Tethers for Small Satellite Applications

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Abstract

This paper begins with a sketch of the history of space tether concepts and then describes the four tether orbital flight tests flown in 1992-94 (TSS-1, SEDS-1, PMG, and SEDS-2). It reviews currently funded flight experiments and studies aimed at near-term flights. Next it provides a brief tutorial on some key aspects of space tether concepts. Finally it homes in on issues and applications relevant to small satellites, and gives specific examples of typical mission scenarios, tradeoffs, benefits, and costs.

Introduction

In 1895 Tsiolkovsky became fascinated with the Eiffel Tower. He imagined an immensely taller tower reaching into space, with a "celestial castle" at the top. He also imagined a free-floating spindle-shaped tower reaching from near the ground to beyond geosynchronous orbit. It would be supported in tension by excess centrifugal force on the part of the tower beyond geosynchronous altitude. These was the first of a series of "space elevator" or "beanstalk" concepts having a tether in a synchronous orbit reaching all the way down to the ground. Payloads would be transported up and down the tether without the use of any propellant. Artsutanov described such a concept in 1960, and Isaacs et al (1966) made a brief analysis of material strength requirements and other issues. Moravec (1977) analyzed a non-synchronous spinning tether, which avoids some of the problems of the long hanging version. Carroll (1983, 1984) noted the advantages of swinging and barely spinning systems. Georg von Tiesenhausen (1984) wrote a history of these concepts and their more modest derivatives. Other early tether proponents included Ivan Bekey, Mario Grossi, Chris Rupp, and the late Giuseppe Colombo. Their efforts led to a series of 4 orbital flight tests of tethers between 1992 and 1994, and plans for 3 more tests in 1996 and 1997. Because these tests and plans are not well known outside the tether community, they are discussed below. Then we step back and provide a brief tutorial on key aspects of tether behavior. The remainder of the paper focuses specifically on issues and applications relevant to small satellites.

Recent Tether Flight Tests

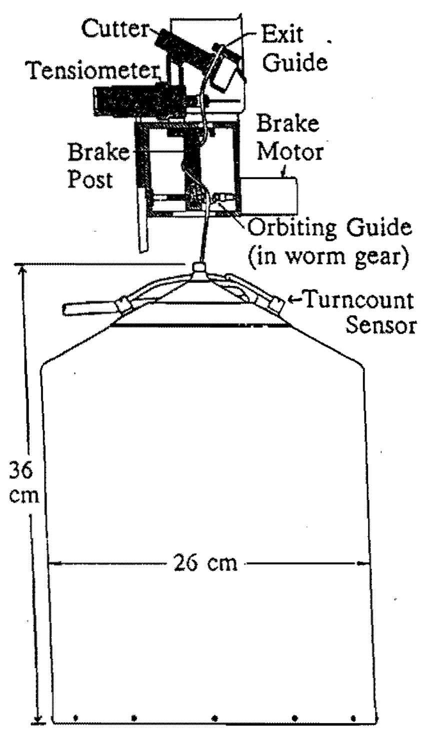
The first orbital flight experiment with a long tether was the Tethered Satellite System (TSS) mission, launched on the Space Shuttle in July 1992. Late design changes resulted in a bolt interfering with the levelwind mechanism, so only about 250 m of the 20 km tether was deployed. This problem resulted in one unexpected benefit, the discovery that a short tether deployed from an active manned vehicle was far more stable than most analysts expected. The tether and satellite were retrieved, and a reflight (TSS-1R) is planned on STS-75 in February 1996. Besides its plasma physics and other science experiments, TSS will investigate deployment and retrieval dynamics of a long tether, an important milestone in showing the ability to control tethers. The major retrieval issue is damping "skiprope" modes in the tether. These are a problem during retrieval because the amplitude grows as the tension and deployed tether mass decrease.

The first fully successful orbital flight test of a long tether system was SEDS-1, which tested the simple deploy-only Small Expendable Deployer System. SEDS was proposed by one of the authors (Carroll) through Energy Science Laboratories in 1983, and developed under NASA SBIR (Small Business Innovation Research) and follow-on funding from NASA Marshall Space Flight Center. Marshall managed the project, and also developed the flight computer and electronics for SEDS. Tether Applications split off from Energy Science Labs in 1989, and assisted Marshall with mission design, testing, and integration of SEDS-1. Also involved were:

NASA Langley (payload instrumentation)
NASA Goddard (integration & telemetry)
NASA JSC (radar data analysis)
McDonnell Douglas (Delta provider)
US Air Force (primary payload provider).

SEDS-1 was launched from Cape Canaveral Air Force Station as a Delta/GPS secondary payload on March 29, 1993. The hardware is shown in Figure 1. An hour after launch a spring loaded Marman clamp ejected a 26 kg payload downward at 1.6 m/s. This impulse was sufficient to allow deployment of enough tether for gravity gradient effects to take over and guarantee the remainder of deployment. Once into this regime, the tether paid off the end of a fixed spool inside the deployer at an increasing rate.

Passive effects caused a smooth rise in tension as the tether unwound faster and faster from a shrinking package. Finally, when 1 km of tether remained, active braking was applied by wrapping the tether around the "barber pole" brake. This increases the tension by 10% for each 30° of wrap. The brake law was frozen 8 months before flight, before deployment testing was completed. This, combined with an open-loop law and a slightly faster than expected deployment, resulted in the active braking slowing the deployment only from 13 to 7 m/s at the end of the tether. This resulted in the payload and tether undergoing a series of bounces. Peak payload accelerations were 0.15 gee during the first bounce, and less during later bounces. The tether swung to the vertical and was cut 1 orbit after the start of deployment. This slung the payload and tether from Guam onto a reentry trajectory off the coast of Mexico. Pre-flight simulations had indicated that the bouncing would have little effect on the reentry location, and the reentry was accurate enough that a pre-positioned observer was able to videotape the payload re-entry and burnup. The last data collected from the payload before reentry showed a predicted tension rise as drag began to blow the tether back and turn it into a kite tail.



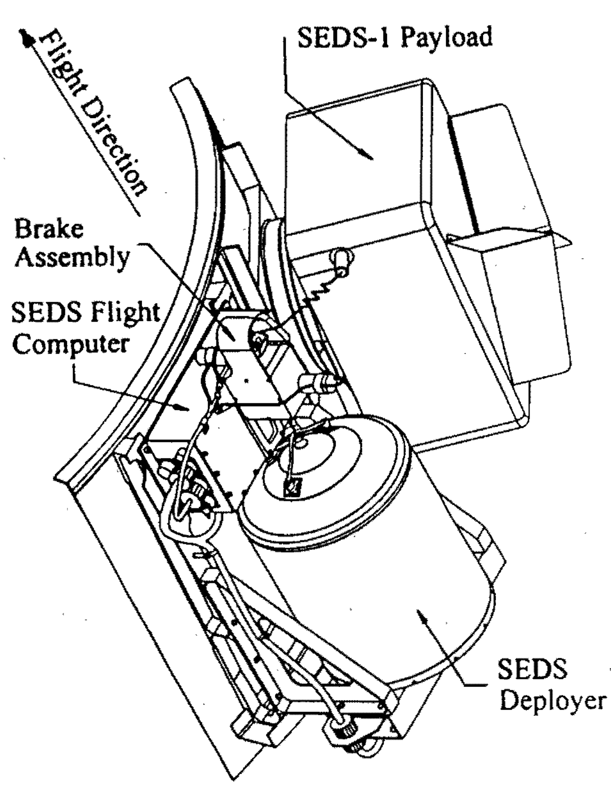


Figure 1. SEDS Hardware & Flight Configuration

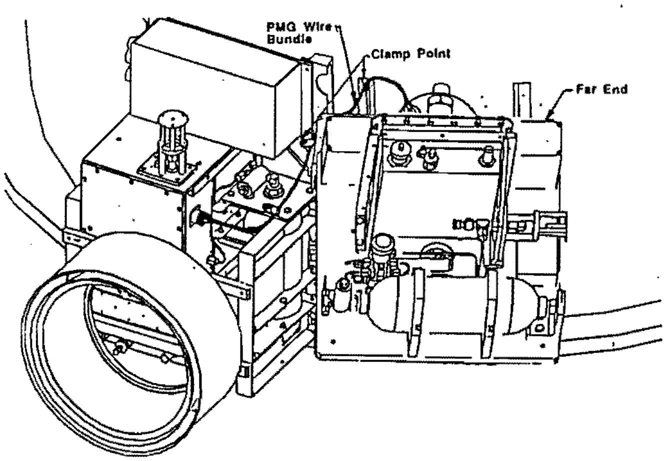


Figure 2. PMG Hardware Layout

Three months after SEDS-1, on June 26, 1993, the Plasma Motor Generator (PMG) was launched. This was also a short-duration Delta/GPS secondary payload experiment. Development of the PMG was led by Dr. James McCoy of NASA JSC. The hardware is shown in Figure 2.

The tether for the PMG was a 500 m length of insulated 18 gauge copper wire. Tether Applications developed the deployer. It was "SEDS-like" in deploying off the end of a fixed spool, but the much heavier, stiffer wire and limitations on available space required a short, fat deployer and elimination of the active brake. Passive braking was provided by winding the innermost layer of wire onto a weak adhesive coating on the deployer core. The PMG used the Marshall-developed SEDS computer to store and format data for telemetry.

As noted in McCoy et al (1995), the PMG demonstrated the ability of hollow cathode plasma contactors to provide bi-directional coupling to the ambient plasma. It demonstrated external current closure of currents ranging up to 1/3 ampere, with external voltage drops of order 25V. (This was at maximum plasma density conditions: daytime, low altitude. Maximum currents at night and at ~700 km altitude were far lower.) The limiting factor on current level appeared to be electron collection. There was a failure in hardware associated with the lowest internal impedance operating mode, but the current variation with external conditions showed that the current was externally limited, so the system performance limits were established. The system demonstrated successful operation in both motor (boost) and generator (deboost) mode, as well as showing the that the hollow cathode could conduct useful amounts of current (up to 1/3 amp) with low collection voltage drops. The PMG experiment led to baselining of a similar hollow cathode for grounding the space station.

The next tether experiment was SEDS-2. It was launched on the last GPS Block 2 satellite launch on March 9, 1994. SEDS-2 used feedback braking starting early in deployment. This limited the residual swing after deployment to 4°. Mission success was defined as deployment of at least 18 km, plus a residual swing angle <15°. The payload returned data for 8 hours until its battery died; during this time tether torques spun it up to 4 rpm. The 19.7 km tether was left attached to the Delta to determine long-term tether stability and micrometeoroid risks. The tether suffered a cut 3.7 days after deployment. The payload end reentered within hours, but the 7.2 km length at the Delta end survived with no apparent further cuts until re-entry on May 7, 1994. Surprisingly, the tether was an easy naked eye object when front lit by the sun and viewed against a dark sky. Intensified videos were made of 20+ passes over a 7 week period; all showed the tether stabilized near the vertical, even after the cut when tension was <4 grams. Figure 3 is from a video before the cut.

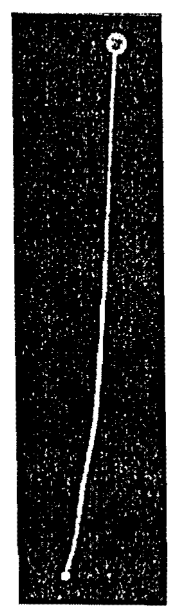


Figure 3. SEDS-2 Tether in Orbit, March 1994

The Proceedings of the 4th Tethers in Space Conference in April 1995 include papers on all these experiments plus several sub-orbital experiments involving tethers up to 1 km long. Smith (1995) gives a good overview of the SEDS-1 and SEDS-2 missions. More details on SEDS are given by Carroll (1995), and Rupp (1995). Carroll and Oldson (1995) discuss characteristics and capabilities of SEDS with small & large payloads.

Future Tether Missions

The TSS-1R (reflight mission) is scheduled for February 1996. The goals are the same as TSS-1: to collect plasma physics and other science data, and to verify the controllable deployment and retrieval of a payload using a reel-type deployer.

In addition to this, there are 2 other funded tether flight experiments. One is the Naval Research Lab's Tether Physics and Survivability experiment (TiPS). This unclassified tether experiment will separate from a classified host spacecraft sometime in 1996. Several hours after separation the two tether endmasses ("Ralph" and "Norton") will separate from each other at 4.9 m/s. A high ejection velocity is needed to give the 12 & 38 kg endmasses enough momentum to deploy a 2 mm SEDS tether 4 km long. One goal of TiPS is to determine risks to a tether much thicker than that used in SEDS-1 & 2. To maximize the deployed tether diameter the tether uses a hollow braid around a resilient acrylic yarn core. The tether has an estimated mean time to failure of 3 years. The projected orbit life is ~10 years, so cuts are quite likely. Another goal of TiPS is to determine the long-term damping and stability of an entirely passive system. Under ground test conditions, the hybrid tether has very high damping, but it is uncertain whether the dynamics resulting from a "brakeless" deployment will settle out quickly enough to allow operational use of simple entirely passive systems. TiPS should be about as bright as SEDS-2, but it will be less dramatic because the subtended angle is only 0.1°, vs 1.5° for SEDS-2. The altitude and inclination of TiPS are high enough to allow observers throughout the US to see it against a clear night sky if the tether is front or sidelit by the sun. Current plans are to time deployment so it can be imaged from the ground.

The other funded orbital tether test is SEDS-3. This will boost the SEDSAT microsat from the Shuttle into a higher, longer-lived orbit (Harrison, 1995). The microsat is a 35 kg satellite being built by students at the University of Alabama, Huntsville. It is manifested for STS-85, which is now scheduled for July 1997. Primary objectives of SEDSAT are to provide an amateur radio communications link, perform near-infrared studies of the atmosphere, and enable active student participation in space research. The Shuttle orbit is a 57° inclination, 160 nmi orbit. SEDSAT's projected orbit life is only 2.5 months from this orbit. The 20 km SEDS-3 tether will boost SEDSAT into a 283x178 nmi final orbit. This increases the projected orbit lifetime to 42 months, a factor of 17 increase in useful life.

A suborbital tether experiment, OEDIPUS-C, is scheduled for launch in October 1995, using a four stage Black Brant XII sounding rocket from Poker Flat, Alaska (James and Rumbold, 1995). The mission is a Canadian experiment to investigate natural and artificial waves in the ionospheric plasma. The 1 km long conducting tether will be launched to an altitude of 800 km during a strong aurora. A similar mission, OEDIPUS-A, was successful in 1989.

Studies Aimed at Future Flights

Additional projects are in planning or early development in the US and Europe. ESA is funding a study of tethered deorbit of the Raduga sample return capsule from a Progress vehicle, using a SEDS-like deployer. Lockheed Martin is developing a possible long-duration tether flight experiment. NASA Marshall, Boeing, and Tether Applications are studying tether uses on the Space Station. In addition, the authors are awaiting a decision on a Tether Applications SBIR Phase II proposal for a multi-purpose tether deboosted re-entry capsule. One version of the capsule is a reentry test vehicle intended for safely testing new thermal protection materials, determining aero accommodation coefficients in transition flow, and collecting data on other low-altitude and reentry phenomena. The other version is a sample return capsule intended to be safer to handle on the space station than a rocket-deboosted capsule.

Tutorial on Orbiting Tethers

A comprehensive tether tutorial would fill a book, so we can only present some key concepts here. For more detail, the reader is referred to NASA's Tethers in Space Handbook (Penzo and Ammann, 1989), and the proceedings of the 4 International Conferences on Tethers in Space. The most recent, in April 1995, is also the best printed source on current tether activities.

The simplest type of tether system to understand is a long vertical dumbbell in circular orbit. If the lower endmass is 1% of the orbit radius below the system center of mass, then gravity will be 2% higher than at the CM, and centrifugal force 1% less. There is an opposite imbalance at the top mass, which (for a symmetrical dumbbell) results in a tether tension equal to 3% of the normal weight of each end mass. For other lengths, the tension scales with length, and (whether or not the masses are equal) the felt acceleration at each end is proportional to the distance to the zero-gee location on the dumbbell, which is slightly below the center of mass. In LEO the acceleration is about 0.4 milligee/km. In higher orbits it varies with $1/r^3$. This $1/r^3$ dependence makes the gradient in low orbit around different bodies scale with the body's density, independent of size.

A vertical dumbbell has interesting uses including fluid management and (if the tether length is adjustable) dial-a-gee low-gravity research. It is also a starting point for understanding propulsion uses of tethers. If the tether is cut, the endmasses are no longer constrained. They fall away from each other into eccentric orbits that vary from 1 tether length apart (at the location of release) to 7 tether lengths apart, 1/2 orbit after release.

A hanging system is stable because it has less energy than swinging, spinning, or "undeployed" dumbbells. In essence, the two masses in a hanging system "straddle" the local convexity of the gravity field. Introducing a swing takes energy, and a spin takes more energy. On the other hand, a widely swinging system has nearly the same energy as the undeployed system, so deployment of tethered masses into a widely swinging state requires less energy absorption (lower deployment tension integrated over length)

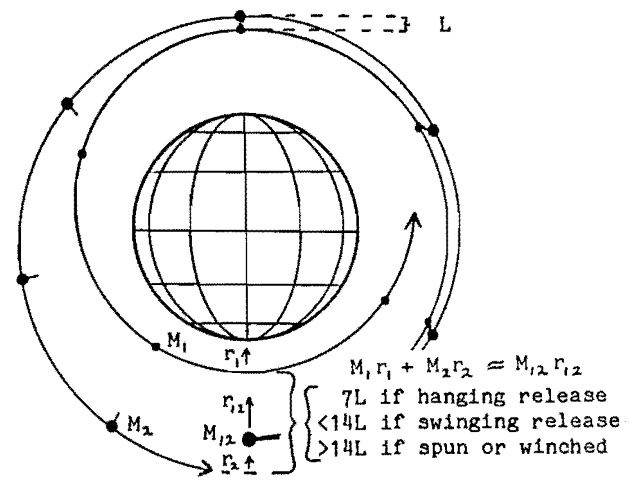


Figure 4. Tether Deployment & Release

than deployment into a hanging condition. (To complete the comparison, deployment into a spin requires deployment into a swing, followed by thrusting or "pumping" the swing into a spin.)

As shown in Figure 4, swinging or spinning systems can also provide much larger orbit changes from a given tether length, when the rotation is forward on top. For swinging systems, release at the vertical provides a maximum altitude change of (7 + 6.93 Sin(Amplitude)) L. As shown in Figure 5, the required tether mass changes only slowly with the swing angle, however, because the wider swings induce a higher tension. Hence the main advantages of swinging systems are the shorter tether and radically reduced braking requirements.

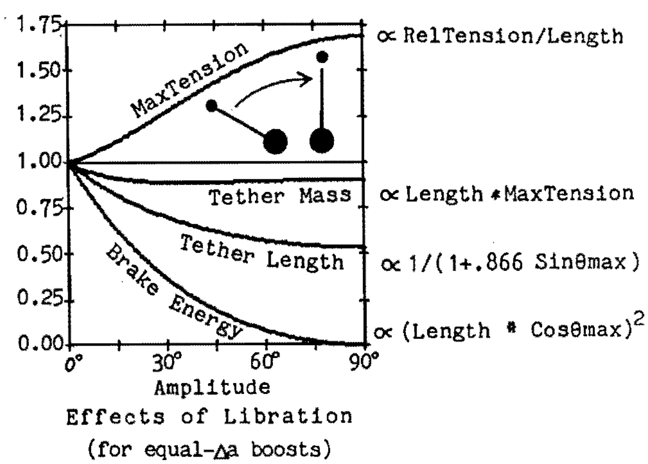


Figure 5. Effects of Swing Amplitude

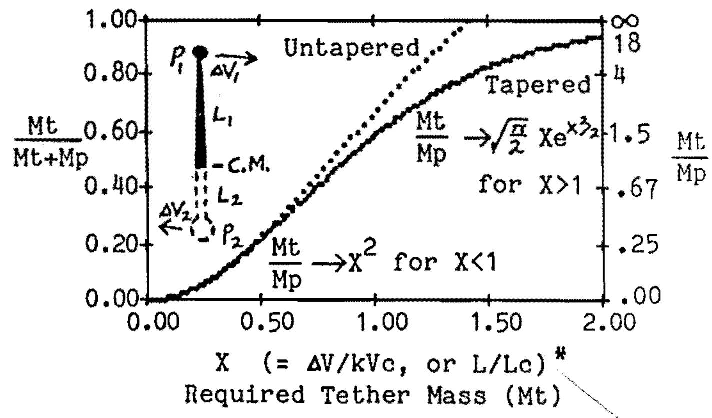
Tether Strength and Mass

Since tension scales with length, the required tether mass varies with the square of the length. As length increases, eventually tether mass and self-weight effects become dominant. Then the tether mass grows exponentially. A constant-stress "heavy" tether has a Gaussian bell-curve variation in cross-sectional area. If the length exceeds 1/3 of the orbit radius, 1/r non-linearities become dominant and the ideal taper becomes strongly skewed, with much faster diameter changes near the bottom than near the top. Pursued to its ultimate length, the tether can be elongated into a highly tapered geostationary beanstalk.

We cannot yet build a beanstalk on Earth with current materials and practical diameter tapers. But some rather ambitious operations are within the realm of possibility, including catching payloads at 60% of orbital velocity and slinging them to escape (Oldson & Carroll, 1995). With current materials, this requires a tether weighing ~50 times the design payload, and a facility with ~10X the tether mass. But here we are mainly concerned with far smaller velocity changes.

The handiest figure of merit for computing tether mass is Sqrt(design stress/density). The units of this parameter are a velocity, so it is referred to as the characteristic velocity (V_c) of a material. V_c has physical meaning: it is the rotation speed at which centrifugal force induces the design stress in a hoop of the material. It is also the tip speed at which centrifugal loads at the center of a rotating bar equal half the design stress. The best material available in commercial quantities is Spectra 1000. Near 200K (a typical on-orbit temperature for the white tether) and including a safety factor of 2 it can be used at a working stress of 300 ksi or 2 GPa. A design stress of 2E9 kg-m/s^2 per m^2 and a density of 970 kg/m^3, gives V_c=1.44 km/s.

Figure 6 shows the variation of tether mass with deltaV. Near-term tether operations with small satellites will generally involve velocity changes (from the center of mass) far less than this, and in such cases the ratio of tether to payload mass is Sqr(V/kV_c). Since rocket propellant mass varies linearly in this regime, tethers will always be better for small maneuvers (typically, < 300 m/s).



* k = 1.00 for spinning operations; 1.15 for hanging operations; 1.21±.01 for swinging operations; 1.41 for winching operations

ΔV = Sum of perigee + apogee boosts

Figure 6. Ratio of Tether to Payload Mass

Combinations of tethers and rockets will be best for maneuvers >300 m/s. This presumes that momentum is available at no cost from the other endmass. In many cases that is an optimistic assumption. In other cases (such as deboosting the shuttle or other objects from the space station) it is pessimistic, because reboosting the station saves propellant. Another essential difference between tethers and rockets is that tethers can often be reused, while rocket propellant is always expended. The maximum justifiable tether maneuver typically scales with the number of uses until it approaches V_c, after which it grows logarithmically as self-weight effects become dominant.

Micrometeoroid and Debris Risk

As shown by SEDS-2, the risk of tethers being cut by micrometeoroids or orbiting man-made debris is often a key design issue for tether systems in LEO. The micrometeoroid and debris risks vary differently with tether diameter, and the debris risk varies far more with altitude than the micrometeoroid risk does. Debris is the dominant risk for large tethers (>3 mm) at LEO altitudes above 400-500 km, but for thinner tethers or lower altitudes, the risk is mostly from micrometeoroids. There are wide ranges in estimates of tether risk. Most are based on extrapolation from tests using light-gas guns, which shoot dense, strong impactors at speeds up to ~7 km/s (vs typical speeds of 20 km/s and low-density weak micrometeoroids). The impactors tend to penetrate tethers rather than "splashing" when they hit, and are of uncertain relevance for evaluating tether risks.

Another approach is based on SEDS-2 experience. The 19.7 km long SEDS-2 tether was cut 3.7 days after deployment, and the remaining 7.2 km length appeared to remain intact for the remaining 54 observable days of its orbit life. This means there was 1 cut in 460 observable km-days of exposure of a 0.78 mm diameter braided Spectra tether. As described in detail in Carroll and Oldson, 1995, we have extrapolated this to other sizes by scaling with crater size distribution data derived from LDEF and other sources. The results fit the following simple expression:

$$\text{Estimated MTBF} = (D_t + 0.3)^3,$$

where the Mean Time Before Failure is in km-years and the tether diameter D_t is in mm.

This is the only available unbiased flight-based estimate of tether MTBF at present. The actual MTBF could be much higher or lower if SEDS-2 was lucky or unlucky. The above formula predicts that a 20 km tether 0.1 mm in diameter should last a day, a 1 mm tether 40 days, and a 10 mm tether 55 years. Since the debris risk is dominant for the 10 mm tether, its actual life should be much shorter than the micrometeoroid-dominated risk estimate indicates unless the tether is actively maneuvered to avoid the ~7000 tracked objects, which cause most of the risk to a 10 mm tether.

Deployment Dynamics

Payload boost/deboost maneuvers typically deploy at low tension, swing towards the vertical, and cut the tether near the vertical. Tethered platforms generally need to be stabilized near the local vertical. This requires energy dissipation during or after deployment equal to the tether length times half the equilibrium tension at full length. If energy dissipation is less than this, the remaining energy ends up in an in-plane tether swing, which has a period of ~1 hour in low earth orbit, independent of tether length. If the energy dissipation during deployment is very low, then deployment is slow and nearly horizontal, and the final swing is very energetic. The fastest deployments are at 45° from the vertical, but micrometeoroid risks are lowest near 58°, which combines fast deployment with a moderately shorter, fatter tether.

Deployment can be initiated and maintained by thrusters, but if the deployment tension is reliably low enough early in deployment, spring ejection and passive payloads can be used. The ejection requires sufficient energy to deploy enough tether (typically ~1 km) for gravity gradient forces to overcome tension and continue the deployment.

As deployment progresses, orbital dynamics cause the lower object to drift in front of the upper one. The horizontal component of tether tension then transfers orbital momentum and energy from the lower mass to the upper one. This retards the lower one, which drops it into a lower trajectory and (for near-horizontal deployments) actually increases the deployment rate after ~12 minutes. As deployment rates increase, a smooth increase in tension is useful to limit the amplitude of a Coriolis-induced curve in the tether. In addition, it is useful to modulate tension during deployment to damp tether and endmass modes of oscillation. In most cases it is useful to have a smooth but rapid tension rise near the end, to reduce tether transverse oscillations and deployment rates.

Vertical stabilization requires high energy dissipation, but the braking can be distributed throughout much of deployment. Deceleration at the end of near-horizontal deployments should be done mostly in the last 12 minutes, because earlier braking increases braking requirements at the end. Restricting braking to shorter periods increases peak braking power and provides less time for radiation or diffusion of heat dissipated in the brake. On SEDS-1 we restricted braking to the last 1.5 minutes to demonstrate capabilities adequate for much heavier payloads.

Boost/deboost applications often need to control the swing amplitude and timing, especially for controlled reentry applications. This requires active feedback braking. Such braking can also ensure a smooth stop at the end of deployment.

To summarize this discussion of tether deployment dynamics, the desired tension characteristics are:

Very low tension early in deployment
Smooth tension rise as deployment progresses
Damping of tether & endmass oscillations
Large but smooth tension rise toward the end
Feedback control of deployment & braking

The design of SEDS provides the first four of these features passively, and the brake plus a suitable control law can provide the last feature when that is needed.

Electrodynamic Tethers

The magnetic field of the earth is ~0.3 gauss at the equator at a few hundred km altitude. The induced voltage from this force acting on a vertical conducting tether moving across field lines at 7 km/s (a typical eastward velocity in low-inclination orbit, relative to the rotating earth) is ~200 V/km. A typical 20 km tether will therefore generate 4000 volts. Away from the equator, the field grows stronger, but the component perpendicular to a vertical tether grows weaker.

Establishing a current in the conducting tether flow requires having a return path through the surrounding plasma. The currently preferred method for doing this is to use hollow cathode electrodes at both ends, as done on the PMG experiment. To increase electron collection capability, a combination of higher gas flowrates, larger conducting surface areas near the contactor, and higher collection voltages should significantly increase the collectable current.

If the natural EMF is used, the system acts as a generator, converting the orbital energy into electrical energy and thus de-boosting the system. If a reverse EMF is applied, then the system becomes a motor boosting itself to a higher orbit. The force is perpendicular to both the field lines and the tether, so it is usually nearly due east or west. This means that wires in inclined orbits see a side force as well as a boosting force. It also means that the EMF varies with eastward velocity, and hence with the cosine of the orbit inclination.

The net power needed excluding ohmic & plasma contact losses) is just that of an electric motor acting against the rotating earth, 7 kw/newton. This is far less than required for other high-Isp electric propulsion such as ion engines, and the mass expenditure is simply the plasma contact gas plus amortization of the tether over its MTBF.

In theory, electrodynamic tethers could be used as a very efficient storage battery or emergency reboost capability for the Space Station or other platforms. Use for day-night storage seems attractive, but it tends to pump a twice-per-orbit out-of-plane swing of the tether. Longer-term storage or pure boosting eliminate these problems, and are now under study for use during space station assembly and during possible vehicle standdowns. A sketch of reboosting an earlier version of the space station is shown in Figure 7.

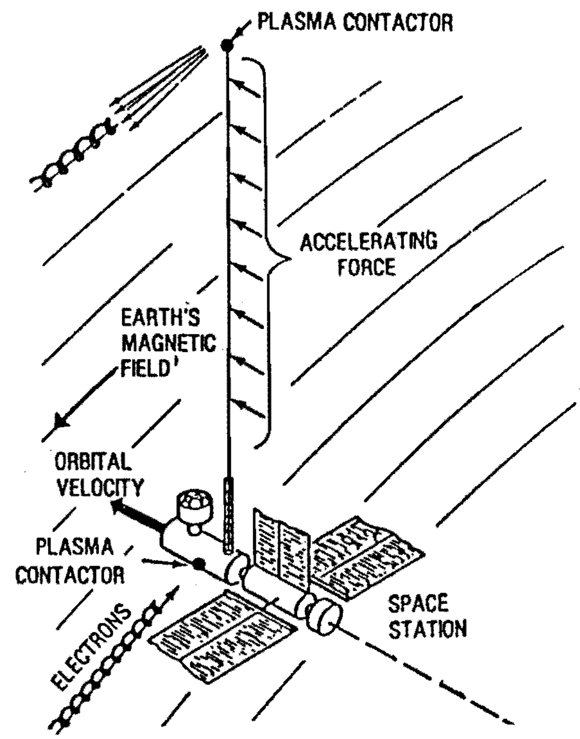


Figure 7. Electrodynamic Orbit Boosting

For small satellites, the potential utility of electrodynamic tethers is limited by the short expected lifetime of a small electrodynamic tether, due to micrometeoroid-induced cuts. However, readers may see some niches where the concept is worthwhile even at small tether sizes.

Generic Space Tether Applications

Space tethers have a wide range of applications, propulsive and non-propulsive. For propulsion, their value is their ability to exchange momentum between two masses in orbit. Both impulses are often useful, as in deorbiting vehicles leaving a space station, or boosting payloads from a launch vehicle, especially a reusable launch vehicle that must be promptly deorbited. In other cases, the impulse on the other mass has neutral value (such as deboosting a spent stage from an already short-lived orbit). And finally, in some cases the impulse on the other mass is undesirable, and another propulsion method is needed to cancel it out. But even in such cases, safety, convenience, or the availability of high-Isp propulsion at the other end may be enough to justify tether boost operations (essentially "remote rocket boosting").

The most elegant use of tethers for small satellites may be to boost and circularize their orbit after launch into an eccentric orbit. This also deboosts or even deorbits the launch vehicle, because of the reduction in its already low perigee altitude. It also looks very attractive for secondary payloads like SEDSAT, because it allows much longer orbit lifetimes than the primary mission altitude can provide, without the risks and complexity of on-board propulsion.

Non-propulsive uses of tethers involve passive spacing of two or more bodies in different orbits without the use of propellants. Several reasons for doing this have been suggested. One is to continually sample data from multiple locations. Using magnetometers or gravimeters for gradient measurements are examples. Second, for some types of remote sensing and for interferometric techniques, widely spaced antennas are desirable or required. Third, there are some facilities which should be distant but still attached: this includes sensitive optical and magnetic devices. Finally, tethers can provide a small steady accelerations, either for research or less exotic tasks such as fluid settling. The fundamental design of these systems is driven mainly by the need to exceed a minimum lifetime due to tether failure from micrometeoroids. Innovative separated-strand designs that can tolerate multiple cuts are being looked at by Hoyt and Forward (1995).

Issues Relevant to Small Satellites

The issues discussed below are relevant to all payload sizes, but different factors are often dominant for small & large payloads, and the focus here will be on small payloads.

Micrometeoroid Risks: Boost or deboost operations involving satellites weighing ~100 kg can use tethers as thin as 0.25 mm. A tether deployment, swing, and release may be completed in one orbit, and the equivalent full-length exposure time may be <1/2 orbit, but even in that brief time the risk of the tether being cut by a micrometeoroid can be significant: 1.4% for a 30 km tether 0.25 mm in diameter. Since such a tether weighs only 1 kg, the tether needs to be sized more to reduce risks than to handle loads.

One way do this is to estimate the cost of a tether failure as some multiple of the payload mass (say 10), and then balance marginal risk and marginal tether mass. This typically doubles the tether diameter for payloads under ~200 kg. (Due to the shape of the risk curve, marginal-risk sizing typically has far less effect with much larger (multi-ton) payloads.)

Safety: Tether cut probabilities of order 0.1-1% introduce safety issues, especially when the host vehicle is manned. On the other hand the issues posed by alternatives such as hydrazine thrusters or solid rockets are often far more serious.

Trades vs Rockets: Marginal risk sizing reduces the justifiable tether deltaV inversely with the tether mass increase, to ~75 m/s. On the other hand, these tethers are light enough that other factors like safety may become dominant.

Secondary Payloads: Secondary payloads often have to accept an orbit that is lower than desired, especially on the shuttle. Tethers can provide cheap boosting into longer-lived orbits. By comparison, boosting the usually much heavier host vehicle can be very expensive, and it is often simply infeasible if payload margins are modest. Another alternative is adding on-board propulsion. This can be very expensive. And if the thruster system can affect primary mission success or safety, it can strongly drive integration costs.

Using and Adapting SEDS

There is no intrinsic need for small satellites to use SEDS hardware for tether operations. But since SEDS is small, adaptable, flight proven, and affordable (as discussed at the end), it is worth discussing in some detail. For a more thorough description, see Carroll & Oldson (1995).

Tether Design Options

The SEDS deployer is a basically a fixed spool of string inside a can. The winding is done on the ground, and various tether diameters, lengths, and materials can be used. There is no need for the whole tether to be one material, diameter, or construction, because the winding equipment can adapt to arbitrary changes in tether properties. Modest test efforts usually can give splices with nearly the full strength of the weaker segment.

SEDS-1 & 2 used 20 km long Spectra 1000 tethers braided from 8 strands of fibers each totalling 375 denier (1 denier=1 gram/9000 meters). Spectra can handle aeroheating down to 130 km altitude, and should burn off between 110 and 120 km when it is a kite-tail on a rapidly descending probe. Oriented expanded PTFE has better resistance to atomic oxygen and heating and should be usable down to ~120 km for several days. Nextel ceramic fibers should tolerate conditions down to ~100 km, but tests are needed to verify that the brittle fibers can handle winding, launch, and deployment. Kevlar has better heat resistance and strength than PTFE, but is far more sensitive to atomic oxygen and generates far more particulates and volatiles during deployment.

The tethers can have either braided or twisted construction. We used hollow 8x375 braids on SEDS-1 & 2 because they are easy to splice and allow other materials to be embedded in the tether. On SEDS-1 we put a radar dipole array in the tether to cause coherent back-scatter at several angles, and segments of solder that caused square-wave changes in deployment tension.

For the TiPS tether, we used a resilient yarn core inside a 12x650 Spectra braid to increase the diameter and hence the micrometeoroid resistance of the deployed tether.

During deployment, the tether acquires a twist as it pays off the end of the fixed core. We put an equal and opposite pre-twist in the tether during winding onto the core so the tether comes off nearly torque-balanced. If desired, non-torque-balanced tethers can be used to impart a modest spin to the payload. The torque is mostly due to tension in the angled fibers rather than to an intrinsic torsional stiffness of the tether.

The tether winding is held in place by weak tie-downs. Once they are broken by payload ejection, the tether unwinds from the outside of the winding and pays out the end of the canister. Each turn interrupts two optical turn-count beams, giving redundant sensing of length and rate. After exiting the deployer the tether passes through a separate brake assembly which also includes a tensiometer, cutter, and exit guide.

The SEDS Brake

The SEDS brake increases deployment tension above the value at the top of the deployer. The "barberpole" design used allows tension to be increased over a wide dynamic range, with a nearly fixed sensitivity over that range. In addition, it amplifies the passive damping provided by inertial effects. With Spectra tethers, every wrap roughly triples the outboard tension compared to the passively determined inboard value. The brake is driven by a stepper motor at the low-tension end of the brake. This allows the exit tension to increase to the tether's breaking strength without overloading the motor. Typically the limiting factor on the brake is a friction-induced temperature rise of the spring-mounted tensiometer guide. This becomes a problem when deployment stops and the hot guide heats up and weakens the whole tether cross-section. Within this constraint the brake can dissipate >60 kJ during a typical final braking phase, far more than needed for most applications.

Adapting SEDS for Specific Missions

The SEDS deployer, brake assembly, control computer, and payload can be mounted separately or together on the host vehicle. The computer weighs 3 kg, the brake 1 kg, and the deployer 3 kg when empty. It can hold up to 7.5 kg of Spectra

1000 tether, or an equal volume of other tether material. SEDS can easily be scaled up or down by changing only the deployer dimensions: in most cases the only change required of the brake assembly is to select a different tensiometer range. We have recently designed, fabricated, and done initial tests on a 18x30 cm mini-deployer that is sized to fit inside an experimental reentry capsule. It uses the same brake & computer as the existing deployer. (Applications suited to both deployer sizes are discussed later.) In scaling the deployer, the aspect ratio can also be adjusted somewhat to fit in a constrained space. And if necessary, the tether can be routed to exit through the base of the deployer rather than at the top, but this increases deployment tension.

SEDS can tolerate a variety of payload mounting and ejection geometries as long as the tether cannot foul on appendages on the host vehicle or payload. The geometries used on SEDS-1 & 2 and SEDSAT all induce large payload attitude oscillation amplitudes, even if ejection induces no attitude rates. To damp these oscillations on SEDS-1 & 2 we put heatshrink tubing around the tether near the payload attachment, to form a flexible but lossy whip. The ejection geometry and whip stiffness had an effect that was not predicted before flight but is now understood: much of the payload oscillation energy went into transverse tether oscillations. This plus low-speed slip-stick effects in the deployer caused uneven deployment rates until deployment tension became inertia-dominated.

A lossy whip at the deployer exit could damp attitude oscillations at the deployer end and allow SEDS deployment from objects without active attitude control. What is needed is a flexible, lossy tube for the tether to exit through. Preliminary tests on corrugated Teflon tubing indicate that it may be suitable. The corrugations increase flexibility and help prevent buckling, which could pinch the tether.

SEDS can be used without its brake if accurate deployment control and braking are unnecessary, as on TiPS. But in most cases active braking is useful because it allows adjustment of the deployment schedule and swing amplitude and enables a smooth stop at the end of deployment.

Applications requiring high heat dissipation generally also tolerate higher tension at the start of deployment. This allows a tortuous tether path throughout deployment. These applications can put a fixed passive capstan brake with good heatsinking downstream of the existing active brake. Putting 1-3 wraps around this fixed brake can increase SEDS heat dissipation capability by a factor of ~3-27, without changing the existing active brake/tensiometer/cutter assembly.

Boost-Deboost Applications

This section presents specific boost/deboost applications of expendable tether systems with small satellites. These operations usually take only 2-4 hours to complete. With payloads <100 kg, tethers usually weigh more than an optimized rocket, but the tether is simpler, safer, and cheaper. A tether system is often lighter than the propulsion systems actually available, which may be severely constrained. For example, hydrazine or solid rockets can drive the integration costs of secondary payloads on the shuttle or ELVs, and pose safety problems in handling reentry capsules designed to return samples from the space station.

Table 1 lists 6 different boost/deboost mission concepts, including SEDSAT options with 20 & 40 km tethers. Two different deployers are used: the existing SEDS deployer, and a recently developed mini-SEDS deployer. SEDS-1 is shown for comparison. The SEDS-1 and Capsule cases are controlled deorbits. The other cases are payload boosts for longer orbit life. The "Any" case is a primary or secondary payloads that need higher orbits than the STS or a Single-Stage-To-Orbit (SSTO) can reach. A 20 km tether can increase orbit life by a factor of 10-20. The benefits are even higher if the host vehicle orbit is slightly eccentric (apogee-perigee= ~100 km). Note that with reusable launch vehicles such orbits can increase payload orbit life ~20% even without tethers, because lower mission perigees also reduce deorbit requirements.

The key parameter to be optimized for different boost/deboost missions is the swing amplitude after deployment. Angles near 60° minimize micrometeoroid risks and hence are optimum with the thin tethers suitable for small satellites. As payloads and tether diameter increase, larger swing angles are useful, because they reduce brake energy requirements. The "Min" tension (in newtons) is what is required early in deployment to give the final swing amplitude listed; "Max" is the highest tension occurring during the swing.

The brake power and energy for the different missions (MaxPwr & Total kJ) vary far more with tether mass than with payload mass. In fact if the payload/host mass ratios, safety factors, swing angles, and mission altitudes were all the same, there would be a strict scaling with tether mass. The reason is that using an equal-mass tether half as long and twice as strong allows twice the original forces (and 4X the payload mass). With twice the forces and half the original lengths and rates, the brake power and energy are unchanged.

Our marginal-risk tether-sizing logic is illustrated best with the high-risk Capsule cases. Consider a space station sample return capsule. The capsule plus payload, tether, and core weigh 64 kg, and the other deployer hardware is reusable. An accurate reentry and recovery must have a value much higher than the launch cost for 64 kg, or the system does not make sense. Direct and indirect crew time spent on the payload & capsule greatly increase the cost and hence the required capsule value. In addition, there are hassle factors resulting from a tether cut, including repeating experiments and possibly having to use a small free-flyer to cut the tether with a hot wire, if the tether fouls on the station. We assume a payload mass multiplier of 10 here. That means that a random failure is a reasonable price to pay if using smaller tethers allows launch of 10 extra capsules and their payloads. Comparing the risks and masses for different tether diameters shows the best to be 0.43 mm, which is close to a 4x215 braid. Thinner tethers could be justified for capsule experiments on an ELV, but using the same tether as the station capsule provides a better flight test, especially if the tether is left attached to the ELV to get more data on cut rates. (This tether should be cut several times before reentry.)

We thought a cut while returning samples from a long-duration shuttle mission might be less acceptable than loss of a station capsule, so we used the same deployer with a thicker tether just long enough to deorbit the capsule from 300 km.

Table 1. Typical Data for Boost/Deboost Missions

Existing SEDS Deployer			SEDS Tether[1]			Swing	Tension[2]		Brake reqts		Impact
			Len	Dia	Mass	Ampl	Min	Max	MaxPwr	Total	Risk[3]
Payload, kg		Host	km	mm	kg	deg	new	new	watts	kJ	%
SEDS-1	26	Delta	20	0.78	6.7	53	0.03	43[4]	43	6	0.12
Sedsat	36	STS	20	0.78	6.7	63	0.03	9	13	6	0.13
"Sedsat40"	36	STS	40	0.59	7.5	61	0.03	19	52	27	0.50
Any	1,000[5]	STS,SSTO	20	0.82	7.5	75	0.3	233	85	40	0.16
Mini-SEDS Deployer			SEDS Tether[1]			Swing	Tension[2]		Brake reqts		Impact
			Len	Dia	Mass	Ampl	Min	Max	MaxPwr	Total	Risk[3]
Payload, kg		Host	km	mm	kg	deg	new	new	watts	kJ	%
Capsule	60	Sp. St.	32	0.42	3.2	62	0.08	21	45	25	0.65
"	60	STS	24	0.49	3.2	62	0.08	17	33	16	0.36

1. Tethers are Spectra. Safety factors are >10 for SEDS-1, Sedsat, & Capsule; >3 for others.
2. "Min" tension is the required average early in deployment; "Max" occurs during the swing.
3. During deployment + swing, based on an unbiased MTBF estimate of $(D_t+0.3)^3$ km-years.
4. Open-loop braking ended in a 43 newton "hard stop"; with closed-loop, Max= ~5 newtons.
5. For fixed tether mass & safety factor, and other payload masses M, tether length varies with $M^{-0.5}$, tension with $M^{0.5}$, brake power & energy are fixed, and risks vary roughly with $M^{-1.1}$.

Tethered Platform Applications

We first proposed near-horizontal deployments partly so SEDS could use a simple low-capacity "squeegee" brake. We added the capstan brake mainly to improve control, but it also enabled near-vertical deployments and hence tethered platform applications. These applications usually have low peak loads, but they have durations from days to years. Micrometeoroid risks usually drive use of the shortest, thickest tether feasible. To increase deployed tether diameter, hollow braids with resilient cores can be used. Other key issues include degradation by radiation & atomic oxygen, and limits imposed by drag and aeroheating.

Retrieval for maintenance or other reasons is likely to be a requirement for most space-station-based platform concepts. But there are interesting platform applications shown below in Table 2 which seem compatible with SEDS-type deployers.

"Ladders" (Low-Altitude Daisychain-Deployed Expendable Research Satellites) is a new concept that daisychains up to eight ~60-kg expendable research satellites together below the shuttle. The satellites are spaced every 1/2 density scale height from 210 km down to 130 km altitude, with closer spacing near the bottom because of the smaller density scale heights there. The satellites can all mount side by side on a Hitchhiker cross-bay truss. The bottom satellite is deployed first. When its tether reaches full length, it pulls out #2, and so forth. Each satellite has a deployer built in, with tethers 1-20 km long and 0.8-2.4 mm in diameter. The top segments are Spectra, but the rest are PTFE to resist heating and atomic oxygen. Three of the eight deployers are listed below to illustrate trends. The deployers can each use fixed capstan brakes with good heat-sinking to limit deployment rates to ~4 m/s. The largest deployer (#7) holds 20 km of 1.6 mm Spectra weighing 30 kg. Tether #8 is just long enough to ensure that tether recoiling from a failure lower down cannot reach the shuttle. It also isolates satellite #8 from shuttle contamination. After 1-3 days, the shuttle can let its altitude decay to get data at the lowest possible altitude. When the bottom tether melts, the shuttle stays at that altitude until remaining satellite batteries reach depletion or OMS margins are used up. Then it cuts the array loose to reenter over the Pacific.

Table 2. Typical Data for Tethered Platforms

Existing SEDS Deployer	SEDS Tether[1]			Swing	Tension		Brake reqts		Impact
	Len	Dia	Mass	Max[2]	Min	Max	MaxPwr	Total	MTBF
Mission	km	mm	kg	deg	new	new	watts	kJ	days
SEDS-2	19.7	0.78	6.7	4	0.02	7	19	20	23[3]
TiPS[4]	4	2.2	5.5	15	0.04	2	1	<1	890[5]
Ladders:[6] #4 (PTFE)	10	1.2	14.3	30	5	100	70	90	61[7]
Mini-SEDS Deployer	SEDS Tether[1]			Swing	Tension		Brake reqts		Impact
	Len	Dia	Mass	Max[2]	Min	Max	MaxPwr	Total	MTBF
Mission	km	mm	kg	deg	new	new	watts	kJ	days
Low-gee processing	1	0.9	0.3	15	0.08	<1	1	<1	630
Ladders:[6] #1 (PTFE)	6	0.8	4.5	45	0.09	25	7	2	40[7]
#8 (Spectra)	1	2.4	3.2	15	100	170	1000	300	7000

1. SEDS-2 was Spectra; Ladders #1 & 4 are PTFE; the rest are Spectra with a resilient yarn core.
2. Max swing is after deployment: actual for SEDS-2, typical requirements for others.
3. SEDS-2 tether was cut after 3.7 days, but remaining 7.2 km lasted till reentry (59 days).
4. TiPS is a passive deployment with no swing reqts; it is expected to settle to $<15^\circ$ in weeks.
5. Due to mission altitude & tether diameter, debris is estimated to add ~60% to the risk.
6. "Ladders" is a shuttle-based chain of 8 60-kg payloads hanging down from 210 to 130 km.
7. PTFE tethers are assumed to have half the MTBF of equal-diameter Spectra tethers.

Increasing the Ladders tether diameters cuts into payload mass including battery life, and near the bottom it also increases drag and raises shuttle reboost requirements, which are ~200 kg/day. Paradoxically, accepting a real risk that some of the array will be lost during the mission can actually increase mission utility and duration, including the probable full-array duration.

Ladders can also be flown from an ELV. Here the array should be deployed both up and down, with the host in the middle, so that a worst-case tether cut causes loss of only half the array. Total propellant use is comparable (or lower, if the reduced risk justifies use of thinner tethers), but engine firings need to be far more frequent, due to the small total system mass.

The low-gee processing concept involves a smart Tethered Reentry Experiment Vehicle (TREV). As shown in Figure 8, it deploys and stabilizes itself ~1 km below an ELV, which is thereafter needed only as a counterweight (i.e., its batteries can go dead). The gravity-gradient acceleration of 0.4 milligee is low enough to be compatible with many low-gravity processes, but high enough to simplify fluid handling. When processing is done, the capsule releases the brake, pays out the rest of the tether (which can be much thinner than the first km), and uses GPS or an uplink to decide when to cut the tether for an accurate reentry. The tether is left in orbit at ~400 km to improve our database on risks at space station altitude.

Missions Better Suited to Other Deployers

The major limitation of SEDS is that it cannot retrieve the tether. For that, reel-type systems are needed. But payloads can sometimes be retrieved without tether retrieval. If the payload can be swung close to the horizontal, then the tether can be cut and a conventional rendezvous made. For low-altitude probes, one could also add thermal protection and a parachute, cut the tether at the right time, and retrieve the payload after reentry.

SEDS tether options also have some limits. When JSC requested that we use SEDS to deploy an 18 gauge insulated copper wire as part of the Plasma Motor Generator (PMG) experiment, we realized that the wire's mass and stiffness would make the deployment tension too high. However we were able to use SEDS experience to design a more suitable short, fat open-ended fixed-core deployer.

Tethers containing optical fibers should probably also use a PMG or reel-type deployer, because the criss-cross winding used with SEDS is likely to crack the fibers. On the other hand, putting optical fibers inside orbiting tethers may be impractical in many cases, because impacts that can crack even an armored optical fiber inside the tether will be far more common than impacts that can sever the whole tether. The same impact sensitivity may limit the utility of tethers with electrical conductors, especially tethers with multiple conductors.

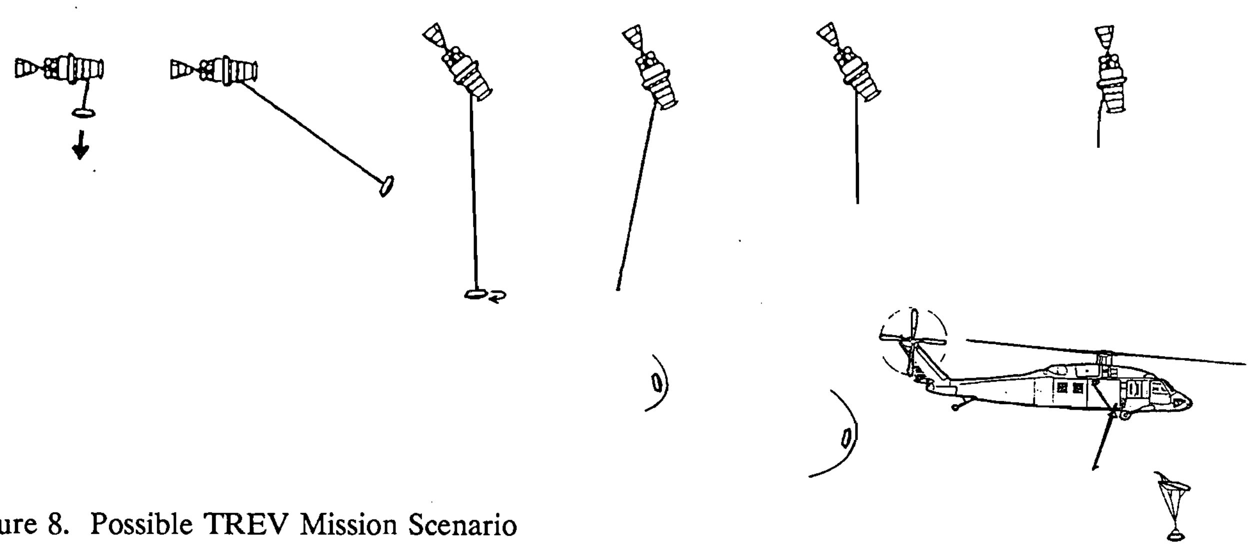


Figure 8. Possible TREV Mission Scenario

One possible exception is a short, heavy extension cord to suspend an instrument platform or wake-shield facility ~100-300 meters above the space station. The short tether length can result in acceptable extension cord masses, even if the entire cord has to be replaced occasionally because of an impact-induced short.

Given the very low forces and high cord stiffness, the best cord design may be a loose coil like a telephone cord, with the coil direction reversed in the middle for torque balance at different lengths. When near full extent, the cord can provide a passive soft suspension to isolate the platform from station jitter. The tethered platform concept is shown below in Figure 9.

For servicing, a small Spectra tether down the center of the coil can be wound onto a fishing-reel-sized winch to retrieve the platform most of the way. Then a manipulator arm on the station can move the platform to a docking adapter. The coiled cord can dissipate ohmic heating even when retrieved.

Finally, it is possible that the most impact-tolerant separated-strand or tape-like tether designs will be difficult to deploy from SEDS for some reason. Suitable deployers for them will depend on the details of their design.

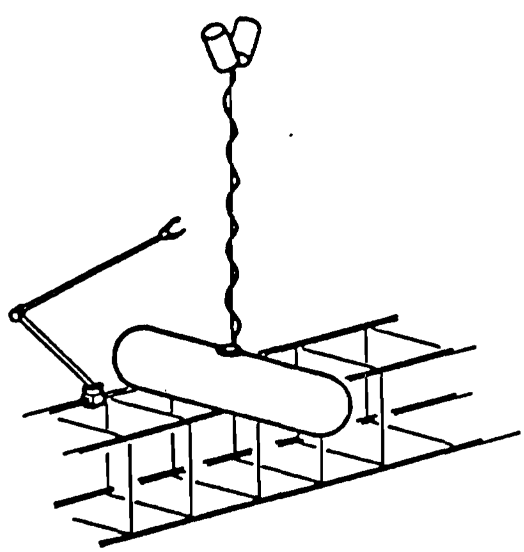


Figure 9. Platform Tethered to a Space Station

SEDS Costs

Development of SEDS from the initial feasibility study in 1983 through delivery of two sets of flight hardware to NASA in 1990 cost $1.3M. (This excludes NASA Marshall's work developing the computer and software.) Recurring costs for SEDS hardware are <$40K for a deployer, tether, and brake-cutter. We do not have cost data on the computer, thermistors, NSI pyros, or cabling, which were developed and provided by MSFC. Brake control laws for SEDS-2 & SEDSAT were developed by Enrico Lorenzini of the Smithsonian Astrophysical Observatory for <$50K each. The actual flight software was written at MSFC.

These SEDS costs are low enough that they will generally be swamped by integration costs. To date the integration costs have been dominated by work on the conventional issues such as structural loads, thermal analysis, outgassing, etc. Our experience with SEDS-1 & 2, PMG, TiPS, and SEDSAT is that overall integration costs are likely to be dominated far more by the degree of rigor & formality required in testing & documentation, than by the amount of new development done on the tether, deployer, or controls.

If existing SEDS hardware, tether designs, control laws, and existing documentation are suitable for a new mission, then they should be used as is. But if any of these items need to be changed, then analyses and tests for the new environment are needed anyway, and the incremental cost of modifying the control law, tether, and/or deployer to better meet the intended goals can be quite low. (We do not apply this argument to the brake or computer, which are fairly flexible as is and which cost more to requalify after changes.)

We can give two examples of past modifications and their costs. The first is the PMG deployer. JSC requested that we find a way to deploy 500 m of 18 gauge insulated copper wire from a SEDS deployer. The deployment tension was far too high, so we used our experience with SEDS to develop a more suitable deployer. It worked very well on the PMG flight experiment. We were able to design, analyze, fabricate, wind, and test two PMG flight deployers (excluding vibration tests) for <$100K. More recently, we were able to assist NRL on TiPS mission design, experiment with resilient-core tether designs, procure 3 tethers, develop and refine the SEDS winding pattern, and perform deployment tests for <$40K. PMG and TiPS were both programs requiring minimal paperwork.

When Tether Applications has provided support for more formal traditional approaches, our costs have averaged ~$200K/mission for support of mission design, simulations, analyses, test procedure development, tests, launch, and data analysis.

Summary and Conclusions

We have sketched the history of space tether concepts, recent flight experience with them, and near-term flight plans and studies. We then provided a tutorial on key aspects of space tether concepts. Then we homed in on applications and issues relevant to small satellites, and gave specific examples of mission scenarios, typical tradeoffs, and benefits of tethers to small satellites. Last, we provided historically-based cost estimates for using SEDS either as is or with modifications.

Together, these items demonstrate that relevant tether technology is available for small satellite applications, that it can serve a variety of useful and potentially valuable roles, and that simple tether systems such as SEDS and PMG can be adaptable, affordable, and reliable.

Acknowledgements

This paper is based partly on papers prepared under NASA Marshall funding. In addition to the SEDS teams at NASA Marshall, Langley, and Goddard, we would like to thank Wubbo Ockels of ESTEC for his suggestion of a two-stage deployment strategy for TREV.

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