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International Space Station Electrodynamic Tether Reboost Study

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July 1998

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ACAD	Attitude Control and Determination
CM	center of mass
DCSU	dc switching unit
DDCU	dc to dc conversion unit
EDT	electrodynamic tether
FGB	functional cargo block
emf	electromotive force
ISS	*International Space Station*
MBSU	main bus switching unit
MSFC	Marshall Space Flight Center
OML	orbital-motion-limited
PM	Parker-Murphy
PMG	plasma motor generator
ProSEDS	Propulsive Small Expendable Deployer System
PV	photovoltaic
SBIR	Small Business Innovative Research
SEDS	Small Expendable Deployer System
S0	ISS truss designation _ S zero
SSU	sequential shunt unit
TSS	Tethered Satellite System

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TECHNICAL MEMORANDUM

INTERNATIONAL SPACE STATION ELECTRODYNAMIC TETHER REBOOST STUDY

1. INTRODUCTION

The *International Space Station* (*ISS*) will require periodic reboost due to atmospheric aerodynamic drag. This is nominally achieved through the use of thruster firings by the attached Progress M spacecraft. Many Progress flights to the *ISS* are required annually. Electrodynamic tethers (EDT's) provide an attractive alternative in that they can provide periodic reboost or continuous drag cancellation using no consumables, propellant, nor conventional propulsion elements. The system could also serve as an emergency backup reboost system used only in the event resupply and reboost are delayed for some reason.

2. STUDY GUIDELINES AND ASSUMPTIONS

The main study guideline was to conceptualize a system capable of providing supplemental reboost capability throughout the life of the *ISS,* reducing the currently required number of annual resupply flights. Eliminating one or more of these flights per year could result in significant cost savings. The study assumed a baseline "bare" tether technology with several design options. The proposed EDT system should be attached to the *ISS* in a location to minimize adverse impacts to the Station.

3. PROPELLANTLESS REBOOST FOR THE *ISS*: AN ELECTRODYNAMIC TETHER THRUSTER

The need for an alternative to chemical thruster reboost of the *ISS* has become increasingly apparent as the Station nears completion. A system is described to utilize *ISS* electrical power to generate thrust by means of a new type of EDT attached to the Station (fig. 1). A flexible system could be developed to generate an average thrust of 0.5–0.8 N for 5–10 kW of electrical power. By comparison, aerodynamic drag on the *ISS* is expected to average from 0.3 to 1.1 N (depending upon the year).

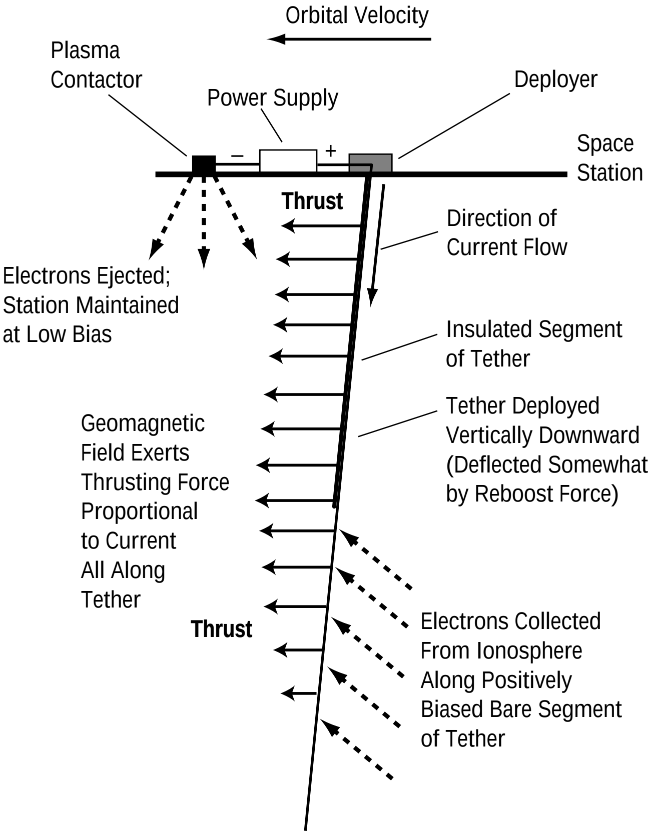
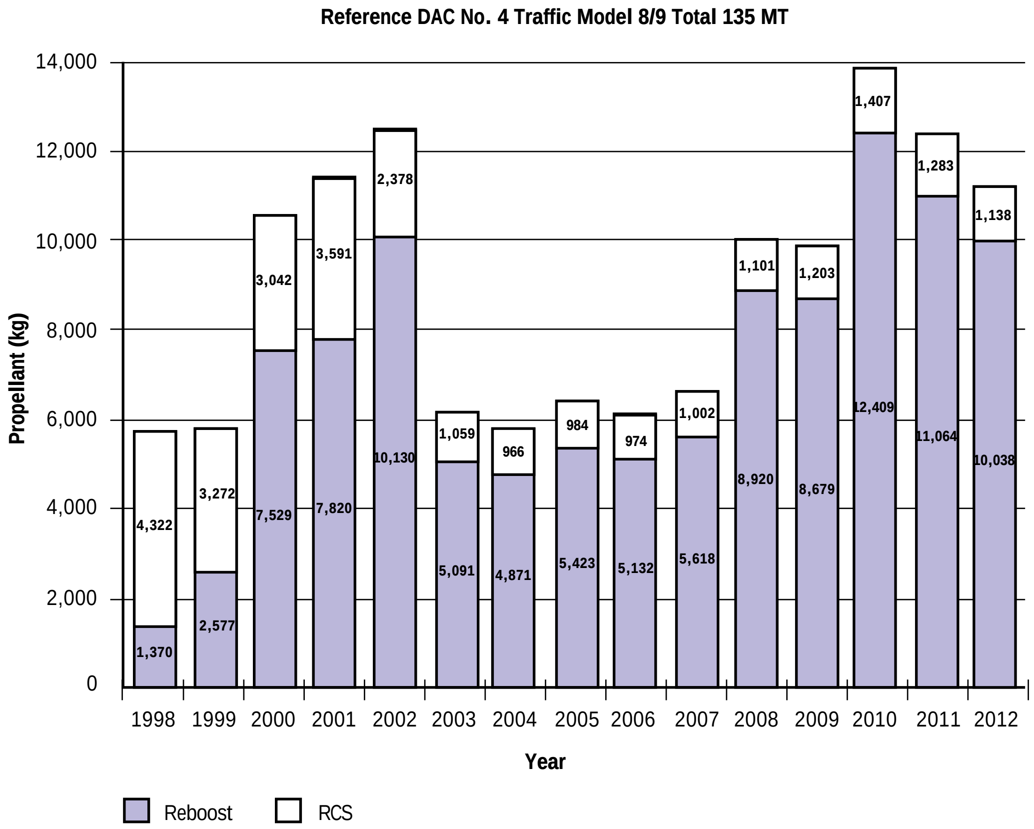


Figure 1. An EDT reboost system for the *ISS*.

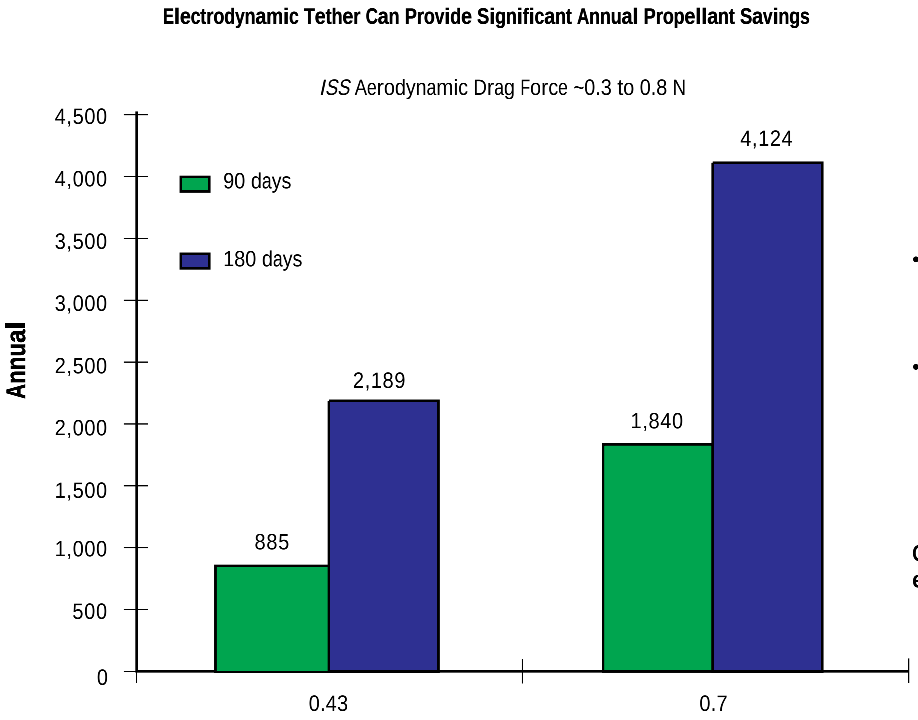
The annual propellant required by the *ISS* for reboost varies by year, as can be seen in figure 2. The EDT can provide a significant annual propellant savings. It was calculated that one resupply flight is eliminated for every 1,000 kg of propellant saved. Assuming a Soyuz launch cost of $15M–$25M per launch and 5 kW of input power, there is a possible $1B savings over 10 yr. Figure 3 shows that with the stated assumptions, 2,189 kg can be saved at an input power of 5 kW (0.43 N force) and 4,124 kg propellant savings at 10 kW (0.7 N force).

The proposed system uses a tether with a kilometers-long uninsulated (bare) segment capable of collecting currents greater than 10 A from the ionosphere. The new design exhibits a remarkable insensitivity to electron density variations, allowing it to operate efficiently even at night. A relatively short and light tether (10 km or less, 200 kg) is required, thus minimizing the impact on the *ISS* (center of mass (CM) shift <5 m).



Reference DAC No. 4 Traffic Model 8/9 Total 135 MT

Figure 2. Total estimated propellant required annually to maintain the *ISS*.



Electrodynamic Tether Can Provide Significant Annual Propellant Savings

ISS Aerodynamic Drag Force ~0.3 to 0.8 N

- Tether propulsive force counters aerodynamic drag force on *ISS*
- System Assumptions
  - Reboost force of 0.43/0.7 N for a 7-km tether with 5–10 kW input power
  - Analysis for years 2003, 2006, 2009

One resupply flight is eliminated for every 1,000 kg of propellant saved

Figure 3. Annual propellant savings.

4. ELECTRODYNAMIC TETHERS

EDT’s have been demonstrated in space previously with the plasma motor generator (PMG) experiment and the Tethered Satellite System–1R (TSS–1R). The advanced EDT proposed for this application has significant advantages over previous systems in that higher thrust is achievable with significantly shorter tethers and without the need for an active current collection device, hence making the system simpler and much less expensive.

5. NEW TECHNOLOGY TETHER ENHANCES CURRENT COLLECTION

A bare-tether design represents a breakthrough that 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.

6. HIGH TETHER CURRENTS FOR *ISS* REBOOST

6.1 Basic Principles and Technical Challenges

An EDT can work as a thruster because a magnetic field exerts a force on a current-carrying wire ($\mathbf{F}=l\,\mathbf{I}\times\mathbf{B}$). This force is perpendicular to the wire and to the field vector. If the current flows downward through a tether connected to the Space Station, the force exerted by the geomagnetic field on the system has a component that accelerates the Station along the direction in which it is already moving.

An orbiting system, by virtue of its motion through the Earth’s magnetic field, experiences an electric field perpendicular to its direction of motion and to the geomagnetic field vector. For an eastward-moving system, such as the *ISS*, the field is such that the electrical potential decreases with increasing altitude (at a rate of around 100 V/km for *ISS* orbit). In order to drive a current in the proper direction through the tether, it is necessary to overcome this induced electromotive force (emf).

Thus, the reboost system requires a power supply and may be considered a type of electrical thruster. Calculations for the preliminary design indicate an average thrust of 0.5 N from 5 kW and 0.8 N from 10 kW. The tether is 10 km long with a mass less than 200 kg. The assumption is that there will be times during the day when surplus power from the solar panels could be utilized for this thruster power and that, depending upon the need and power reserves, night operation on battery power may also be possible.

The design will utilize a plasma contactor on the *ISS* to eject electrons; thus, the design is driven to deploy the tether vertically downward for a reboost application. Due to the power supply being placed in series between the plasma contactor and the upper end of the tether (see fig. 1), the upper end of the tether 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. Now the ionospheric electrons below the Station would “like” to get to the higher potential at the upper end of the tether. If the electrons can make contact with the tether, they will travel up it’s length, giving a current flow in the correct direction for reboost. The approach is illustrated in figure 4.

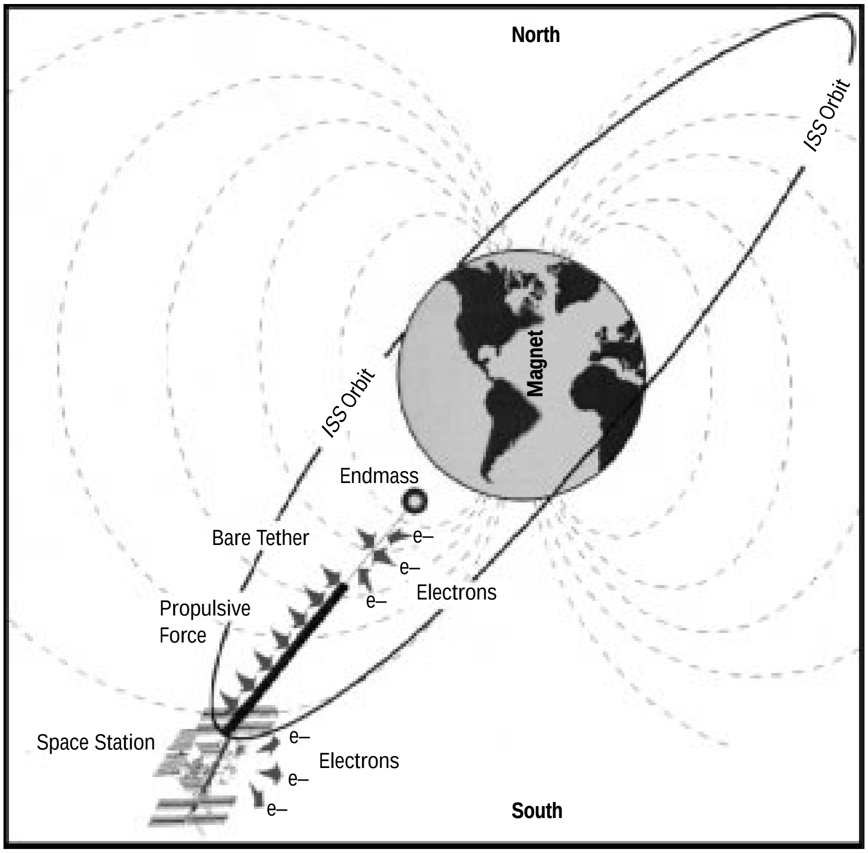


Figure 4. Illustration of the physics behind EDT thrust in Earth orbit.

The way in which the charge exchange between tether and plasma takes place depends upon the specifics of the system, and it is on this aspect (specifically the electron collection, which is the difficult part) that the engineering team has focused in designing a system capable of producing sufficient thrust with a reasonably short tether for the *ISS*.

The magnitude of the thrust force is dependent upon the motional emf (between the two ends of the tether), the average current in the tether, and the orbital speed. Thus, the product of the tether length and average tether current determines the thrust for given orbital/magnetic conditions. Generally speaking, a shorter tether will have a smaller impact on the *ISS* environment, so a combination of high current with short tether length is the goal.

ISS reboost (thrust forces of order 1 N) with a tether no longer than 10 km requires tether currents of order 10 A. 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: TSS–1R carried a passive metallic sphere as anode; PMG carried an active (plasma-ejecting) contactor.

Current collected to a passive, biased sphere in a magnetized plasma calculated by the standard Parker-Murphy (PM) model (taking into account magnetic effects, which are dominant) grows as the square root of the bias voltage, an important fact for fixed-area collectors.

A preliminary analysis of the measured TSS–1R currents indicates that they were typically greater than the PM model predictions (using values of the electron density and temperature estimated from ionospheric models and a satellite voltage calculated with some uncertainty). The TSS–1R data do not, however, appear to point to a dependence of current on voltage greatly different from that of PM for higher voltages. Even though, for example, a TSS–1R current of 0.5 A at 350 V bias may surpass PM model estimates, it could still imply a voltage of roughly 35 kV to reach 5 A for the same plasma parameters (which would require over 175 kW for a thrust of 0.7 N with a 10-km-long tether!).

Active anodes (plasma contactors) have been developed in an attempt to solve both space-charge shielding and magnetic guiding effects by creating a self-regulating 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 was the PMG, which reached 0.3 A in flight under a 130-V bias and the best ionospheric conditions. Unfortunately, there is no way to scale the results to high currents. The discouraging fact was that collected current decreased sharply with the ambient electron density at night.

Fortunately, there is another tether design option—the bare tether.[1]

6.2 The Bare-Tether Breakthrough

The bare-tether design represents a breakthrough that makes short-tether electrodynamic reboost with moderate power requirements for the *ISS* practical. To work on the *ISS*, a reboost system must not only be capable of delivering adequate thrust (preferably night and day); it must do so with small impact on the *ISS* environment while requiring minimal accommodation by the baseline *ISS* systems. It should also be simple to operate and maintain, and it must be competitive in terms of its use of resources for the benefits it provides.

The reference concept uses the tether itself, left uninsulated over the lower portion, to 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.

The following features argue in favor of the bare-tether concept:

1. 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 is a large sphere (such as the TSS–1R satellite) at equal bias (fig. 5). 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.

2. 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 upper end of the tether. This substantially reduces the center of gravity shift in both cases and reduces the cost and complexity in the case of the active contactor.

3. The system is self-adjusting to changes in electron density. This is accomplished by a natural expansion of the portion of the tether that is biased positively relative to the ionosphere whenever the density drops (fig. 6) as described by Sanmartín et al. A bare-tether thruster designed to adjust to lower electron density (as at night). A shift in the zero point of bias further down the tether increases the collecting surface and maintains a nearly steady thrust for constant input power and induced emf.

Features (1) and (2) combine to provide an ability to collect large currents with modest input power levels. A candidate system is presented below that can produce average thrusts of 0.5–0.8 N, for input power of 5–10 kW.

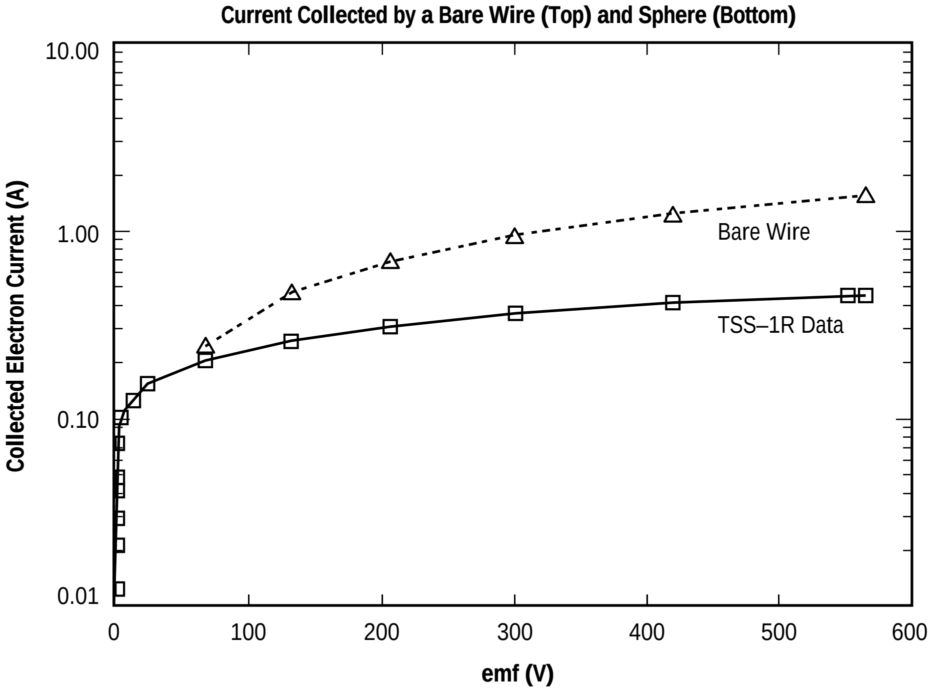


Figure 5. Electron collection performance of a bare wire versus a large conducting sphere. Calculation assumes a plasma density of 8.1×10^{11} m^{-3}, 0.7-mm-diameter tether, 4-km tether length, and 0.6 m sphere radius.

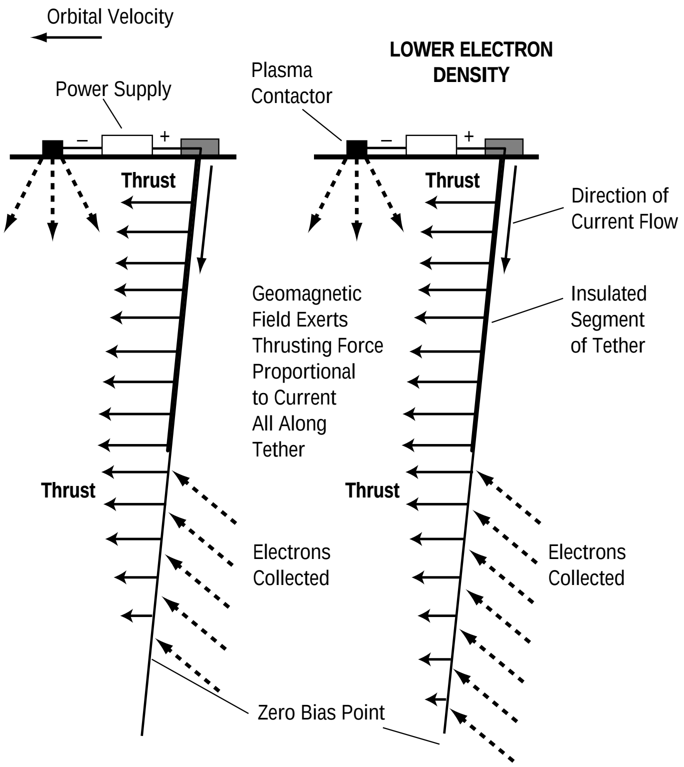


Figure 6. Sensitivity to electron density thrust.

6.3 The Bare-Tether Solution: Theoretical and Experimental Basis

Considering the tether design, the current-collecting properties of a long, thin cylinder for which there are well-established theoretical and experimental results will be reviewed. Charged-particle collection 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.

For a small radius, compared to both Debye length and gyroradius, there are neither space-charge nor magnetic-guiding effects, and this is in the OML regime of standard Langmuir theory. In the OML regime, the current takes the largest possible value for the given geometry and bias. In cylindrical geometry the OML regime holds for radius-to-Debye length ratios even of order unity.[2] Hence, a cylinder of 5-mm radius (about one Debye length, and small compared with gyroradius) works in the OML regime.

For a cylinder of 2-mm radius and 2.5-km length in a plasma with an electron density and temperature of 10^{12} m^3 and 0.15 eV, respectively, the bias voltage required to collect 10 A is only 100 V. A tether is just a long, thin cylinder, and if left uninsulated along part of its length, a tether can act as its own anode, capturing electrons efficiently over some positively biased segment.

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). Assuming 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.

The bias required to collect a given OML current varies as the inverse square of the collecting area, making it possible to reduce the required bias substantially by modestly increasing the collecting area. Since 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 (fig. 6). This ability to maintain thrust levels with low electron densities makes nighttime reboost possible. Variation in thrust with electron density for a 10-km tether with a 5-km-long bare segment is shown in figure 7. Thrust drops only 10 percent as density drops by a factor of 10. The reason is clear: the collecting length has increased from 1 to 4 km with an emf of 1,200 V and input power of 10 kW.

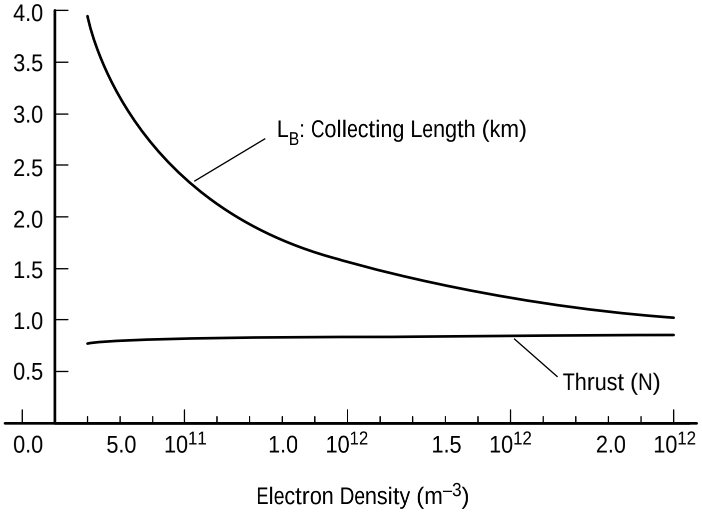


Figure 7. Electron density variation versus tether length.

Another important fact is that the OML current is identical for all cylinders with convex cross-sections of equal perimeter.[3] With maximum crosswise dimension (here, about 10 mm) fixed by OML considerations, one is allowed to choose the cross-sectional shape. This provides an opportunity to choose a tape- or ribbon-like tether, for example. The tape-like geometry gives somewhat better performance than a circular cross-section tether of equal length and mass and appears to have advantages related to deployment and thermal concerns. Tether geometry is one of the issues to be addressed in a later study.

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. The OML theory has been substantiated for both quiescent and flowing plasmas in the laboratory, and also in rocket and satellite flights, at moderate voltages.[4–6]

7. SYSTEM CONCEPT

7.1 Tether

The baseline EDT selected is an aluminum flat-braided ribbon coated with Spectra™, capable of delivering 0.5–0.8 N of thrust to the *ISS* at a cost of 5–10 kW of electrical power. The braided ribbon was chosen to help resist complete severance by micrometeroid damage. The length of 7 km was chosen to give a moderate force using current levels within the plasma contactor's reserve capability, while keeping voltages at levels that do not pose undue hazard to the *ISS*. The 106-kg tether has a width of 10 mm with a thickness of 0.6 mm. Since 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. Beyond that, the insulation provides for greater thrust at a given input power. This is due to the fact that 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. Thrust can be substantially increased 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 percent 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 figure 8. This graph shows the variation of thrust with input power for a nominal 10-km system. The motional emf is 1.2 kV.

The bare-tether design has essentially "cured" the problem of day/night thrust fluctuations. But 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 9 and 10 show the thrust variations around the *ISS* orbit with different input power levels. This assumes a 10-km-long EDT thruster described in this section, as it operates at a constant power of 10 kW. Dependence on electron density is weak and the thrust curve basically tracks emf. Figure 10 shows a comparison of thrust generated for input powers of 5 and 10 kW for the same tether and orbit as figure 9.

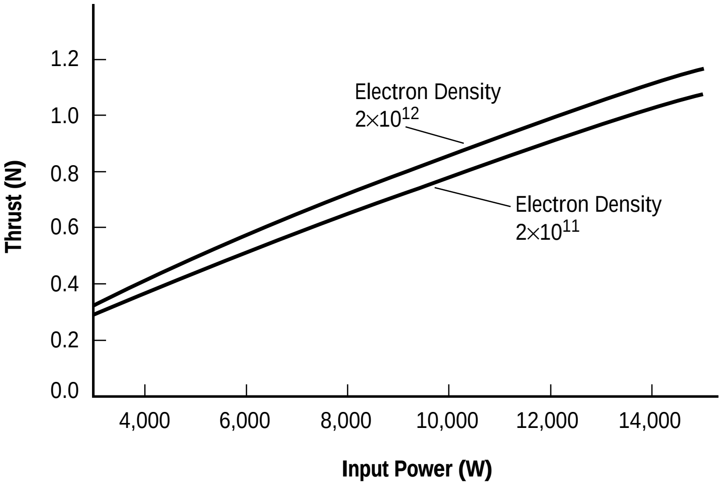


Figure 8. Variation of thrust with input power.

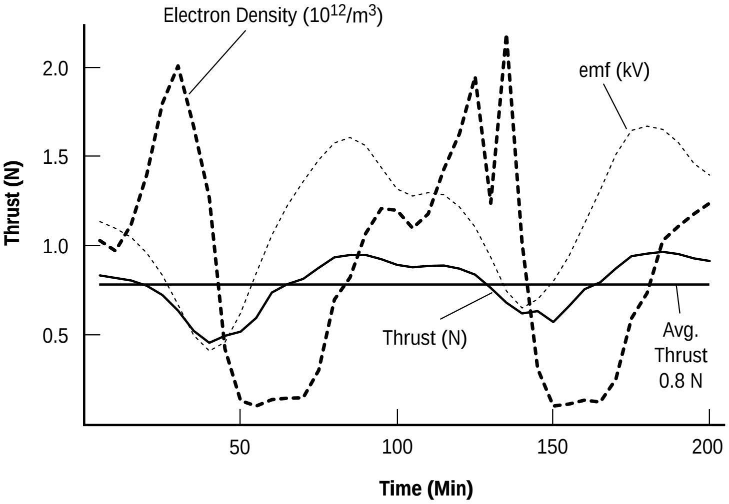


Figure 9. Variations in thrust over two *ISS* orbits.

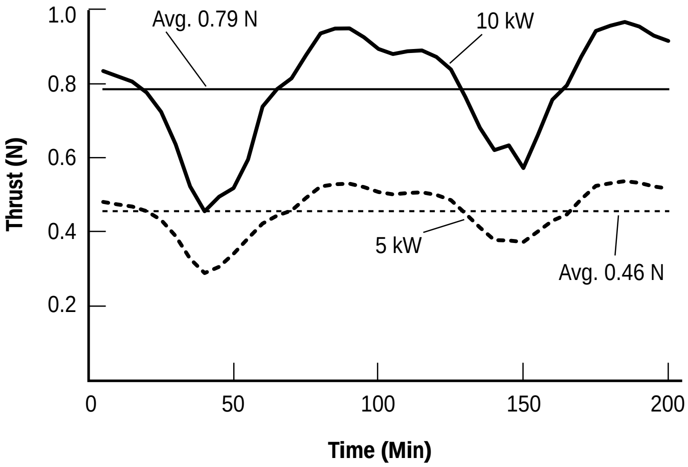


Figure 10. Thrust over time with input powers of 5 and 10 kW.

7.2 Plasma Contactor

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 to eject electrons collected out of space to maintain the *ISS* structure's potential within ±40 V of ambient plasma. The contactors currently under development at NASA Lewis Research Center 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, since currents over the 10-A rating of the contactors could be required.

7.3 Deployer Options

Two types of deployers were considered in this study. Since no firm retrieval requirement has been established, both expendable and retrievable systems were considered. Table 1 shows the issues associated with each type system.

Table 1. Deployer design retrieval issues.

Circumstance	Retrieval System	Expendable
Tether Deployer Complexity	Higher	Lower
Tether Dynamics—Payout	Feasible	Feasible
Tether Dynamics—Retrieve	Whip for Short Tether	N/A
Tether Replacement Cost	Low	Medium
Length Adjustments	Available	N/A
Emergency Abort Method	Cut and Discard*	Cut and Discard*
Response to an Arriving S/C	Retrieve	Cut and Discard*

*Cut tether drops into lower orbit and reenter within days

7.3.1 Expendable

The expendable self-deployer (fig. 11) is a derivative of the successful flight-proven Small Expendable Deployer System (SEDS). Such a deployer would be mounted on the endmass and, at the appropriate time, a spring ejection initiates the tether deployment. The deployer, therefore, deploys itself away from the *ISS*. This design simplifies the loading and deployment of replacement tethers.

7.3.2 Retrievable

At present, there are no retrievable tether deployers in the NASA inventory. The TSS (shown in fig. 12) was recently deintegrated from its pallet and surplused. The TSS approach was considered in the trade studies as an alternative to the expendable SEDS-type deployer, realizing that a new design would most likely be required for *ISS* implementation.

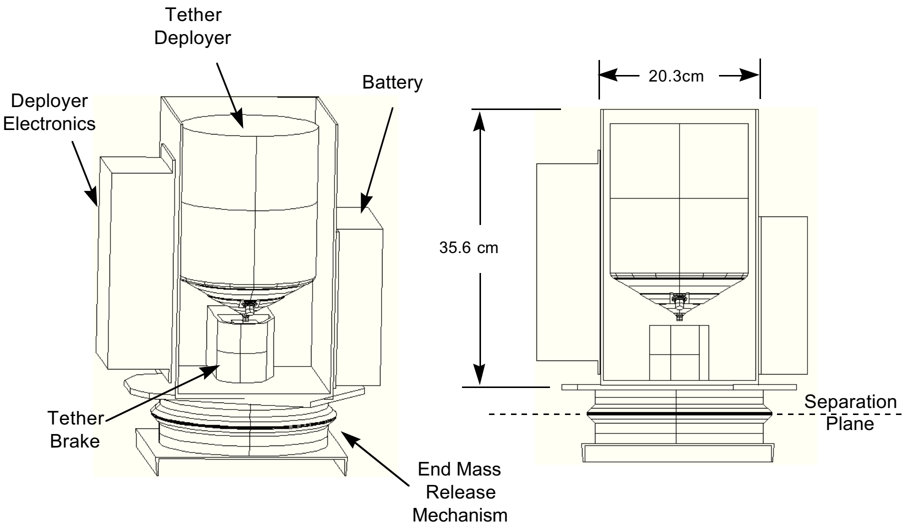


Figure 11. The expendable self-deployer concept.

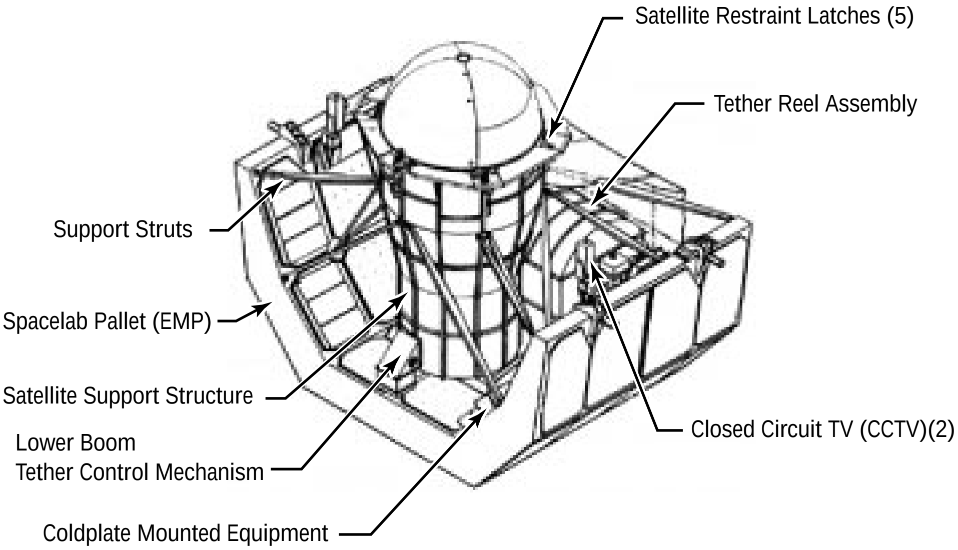


Figure 12. The Tethered Satellite System deployer.

7.3.3 Endmass

A total endmass weight of 200 kg was assumed for analysis. In the case of the expendable self-deployer, a fraction of this weight is comprised of the deployer itself. For a retrievable system, a simple “dead” weight was assumed.

8. *ISS* INTERFACE AND IMPACTS

8.1 Attachment

One of the key issues affecting the tether system integration with the Space Station is the physical accommodation of the tether on the Space Station structure. During this study, different attachment locations were evaluated to determine how the tether attachment would affect the Space Station and the desired tether functionality. When evaluating the different locations, the team focused on the following criteria:

- Avoiding the interference of the tether reboost system hardware with Space Station structures and operations
- Minimizing the effects on the microgravity environment of the Space Station
- Minimizing the effects on the Space Station dynamics and orientation.

It was determined that the tether should be mounted through or near the *ISS* CM to reduce induced torque. Incorporation of a boom to the tether system would provide control to minimize adverse effects on the microgravity environment (fig. 13).

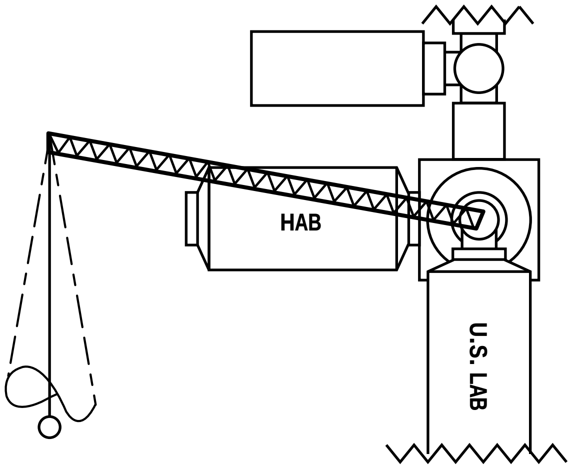


Figure 13. A boom could be used to move the tether line of action closer to the *ISS* center of mass.

8.2 Impact on *ISS* Center of Mass

There is a displacement of the CM due to the components of the tether system. As the deployer, motor, and electrical control system are located on *ISS*, their change of CM in the +*z* direction is minimal. However, the long tether and endmass would have an impact. For 200 kg endmass and an aluminum tether, the +*z* displacement is shown in figure 14.

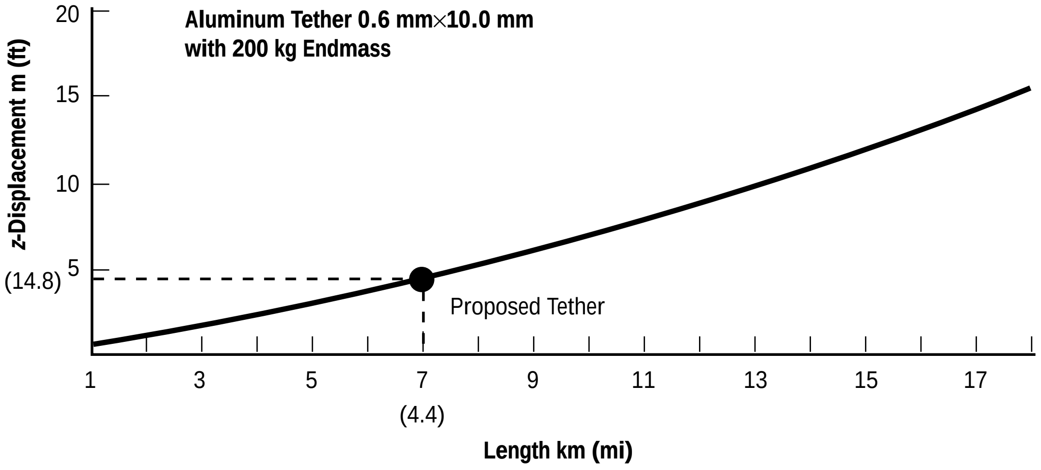


Figure 14. Tether impact on the *ISS* center of mass.

8.3 Impact on *ISS* Microgravity Environment

The microgravity environment for the *ISS* for assembly complete shows a portion of the U.S. Lab falling outside the 1 µg envelope and within the 2 µg envelope (fig. 15).

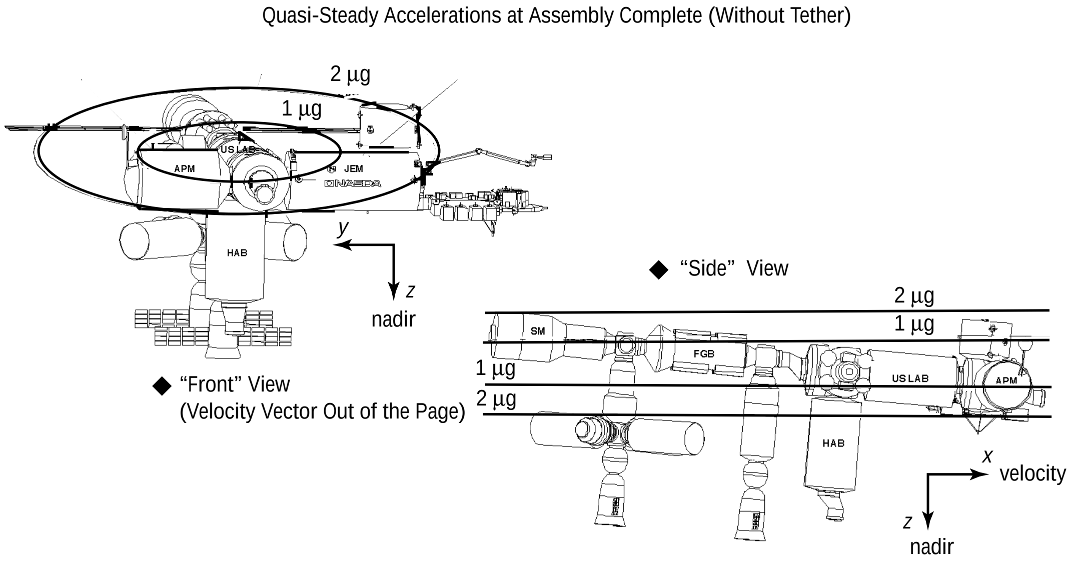


Figure 15. *ISS* microgravity environment impact.

With the addition of the tether system, there results a change in the microgravity conditions at *ISS*. For the 7-km tether with a 200-kg endmass, the U.S. Lab still has a portion of it which falls within the 1 μg boundary. The entire U.S. Lab fits within the 2 μg envelope. Figure 16 shows a lowered microgravity environment after attachment of the tether reboost system.

Quasi-Steady Accelerations at Assembly Complete (With Tether)

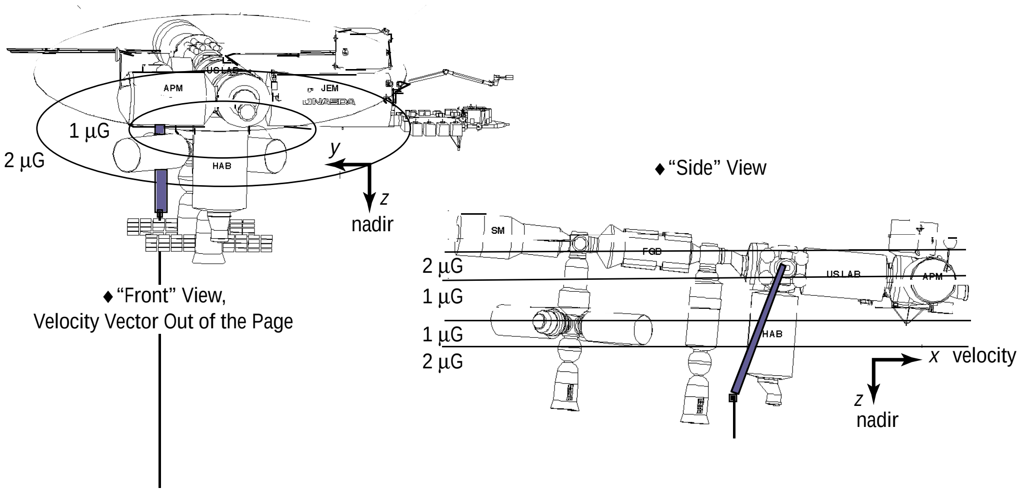


Figure 16. *ISS* microgravity environment lowered by tether.

To avoid mechanical interference, the tether must stay within a 10° conical envelope to assure clearance of all *ISS* hardware under normal, abnormal, and abort conditions. The recommended mounting location for the tether system is on Node 1.

The tether system requires power from the *ISS*. Multiple locations for power extraction were considered, but the main bus switching unit (MBSU) on the S0 truss is the preferred location.

9. POWER SYSTEM REQUIREMENTS

To generate 0.4 N thrust, the system will require approximately 6 kW from the *ISS*—delivering 5 kW to the tether.

There are three potential power connection locations on the *ISS*: the dc switching unit (DCSU), the dc to dc conversion unit (DDCU), and the MBSU.

The MBSU on the S0 truss is the recommended location for the attachment of the tether reboost system. The *ISS* supplies 160 V dc power from the photovoltaic (PV) array to the sequential shunt unit (SSU), the DCSU, and to the MBSU. From the MBSU, the power enters the tether power supply where it is converted from 160 V dc (>5 kW) to about 1,500 V dc (5 kW). Figure 17 shows a block diagram of the tether reboost system interface with the *ISS*.

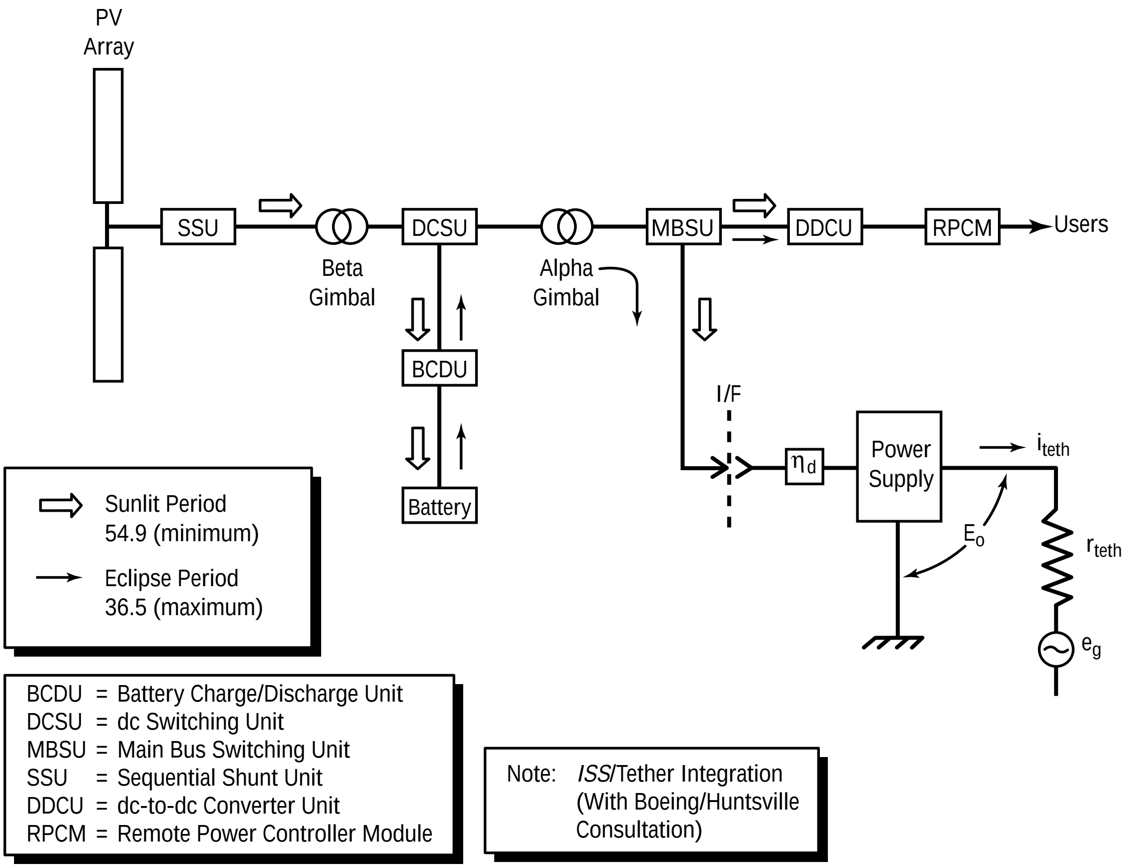


Figure 17. Tether reboost interface with the *ISS*.

The power supply for the tether system will consist of the following components:

Inverter—Transforms 160 V dc to ac
Transformer—Changes voltage
Rectifier—Converts ac to dc
Filter—Removes noise and ripple from dc
Regulator—Maintains constant voltage.

Surplus power is often available after the *ISS* is assembled and at optimum Sun angles. Figure 18 shows the power availability as a function of solar beta angle. Top level power conditioning is shown in figure 19.

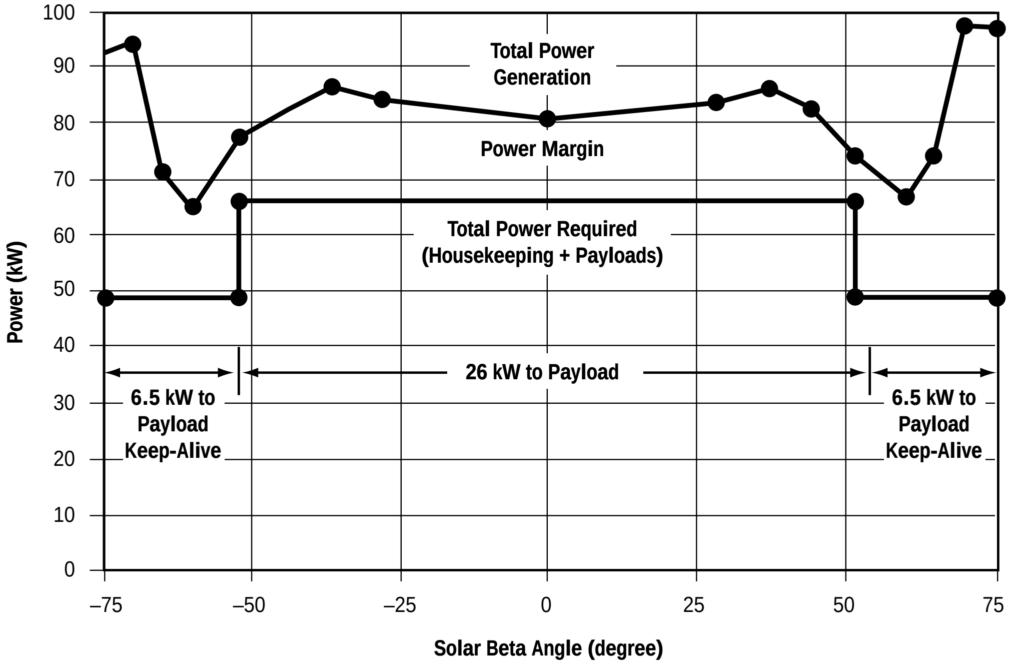


Figure 18. Power is available to operate an EDT reboost system during sunlit portions of the *ISS* orbit.

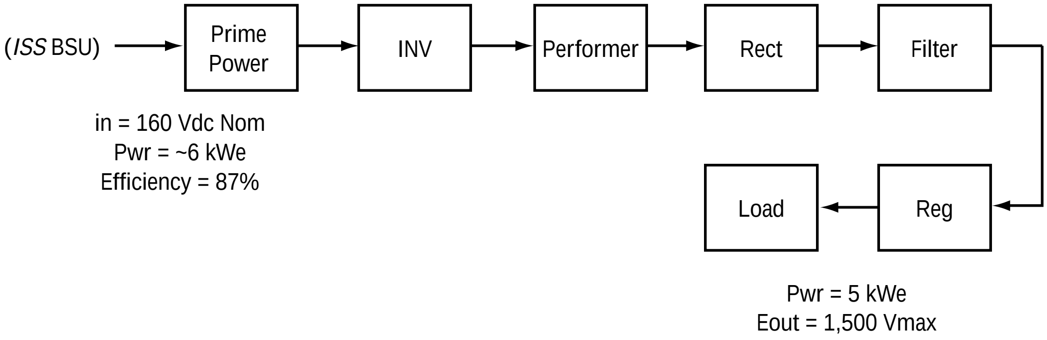


Figure 19. Power conditioning sequence for tether reboost system.

10. TETHER DYNAMICS

Electrodynamic forces acting upon the tether during operation will result in tether deflections that must be understood and, if possible, controlled. These deflections occur both in and out of (perpendicular to) the orbit plane. The tension in the tether, provided by the gravity gradient forces acting upon it, provides the restoring force to oppose the electrodynamic “disturbance” forces to keep the tether from “rotating over” the *ISS* (excessive libration) or from “folding up” (excessive curvature).

The first and least troublesome deflection is tether curvature (fig. 20). With differential forces acting upon the length of the tether, which is simply a wire, the tether will bow slightly. The magnitude of this bowing along the total length of the tether is estimated to be on the order of a few tens of meters.

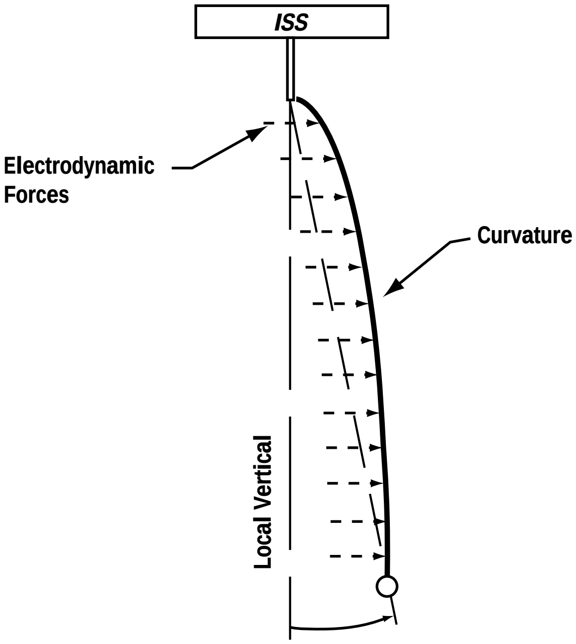


Figure 20. Tether curvature results from the reboost forces acting upon the wire during operation.

The electrodynamic force is primarily eastward, therefore, operation in an inclined orbit will produce both in-plane (reboost) and out-of-plane forces. The out-of-plane tether libration (pendulous motion) can resonate with out-of-plane forces and drive tether motion to large, unacceptable amplitudes. This resonance is primarily caused by day/night fluctuations in the tether current from natural plasma density variations. Even using the relatively insensitive bare tether, this resonant “pumping” must be controlled.

To maintain libration angles of <10°, a control system is required to monitor and control tether current, and hence, tether motion. Such a system can dramatically reduce the out-of-plane libration experienced by an uncontrolled system (fig. 21).

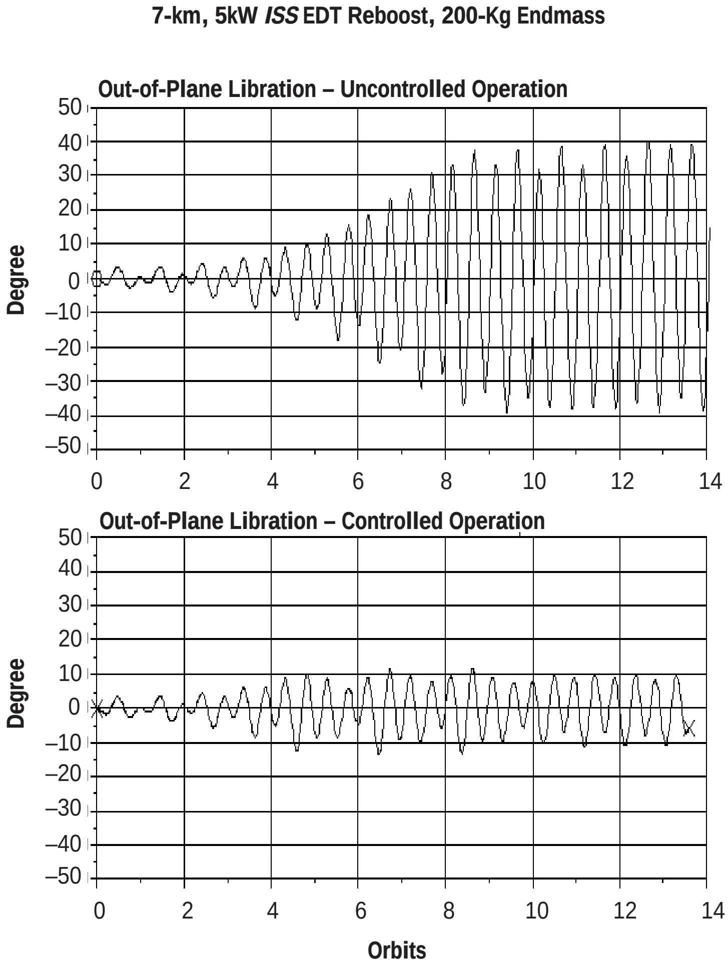


Figure 21. Uncontrolled out-of-plane tether libration (top) versus controlled (bottom).

11. MICROMETEOROID EFFECTS

Meteoroids and orbital debris contribute to the risk of severing the tether. Impactor diameters used in the study analysis are 0.12 mm (1/5 tether thickness) for degrading the tether and for a single-cut impactor, the diameter is 3 mm (1/3 tether width). The probability of survival for a single-cut impact is shown in figure 22 for a 350-km altitude and a 460-km altitude environment. During quiescent periods (lasting 30–40 days), the tether has a greater than 99.5-percent survival probability.

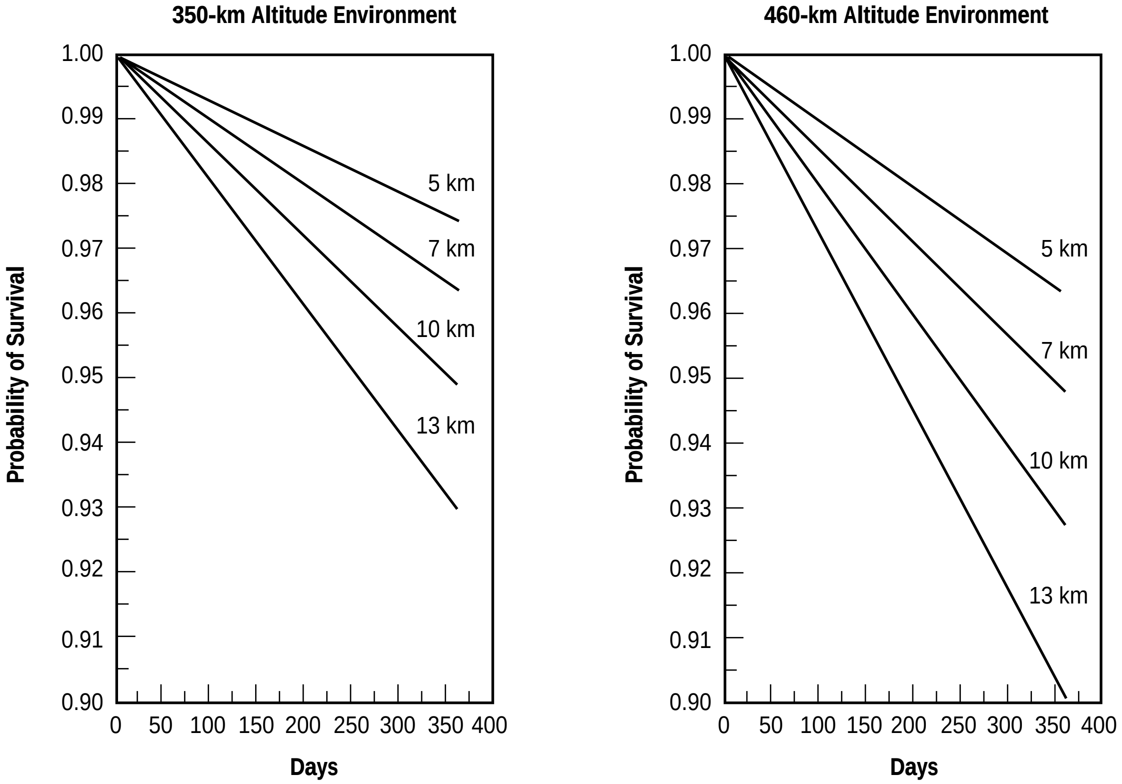


Figure 22. Probability of tether survival for single-cut impact.

Long-life tethers are being developed under phase II Small Business Innovative Research (SBIR) that are directly applicable to the *ISS* systems. These tethers would increase the survival probability to greater than 99 percent for 1 yr of continuous deployment.

Even though the probability of tether severing is low, if a sever occurs the tether remnant still attached to the *ISS* will recoil. The recoil velocity and impact energy will be low due to low tether tension and stretch. To prevent recoil, the tether can be cut at the *ISS* after a sever occurs which would require a tether integrity monitoring system.

12. ASSESSMENT OF SPACE APPLICATION AND BENEFITS TO THE *ISS*

12.1 Mission Benefit

The value in an EDT 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 the *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 a tether and some additional storage capacity for supplies, a 1-yr interval between visits to the Station becomes conceivable.

Even if the current frequency of resupply flights to the Station is maintained, with an EDT the Station program has the option to trade kilowatts for increased payload capacity. Resupply vehicles can deliver useful cargo like payloads, replacement parts, and crew supplies rather than propellant. Within the range of 5 to 10 kW, a crude approximation of 1,000 kg of user payload gained per kilowatt expended per year appears reasonable; further analysis will refine this estimate.

As a bonus, propellantless reboost is exhaustless reboost: external contamination around the Station is considerably reduced. The Station reboost propellant is hydrazine. Any consumption of propellant may result in residual chemical deposits and contamination on the Station's exterior surface. An EDT provides a means to reboost the Station without the complications of chemical combustion. The purity of the external environment for science payloads is enhanced, and beneficial operational impacts of reduced propellant exhaust on external systems and optics will be realized. Electrodynamic thrust truly represents solar power at its finest.

Yet another dimension to propellantless reboost must be considered. Station users have been allocated a minimum of 180 days of microgravity per year. Current planning essentially halts science activity during reboost maneuvers. Low-thrust EDT reboost could be performed over long-duration, as opposed to short-duration, high-thrust propulsive maneuvers. The 0.5 to 0.8 N thrust provided by a 10-km tether more than counteracts the Station's atmospheric drag on a daily basis. Thus, the question arises: can an EDT compensate for the drag while it is occurring, without disrupting the microgravity environment? Fluctuations in the induced voltages from the Earth's magnetic field and in electron densities will create "turbulence" through which the EDT-driven Station must fly. Can load-leveling control systems compensate for these pockets and maintain microgravity levels? In this case, a new realm of possibilities opens up for long-duration microgravity experiments. The allure of this self-propelled space facility is certainly remarkable, and offers potential advantages.

12.2 Risk Reduction

Aside from replacement of failed components, an electrodynamic reboost tether on the Station makes the vehicle itself essentially independent of propellant resupply from Earth. The primary resupply consideration becomes the inhabitants of the Station and not the Station itself. This is a new view for development of space operations. There ceases to be concern over the “180-day countdown to reentry at 150 nm” which currently permeates every aspect of Station mission planning. With the multibillion-dollar investment in the vehicle virtually secured and free from concern over long resupply vehicle launch delays, particularly Russian Progress or Functional Cargo Block (FGB) tanker delays, the program will be able to focus much more strongly on the *ISS* mission rather than on *ISS* itself.

12.3 Cost Payback

The cost of the proposed system comes in the form of the development, launch, and installation of an operational tether reboost system on the Station. The payback comes in the form of reduced propellant upmass requirement. For 2003 to 2012, nearly 90,000 kg of propellant must be launched. Using a figure of \$20,000 per kg, this represents a sum of \$1.8B. An EDT supplying 90 percent of this requirement would reduce the operational cost by \$1.6B, paying for itself many times over. More modest estimates still result in a return on investment tens of times the cost of development and operation of an electrodynamic reboost tether.

12.4 Comparison to Competing Technologies

To determine the overall benefits of EDT thrust, it is necessary to compare its potential performance with other advanced propulsion concepts that might be considered for *ISS* implementation in the same timeframe. Table 2 shows how the approach compares with other techniques operating at a similar power level. Figure 23 illustrates how the systems compare in terms of total mass required on-orbit, assuming a 10-yr operational lifetime.

Table 2. Performance comparison of EDT’s with other competing approaches for *ISS* reboost.

	ED Tether	**Ion**	**SPT**	**Arcjet**	**Resistojet**	**Bipropellant**
Input Power (kW)	5	5	5	5	1.2	0
Thrust (N)	0.40	0.13	0.27	0.49	0.80	400
Isp (s)	n/a	3,800	1,700	650	302	310
Efficiency	0.6	0.75	0.46	0.33	0.9	n/a
Lifetime (days)	years	338	129	35	16	n/a
N/kW	0.08	0.03	0.05	0.10	0.66	n/a

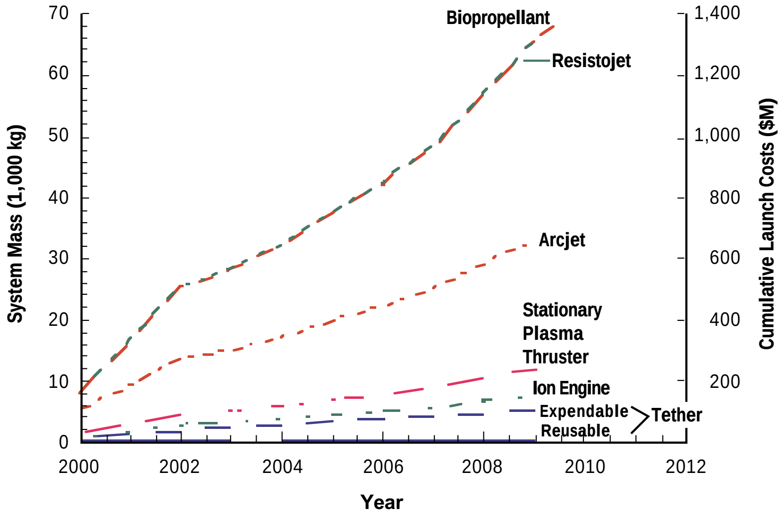


Figure 23. Both a reusable and expendable tether system compare very favorably with competing systems over a 10-yr operational life.

It should also be noted that the commercial satellite industry may also be a beneficiary in the application of an electrodynamic reboost tether system. One of the most significant costs for satellites is launch weight, and a substantial portion of launch weight is propellant weight. If conventional propellant systems can be replaced by EDT systems, new barriers will be broken in satellite longevity. It is repeatedly stated that satellite components are reliable but the available onboard propellant limits the useful life of the satellite. Initiating use of an EDT at *ISS* may revolutionize design of future spacecraft.

12.5 Schedule Compatibility

If the Russians meet their current propellant resupply commitments, assembly phase priorities for power will most likely not change. Upon installation of the final photovoltaic arrays, there would presumably be sufficient power availability margin that the user community would be willing to trade 6 to 9 kW for an increase of 6,000 to 9,000 kg per year in payload upmass. Thus, the installation of an operational EDT would have to be complete by 2002 or 2003.

If, however, propellant resupply turns out to be the program’s main bottleneck during assembly, work could be accelerated to install the system as early as late 1999 or early 2000. Power margins are particularly thin during the initial buildup, so electrodynamic reboost would most likely come at the expense of payload user power.

Before an operational EDT reboost system for the *ISS* can be designed, a series of ground- and space-borne experiments and computer simulations must be performed. In addition, thorough systems analyses must be performed to determine the physical integration and operational issues associated with its implementation on the *ISS*.

Among the issues to be addressed in the analyses of the reboost system are the attachment location for the tether, need for retrieval capability, microgravity impact, power interfacing, and safety. These are in addition to design issues specific to the tether itself, such as tether material, length, and geometry.

13. ISSUES

Before an EDT reboost system can be recommended for implementation on the *ISS*, several technical questions and issues must be addressed:

1. Does the shift of the *ISS* CM, however slight, produce unacceptable problems for microgravity research?

2. What constraints will be placed on the system for safety during orbiter rendezvous and exterior crew operations?

3. A system to monitor tether integrity must be developed to allow for quick severing of the tether at the *ISS* in the event of a break. Real-time current monitoring is a possibility.

4. Power availability (day and night). Without the addition of additional batteries or severely impacting *ISS* operations during eclipse, the EDT reboost system is constrained to operate only during sunlit portions of the orbit. Such periodic operation drives undesirable tether dynamics and reduces the overall efficiency of the system.

5. High-current tether operation may require either an enhanced *ISS* hollow cathode plasma contactor or an additional one. Current reconnection between two cathodes operating so closely together is an open issue.

14. CONCLUSION

An EDT reboost system has many advantages over other, more conventional propulsion systems planned or being considered for the *ISS*. With a relatively low development and operations cost (<$50M), a tether reboost system on the *ISS* could potentially save the program up to $2B over 10 yr. With the added benefit of increasing the total time available for microgravity experimentation and the effective cancellation of much of the aerodynamic drag forces acting on the experimenters' payloads, the total payoff resulting from its use is considerably more.

APPENDIX A. THE PROPULSIVE SMALL EXPENDABLE DEPLOYER SYSTEM (ProSEDS) SPACE EXPERIMENT

A.1 Abstract

The Propulsive Small Expendable Deployer System (ProSEDS) space experiment will demonstrate the use of an EDT propulsion system. The flight experiment is a precursor to the more ambitious EDT upper stage demonstration mission which will be capable of orbit raising, lowering, and inclination changes—all using EDT. ProSEDS, which is planned to fly in 2000, will use the flight-proven SEDS to deploy a tether (5-km bare wire plus 15-km spectra) from a Delta II upper stage to achieve ~0.4 N drag thrust. The experiment will use a predominantly “bare” tether for current collection in lieu of the endmass collector and insulated tether approach used on previous missions. ProSEDS will utilize tether-generated current to provide limited spacecraft power. In addition to the use of this technology for orbit transfer and upper stages, it may also be an attractive option for future missions to Jupiter and any other planetary body with a magnetosphere.

A.2 Introduction

Since the 1960’s there have been at least 16 tether missions. In the 1990’s, several important milestones were reached, including the retrieval of a tether in space (TSS–1, 1992), successful deployment of a 20-km-long tether in space (SEDS–1, 1993), and operation of an EDT with tether current driven in both directions—power and thrust modes).[7] A list of known tether missions is shown in table 3. The ProSEDS mission, to be flown in 2000, is sponsored by NASA’s Advanced Space Transportation Program Office at Marshall Space Flight Center (MSFC).

Table 3. Known tether flights.

Name	Date	Orbit	Length
Gemini 11	1967	LEO	30 m
Gemini 12	1967	LEO	30 m
H–9M–69	1980	Suborbital	500 m
S–520–2	1981	Suborbital	500 m
Charge–1	1983	Suborbital	500 m
Charge–2	1984	Suborbital	500 m
ECHO–7	1988	Suborbital	?
Oedipus–A	1989	Suborbital	958 m
Charge–2B	1992	Suborbital	500 m
TSS–1	1992	LEO	<1 km
SEDS–1	1993	LEO	20 km
PMG	1993	LEO	500 m
SEDS–2	1994	LEO	20 km
Oedipus–C	1995	Suborbital	1 km
TSS–1R	1996	LEO	19.6 km
TiPS	1996	LEO	4 km

A.3 Experiment Overview

The ProSEDS experiment will be placed into a 400-km circular orbit as a secondary payload from a Delta II launch vehicle (fig. 24). Once on orbit, the flight-proven SEDS will deploy 15 km of insulating Spectra™ tether attached to an endmass, followed by 5 km of predominantly bare wire tether (fig. 25). Upward deployment will set the system to operate in the generator mode, thus producing drag thrust and electrical power. The drag thrust provided by the tether, with an average current of 0.5 A, could deorbit the Delta II upper stage in approximately 17 days, versus its nominal ≥6-mo lifetime in a 400-km circular orbit (fig. 26).[8] Approximately 100 W electrical power will be extracted from the tether to recharge mission batteries and to allow extended measurements of the system's performance. A plasma contactor will be attached to the Delta II to complete the circuit and emit electrons back into space. Performance and diagnostic instruments mounted on the Delta II will be used to correlate the propulsive forces generated by the EDT and the existing plasma conditions. These instruments will measure plasma density, temperature, energy, and potential. ProSEDS will be the first tether mission to produce electrodynamic thrust, use a bare-wire tether, and recharge mission batteries using tether-generated power.

Figure 24. Artist concept of ProSEDS on a Delta II upper stage.

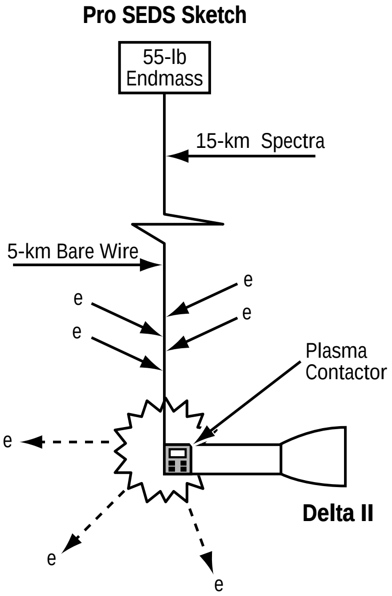


Figure 25. ProSEDS operational sketch.

A.4 Electrodynamic Tethers

The ProSEDS flight experiment will demonstrate electrodynamic propulsion (through drag thrust) in space. From theoretical analyses and preliminary plasma chamber tests, bare tethers appear to be very effective anodes for collecting electrons from the ionosphere and, consequently, attaining high currents with relatively short tether lengths. A predominantly uninsulated (bare-wire) conducting tether, terminated at one end by a plasma contactor, will be used as an electromagnetic thruster. A propulsive force of $\mathbf{F}=I\mathbf{L}\times\mathbf{B}$ is generated on a spacecraft/tether system when a current, *I*, from electrons collected in space plasma, flows down a tether of length, **L**, due to the emf induced in it by the geomagnetic field, **B**. Preliminary tests indicate that a thin uninsulated wire could be 40 times more efficient as a collector than previous systems (fig. 26).[8]

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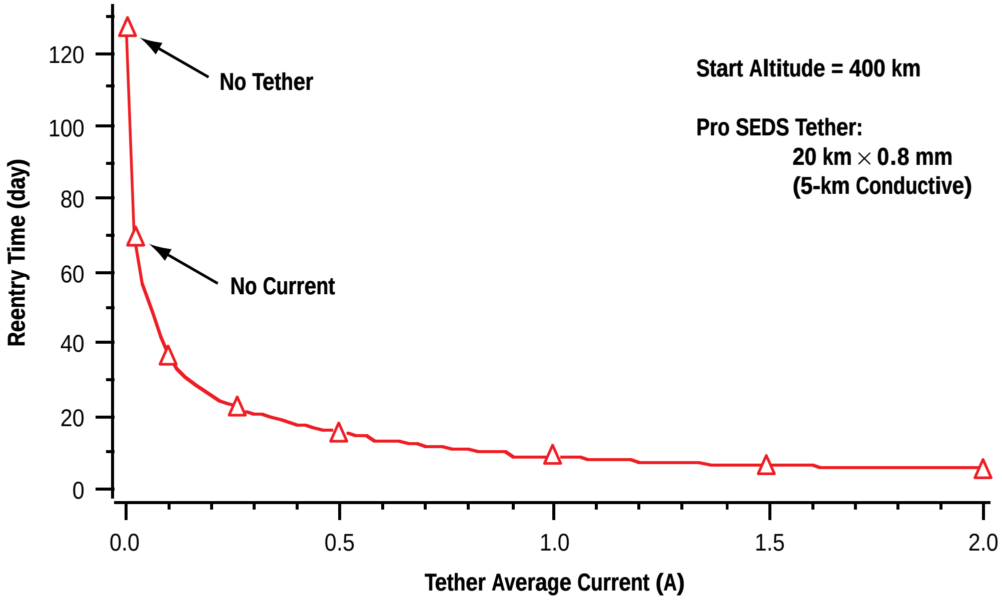

Figure 26. Predicted demonstration of ProSEDS propulsive drag thrust. The upper stage reentry time versus tether average current is shown.[8]

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APPROVAL

INTERNATIONAL SPACE STATION ELECTRODYNAMIC TETHER REBOOST STUDY

L. Johnson and M. Herrmann

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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DIRECTOR, PROGRAM DEVELOPMENT DIRECTORATE

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13. ABSTRACT *(Maximum 200 words)*

The *International Space Station (ISS)* will require periodic reboost due to atmospheric aerodynamic drag. This is nominally achieved through the use of thruster firings by the attached Progress M spacecraft. Many Progress flights to the *ISS* are required annually. Electrodynamic tethers provide an attractive alternative in that they can provide periodic reboost or continuous drag cancellation using no consumables, propellant, nor conventional propulsion elements. The system could also serve as an emergency backup reboost system used only in the event resupply and reboost are delayed for some reason.

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