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Space Station Reboost with Electrodynamic Tethers

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The results of a study of an electrodynamic tether system to reboost the International Space Station (ISS) are presented. One recommendation is to use a partially bare tether for electron collection. Locations are suggested as to where the tether system is to be attached at the space station. The effects of the tether system on the microgravity environment may actually be beneficial, because the system can neutralize aerodrag during quiescent periods and, if deployed from a movable boom, can permit optimization of laboratory positioning with respect to acceleration contours. Alternative approaches to tether deployment and retrieval are discussed. It is shown that a relatively short tether system, 7 km long, operating at a power level of 5 kW could provide cumulative savings of over a billion dollars during a 10-year period ending in 2012. This savings is the direct result of a reduction in the number of flights that would otherwise be required to deliver propellant for reboost, with larger cost savings for higher tether usage. In addition to economic considerations, an electrodynamic tether promises a practical backup system that could ensure ISS survival in the event of an (otherwise) catastrophic delay in propellant delivery.

Nomenclature

A = wetted surface area, m^2
a = semimajor axis, m, km
C_d = drag coefficient
D = atmospheric drag force, N
F_t = tether force, N
g_0 = gravitational acceleration at the Earth's surface, m/s^2
h = orbital altitude, m
I_{sp} = specific impulse, s
m = International Space Station mass, kg
m_r = reboost mass (including resupply vehicle), kg
n = orbital angular motion, rad/s
R_e = Earth radius, m, km
T = tangential perturbation acceleration, m/s^2
t = tether thickness, m, mm
t_f = end time for orbital perturbation calculation, s
t_i = start time for orbital perturbation calculation, s
w = tether width, m, cm
α = force ratio parameter $\rho C_d A\mu/2F_t$, m
γ = intermediate term carrying time dependence of perturbed orbit
η = orbital velocity ratio from Hohmann transfer
μ = Earth mass parameter, 398,600.5 km^3/s^2
v = orbital velocity, m/s
ρ = atmospheric density, kg/m^3
σ = orbital growth factor

Introduction

THERE has been a renewed focus on reboost of the International Space Station (ISS), caused in part by delays in the delivery of the Russian Service Module and the use of the Progress spacecraft. The current approach to reboost the ISS is by regular flights of the Russian Progress M to replenish propellant. Several other reboost propellant carriers/reboost vehicles have been proposed such as the Progress M2, Propulsion Control Module, Interim Control Module, and a variation of the Inertial Upper Stage. The Progress M is the only existing vehicle that performs this task. All other prospective vehicles must undergo major modification or have yet to be designed and built. A different approach, presented in this paper, provides reboost by a propellantless method.

There has been extensive work carried out with tethers in space. Most of this work has been documented in conference proceedings up to 1995.[1] The first demonstration of a nonconducting tether took place in 1967 with Gemini II in low Earth orbit illustrating gravity gradient stabilization. Most of the flight demonstrations, however, have taken place in this decade for both nonconducting and conducting tethers. Electrodynamic tethers have been demonstrated in space on a number of missions. The Tethered Satellite System (TSS) was an orbiter-based system, which deployed to a length of 19 km and generated approximately 2 kW of electrical power. The Plasma Motor Generator was flown as a secondary payload on a Delta II, which deployed to a length of 0.5 km and successfully demonstrated the principles of electrodynamic tether reboost. The Small Expendable Deployer System flew twice as a secondary payload on Delta II launches, which demonstrated hollow cathode current collection limits from 200–900 km. In addition, an electrodynamic tether propulsion for upper-stage applications is planned for development as part of the Advanced Space Transportation Program.

Stability of the ISS's low Earth orbit will be reduced as a tradeoff for improvement in economy of access. Low-altitude orbits are economically viable because of the greater payload that each supply flight can deliver, even at the cost of aerodynamic drag so high that the orbit is vulnerable to collapse if not reboosted every few months. With frequent reboost thus designed to be an essential part of the ISS' life cycle, the practicality and economics of alternative reboost methods need to be evaluated carefully.

An electrodynamic tether is the only reboost method capable of using solar energy as an alternative to consuming propellant. It exploits the fact that, although this near-Earth environment burdens us with significant aerodynamic drag, it also provides us with both a magnetic field and a conductive medium. The thin environmental plasma is capable of closing a tether circuit without transmitting the resulting electrodynamic deceleration to the tether or its attached platform. In fact, the environmental conductivity is large enough that the tether must be insulated along any portion intended to generate voltage or thrust, so as to keep the surrounding plasma from shorting it out.

Because it is easier to collect electrons at the far end of a tether and easier to reemit them from an electron gun (a plasma contactor) on the platform, electrodynamic tethers are usually operated with their negative end at the platform. They are directed to nadir for reboost or to zenith for power generation. This mechanism is fortuitous, but the driving current is limited to the excess capacity of the station's

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plasma contactor, assumed now to be about 5 A. Powering the tether with 5–10 kW will therefore require approximately 1–2 kV, which is roughly the voltage limit of what is presumed acceptable at the station surface for even an insulated connection. To achieve this voltage, the tether length would need to be between 5 and 15 km long.

This paper will review the principles of using an electrodynamic tether to counteract aerodynamic drag. We then present several associated practical design issues with alternative approaches to their resolution. The mechanics of flight and reboost in a quasi-stable orbit are presented in the next section. Deployment issues are then discussed, including novel approaches, followed by consideration of requirements for power management and physical attachment. The following section considers alternative policies for reboost scheduling. We conclude with discussion of a tether's physical and operational impacts on the ISS and a calculation of net cost savings.

ISS Drag and Reboost Propellant Needs

The results presented in this paper are derived from a study[2] conducted in 1996, which assumed that the first element of the ISS would be in orbit in late 1997. Even though there is a delay in the flight assembly sequence, the trends illustrated here remain valid. With the initial flight having taken place in 1998, full ISS assembly is expected in 2005.

This study uses results from Design and Analysis Cycle 4 (DAC #4) as a baseline for the altitude profile and reboost propellant needs of the ISS.[3] During the buildup phase and subsequent years of operation, the planned altitude of the ISS is shown in Fig. 1. The altitude profile of the ISS is subjected to a number of competing performance requirements, such as the microgravity quality, resupply limitation, and the demand for 180 days per year of acceptable microgravity. Satisfying these requirements is complicated by the variations in atmospheric density, which exhibits daytime highs and nighttime lows, as well as larger but slower variations driven by the 11-year solar cycle. In Fig. 1 the steep negative slopes are the result of orbital decay caused by aerodynamic drag, whereas the sharply positive slopes are the result of orbit raising propellant reboost maneuvers. Note that these reboost maneuvers do not occur during quiescent microgravity periods. The propellant required to keep the station in its planned orbit is approximately 135 metric tons over the assembly phase from 1998 to 2005, and the 10-year operational phase from 2005 to 2014 . The distribution of propellant over this period of time is shown in Fig. 2. An agreement made between the United States and Russia in June 1996 stated that the United States was responsible for 71% of the total propellant demand. In addition to maintaining orbit altitude, propellant is required by the reaction control system to periodically off-load the momentum accumulated in the attitude control system to prevent its saturation.

The aerodynamic drag force D exerted on the ISS is directed opposite its orbital velocity vector according to the familiar relationship

$$D = \tfrac{1}{2}\rho v^2 C_d A \tag{1}$$

For the range of altitudes shown in Fig. 1, atmospheric density varies between 10^{-13} and 10^{-11} kg/m.[3] The circular orbital velocity of the ISS is described by

$$v = \sqrt{\mu/(R_e + h)} \tag{2}$$

The wetted surface area was computed from

$$A = m/\beta C_d \tag{3}$$

The DAC #4 data for ballistic coefficient β and ISS mass m were used. The drag coefficient was set to $C_d = 2.35$, which corresponds to a worst case of low-density free molecular flow. Note that changes in A are small following assembly completion. This results in the orbit-averaged aerodynamic drag profile illustrated in Fig. 3.

Tether Environment and Electron Collection

Tether Thrust

The thrust produced by a conducting tether, driven by a given power level, depends on the magnetic field, the orbital velocity, and the tether current. Whereas velocity is predictable and constant for a circular orbit, the Earth's magnetic field can vary by a factor of two. Furthermore, the current depends upon the combination of driving voltage and plasma electron density, the latter affecting the conductivity of the current's return path. The local electron density depends upon the effects of solar radiation; it therefore depends upon the phase of the solar cycle and whether the orbital segment is

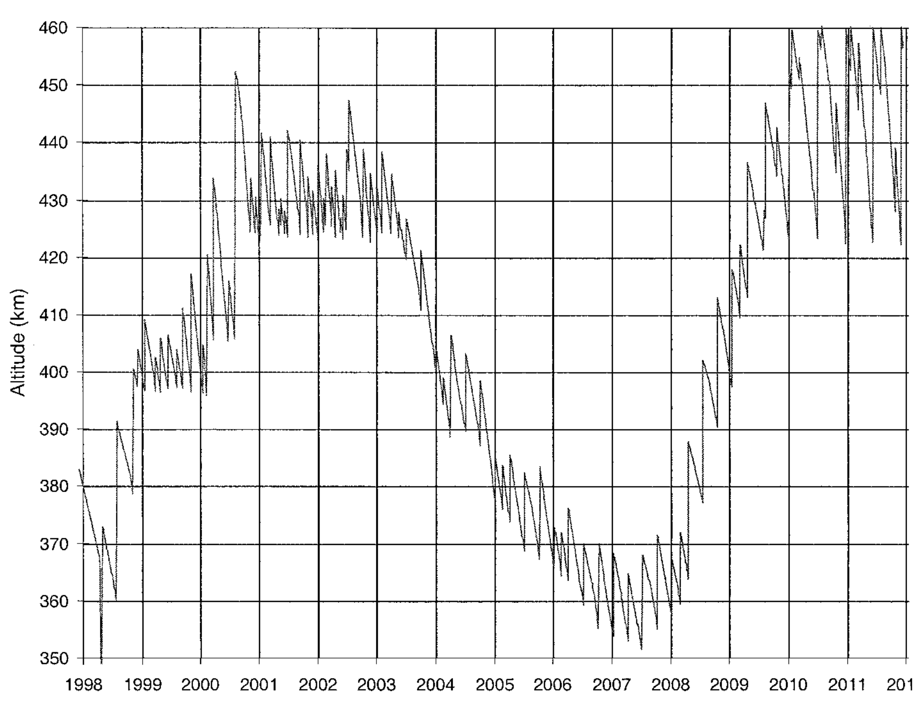

Fig. 1 Recommended space station altitude.

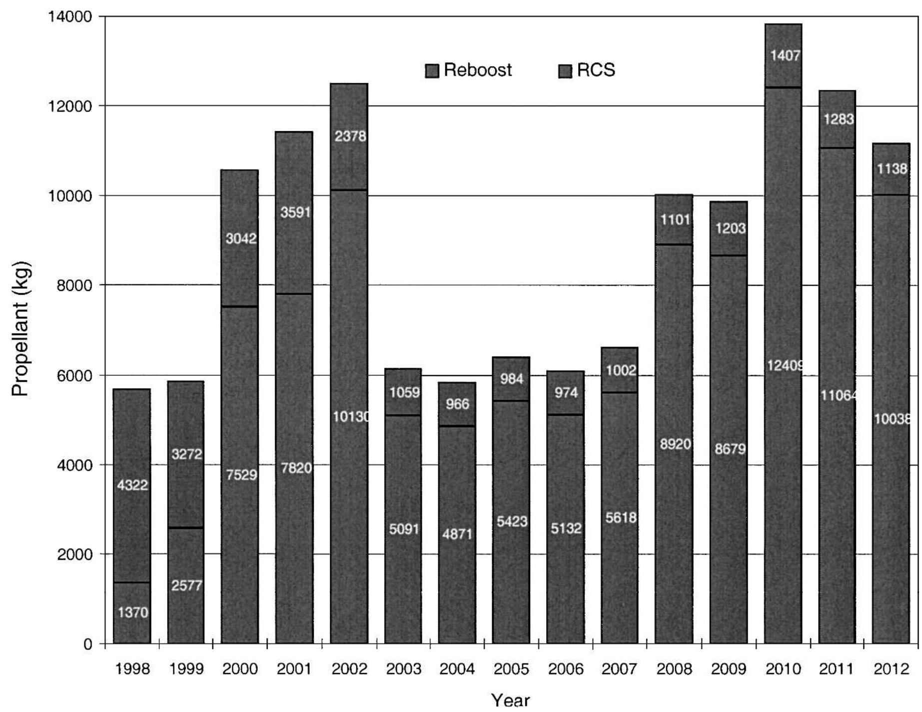

Fig. 2 ISS annual propellant requirement.

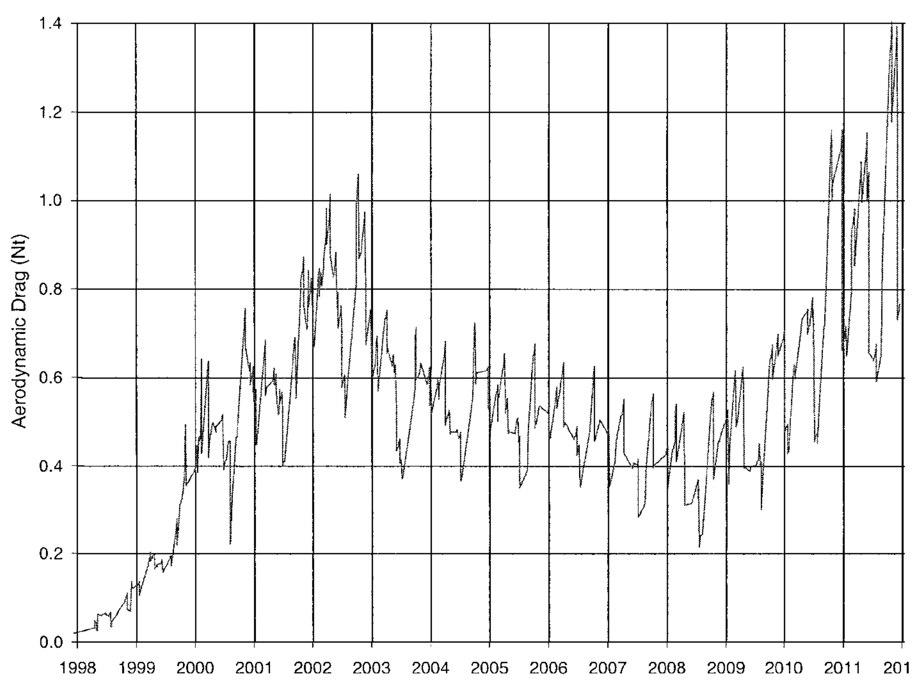

Fig. 3 Space station orbit: averaged aerodynamic drag.

in sunlight and can easily change by an order of magnitude over a single orbit. Figure 4 shows the dramatic variation of electron density as the 90-min orbit moves between day and night environments. The strongest fluctuations are caused by variations in exposure to sunlight and the solar wind, with other periodicities caused by the changing regions of the magnetosphere intercepted by the orbit. The voltage induced by the orbital motion, which affects the voltage that a power supply must impose upon the tether to achieve a given current, follows a similar curve, Fig. 5, and reflects variations in the field magnitude and the angle between field and orbit plane. These factors cause variations in tether efficiency, effective tether length (with a bare-tether electron collector), and the driving voltage required to compensate changes in induced voltage and plasma conductivity. Under reasonable assumptions, the resulting orbital variations in tether thrust are shown in Fig. 6 for a 7-km tether driven with 5 kW and are seen to vary between 0.22 and 0.53 N.

Electrodynamic Tether Drag

Determination of the tether's own aerodynamic drag force only differs from the ISS drag-force calculation in that the values used for the wetted surface area and drag coefficient are different. The projected area of a nadir directed tether of rectangular cross section will vary as it rotates and/or twists. For a tether of thickness

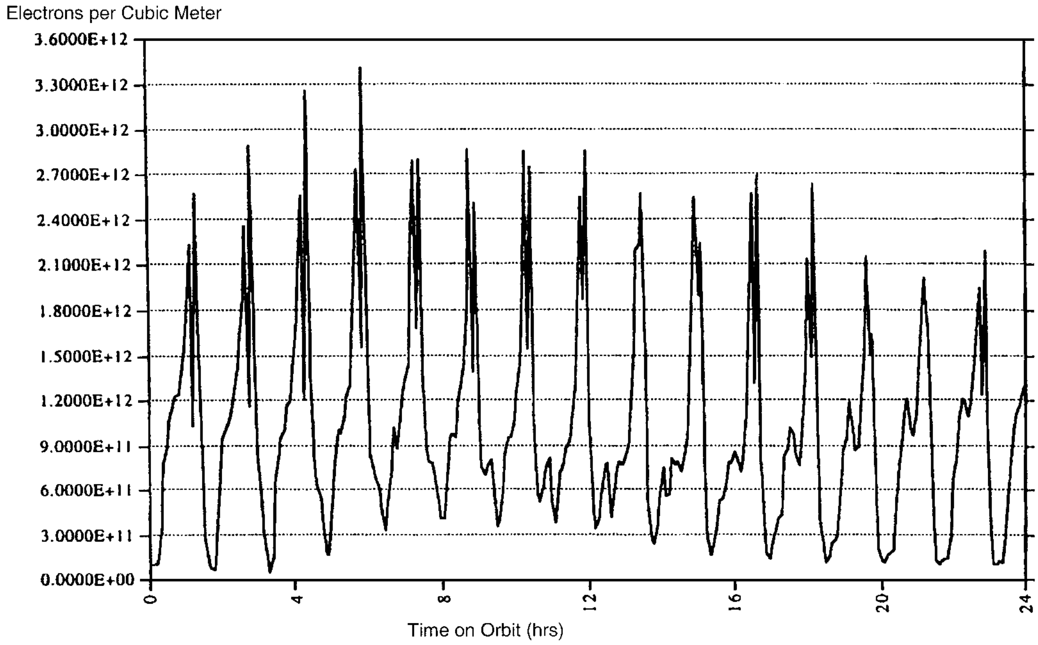

Fig. 4 Electron density variations.

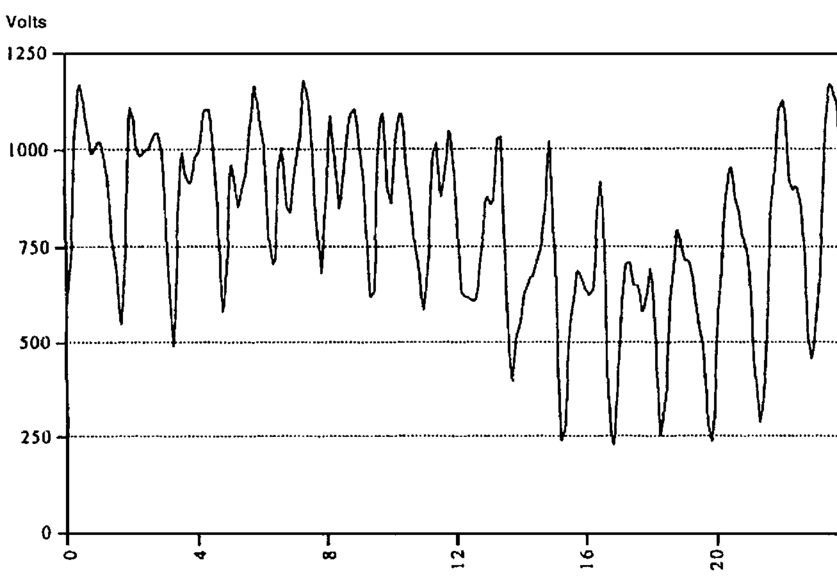

Fig. 5 Motional voltage variations.

t = 0.6 mm and width w = 1.1 cm, the wetted surface area per km is at most

$$1000(w + t)2/\pi \approx 6.8 \text{ m}^2/\text{km}$$

A tether drag coefficient of 2.2 was used, which is a nominal value for a platelike object in low-density free molecular flow. As illustrated in Fig. 7, the total tether drag force was found to be approximately 6% of the ISS drag-force value.

Bare Tether for Electron Collection

Any metallic surface at the end of the tether will serve to collect electrons. A long thin collector, such as an uninsulated extension of an insulated conducting tether, is more efficient at electron collection than a sphere of the same surface area. This bare-tether collector has the interesting property that its active collecting length naturally varies to compensate for the significant changes in plasma electron density that occur as the platform moves through different regions of the magnetosphere, especially between the day and night sides of the Earth. This process is illustrated schematically in Fig. 8, in which the continuous behavior of the tether is approximated by a series of discrete incremental segments of length ΔL. Each ΔL has resistance ΔR. Most of these lie in the insulated portion L_1, from which current cannot leak. Along the uninsulated end of the tether, the continuous distribution of leakage path is shown as a discrete set of diodes to indicate that current can leave but not enter the tether (i.e., electrons can be captured but not emitted). The y of a diode corresponds to its connection to the plasma. If the forward conductivity of the diode in the first segment ΔL of uninsulated tether (the first diode path I_1) is sufficiently great, most of the current I follows this path so that $I \cong I_1$, and the remaining currents (I_n for $n > 1$) are all nearly zero. If the plasma conductivity of the first uninsulated segment is less than perfect, however, the next ΔL will have some voltage drop ΔV across it, and part of the remaining tether current $(I - I_1)$ will flow as I_2. At night, or under other conditions of lowered free electron density in the plasma, these diode conductivities will be lower. More

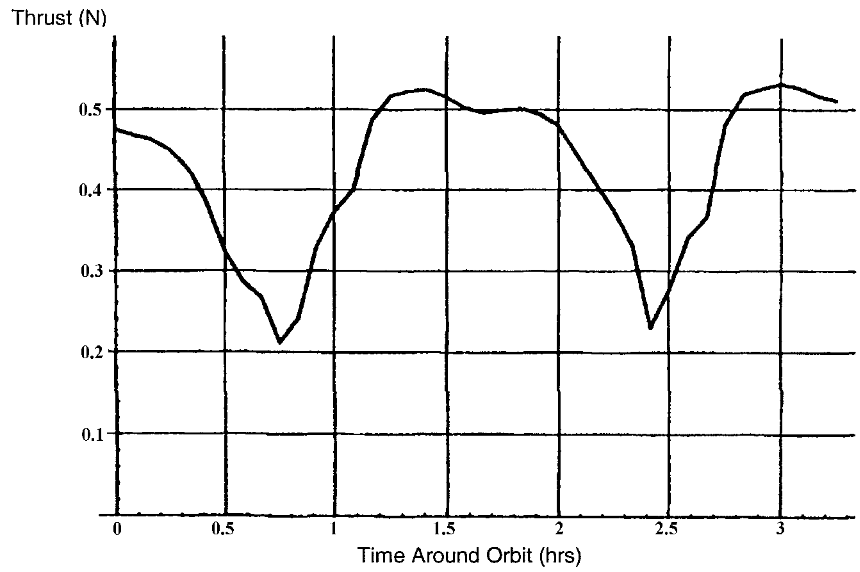

Fig. 6 Thrust for the 7-km-long tether at 5 kW.

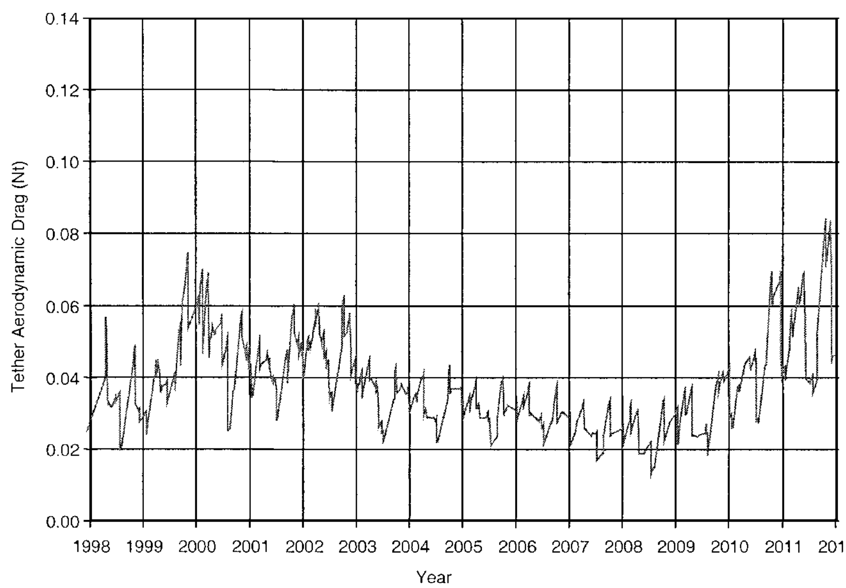

Fig. 7 Ribbon tether aerodynamic drag.

of them will then be involved in conducting the full current I, and the positive voltage will extend further along the bare tether. Thus, the bare tether must be long enough to accommodate the lowest anticipated electron densities, but only as much of it that is needed will actually carry current.

Tether Deployment

Deployer Strategies

We have considered alternatives in deployer design, grouped into three general types: 1) expendable, 2) payout and retrieve, and 3) up and down.

Expendable

Expendable tether systems, in which the tether is simply cut after use and allowed to naturally drift away from the platform to eventually fall and burn in the upper atmosphere, are generally simpler, lighter, and cheaper to build. The obvious downside of expendable tethers is that they are good for a single use and must be discarded and replaced in cases where damage or environmental factors may only temporarily require its removal. If a deployed tether is judged incompatible with the arrival of any spacecraft, then many expendable tethers would be discarded per year.

Retrievable Deployment

The principal example of a deployer designed to retrieve a tether, as well as paying it out, is the design by Martin Marietta for the TSS1 and TSS-1R tethered satellite experiments.[4] This deployer was heavy (2000 kg) with a large deployment boom. Part of the reason for this weight was undoubtedly its intended generality. It was built to accommodate tethers up to 100 km long with end weights of up to 500 kg mass. This deployer was flown twice and suffered from problems of tether snagging and breakage.

Payout is similar for both expendable and retrievable tethers, but retrieval does lead to potentially severe problems of control. Any lateral motion is amplified by the conservation of angular momentum as the tether's moment arm is shortened. This leads to instabilities, which require active control strategies. This is most acute in the late stages of retrieval, where each meter-of-length reduction leads to an increasingly large fractional change in the tether's moment arm. Solving these retrieval problems will be necessary in maintaining a significant permanent presence in the magnetosphere over extended periods. The tether itself may be a heavy and expensive instrument intended for use over periods much longer than a deployment cycle, as it would be over the life of a space station approached by many service vehicles per year.

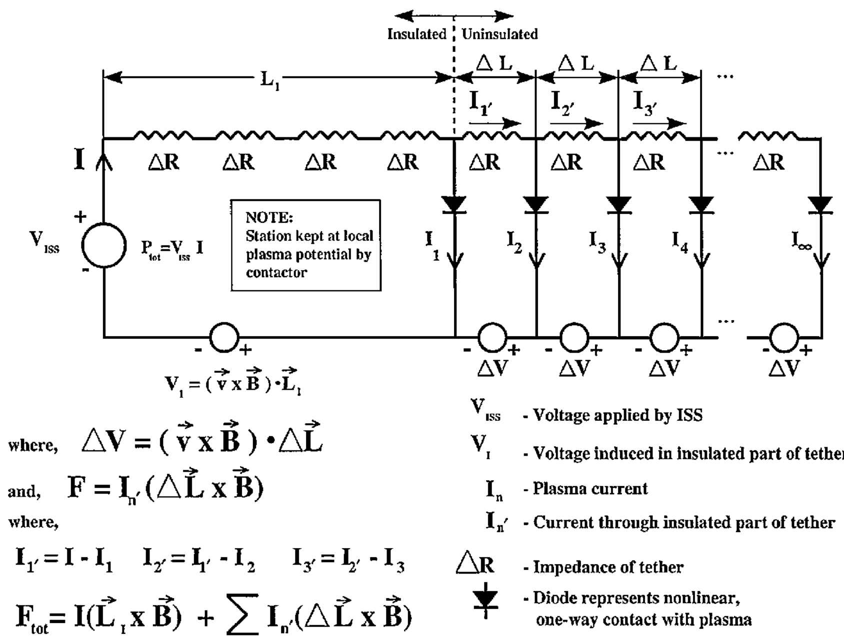

Fig. 8 Bare-tether currents and forces.

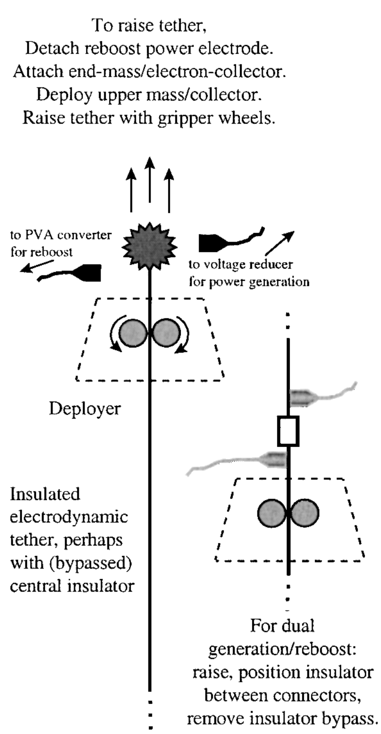

Fig. 9 Pass-through electrodynamic tether.

Pass-Through Redeployment

The worst retrieval problems are likely to occur in the later stages of rewinding. These and other considerations led us to consider the merits of a rather different approach to retrieval: rather than winding the tether back on its spool, let it pass straight on through the deployer to effectively redeploy on the opposite side (Fig. 9).

Bidirectional tethers, which extend in both directions (nadir and zenith) from the platform, have been considered. These allow easy switching between power generation and reboost functions (functional reversal) and have minimal effect on the platform's orbit or center of mass (CM). Although it can provide either reboost or power, power generation is likely to be a secondary function, supplementing solar power only in unusual or emergency circumstances because it operates by draining orbital energy.

Advantages of pass-through deployment and retrieval include possible functional reversal and snag-free redeployment.

The general requirements for pass-through tether retrieval are as follows: 1) electrical disconnection from platform power sources or loads, 2) attachment of an alternative endmass for stability/control or an electron collector for functional reversal in place of an end mass power source or load, 3) a mechanical means of gripping and moving the tether at any point along its length, and 4) a path through the platform to the other side with sufficient angular clearance for both deployment and retrieval.

Other specific advantages and disadvantages depend on whether the intent is to redeploy fully the tether on the opposite side of the platform or to stop midway at a balanced configuration. This choice depends on the motivation for retrieval. The pass-through extension does not affect the retrieval control problem.

Full Pass Through

If the motivation is either to 1) remove the tether from potential interference with a service vehicle approaching from beneath, 2) shift the platform's CM, or 3) repair damage at or near the tether's outer end, then a nonrewinding retrieval must pass the full tether length through or past the deployer and its platform. The process is illustrated in Fig. 10.

A full pass through has the following advantages: 1) fine tuning of platform CM and torque equilibrium angle (TEA); 2) control by rotating tether boom about the y axis; 3) freedom from conflict with approaching vehicles on the original side; 4) ability to access a damaged region anywhere along its length; 5) full functionality for both power generation and reboost; 6) electrical reconnection at original site of the electron collector; and 7) if configuration acceptable, bare-tether original electron collector can remain unretrieved without electrical hazard.

Disadvantages include the following: 1) disconnection of original electron collector; 2) if bare tether originally used for electron collection, then rewinding or separate retrieval needed to resolve vehicular conflict; 3) CM and TEA shift possibly significant, and 4) electrodynamic functional suspension likely if adjustment of CM or TEA is motivation (because connection points may not be near platform).

Again, this design neither helps nor worsens the retrieval control problem.

Alternative Power Sources and Locations

The current design of the ISS was used to determine suitable locations for the physical and electrical attachment of a deployer and

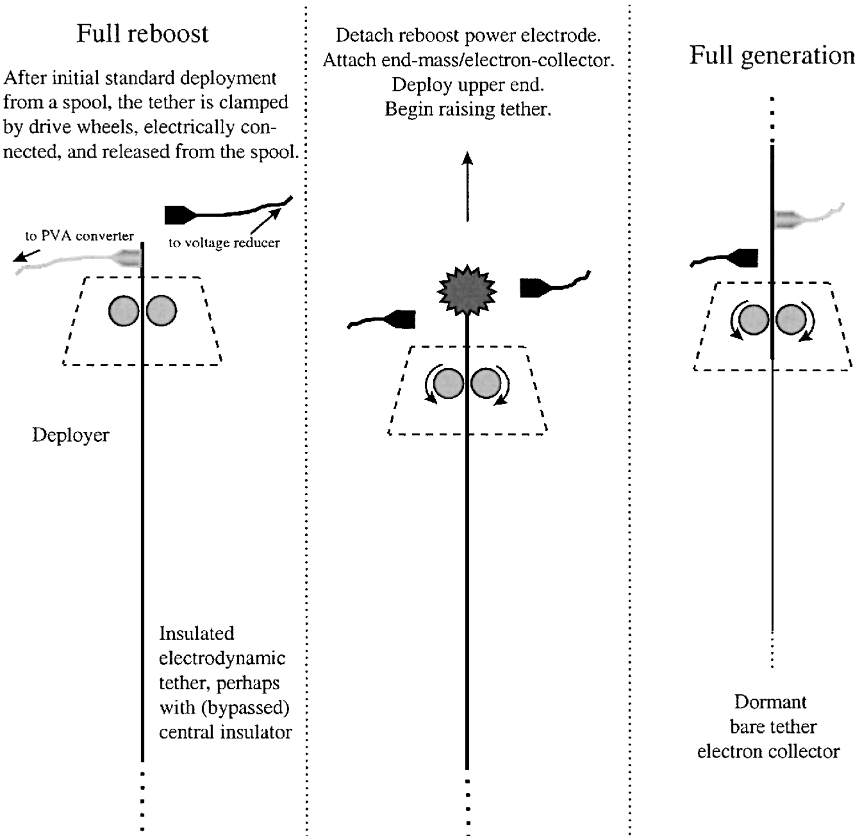

Fig. 10 Fully bidirectional tether concept.

its power supplies. The full-up station carries four pairs of photovoltaic arrays capable of generating 20 kW each. Of this 80 kW, 54 kW are intended for housekeeping functions. It is not expected that the 5 kW planned for reboost would overburden the remaining user allocation. The station's batteries will support the same power availability as sunlight operation.

The tether current is limited by the excess electron rejection capacity of the currently designed plasma contactor. This contactor has a nominal design rating of 10 A, with normal operation requiring 2–3 A to maintain the station to within 40 V of ambient plasma potential. This should readily permit a 5 A default allocation to tether reboost power. Modest short-term overcurrent demands are not harmful, other than somewhat increasing the normal depletion of the hollow cathode's xenon supply. Nevertheless, if a stronger tether thrust is to be used, to totally compensate drag with a shorter duty cycle or even gain altitude, this contactor should be replaced by one with larger design capacity.

Tether reboost operation can be treated as a low-priority resource demand, so long as long-term planned duty cycle requirements are met on average. Thus, tether power can be cut to accommodate peak user demand times with no effect other than a change in net aerodynamic drag forces averaged over time. The acceleration induced by tether thrust is approximately 0.4 N/400,000 kg $= 10^{-6}$ m/s$^2 \approx 0.1\ \mu g$, which is low for even the station's best μ-gravity environments. This tether thrust will normally improve the μ-gravity environment by canceling the comparable deceleration from aerodynamic drag, although it is possible that extremely sensitive payloads might be affected by rapid changes in this range.

Likely physical attachment locations for a tether deployer are on the S0 truss, the Z1 truss, or a direct mounting on node 1. Node 1 is considered a good choice because it is close to the station's CM, although a truss location may be preferable if any of the pass-through deployment options presented in this paper are adopted. To avoid mechanical interference, the tether must honor an envelope to ensure clearance of all ISS hardware under normal, abnormal, and abort conditions. A 10-deg cone of operational clearance should suffice because tether libration must be controlled to less than that value. In principle, one may attach a small truss at any convenient location, as long as it extends to a position below station where the deployer boom can give a tether alignment that exerts the desired torque levels (or lack thereof) on the station. For the most flexible control of the tether's applied torque and its consequent effect on the station's torque equilibrium angle, the tether's force vector should pass reasonably near the CM, but guided by a boom with freedom of rotation about a y axis, as shown in Fig. 11.

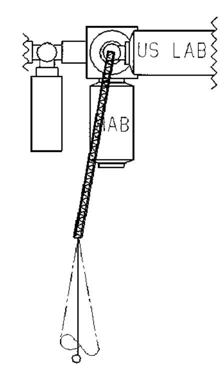

Fig. 11 Tether attachment.

Electrical power can be obtained by connection to the station's main bus switching unit, where power has been conditioned to 160 volts direct current (VDC) (Fig. 12). The tether's own power supply will raise this 160 VDC to the 1500 VDC required to overcome the tether's motion-induced voltage and drive as much as 5 A of downward current. This power supply includes an inverter, transformer, rectifier, filter, and regulator as shown in Fig. 13. Because of its high voltage output, the power supply should be located close to the deployer rather than to its power source.

Reboost Options

The primary benefits of the electrodynamic tether system are the savings to the ISS from reduced propellant mass requirements and the extension of time between disruptions from planned propellant reboosts. To characterize these savings, the altitude profile for approximately three one-year periods following assembly complete were analyzed assuming an operational electrodynamic tether system. The time periods chosen were 2003, 2006, and 2009, which, from Fig. 1, are collectively representative of the ISS orbital decay profile. The assumed electrodynamic tether force ranged from 0.43 to 0.7 N, with a duty cycle ranging from 25 to 50%.

Gauss's form of Lagrange's variational equations can be used to describe the decay of the ISS orbit.[5] For a circular orbit the mean orbital angular rate is given by

$$n = \sqrt{\mu / a^3} \tag{4}$$

The time rate of change in the semimajor axis a is described by

$$\dot{a} = 2T/n \tag{5}$$

The tangential perturbation acceleration T

$$T = -\tfrac{1}{2}\rho v^2 C_d A/m + F_t/m \tag{6}$$

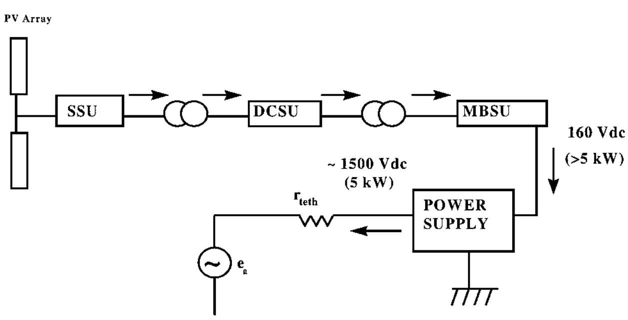

Fig. 12 Tether power connection: SSU, sequential shunt unit; DCSU, direct current switching unit; MBSU, main bus switching unit; r_{teth}, tether's electrical resistance; and e_s, tether's induced voltage.

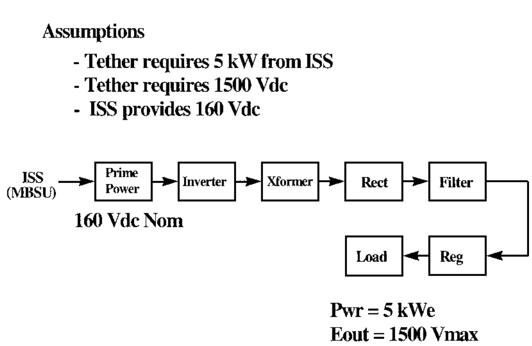

Fig. 13 Power supply for tether.

possesses two components: the first from aerodynamic drag, as already described, and the second from the electrodynamic tether thrust acting on the ISS mass. Equation (5) is separable and can be integrated in closed form by assuming constant values for the slowly varying parameters. This restricts the validity of the solution to small time intervals or equivalently small altitude changes.

We use the subscript i to denote an initial configuration at a starting time t_i and semimajor axis a_i, and the subscript f to denote the value at some future time t_f, where $t_f > t_i$ and the semimajor axis has evolved to a_f. Integrating Eq. (5) from t_i to t_f, the new semimajor axis a_f can be expressed as

$$a_f = \begin{cases} \alpha\sigma & \text{for} \quad a_i < \alpha \\ \alpha/\sigma & \text{for} \quad a_i < \alpha \\ \alpha & \text{for} \quad a_i = \alpha \end{cases} \tag{7}$$

where

$$\alpha \equiv \rho C_d A \mu / 2F_t \tag{8}$$

$$\sigma \equiv [(1+\gamma)/(1-\gamma)]^2 \tag{9}$$

with

$$\gamma = \left[\frac{\left(\pm\sqrt{a_i} - \sqrt{\alpha}\right)^2}{\pm a_i \mp \alpha}\right] \exp\left\{\pm\left[(2F_t/m)\sqrt{\alpha/\mu}\right](t_f - t_i)\right\} \tag{10}$$

The upper sign is used over the interval of integration when $a > \alpha$ and the lower sign for $a < \alpha$. Here, α can be understood as the semimajor axis multiplied by the ratio of the aerodynamic drag to the tether force. When these opposing forces balance, then

$$a_f = \alpha = a_i \tag{11}$$

When drag and tether forces are unbalanced, the semimajor axis will deviate from a_i. As expected, if the tether force dominates drag and $a_i > \alpha$, then the semimajor axis will increase, and the station will gain altitude. If drag dominates and $a_i < \alpha$, then the station will slowly fall.

As mentioned earlier, this solution becomes less accurate for large altitude changes, which necessitates a piecewise approach to its evaluation. By evaluating this expression for small time intervals, the variation in those parameters held constant during the analysis can be accommodated by iteratively specifying updated values for each subsequent evaluation period.

This approach was used to construct a modified reboost profile for the time periods mentioned earlier (Fig. 14). The electrodynamic tether system was assumed to operate at 5 kW, which provides a propulsive force of 0.43 N, slightly less than the aerodynamic drag force illustrated in Fig. 3. Tether reboost, free decay, and propellant reboost correspond in Fig. 14 to changes in slope between successive

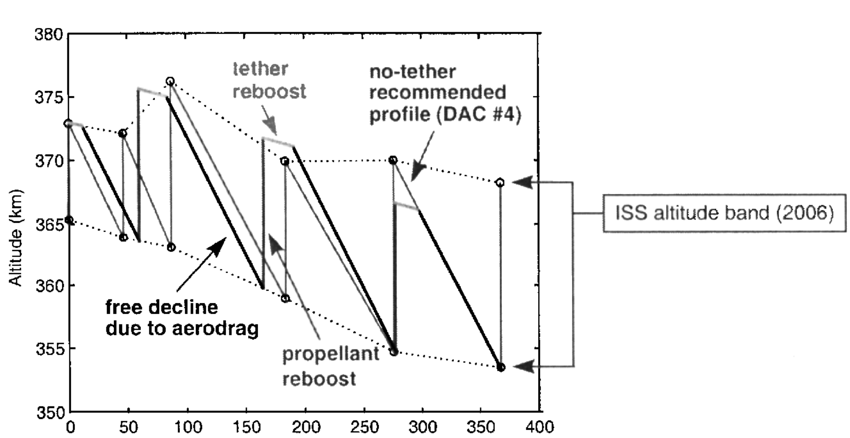

Fig. 14 Tether reboost profile: 5 kW.

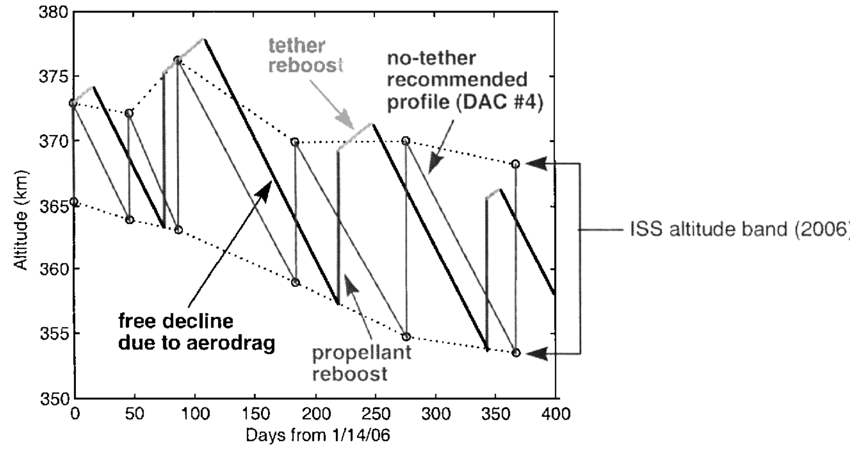

Fig. 15 Tether reboost profile: 10 kW.

events. The elapsed time between the start of tether reboost and the end of free decay was iteratively determined. Propellant reboost maneuvers were initiated at the lower boundaries of the altitude band (as defined by Fig. 1), subject to the constraint that tether reboost occurs during 25% of this interval (i.e., 25% duty cycle). Propellant reboost maneuvers are very short compared to orbital decay times and were assumed to occur instantaneously.

Altitude change caused by propellant reboost was determined using the familiar rocket equation and Hohmann transfer relationships. At the end of the free decay, the semimajor axis a_1 and the circular orbital velocity $\upsilon_1 = \sqrt{(\mu/a_1)}$ are known. As usual, the two impulsive maneuvers are assumed to occur instantaneously. The first maneuver raises apogee, whereas the second maneuver circularizes the orbit by raising perigee an equivalent distance. Theoretically, the minimum elapsed time between these two maneuvers is one-half the orbital period, which is negligible on the scale of Fig. 14. The total velocity increment $\Delta\upsilon$, impulsively delivered by the $\Delta m = 1000$ kg of propellant supplied by the Progress M, was determined from the rocket equation as

$$\Delta\upsilon = -g_0 I_{sp} \log(1 - \Delta m/m_r) \qquad (12)$$

using gravitational acceleration $g_0 = 9.81$ m/s^2, specific impulse $I_{sp} = 300$ s, and reboost mass m_r, which exceeds m by the mass of the resupply vehicle. Denoting the velocity on the raised circular orbit by υ_2, the velocity ratio $\eta = \upsilon_2/\upsilon_1$ can be determined from the Hohmann transfer relationships as

$$\Delta\upsilon/\upsilon_1 + (1-\eta)\left[1 - (1-\eta)\sqrt{2/(1+\eta^2)}\right] = 0 \qquad (13)$$

Solving numerically for η, the velocity on the raised circular orbit is then determined from $\upsilon_2 = \eta\upsilon_1$ with the corresponding semimajor axis $a_2 = \mu/\upsilon_2^2$ and, hence, altitude $h_2 = a_2 - R_e$.

The effects on the reboost profile of operating the electrodynamic tether at higher power can be seen in Fig. 15. This figure illustrates the savings of two propellant reboost flights (or equivalently 2000 kg of propellant) to the ISS for the year 2006. The electrodynamic tether system was assumed operating at 10 kW, which provides a propulsive force of 0.7 N that is somewhat greater than the aerodynamic drag force illustrated in Fig. 3. The duty cycle for the tether reboost was again 25%. The higher tether power postpones the fourth resupply flight by over two months. Clearly, the savings here will increase rapidly if the duty cycle can be increased.

A similar analysis was performed for the years 2003 and 2009. Figure 16 summarizes these results by illustrating the annual propellant savings accrued from the electrodynamic tether reboost system. Based upon the range of parameters considered here, the tether reboost system can reduce the number of propellant resupply flights by one to four annually.

Impacts to ISS

The use of an electrodynamic tether to provide reboost to the space station raises several issues, some of which will be addressed in this section.

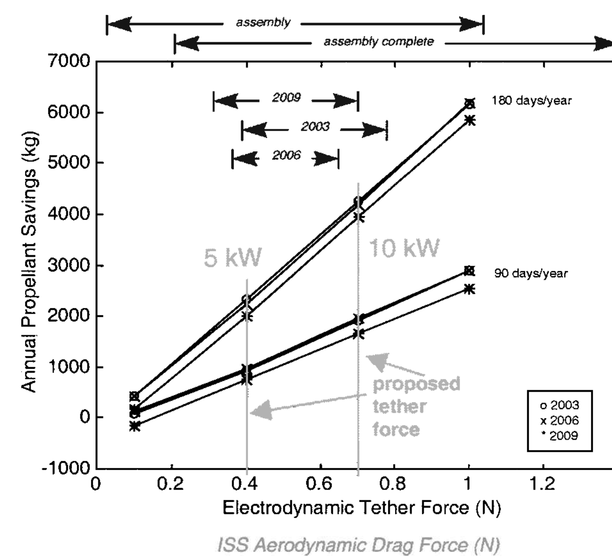

Fig. 16 Annual propellant savings.

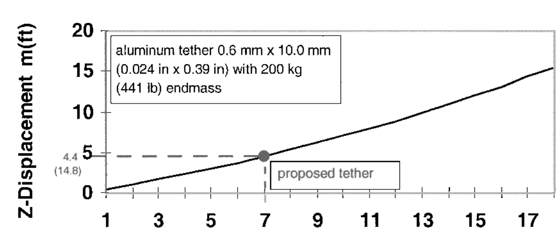

Fig. 17 Displacement of ISS CM by tether.

Effects on CM and θ Gravity

The proposed tether does have a significant impact on the Z component of the station's CM. The tether itself would impact the CM because of its long moment arm. Figure 17 shows that a 7-km tether of the proposed type, with a 200-kg end mass, would lower the station's CM by about 4.5 m. The prepared tether configuration would lower the projected μ-gravity contours from those currently planned without a tether to those shown in the bottom part of Fig. 18. Using the tether, the region of best μ gravity has been shifted from the top of the U.S. laboratory to the bottom, with a similar shift—and possibly even an improvement—for the European and Japanese laboratories. If this shift is deemed undesirable, it could be reduced by maneuvering the tether boom, shown in Fig. 11, to adjust the station's TEA so as to lower its leading edge.

The effect of the tether's deployer on the X component of the station's CM is negligible because even a 500-kg deployer located 20 m forward of the CM would move the CM forward by only

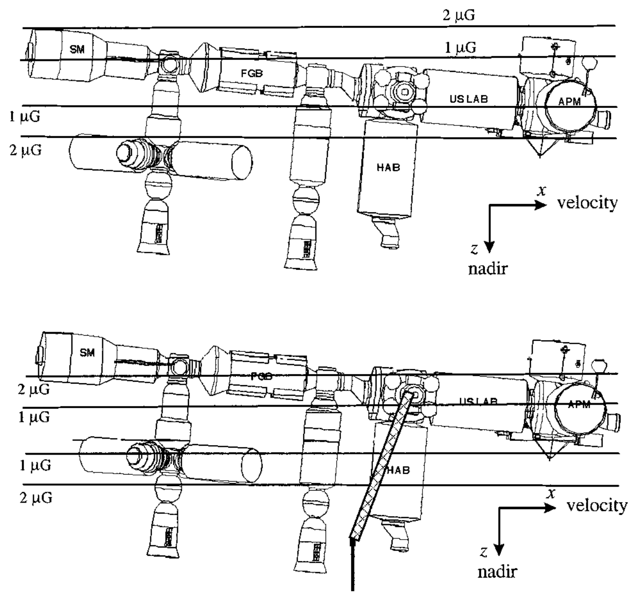

Fig. 18 Microgravity environment: top, without tether, and bottom, with tether.

2.5 cm. X-axis displacements are thus of less concern than vertical (z axis) displacements because of the tether mount's small moment arm and the low-gravity gradient force.

Power Demands upon ISS

The tether requirement for 5 kW (or 10 kW) of power from the 80 kW available from the generating sources does not appear excessive during the daylight hours. Extracting this level of power from the batteries during night operation may not be satisfied at all times. Under these conditions, the tether power and the reboost thrust would be reduced accordingly.

Retrieval or Jettison of Tether: Normal Conditions

The tether system for reboost is intended to be used during quiescent periods because it would tend to nullify the station drag and thus improve rather than degrade the quality of microgravity. At times when visiting spacecraft come to the ISS, the extended tether might interfere with their docking procedure. Under these circumstances, the tether would need to be retrieved, or cut and discarded, prior to the spacecraft's visit. It is expected that spacecraft will be visiting on a fairly regular basis—six flights at least for orbiter, four to six flights for Progress M, and flights by other spacecraft—so cutting and discarding the tether may become a cost issue. Retrieval of the tether appears a candidate solution but raises control issues, particularly when the tether length is short (less than approximately 1 km). Retrieval systems inherently carry higher initial costs than expendable systems. Further analysis and design will be needed to resolve these issues.

Maneuverable Boom to Guide Tether

A boom may be used for tether deployment. The boom can move the tether away from other elements of the ISS and place the x component of the tether c.g. near the c.g. of the Station. Furthermore, a boom may be used to optimize the station's torque equilibrium angle to minimize the frequency of rocket firings to desaturate the control moment gyros and thus save even more propellant.

ISS Survivability and Cost Savings

Over the past several years, the Russian resupply vehicle Progress M has proven itself to be a highly reliable means of delivering life-support materials and reboost capability to low Earth orbit. Of the propellant reboost options considered for the ISS, only the Progress M is operational. The Soyuz launch vehicle is used to insert Progress M into low Earth orbit at a cost of approximately $\$15 \times 10^6$–$\$25 \times 10^6$ (Ref. 6). The propellant cost is an additional $\$20 \times 10^6$ for a total cost of between $\$35 \times 10^6$ and $\$45 \times 10^6$. Commercial sources indicate that this value may be as high as $\$65 \times 10^6$. The $\$35 \times 10^3$–$\$45 \times 10^3$/kg estimate of Progress M propellant launch cost (i.e., the lower cost number) is used in this paper to ensure more conservative estimates of cost saving.

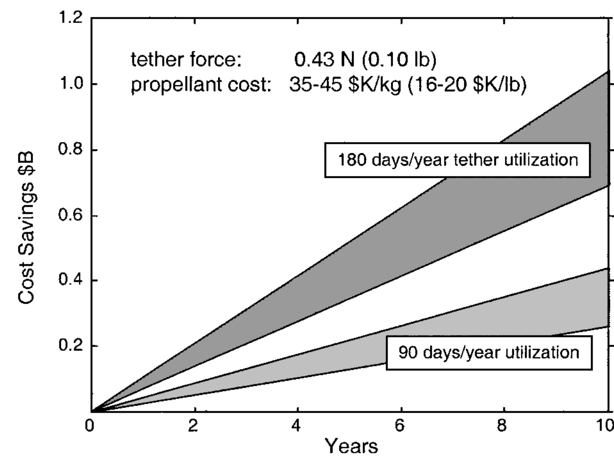

Fig. 19 Cumulative cost savings.

Propellant savings provided to the ISS are illustrated in Fig. 16. These can be converted to dollar savings using the $\$35 \times 10^3$/kg launch estimate for propellant. Figure 19 illustrates the results of this conversion expressed as cumulative cost savings for the ISS over 10 years of operation. The two shaded regions correspond to 25 and 50% duty cycles of tether reboost operation for a tether force of 0.43N(5 kW). The widening of these regions with time results from the differences in the computed annual propellant savings between the three different one-year periods considered. At the higher duty cycle a savings in excess of one billion dollars over the operational life of the ISS is possible by using an electrodynamic tether to supplement propellant usage. At the higher reboost value of 0.7N(10 kW), the savings are approximately twice as much.

These estimate savings may pale in significance, however, in comparison to the role of a tether as a backup system to ensure ISS survival in case propellant resupply flights should be interrupted for any extended period. During an extended period of isolation, a tether could provide service for an extended duration with a much higher duty cycle than has been considered here, even if the tether were judged incompatible with safety requirements for vehicle docking and even if only a nonretrievable tether were available.

Conclusions

Multiple benefits are accrued by the use of a propellantless system to reboost the ISS. Because the ISS is designed as a research and test facility to fly in an inherently unstable orbit to ensure reachability for over 10 years, means of providing reboost is a critical concern. The electrodynamic tether-based reboost system could satisfy some of the total reboost needs of the ISS, resulting in a reduction in flights that deliver propellant. The higher the usage of the electrodynamic tether, the larger the cost savings because of the need for fewer propellant resupply flights. Use of this method of reboost would provide for additional quiescent days as the system would have no major impact on the microgravity environment and under certain conditions could improve the microgravity environment. In addition, a maneuverable boom could provide some variation/control in the ISS torque equilibrium attitude. In addition to economic considerations, an electrodynamic tether offers a practical backup system to ensure ISS survival in the event of an (otherwise) catastrophic delay in propellant delivery.

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