JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 37, No. 2, March–April 2000

Bare Tethers for Electrodynamic Spacecraft Propulsion

R. D. Estes* and E. C. Lorenzini†
Harvard–Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
J. Sanmartín‡ and J. Peláez§
Universidad Politécnica de Madrid, 28040 Madrid, Spain
M. Martínez-Sánchez¶
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
C. L. Johnson**
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
and
I. E. Vas††
The Boeing Company, Huntsville, Alabama 35824

Electrodynamic tether thrusters can use the power provided by solar panels to drive a current in the tether and then the Lorentz force to push against the Earth's magnetic field, thereby achieving propulsion without the expenditure of onboard energy sources or propellant. Practical tether propulsion depends critically on being able to extract multiamp electron currents from the ionosphere with relatively short tethers (10 km or less) and reasonably low power. We describe a new anodic design that uses an uninsulated portion of the metallic tether itself to collect electrons. Because of the efficient collection of this type of anode, electrodynamic thrusters for reboost of the International Space Station and for an upper stage capable of orbit raising, lowering, and inclination changes appear to be feasible. Specifically, a 10-km-long bare tether, utilizing 10 kW of the space station power could save most of the propellant required for the station reboost over its 10-year lifetime. The propulsive small expendable deployer system experiment is planned to test the bare-tether design in space in the year 2000 by deploying a 5-km bare aluminum tether from a Delta II upper stage to achieve up to 0.5-N drag thrust, thus deorbiting the stage.

Nomenclature

$\boldsymbol{B}$ = Earth's magnetic field vector
c_E = cost of electricity per unit of power
c_H = cost of hardware per unit mass
c_p = cost of propellant per unit mass
e = electron charge
F = propulsive force
F_{sc} = Space-charge collection function
g = acceleration of Earth's gravity
I = current collected from plasma
I_{OML} = current collected by cylindrical anode in orbital-motion-limited limit
I_{PM} = limit on current collected by spherical anode according to Parker–Murphy formula
I_{sc} = current collected by spherical anode according to space-charge formula
I_{sp} = specific impulse
J_{th} = thermal current density
k = Boltzmann constant
L_B = electron-collecting length
L_c = cylinder length
l_e = electron gyroradius
M_H = mass of hardware
M_p = mass of propellant
m_e = electron mass
N_e = local electron density
N_∞ = unperturbed plasma density
P = electrical power
R_c = cylinder radius
R_s = sphere radius
T_e = electron temperature
T_i = ion temperature
V_a = anode bias voltage with respect to plasma
$\boldsymbol{v}$ = orbital velocity of tethered system
η = thruster efficiency
η_T = thruster efficiency for tethered system
λ_D = Debye length

Received 16 October 1998; revision received 19 May 1999; accepted for publication 12 June 1999.

*Physicist, Radio and Geoastronomy Division, MS 80, 60 Garden Street.
†Space Scientist, Radio and Geoastronomy Division, MS 80, 60 Garden Street. Senior Member AIAA.
‡Professor, Applied Physics, Escuela Técnica Superior de Ingenieros Aeronáuticos, Ciudad Universitaria.
§Associate Professor, Applied Physics, ETSI Aeronáuticos, Ciudad Universitaria.
¶Professor, Aeronautics and Astronautics, 37-341, 77 Massachusetts Avenue. Senior Member AIAA.
**Manager, Interstellar Propulsion Research, Advanced Space Transportation Research Program, Mail Code TD15.
††499 Boeing Boulevard. Associate Fellow AIAA.

Introduction

IN this section we shall briefly present the basic principles by which an electrodynamic tether propulsion system works and then examine the problem that inadequate electron collection poses for practical thrusters based on standard electrodynamic tethers. The following sections will then deal with our proposed solution: the bare-tether system, in which a portion of the conductive tether is exposed to the ionosphere to act as an efficient anode. Application of a bare tether to the International Space Station (ISS) reboost problem will be considered in some detail with direct comparisons made to other electrical propulsion systems.

An electrodynamic tether can work as a thruster because a magnetic field exerts a force on a current-carrying wire. This force is perpendicular to the wire and to the field vector. If the current flows downward through a tether connected to an eastward-moving spacecraft, the force exerted by the geomagnetic field on the system has a component that accelerates the satellite along the direction in which it is already moving.

An orbiting system, by virtue of its motion through the Earth's magnetic field at velocity $\boldsymbol{v}$, experiences an electric field $(\boldsymbol{v} \times \boldsymbol{B})$

perpendicular to its direction of motion and to the geomagnetic field vector $\boldsymbol{B}$. For an eastward-moving system, such as most Earth-orbiting spacecraft, the field is such that the electrical potential decreases with increasing altitude (at a rate of around 80–150 V/km for a 400-km circular orbit). To drive a current down the tether, it is necessary to overcome this induced electromotive force. Thus, this propulsion system requires a power supply and may be considered a propellantless electrical thruster. Electrical power from solar panels could be utilized for this thruster with night operation on battery power as an option.

A hollow cathode plasma contactor (or other active device) would be used on the spacecraft to eject electrons; thus, the tether must be deployed vertically downward for a boost application. Because of the power supply, which is placed in series between the plasma contactor and the upper end of the tether, the upper end is at a higher electrical potential than the plasma for some distance below it. This distance may be greater than the tether length if the applied voltage exceeds the motional emf. If the ionospheric electrons below the spacecraft can make contact with the tether they will travel up it to the higher potential at the upper end of the tether, giving a current flow in the correct direction for boost.

The way in which the charge exchange between tether and plasma takes place depends on the specifics of the system, and this aspect (specifically the electron collection, which is the difficult part) is the focus in designing a system capable of producing sufficient thrust with a reasonably short tether. The product of tether length and average-along-tether current determines the thrust for given orbital/magnetic conditions. Generally, a shorter tether will have a smaller impact on the spacecraft acceleration environment, and so a combination of high current with short tether length is the goal. For ISS reboost, thrust forces of order 1 N are required from a tether no longer than 10 km, the induced emf being about 1 kV. This set of requirements implies tether currents of order 10 A. Consequently, the critical issue is how to draw ionospheric electrons at that rate.

The standard tether carries insulation along its entire length, exchanging current with the ionosphere only at the ends. The TSS-1R tether used a large metallic sphere of radius $R_s = 0.8$ m to collect electrons passively. There is no established description of the current-voltage $(I - V_a)$ characteristics of such an anode. The Parker–Murphy (PM) current law[1]

$$I_{\mathrm{PM}} = J_{\mathrm{th}} \times 4\pi R_s^2 \times \left(\tfrac{1}{2} + (l_e / R_s)\sqrt{2eV_a / kT_e}\right) \tag{1}$$

takes into account magnetic effects (disregarding the way current disturbances die off far from the sphere) but ignores space-charge and tether velocity effects. In Eq. (1), l_e is the electron gyroradius at the thermal speed $\sqrt{(kT_e/m_e)}$($l_e \sim$ 25–30 mm in the F-layer of the ionosphere) and $J_{\mathrm{th}} = eN_\infty \sqrt{(kT_e/2\pi m_e)}$. TSS-1R results have suggested a modified law, $I \approx \alpha I_{\mathrm{PM}}$ with $\alpha \sim$ 2–3 (Refs. 2–5). In any case, for a collected current proportional to I_{PM}, the small factor l_e / R_s would have kept the TSS-1R current far below 10 A even if the entire motional emf (3–4 kV) could have been used to charge the satellite, that is, had there been no other impedances in the circuit. Under the best F-layer conditions ($N_e \sim 10^{12}$ m^{-3}, $kT_e \sim$ 0.15 eV, and $J_{\mathrm{th}} \sim 0.01$ A/m^2), the modified law gives a 10-A current to the TSS-1R sphere only if it is biased above 100 kV (thus requiring, for thruster applications, over 1-MW power for just the anodic impedance). It is clear from Eq. (1) that attempts to increase current by increasing R_s will only lead to collection of the thermal current, as the second term becomes insignificant.

Actually, for efficient thrust, the anodic bias V_a should be a small fraction of the induced emf ($\sim$1 kV). For example, with $V_a < 200$ V and the best ionospheric conditions, a sphere drawing a 10-A current under the modified PM law would need a surface area two orders of magnitude larger than the TSS-1R sphere. Furthermore, because $I_{\mathrm{PM}} \propto N_\infty$, a strong drop in current would follow the strong drop in electron density encountered during the portion of the orbit that is in the Earth's shadow.

A second current law takes into account space-charge effects but ignores magnetic and tether velocity effects:

$$I_{\mathrm{sc}} = J_{\mathrm{th}} \times 4\pi R_s^2 \times F_{\mathrm{sc}}\left[(\lambda_D / R_s)^{\frac{4}{3}}(eV_a / kT_e)\right] \tag{2}$$

where F_{sc} is a monotonically increasing function of its argurment given approximately by Lam[6] and Alpert et al.[7] It has been suggested that Eq. (2) fits the TSS-1R results better than the modified PM law.[8] Again, with λ_D ranging from 2.5–3 to 7.5–9 mm for the conditions of interest, the small factor λ_D / R_s precludes reaching high current unless V_a is very high or R_s is very large.

Active anodes (plasma contactors) have been developed in an attempt to solve both space-charge and magnetic guiding effects, by creating a self-regulated plasma cloud to provide quasi neutrality and by emitting ions to counterstream attracted electrons and produce fluctuations that scatter those electrons off magnetic field lines. The only tether experiment to use an active anode so far has been the plasma motor–generator[9] (PMG), which reached $I = 0.3$ A in flight under the best ionospheric conditions and with V_a under 100 V. Unfortunately, the required active anode has to achieve a current 30 times larger for a bias around twice as large. There is no clear way to attain this scaling goal, there being no broad theory of contactors and no way to fully simulate flight conditions within the laboratory.[10,11] A further discouraging fact with PMG was that the collected current decreased sharply with the ambient electron density N_e, as in the case of a passive spherical anode.

There is, however, another tether design option: the bare tether.[12,13] A bare-tether design makes short-tether electrodynamic reboost with moderate power requirements practical. The tether itself, left uninsulated over the lower portion, will function as its own very efficient anode. The tether is biased positively with respect to the plasma along some or all of its length. The positively biased, uninsulated part of the tether then collects electrons from the plasma.

Attractive Features of the Bare Tether

The following features argue in favor of the bare-tether concept. First, the small cross-sectional dimension of the tether makes it a much more effective collector of electrons (per unit area) from the space plasma than a large sphere (such as the TSS-1R satellite) at equal bias. This is because the small cross dimension of the tether allows its current collection to take place in the orbital-motion-limited (OML) regime, which gives the highest possible current density.[11] Second, the large current-collection area is distributed along the tether itself, eliminating the need for a large, massive, and/or high-drag sphere or a resource-using plasma contactor at the lower end of the tether. This mass distribution substantially reduces the center of gravity shift in both cases and reduces the cost and complexity in the case of the active contactor. Finally, the system is self-adjusting to changes in electron density. The self-adjustment is accomplished by a natural expansion of the portion of the tether that is biased positively relative to the ionosphere whenever the density drops[13] (Fig. 1).

The first two features combine to provide an ability to collect large currents with modest input power levels. A candidate system that can produce average thrusts of 0.5–0.8 N for input power of 5–10 kW is shown in the following section.

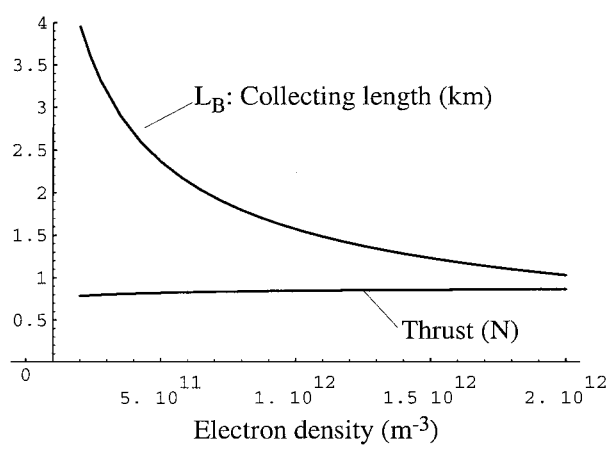


Fig. 1 Variation of thrust with electron density for a 50%-insulated, 10-km, 10-kW bare-tether system at motional emf of 1200 V.

A tether is just a long, thin cylinder. Charged-particle collection by a bare tether is governed by the stronger gradients associated with the smaller dimensions and is, thus, a two-dimensional process, the length being irrelevant to the density of current collected, that is, the bare tether will collect current as a cylindrical Langmuir probe. If thin enough, a cylindrical probe collects current in the optimal OML regime: for $eV_a \gg kT_e$, the well-known OML current law[11] is

$$I_{\mathrm{OML}} = J_{\mathrm{th}} \times 2\pi R_c L_c \times \sqrt{4eV_a/\pi kT_e} \tag{3}$$

A comparison of Eq. (3) to Eqs. (1) and (2) shows clearly how magnetic and space-charge effects are absent from the OML law (which has been established in the laboratory for both quiescent[14] and flowing[15,16] plasmas, for some domain in the space of the dimensionless ratios R_c/λ_D, eV_a/kT_e, and T_e/T_i). For a numerical comparison, note that, to collect 10 A, a cylinder of 2 mm radius and 2.5 km length, in a plasma with $N_\infty = 10^{12}\ \mathrm{m}^{-3}$, $kT_e = 0.15$ eV, requires a bias voltage of only 100 V.

Concerning space-charge effects and the validity of Eq. (3) in the tether case, a recent analysis[17] has shown that, for $T_e/T_i \sim 1$ as in the ionosphere, and for the high eV_a/kT_e values of interest, the OML law holds if R_c/λ_D is less than about 1. This is actually conservative because I remains close to I_{OML} for some R_c/λ_D range beyond that bound. Because λ_D has a minimum of 2.5–3 mm, at the maximum N_∞, this places a loose upper bound on R_c (<3 mm) for tether applications. Moreover, electrons trapped in bounded orbits around the tether have been shown to produce a negligible space charge.[17]

Concerning magnetic effects, it has also been shown[17] that for such effects to be absent both R_c/l_e and λ_D/l_e should be small. Because l_e is about 25–30 mm, this is again satisfied in the F-layer (maximum $\lambda_D \sim 7.5$–9 mm). Experiments onboard rockets and elliptical-orbit satellites did show, in fact, that magnetic effects set in when λ_D/l_e becomes about unity, at low and very high altitudes.[18,19]

An important property for bare tethers is that the OML current is identical for all cylinders with convex cross sections of equal perimeter. In general, one just needs to replace $2\pi R_c$ in Eq. (3) by the perimeter of the cross section.[20] It was recently shown that, for a thin tape, space-charge effects are absent for full tape width $<4\lambda_D$. Thus, tape widths as large as 12 mm could be used.[17] It might be convenient to use a tape as tether for another reason: the area of the tether cross section is determined by requiring that ohmic effects be moderately weak (light and efficient thruster) and, for equal area, a tape would have a larger perimeter than a wire, and would thus result in a shorter tether length.

The OML law is quite robust, and it applies even if the potential around the probe has no rotational symmetry, as is the case for a tape. The law is valid whatever the unperturbed electron distribution function (if isotropic, the tether velocity does not break this isotropy): Note that I_{OML} in Eq. (3) is independent of T_e. The law is also valid for any ion distribution function. The domain of validity of the law does depend, naturally, on the parametric conditions. Concerning tether velocity effects, preliminary calculations suggest that if other conditions (tether radius and bias, plasma density, etc.) are such that the OML law would hold in the absence of tether velocity, the law does approximately hold when the tether velocity is considered.

For an orbiting, current-carrying tether, the bias will actually vary along the tether because of both the motional electric field and the ohmic voltage drop. The electron current to the tether will, thus, vary with height. Along the uninsulated part of the tether, the tether current will decrease with decreasing altitude, until the point is reached at which the tether is at zero bias with respect to the plasma (or the end of the tether is reached). If we assume that there is a point of zero bias on the tether, then below that point an ion current (much smaller because of the high ratio of ion mass to electron mass) that decreases somewhat the average tether current will be collected, due to the negative bias.

Because the current collected by an electron-collecting length L_B grows roughly as $(L_B)^{3/2}$, the tether can automatically accommodate drops in density by increasing the length of the collecting segment, shifting the zero bias-point downward.[13] This is illustrated for a specific case in Fig. 1, which shows the thrust variation as a function of plasma density for a half-insulated, 10-km-long tether at a constant end-to-end motional emf of 1200 V and a current-driving input power of 10 kW. Thrust drops only 10% as the density drops by a factor of 10. The reason is clear: the collecting length has increased from 1 to 4 km. The ability to maintain thrust levels with low electron densities makes nighttime boost possible.

On the whole, the simplicity of the design, in addition to the ability to collect high currents and to accommodate density fluctuations by varying the collecting area, make the bare-tether concept particularly attractive. Bare tethers are mostly free of the gross performance uncertainties that cloud the use of active, or sphere-like passive, contactors. Ground simulation of electron collection in orbital conditions (except for orbital velocity) is possible because there is no need to reproduce the cylinder length-to-radius in the laboratory. A series of plasma chamber tests were conducted at the NASA Marshall Space Flight Center in the spring of 1997 with promising results (private communication from K. H. Wright Jr.). The two-dimensional geometry also makes a large-scale program of particle-in-cell simulations feasible, and we anticipate using such simulations to study various tether geometries in our search for increased performance with lower mass.

Propulsion Applications of the Bare-Tether Design

Reboost of the ISS

A concept design for an electrodynamic tether thruster capable of delivering 0.5–0.8 N of thrust to the ISS at a cost of 5–10 kW of electrical power consists of a 10-km-long aluminum tether in the form of a thick ribbon (0.6 × 10 mm). Despite its length, the tether would weigh only around 200 kg. Because the bare portion of the tether is to act as the electron collector, a downward deployment of the tether is dictated by the physics of the eastward-moving platform.

The upper part of the tether will be insulated. There are two reasons for this. First, there is the necessity for preventing electrical contact from developing across the plasma between the upper portion of the tether and the space station, which (when the system is operating) are separated by an electrical potential difference of around a kilovolt. Second, the insulation provides for greater thrust at a given input power. This benefit results because the largest tether-to-plasma bias occurs at the upper end and decreases down the tether. A completely bare tether would draw the maximum current through the power supply, but the current would be strongly peaked at the upper end of the tether. Keeping the input power constant, we can substantially increase the average current in the tether, and hence the thrust, by insulating the tether over much of its upper portion, collecting current with the lower portion, and having a constant current in the upper part.

Determining the optimal fraction to insulate is part of the design effort for a bare-tether reboost system. The preliminary design has the upper 50% of the tether insulated. Even greater thrust during daytime operation could be obtained with a higher fraction, but the nighttime adjustability would suffer. The system provides flexibility in the sense that the thrust obtained depends almost linearly on the input power, as seen in Fig. 2.

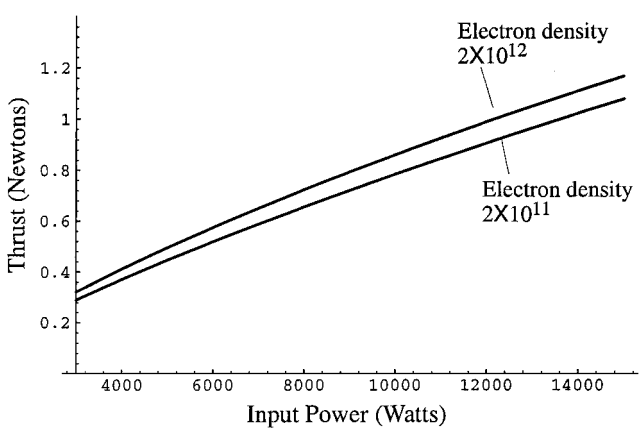


Fig. 2 Variation of thrust with input power for 50%-insulated, 10-km bare-tether system at motional emf of 1200 V.

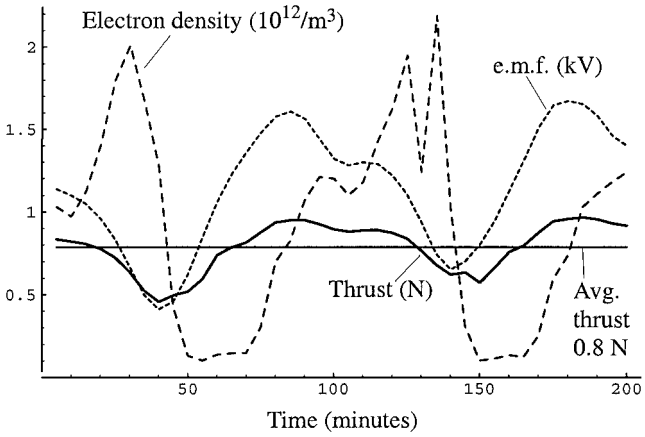


Fig. 3 Variation of thrust, electron density, and motional emf around two typical revolutions of space station orbit with a 50%-insulated, 10-km, 10-kW bare-tether system.

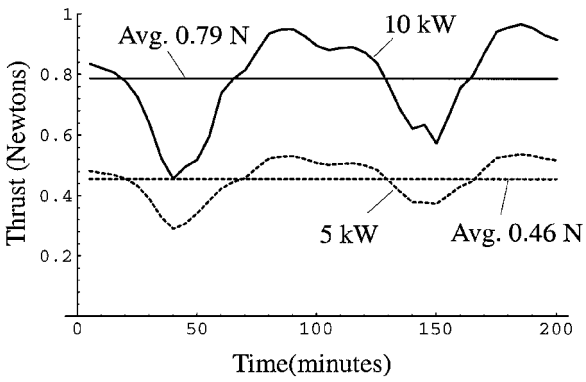
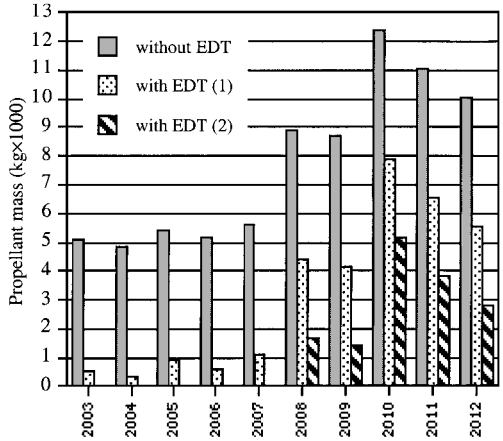
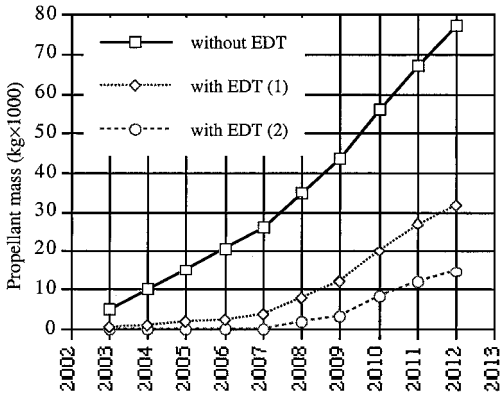


Fig. 4 Comparision of thrust generated around two typical revolutions of space station orbit by a 50%-insulated, 10-km bare-tether system for input powers of 5 and 10 kW.



a) Annual propellant requirements by year



b) Cumulative propellant requirements by year

Fig. 5 Propellant required by space station with and without an ED bare tether under two assumptions of thruster duty cycle.

The bare-tether design has largely cured the problem of day/night thrust fluctuations. However, fluctuations in thrust due to fluctuations in the induced emf as the system encounters a varying geomagnetic field around the orbit are a fact of life for any tether-based system. Figures 3 and 4 show the thrust variations for a the half-insulated, 10-km-long tether around two typical revolutions of the ISS orbit with input power levels of 5 and 10 kW, superimposed on electron density and emf variations. The dependence of thrust force on electron density is weak, as expected, and the thrust curve basically tracks the variations in emf.

Given the level of the current the system may draw, the system will almost certainly require its own cathodic plasma contactor at the station end. The contactors currently under development at NASA John H. Glenn Research Center at Lewis Field should be well suited for this function. If thrusts over 0.5 N are desired, it is likely that the system will also have to rely on the ISS's plasma contactor as well, or on a second dedicated contactor, inasmuch as currents over the 10-A rating of the contactors could be required.

The value in an electrodynamic tether reboost system lies in its ability to couple power generation with thrust. Heretofore the electrical and propulsion systems have been effectively totally separate entities. Outfitting ISS with an electrodynamic reboost tether severs the most critical and constraining dependency on Earth, propellant resupply. The station can supply its own power, but not its own propellant. With the addition of the electrodynamic tether system, a 1-year interval between visits to the station becomes conceivable. Even if the current frequency of resupply flights to the station is maintained, with an electrodynamic tether the station program has the option to trade kilowatts for increased payload capacity. Resupply vehicles can deliver useful cargo such as payloads, replacement parts, and crew supplies rather than propellant.

Figures 5a and 5b show the propellant demand by the space station computed on a yearly and cumulative basis with and without a bare-tether system for reboost. Figures 5 are representative of a 10-kW system operated only 50% of the time (system duty cycle) in case 1. The amount of propellant saved over 10 years of operations under the conditions specified earlier is 45 ton out of the 77 ton required. This is a very conservative estimate of the possible savings in which we assume that the reboost system is not operated during microgravity experiments. However, because of its very low-thrust level, a bare-tether reboost system could be operated during microgravity experiments. Under this assumption (case 2 in Fig. 5), the system duty cycle could be varied between 54–80%, and the reboost demand of the space station could be fully covered by the bare tether over the first five years of operation and mostly covered during the last five, for a total propellant savings of 62 ton. The maximum 80% duty cycle would allow for the periodic visits of space vehicles to the station during which the bare tether would be retracted.

Station users have been allocated a minimum of 180 days of microgravity per year. However, current planning essentially halts science activity during reboost maneuvers. Low-thrust electrodynamic tether reboost could be performed over long duration, as opposed to short-duration, high-thrust propulsive maneuvers and, consequently, allow microgravity experiments that are not interrupted by the reboost maneuvers.

As a rule of thumb, the bare-tether system that we are proposing for the space station reboost would save about 1000 kg of propellant per kilowatt expended per year if operated continually. Various propulsive schemes can be considered for space station reboost, and their costs can be compared to the electrodynamic tether option. The yearly cost of operation can be broken down into contributions from the propellant cost, the cost of electricity (if used), and the hardware cost:

$$\$\text{cost/year} = c_p M_p + 8760 c_E P + c_H M_H \tag{4}$$

Table 1 Thruster performance assumption

Thruster type	I_{sp}, s	η
Chemical	330	——
Ammonia arcjet	800	0.4
Xe, Hall	1,600	0.55
Xe, ion	2,600	0.7
ED tether	300,000[a]	0.6

[a]Equivalent specific impulse devised for propellant consumption comparison.

where c_p (\$/kg) is the cost of propellant placed in orbit, M_p (kg/year) the mass of propellant used per year, c_E (\$/kW · h) is the cost of electricity on the space station and P (kW) is the mean power for reboosting (the factor 8760 converts years to hours). Finally, c_H (\$/kg) is the cost of hardware (placed in orbit), and M_H (kg/year) is the hardware mass needed per year for reboosting. In terms of the device's specific impulse I_{sp},

$$M_p = 3.15 \times 10^7 (F/gI_{sp}) \tag{5}$$

where F is the propulsive force in newtons.

The I_{sp} values assumed for chemical, arcjet, Hall, and ion thrusters are listed in Table 1. For the electrodynamic tether, the only mass consumption occurs in the hollow cathode. Basing our estimate on the gas usage of the 10-A-rated ProSEDS hollow cathode, we arrive at an "equivalent specific impulse" of 300,000 s for the tether system.

The required power (kW) is zero for the chemical thruster. For electric thrusters,

$$P = (1/1000)(FgI_{sp}/2\eta) \tag{6}$$

where η is the thruster efficiency (Table 1). Similarly, for the tether,

$$P = (1/1000)(Fv/\eta_T) \tag{7}$$

where an orbital velocity $v = 7.6$ km/s has been used and η_T is the tether efficiency, also listed in Table 1.

The hardware mass is small for a chemical thruster and will be neglected. For ion and Hall thrusters, the mass is dominated by that of the power and fuel delivery systems. For a Hall thruster, the power processing unit (PPU) has typically a mass of 6 kg/kW (Ref. 21), or 100 kg/N, and the tankage and plumbing adds about 20% of the propellant mass. Assuming tankage for 1 year and spreading the cost over a 10-year life, this gives an extra 40 kg/year/N for a total $M_H \approx 140\,F$ (N).

This estimate is also used for ion engines (heavier PPU, lighter fuel system). For arcjets, with their much higher thrust/power, the PPU mass per unit thrust is smaller, and we adopt as an estimate of M_H one-half that given earlier.

For the tether mass, a more detailed design study[21] yields a mass estimate of about 200 kg/N. If we assume a tether life of 1 year, this is also 200 kg/year/N. The auxiliary tether system masses (reel, PPU, etc.) are estimated to have a mass equal to that of the tether itself, but to last for 5 years, giving an additional 40 kg/year/N. Therefore, for the reboosting tether $M_H = 240F$ (N).

The unit cost fuel in orbit is taken as $c_p = \$1.5 \times 10^4$/kg and that of hardware in orbit is assumed to be $c_H = \$3 \times 10^4$/kg. For the cost of electricity, we assume a cost of $\$1 \times 10^6$/installed kW in orbit, and a system life of 10 years, giving $c_E = \$11.4$/kW · h. The results of using Eq. (4) with the assumptions just outlined are listed in Table 2.

As Table 2 clearly indicates, electrodynamic (ED) tethers are by far the most economically attractive option, followed at some distance by plasma electric thrusters. If the average space station drag is 0.7 N, the ED tether system over a 10-year period is seen to save a minimum of $10 \times 0.7 \times (24.7 - 8.7) = \$112 \times 10^6$ (in comparison to an ion engine system). In comparison to a chemical thruster system that is presently planned for the space station, the saving approaches $\$1 \times 10^9$.

Table 2 Reboosting costs per year ($\$1 \times 10^6$/year/N)

Thruster type	Propellant	Power	Hardware	Total
Chemical	146.0	——	——	146.0
Ammonia arcjet	60.2	1.0	2.2	63.4
Xe, Hall	30.1	1.4	4.4	35.9
Xe, ion	18.5	1.8	4.4	24.7
ED tether	0.2	1.3	7.2	8.7

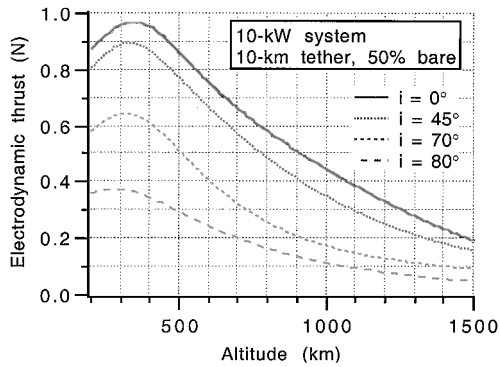


Fig. 6 Average thrust generated by a 50%-insulated, 10-km, 10-kW bare-tether thruster shown as a function of altitude and orbital inclination *i*.

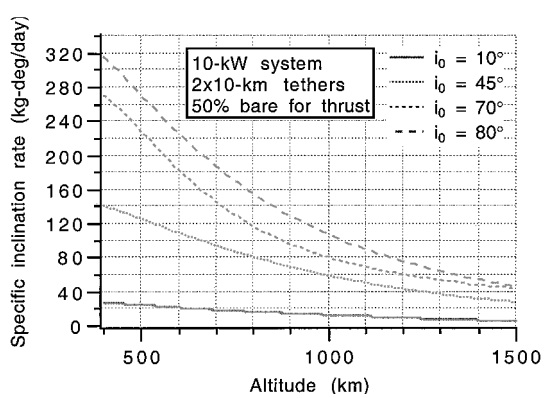


Fig. 7 Rate of change in orbital inclination (for 1-kg mass) generated by a (dual) 10-km, 10-kW bare-tether system shown as a function of altitude and initial orbital inclination i_0.

Reusable Upper Stage Propulsion

An electrodynamic upper stage could be used as an orbital tug to move payloads in low Earth orbit (LEO) after launch from a reusable or other launch vehicle. The tug would rendezvous with the payload and launch vehicle, dock/grapple the payload, and maneuver it to a new orbital altitude or inclination within LEO without the use of boost propellant. The tug could then lower its orbit to rendezvous with the next payload and repeat the process. Such a system could conceivably perform several orbital maneuvering assignments without resupply, making it a low recurring cost space asset. The performance of a 10-kW, 10-km tether system is shown in Figs. 6 and 7 (Ref. 21). Figure 6 shows the thrust of a 10-kW tether system vs altitude, whereas Fig. 7 shows the specific (for a system with unit mass) inclination rate of change vs altitude. For a system of mass m, the inclination change is obtained as the specific rate divided by m.

Propulsive Small Expendable Deployer System (ProSEDS) Flight Experiment

A flight experiment to validate the performance of the bare electrodynamic tether in space and demonstrate its capability to perform thrust is planned by NASA for August 2000 (Ref. 22). The propulsive small expendable deployer system (ProSEDS) experiment will be placed into a roughly 400-km nearly circular orbit as a

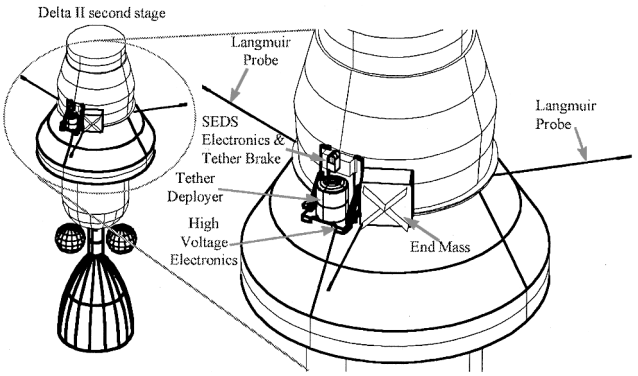


Fig. 8 ProSEDS experiment hardware on the Delta II upper stage (by G. Hajos, courtesy of NASA Marshall Space Flight Center).

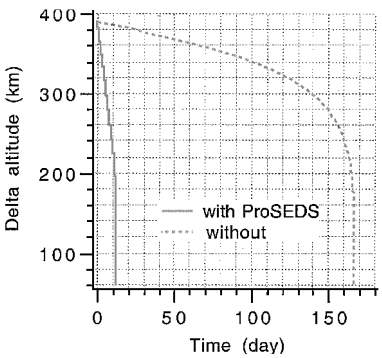


Fig. 9 Orbital decay rate of Delta stage with and without ProSEDS.

secondary payload from a Delta II launch vehicle. The flight-proven small expendable deployer system (SEDS)[23] will be used to deploy a 5-km predominantly bare aluminum wire attached to 10 km of insulating Spectra® (an oriented polyethylene fiber made by Allied Signal, Inc.) tether and 20-kg endmass for stabilization. The deployer and endmass mounted on the Delta II upper stage are shown in Fig. 8.

Once on orbit, the SEDS will reel out the tether and endmass system to a total length of 15 km. Upward deployment will set the system to operate in the generator mode, thus producing drag thrust and producing electrical power. A hollow cathode plasma contactor will maintain the platform to around 30 V of the local plasma potential. The ED drag thrust provided by the tether is estimated to be up to 0.5 N (Ref. 24). Assuming that the tether survives the descent through the upper atmosphere, it should deorbit the Delta II upper stage in less than 2 weeks vs the almost 6-month lifetime for the Delta stage decaying from the same low-eccentricity orbit with an initial altitude of about 400 km (Fig. 9). Approximately 120-W average electrical power will be extracted from the tether to recharge mission batteries and to allow extended measurements of the system's performance until it reenters.

Onboard instruments will periodically measure plasma density and temperatures, the open-circuit voltage (which is close to the motional emf across the conductive tether), and the voltage of the platform with respect to the plasma. The tether current reaching the Delta, which is the primary measure of success from the standpoint of future applications, will be measured frequently. Postflight analysis of the data will allow an evaluation of how closely the current collection followed the OML model's predictions and of the scalability of the ProSEDS technology to other space-transportation applications.

Conclusions

Tether technology has advanced significantly since its inception over 30 years ago. The recent successes of the SEDS system and of the TSS-1R and PMG demonstrations of the soundness of ED tether principles have shown that tethers are ready to move from experiment and demonstration to application. One of the most promising applications for ED tethers is space propulsion and transportation. The use of ED tether propulsion for most applications such as reusable upper stages, space station reboost, space vehicles deorbit, and planetary missions depends on the ability to collect multiamphere electron currents from the ionosphere with reasonably sized systems. The use of bare-tether anodes promises to make this goal achievable. The first test of the bare-tether concept will soon be carried out during the ProSEDS mission, which should also clearly demonstrate the effectiveness of ED tether propulsion.

References

[1]Parker, L. W., and Murphy, B. L., "Potential Buildup on an Electron-Emitting Ionospheric Satellite," *Journal of Geophysical Research*, Vol. 72, No. 5, 1967, pp. 1631–1636.

[2]Thompson, D. C., Bonifazi, C., Gilchrist, B. E., Williams, S. D., Raitt, W. J., Lebreton, J. P., Burke, W. J., Stone, N. H., and Wright, K. H., Jr., "The Current-Voltage Characteristics of a Large Probe in Low Earth Orbit: TSS-1R Results," *Geophysical Research Letters*, Vol. 25, No. 4, 1998, pp. 413–416.

[3]Gilchrist, B. E., Bonifazi, C., Bilen, S. G., Raitt, W. J., Burke, W. J., Stone, N. H., and Lebreton, J. P., "Enhanced Electrodynamic Tether Currents due to Electron Emission from a Neutral Gas Discharge: Results from the TSS-1R Mission," *Geophysical Research Letters,* Vol. 25, No. 4, 1998, pp. 437–440.

[4]Laframboise, J. G., "Current Collection by a Positively Charged Spacecraft: Effects of Its Magnetic Presheath," *Journal of Geophysical Research*, Vol. 102, No. A2, 1997, pp. 2417–2432.

[5]Cooke, D. L., and Katz, I., "TSS-1R Electron Currents: Magnetic Limited Collection from a Heated Presheath," *Geophysical Research Letters*, Vol. 25, No. 5, 1998, pp. 753–756.

[6]Lam, S. H., "Unified Theory for the Langmuir Probe in a Collisionless Plasma," *Physics of Fluids*, Vol. 8, No. 1, 1965, pp. 73–87.

[7]Alpert, Y. L., Gurevitch, A. V., and Pitaevskii, L. P., *Space Physics with Artificial Satellites*, Consultants Bureau, New York, 1965, Chaps. 8–10.

[8]Vannaroni, G., Dobrowolny, M., Lebreton, J. P., Melchioni, E., De Venuto, F., Harvey, C. C., Iess, L., Guidoni, U., Bonifazi, C., and Mariani, F., "Current-Voltage Characteristics of the TSS-1R Satellite: Comparison with Isotropic and Anisotropic Models," *Geophysical Research Letters*, Vol. 25, No. 5, 1998, pp. 749–752.

[9]McCoy, J., O'Neill, C., Stanley, J., Settecerri, T., Grossi, M. D., Estes, R. D., Dobrowolny, M., Vannaroni, G., Melchioni, E., Bonifazi, C., Cosmovici, C., Iess, L., Jost, R. J., Olsen, R. C., Ferguson, D. C., Tolbert, R., Rau, D., Katz, I., Lilley, J., Carroll, J. A., Tacconi, G., Mina, L., and Goree, W., "Plasma Motor-Generator (PMG) Flight Experiment Results," *Proceedings of the Fourth International Conference on Tethers in Space*, Science and Technology Corp., Hampton, VA, 1995, pp. 57–82.

[10]Katz, I., and Davis, V. A., "On the Need for Space Tests of Plasma Contactors as Electron Collectors," *Proceedings of the second International Conference On Tethers in Space, Space Tethers for Science in the Space Station Era*, Società Italiana di Fisica, Bologna, Italy, 1987, pp. 241–244.

[11]Savich, N. A., and Sanmartín, J. R., "Short, High Current Electrodynamic Tether," *Proceedings of the International Round Table on Tethers in Space*, European Space Research and Technology Centre –ESA, Noordwijk, The Netherlands, 1994, pp. 417–423.

[12]Sanmartín, J. R., Martinez-Sanchez, M., and Ahedo, E., "Bare Wire Anodes for Electrodynamic Tethers," *Journal of Propulsion and Power*, Vol. 9, No. 1, 1993, pp. 353–360.

[13]Estes, R. D., Sanmartín, J., and Martínez-Sánchez, M., "Performance of Bare-Tether Systems Under Varying Magnetic and Plasma Conditions," *Journal of Spacecraft and Rockets*, Vol. 37, No. 2, 2000, pp. 197–204.

[14]Chen, F. F., Etievant, C., and Mosher, D., "Measurement of Low Plasma Densities in a Magnetic Field, *Physics of Fluids*, Vol. 11, No. 4, 1968, pp. 811–821.

[15]Chung, P. M., Talbot, L., and Touryan, K. J., *Electric Probes in Stationary and Flowing Plasmas: Theory and Application*, Springer–Verlag, New York, 1975, pp. 10–13.

[16]Mercure, H. P. E., "Ion Temperature Measurement in a Flowing Collisionless Plasma Using an End Effect of Cylindrical Langmuir Probes," Inst. of Aerospace Studies, Univ. of Toronto, Rept. 202, Toronto, ON, Canada, July 1976.

[17]Sanmartín, J. R., and Estes, R. D., "The Orbital-Motion-Limited Regime for Cylindrical Langmuir Probes," *Physics of Plasmas*, Vol. 6, No. 1, 1999, pp. 395–405.

[18]Szuszczewicz, E. P., and Takacs, P. Z., "Magnetosheath Effects on Cylindrical Langmuir Probes," *Physics of Fluids*, Vol. 22, No. 12, 1979, pp. 2424–2429.

[19]Miller, N. J., "Some Implications of Satellite Spin Effects in Cylindrical Probes Measurements," *Journal of Geophysical Research*, Vol. 77, No. 16, 1972, pp. 2851–2861.

[20]Laframboise, J. G., and Parker, L. W., "Probe Design for Orbit-Limited Current Collection," *Physics of Fluids*, Vol. 16, No. 5, 1973, pp. 629–636.

[21]Martinez-Sanchez, M., and Pollard, J. E., "Space Electric Propulsion: An Overview," *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998, pp. 688–699.

[22]Johnson, L., and Ballance, J., "The Propulsive Small Expendable Deployer System (ProSEDS) Experiment," *Proceedings of the Tether Technology Interchange Meeting*, NASA CP-1998-206900, 1998, pp. 103–108.

[23]Lorenzini, E. C., Bortolami, S. B., Rupp, C. C., and Angrilli, F., "Control and Flight Performance of Tethered Satellite Small Expendable Deployment System-II," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 5, 1996, pp. 1148–1156.

[24]Lorenzini, E. C., Estes, R. D., and Cosmo, M. L., "In-Space Transportation with Tethers," Smithsonian Astrophysical Observatory, Annual Rept. 2, NASA Grant NAG8-1303, Aug. 1998.

I. E. Vas
Associate Editor