursor Flights, later suppressed. Following a White Paper to NASA,[3] an experiment (ProSEDS) on board a GPS-replacement Delta-II rocket will test the BT concept in September 2002. BT's are being considered for reboost of the International Space Station. BT operation is simple and its electron-collection capability is both greater and more mass-efficient than collection by big spheres at tether end.[4]

Polar Tethers

The market for deorbiting S/C in high-inclination orbits will grow in the near future. Such orbits pose a problem for deorbiting ED tethers. The instantaneous magnetic drag is

$$Drag = I_{av} B_{\perp} L, \qquad (1)$$

where L and I_{av} are tether length and tether-current averaged over its length, and $B_{\perp}$ is geomagnetic component perpendicular to both tether and velocity. As a consequence, the usual vertical tethers, for which $B_{\perp}$ is perpendicular to the orbital plane, become less efficient for highly inclined orbits, when that component is small.

The loss of drag in moving to high inclination orbits is made more dramatic because current itself in Eq. (1) is limited by the component $B_{\perp}$. The induced bias that drives the current is

$$Induced\ bias = v_{sat} B_{\perp} L, \qquad (2)$$

and the short-circuit (ohmic limited) current is

$$Short\text{-}circuit\ current = \sigma v_{sat} B_{\perp} A, \qquad (3)$$

both decreasing with $B_{\perp}$. In Eqs.(2) and (3), v_{sat}, σ, and A are tether velocity, conductivity and cross-section area.

For tethers horizontal and perpendicular to the orbital plane (call them "polar" tethers) $B_{\perp}$ would be vertical. In near-polar orbit, the geomagnetic dipole model with tilt (about 11 degrees) but no center off-set makes the orbit-averaged $B_{\perp}$ value for polar tethers 10 times greater than the corresponding value for vertical tethers. A Study commissioned by ESA suggested using polar tethers for near-polar deorbiting.[5] It has been proposed to test polar tethers on board the Belgian Satellite Proba II, to be launched in 2003/2004.[6]

Polar tether scheme

The gravity gradient at the orientation of polar tethers is compressive, as opposite vertical tethers. This will require the tether to be rigid, and short in some way, to avoid buckling. Booms or masts that can be rolled up flat on a drum, but become hollow and rigid when deployed, have been validated in space. They are easier to deploy than flexible tethers and are free of the instabilities of flexible, current-carrying tethers recently discovered. To allow, in principle, balancing out the magnetic torque associated with magnetic drag, two bare booms of length $\frac{1}{2} L$ would be used, one boom on each side (the magnetic torque on a vertical tether can be balanced by the gravity-gradient force itself, which is not compressive). With boom length limited by structural considerations, as later shown, this use of two booms also results in doubling the tether length and thus the *specific impulse.*

Tether drag in Eq. (1) decreases as tether length is decreased both directly, and indirectly through reduced current, because BT current is itself proportional to length; this will mean that (short) polar-tether deorbiting will work best for small S/C. Ohmic effects in (3) are clearly negligible. Bias in Eq. (2), however, is too small to drive the current, electrical power, assumed available from end-of-life S/C solar panels, being required as in the case of electrical thrusters. The (vertical, or radial) component $B_\perp$ for a polar tether will change direction repeatedly in orbit; in case of polar orbit in a no-tilt/no center-offset dipole-field, $B_\perp$ changes direction at the Equator, pointing inwards and outwards in the (geographic) North and South hemispheres, respectively. Since current driven by the induced bias would change direction as bias changes with $B_\perp$, the magnetic force on bias-driven current would keep opposite the S/C velocity throughout, as thermodynamics requires. In the case of current driven by applied power, however, an electrical switch in the power source must reverse the current.

In a baseline scheme, each boom would carry a PC at its end. At any given time, one (anodic) boom would be polarised at a positive bias near the power-source voltage V_s (~200 volts); it would collect electrons in or around the OML regime of cylindrical Langmuir probes, with its PC idle or switched off. The PC at the end of the opposite (cathodic) boom would eject the collected electron current at a negative bias one order of magnitude below V_s (at less than 20 volts); ion current to this boom would be negligible because the cathodic-to-anodic ratios for both bias and collected-particle mass are small. Magnetometers could determine when $B_\perp$ vanishes and changes direction, signaling power switching of bias, to reverse current and the way each boom works. The bias change would then signal to each PC the change of its function, activating the PC that becomes anodic, idling or switching off the opposite one. Since $B_\perp$-vanishing roughly occurs every half-orbit (~ 50 minutes), and drag would vanish with $B_\perp$ independently of current, and keep low some time around vanishing, PC activation, which only requires a few minutes typically, would pose no timing difficulty.

Length of polar tether

Structural requirements on the deployed thin-tube boom (to avoid buckling under the compressive gravity gradient) impose a minimum tube perimeter $p \propto (\frac{1}{2}L)^2$, with thickness $\propto p$. Minimum tether mass is therefore proportional to L^5,

$$\text{Tether mass} \propto L^5 \qquad (4)$$

Too long booms would require too gross cross sections, boom mass thus rapidly growing with length L to reach impractical values.

Independently, too large a cross section could affect the efficiency of current collection by the anodic bare boom. The theory of BT current collection has been fairly well established recently. Results from the theory allow to determine the current collected within the OML-regime of cylindrical Langmuir probes by tethers of arbitrary cross section (such as the partially convex/partially concave cross section of collapsible tube booms). The theory also allows to determine collection by tethers of large cross sections, with current well below the OML value.[7] It is now possible to perform effective tether design.

At the other end of the length range there are limitations too. Plasma Contactor mass (mass of expellant plus Contactor itself) is proportional to the ratio *deorbiting impulse/specific velocity,* being therefore inversely proportional to tether length,

$$\text{PC mass} \propto \text{deorbiting impulse} / L. \qquad (5)$$

A length $L \approx 100$ m yields a value of specific impulse comparable to values for electrical thrusters; boom lengths much shorter than $\frac{1}{2} L \sim 50$ m would be inefficient as regards PC-expellant mass (that is, as regards specific impulse). In fact, too short booms are to be avoided for a different reason: With OML current satisfying

$$I_{av} \propto pL \propto L^3 \qquad (6)$$

and the duration τ of the deorbiting operation given by

$$\tau \times Drag = deorbiting\ Impulse, \qquad (7)$$

Eqs. (1), (6) and (7) yield

$$\tau L^4 \sim deorbiting\ impulse. \qquad (8)$$

Too short a tether would lengthen the deorbiting time, possibly making it comparable to the half-period of the solar cycle.

In deorbiting S/C as light as Proba II (~ 100kg) from the topside ionosphere (altitude ~ 600-800km), too heavy tether and PC, rather than too heavy the required power system (involving a DC/DC converter to 200 volts), would be an issue. With mass associated to power requirements neglected, Eqs. (4) and (5) show that, for a given deorbiting impulse, there exists an optimal tether length L_{opt} that makes the overall mass of a tether-system minimum; this length varies weakly with the total impulse of the deorbiting mission, $L_{opt} \propto (deorbiting\ impulse)^{1/6}$. There is thus a broad range of deorbiting impulses with L_{opt} around 100 m. For $L = L_{opt}$, tether mass comes out 1/6 of total mass. The rapid decrease of deorbiting duration with tether length, as shown in (8), may make preferable choosing lengths somewhat larger than L_{opt}; this results in comparable masses for tether and PC in (4) and (5). For $L \approx 100$ m, the induced bias in Eq.(2) is about the bias at the PC (20 volts), leaving the entire supply voltage for driving the current.

Because of its small $B_\perp$ value in near polar orbit, a 10 km long vertical tether would have specific impulse only 10 times greater than our 100 m polar tethers. Actually, an equal-mass comparison between polar and vertical tethers would require the 10 km long tether to have its mass comparable to the polar-tether mass; this would lead to an impractically small cross-section area. Vertical tethers 1 km long would have cross sections reasonably small; their specific impulse would be now also comparable to both our 100 m long polar tethers and to electric propulsors.

Polar tether issues

A number of issues on the baseline scheme described above must still be resolved. Plasma Contactors of Hollow Cathode type can function both as cathodic contactor, ejecting an electron current to the ambient plasma, and as anodic contactor, collecting electrons from that ambient plasma. For booms as short as 50m, it might pay to leave each PC on as its boom becomes anodic, thus adding the current it would collect to the bare-boom collected current. This will affect the choice of PC to be used. It may also affect the PC's baseline disposition, which, for reasons discussed below, may need be different from the simplest disposition previously discussed (just one PC at each boom end).

Current exchanged between tether and ionospheric plasma makes its way through the ionosphere to close a circuit. This current closure determines an impedance which is typically negligible in the overall electric circuit. However, if closure occurs near the tether it may modify the way contactors collect current and thus contactor impedance. This might be an issue for our 50 m short booms. Also, if the anodic PC is left on, whether and how its plume would affect electron collection by the anodic boom remains to be examined. Independently, the plume of the cathodic PC, which will certainly be on, might distort results from required plasma measurements such as carried out by Langmuir probes. In any case, in near-polar orbits the polar tether will be almost perpendicular to the geomagnetic field, with no field lines (and no easy path for electrons) connecting the cathodic and anodic regions at tether ends.

The Belgian satellite Proba I was kept three-axis-stabilized by means of attitude measurements through autonomous star-trackers, and on-board control through sets of reaction wheels and magnetotorquers, designed in principle for initial attitude acquisition and angular momentum dumping. Proba II would have, at least, similar attitude control capabilities for its regular operational life. S/C stabilization during deorbiting at end of life might increase, however, the complexity of attitude control. This complexity arises *i*) from the active interaction with the geomagnetic field and *ii*) from the particular boom orientation required, both features being essential to the deorbiting process proposed.

i) Both the magnetic force and torque on the current-carrying booms, when (nominally) oriented perpendicular to the orbital plane (polar tethers), lie in this plane. In the simplest case of polar orbits, and the approximation of *no center-offset/no-tilt* magnetic dipole, the geomagnetic field itself lies in that plane, fully rotating once per orbit in the orbital frame. As previously noted, its vertical component $B_\perp$ would be radially inwards in the (geographic) North hemisphere, and outwards in the South hemisphere; the horizontal component would have the direction of S/C velocity in going from South to North poles, and opposite direction from North to South. Similar though more irregular rotation of the actual geomagnetic field will occur for any high-inclination orbit.

With the proper current-switching that would keep booms dragging the S/C throughout deorbiting, the vertical component of the magnetic force averages out, changing direction every ¼-orbit: it points downwards when approaching the poles, upwards moving off them. With Plasma Contactors at boom ends, current on the anodic boom (at nearly uniform bias) would grow linearly toward the S/C, and keep constant throughout the cathodic one, being expelled at its PC. This makes for an unbalance of opposite boom-torques at the S/C, and a net magnetic torque

$$\textit{Net torque} \approx \frac{1}{9} L^2 I_{av} \overline{B}_{pl} \qquad (9)$$

with the average current I_{av} being ¾ of the accumulated bare-tether current reaching the S/C (and expelled at the cathodic PC). The above torque is always in the direction of the full projection of magnetic field on the orbital plane $\overline{B}_{pl}$, which is made of component $B_{\perp}$ and the component along S/C velocity, and rotates with it, because current always flows towards the (anodic) boom exerting the smaller torque.

For boom length ½ L = 50 m, a typical field $\overline{B}_{pl}$ ~ 0.4 gauss, and a representative current about 0.3 A, the net torque is of order 0.01 N×m. The problem of S/C attitude control would appear more feasible if that rotating torque could be (nominally) made to vanish by balancing out the opposite boom torques. This can indeed be achieved by special arrangements of the Plasma Contactors, which would result, however, in some average-current, and thus deorbit performance, decrease. A possible arrangement would set the PC's at a distance $L/2\sqrt{3}$ from the S/C, the average current then decreasing by a factor 0.72 if the anodic *PC* is off. An alternative arrangement would keep PC's at boom-ends, using a third PC at the S/C to expel 2/3 of the full bare-tether current; I_{av} is now reduced by a factor 0.55, with the anodic *PC* again off.

ii) Passive S/C equilibrium in the orbital frame occurs with the principal axes of inertia lying along vertical, S/C velocity, and perpendicular-to-orbit directions. Such equilibrium is stable for particular dispositions of principal axes on those directions, although, if weak internal dissipation of energy is allowed, stability is restricted to the single case of *minimum inertia (minor axis) along vertical/ maximum inertia (major axis) along perpendicular to orbit* (in correspondence with the case of free rotation in free space: attitude equilibrium with spin around any principal axis; stable equilibrium, for axes of minimum and maximum inertia; stable equilibrium with weak internal dissipation, for major axis only).

For our polar tethers, the axis of minimum inertia, rather than the major axis, nominally lies along the perpendicular to orbit, with the system near axisymmetric as regards inertia, and that minimum moment of inertia being about 2 orders of magnitude smaller than the other two moments (basically arising from the booms). That large inertia disparity could make keeping three-axis-stability (with the S/C platform either Earth pointing or inertially fixed) difficult.

Actually our polar tether disposition may itself be stable. There exists an attitude (Thomson) equilibrium, which requires a spin along the (tether) axis perpendicular to orbit, in addition to the small orbital angular velocity. The Thomson spin must be a few times greater than the orbital angular velocity × the large moment-of-inertia ratio. That spin is here still slow (about 1 rpm in the case of Proba II plus booms), amounting to angular momentum of order 10 N×m ×s.[8]

The Thomson equilibrium can be stable under internal dissipation. Thomson's equilibrium might be useless, however, in case of strong dissipation arising from structural damping associated to the so-called "whirling" instability. That instability requires a spin greater than the frequency of the fundamental vibrational mode. This frequency decreases with increasing length as $1/L^{3/2}$. On the contrary, the Thomson spin increases with length as *tether mass* × $L^2 \propto L^7$, as follows from (4), meaning that the threshold for the instability is a sharp function of L. For Proba II and the booms being considered, a boom length ½ L ~ 50 m would be stable, whereas ½ L ~ 100 m would not. Actually, nonlinear effects appear to saturate the "whirling" instability, this making it (along with any nutation) less dangerous for our polar booms, which, as opposed to many scientific instruments, are not stringent as regards pointing or straightness requirements.[9]

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