SECTION 2.0 PROPOSED TETHER FLIGHTS

2.1 Electrodynamic Tethers For Reboost of the International Space Station

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 new type of electrodynamic tether attached to the Station (Figure 1) could be developed to generate an average thrust of 0.5-0.8 Newtons for 5-10 kW of electrical power. By comparison, aerodynamic drag on ISS is expected to average from 0.3 to 1.1N (depending upon the year).
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 shift less than 5 m).

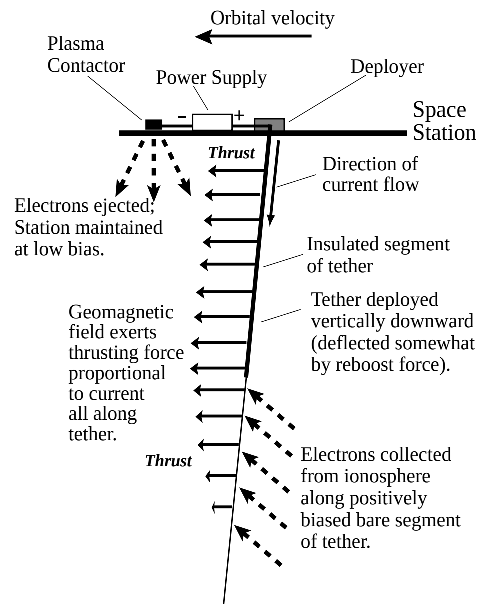

Figure 1. An electrodynamic tether reboost system for the International Space Station.

High Tether Currents for ISS Reboost

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 0.5A 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 quasineutrality 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 0.3A 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 - as proposed by Sanmartín .

The Bare-Tether Breakthrough. The bare-tether design represents a breakthrough that makes short-tether electrodynamic reboost with moderate power requirements for the ISS a possibility. 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.

Our proposed design 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. This is because the small cross dimension of the tether allows its current collection to take place in the orbital-motion-limited 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 (Figure 2).

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

Developing an ISS Reboost System. Our preliminary design for an electrodynamic tether thruster capable of delivering 0.5-0.8 N of thrust to the ISS at a cost of 5-10 kW of electrical power consists of an 10-km-long aluminum tether in the form of a thick ribbon (0.6 mm by 10 mm). Despite its length, the tether would weigh only around 200 kg. Since the bare portion of the tether is to act as our electron collector, a downward deployment of the tether is dictated by the physics of the east-ward-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 comes from 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

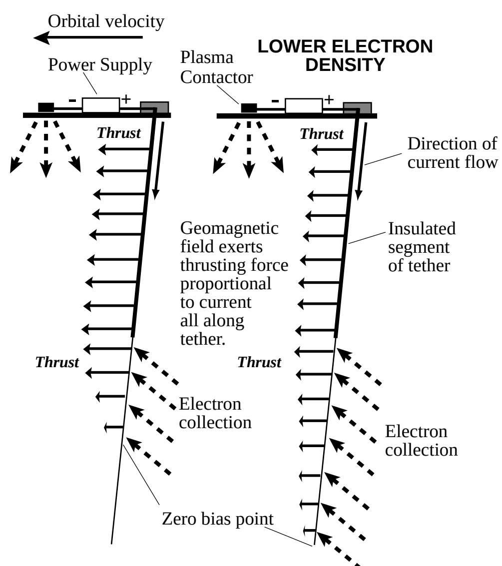

Figure 2. A bare-tether thruster designed to adjust to lower electron density (as at night). A shift in the zero point of bias further down the tether increases the collecting surface and maintains a nearly steady thrust for constant input power and induced e.m.f.

current through the power supply, but the current would be strongly peaked at the upper end of the tether. Keeping the input power constant, we can substantially increase the average current in the tether, and hence the thrust, by insulating the tether over much of its upper portion, collecting current with the lower portion, and having a constant current in the upper part.

Determining the optimal fraction to insulate is part of the design effort for a “bare” tether reboost system. Our preliminary design has the upper 50% of the tether insulated. Even greater thrust during daytime operation could be obtained with a higher fraction, but the night–time 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 4.

The bare-tether design has essentially solved the problem of day/night thrust fluctuations. But fluctuations in thrust due to fluctuations in the induced e.m.f. as the system encounters a varying geomagnetic field around the orbit are a fact of life for any tether-based system. Figure 5 show the thrust variations around the ISS orbit with different input power levels.

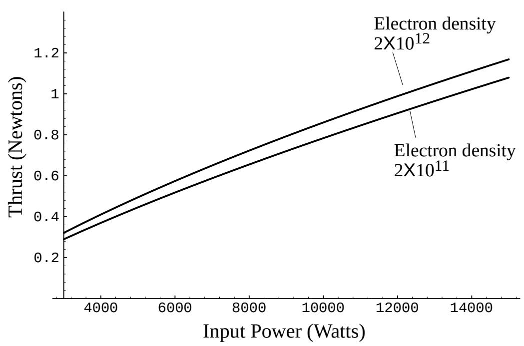

Figure 4. Variation of thrust with input power for nominal 10-km system. Motional e.m.f.: 1.2 kV.

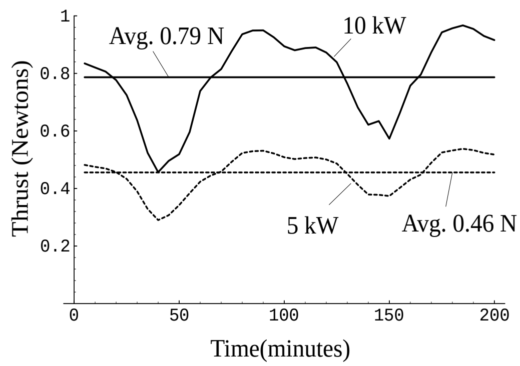

Figure 5. Comparison of thrust generated for input powers of 5 kW and 10 kW

Given the level of the current the system may draw, the system will almost certainly require its own cathodic plasma contactor at the Station end. The contactors currently under development at NASA 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.

Before an operational electrodynamic tether 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.

Assessment of Space Application and Benefits to the ISS

1) Mission Benefit. The value in an electrodynamic tether reboost system lies in its ability to couple power generation with thrust. Heretofore the electrical and propulsion systems have been effectively totally separate entities. Outfitting ISS with an electrodynamic reboost tether severs the most critical and constraining dependency on Earth - propellant resupply. The Station can supply its own power but not its own propellant. Without an electrodynamic tether, the specter of SkyLab and the

words "reentry" and "atmospheric burnup" will forever haunt the minds of anyone who has an interest in the program. Add a tether and some additional storage capacity for supplies, and suddenly a one year interval between visits to the Station becomes conceivable.

Even if the current frequency of resupply flights to the Station is maintained, with an electrodynamic tether the Station Program has the option to trade kilowatts for increased payload capacity. Resupply vehicles can deliver useful cargo 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 kW 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 electrodynamic tether 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 electrodynamic tether 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 electrodynamic tether 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 electrodynamic tether 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.

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 nautical miles" which currently permeates every aspect of Station mission planning. With the multi-billion dollar investment in the vehicle virtually secured and free from concern over long resupply vehicle launch delays, particularly Russian Progress or FGB tanker delays, the Program will be able to focus much more strongly on the ISS mission rather than on ISS itself.

3) Cost Pay Back. 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 $1.8 billion. An electrodynamic tether supplying 90 percent of this requirement would reduce the operational cost by $1.6 billion, 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.

Contacts:
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2.2 An Upper Atmospheric Tether Mission (ATM)

Introduction

The Atmospheric Tether Mission (ATM) is a Shuttle based scientific experiment that will deploy a set of eleven instruments to collect valuable atmospheric data never before obtained. This set of instruments will be housed in an endmass/spacecraft that is deployed downward from the Shuttle by a 90 km tether. The instrument package will cut through the atmosphere, collecting data, at three different altitudes over a six day mission. A team was formed at the Marshall Space Flight Center (MSFC) to conduct a preliminary concept study defining a system that would accomplish the objectives of the ATM. A detailed report will be published by the team at the conclusion of the study.

Science Instrument Requirements

A Science Definition Team (SDT) was formed by NASA Headquarters to define the scientific objectives of the Atmospheric Tether Mission (ATM). The SDT proposed a set of eleven science instruments that together would meet all of the ATM mission objectives. The instruments, their requirements and locations are shown in Table 1 and in Fig. 6, respectively.

Instrument Description	*Sensor Dimensions (cm)*	*Electronics Dimensions (cm)*	*Sensor Mass (Kg)*	*E-Box Mass (Kg)*	*Instrument Power (W)*	*Telemetry Rate (bps)*
Ion Drift Meter	12 dia 7 deep	21x12x16	0.9	2.3	3	2000
Retarding Potential Analyzer	12 dia 7 deep	21x12x16	0.9	2.3	4	1000
Ion Mass Spectrometer	18x12x11	18x12x16	1.8	2.0	6	500
Langmuir Probe	1 dia 15 long boom mount	15x15x10	0.35	3.0	4	5600
Neutral Wind Meter	16 dia 19 deep	18x12x16	2.1	2.2	8	1000
Neutral Mass Spectrometer	18x12x11	18x12x16	2.0	2.5	10	1000
Energetic Particle Spectrometer	19x15x18	Included in Sensor	2.2	N/A	2	8000
E-Field Double Probes	20 cm dia 6 deep	12x12x8	18.0 (3x6)	3.0	10	50K
IR Spectrometer	10x10x21	18x18x13	7.0	2.0	13	128K
UV Photometer	10x10x25	inc. in sensor	2.8	inc. sens	5	320
3-Axis Magnetometer	8x8x21	18x18x13	1.0	2.5	2	1600
Total Payload			39.1	21.8	67	199K

Table 1. Science Instrument Requirements

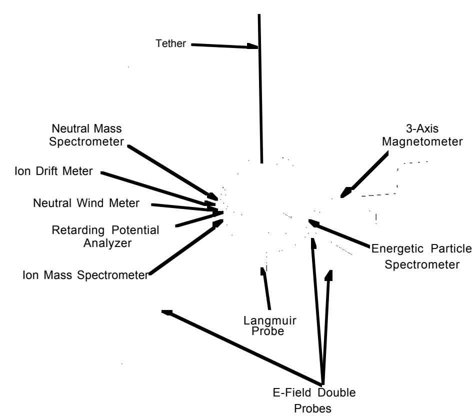

Figure 6. Preliminary drawing of the ATM endmass

Mission Scenario

The baseline mission scenario is that the Orbiter will enter a 220 km circular orbit at a 57 degree inclination. The tether length for this scenario is 90 km and will operate in a deploy only mode. On the first day the tethered endmass will be deployed downward 50 km to 170 km altitude and remain there for two days. On day three, an additional 20 km will be deployed, lowering the endmass to an altitude of 150 km for two days. On day five, the final 20 km of tether will be deployed, lowering the endmass to its final 130 km altitude and will remain at this altitude for two days. The Orbiter altitude will be maintained by use of the Primary Reaction Control System (PRCS) thrusters on the Orbiter. On day seven, the tether is cut and the endmass begins a reentry course. The current estimate of fuel required for this scenario is 1996 kg (4400 lb.).

Five of the science instruments are required to face the RAM direction with two in the wake. A series of E-field double probes and Langmuir probes are placed at specific locations around the 1.6 m diameter satellite shell. This concept shows an aerodynamic tail used to increase yaw stability.

Aerodynamic Analysis of Endmass

The drag for a spherical shaped endmass of 1.6 m in diameter ranges from 0.92N at 130 km altitude to 0.11N at 170 km altitude. A bullet shaped endmass was considered to ease packaging constraints of the endmass subsystems. The drag analysis showed that the drag for a sphere is 20 percent lower than the equivalent bullet shape endmass. The diameter of the spherical endmass was increased from 1 m to 1.6 m in diameter to alleviate packaging constraints.

Endmass Attitude Control System

There are several constraints impacting the endmass attitude control system design. Two major constraints on the system are; avoidance of large torques that will disturb the endmass force and acceleration measurements, and the inability of using magnetic torquers because they cause disturbances in the magnetic field flux measurements. The science instrument requirements state that the endmass should be pointed within plus or minus 3 degrees of RAM with a plus or minus 0.1 degree post-flight knowledge requirement. An attitude control system combining the use of reaction wheels and strategically placed cold gas thrusters is the current proposed baseline. The location of thrusters will be determined using Direct Simulation Monte Carlo (DSMC) analysis to avoid instrument and endmass contamination. The control system is estimated to weigh 15 kg.

Electrical Power System

The mission lifetime of six days requires seven Li/SOCL2 type batteries weighing 105 kg. The additional cables, harnesses and distribution weights bring the electrical power system to an estimated 155 kg. The total desired power loads are estimated at 176.6 watts including a 25 percent contingency. This total includes the science instruments and electronics, and the endmass major subsystem equipment. A summary of the electrical power system mass versus mission durations is seen in Figure 7.

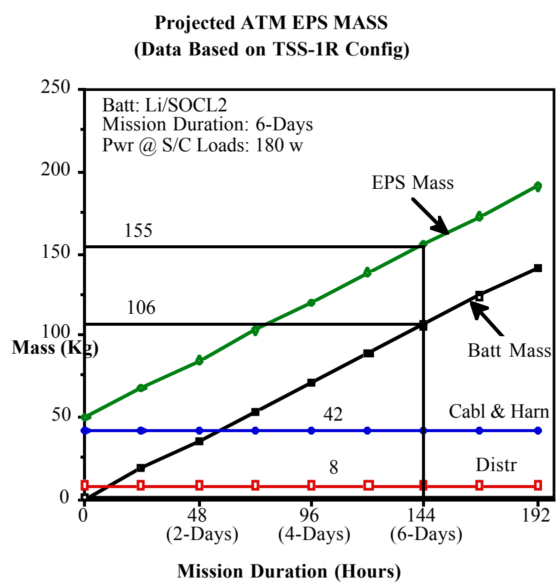

Fig. 7. ATM Electrical Power System Mass

Thermal Control System

A flowfield temperature analysis was performed at an altitude of 130 km. The temperature variations occur in shock-layers ranging from 800 K to 12000 K. The maximum aero-heating on the endmass surface is shown in Figure 8.

A combination of thermal blankets and heaters comprise the current endmass thermal control system. The estimated weight of the system is 7 kg requiring 4 W of power.

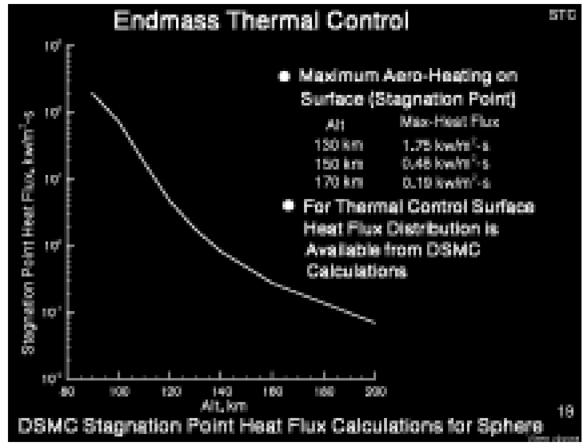

Fig. 8. ATM endmass thermal control

Endmass Structure

The recommended material for the endmass structure is Aluminum 2219. The endmass structure is composed of an equatorial ring with a mounting panel with two hemispheres of four flanged quadrants each. Local stiffening will be required for the mounting of deployables and some instruments, and attachment of the aerodynamic tail. A smooth surface is desired for aerodynamics requiring the use of closeouts. The estimated weight of the endmass structure is 81.9 kg.

Baseline Tether Concept

The current tether concept is a 1.65 mm diameter Kevlar strength member surrounded by a Nomex jacket with a total diameter of 2.16 mm. A magnification of the baseline tether is shown in Figure 9.

The tether has a break strength of 2892 N and weighs 4.03 kg per km. The tether is non-conducting and is currently 90 km in length. The probability of survival of the baseline tether over a six day mission, assuming a critical particle size of 0.3 of the tether diameter, is approximately 0.93. The probability of survival is highly sensitive to critical particle size. A graph showing a particle size of 0.2,0.3, and 0.5 of the tether diameter is seen in Figure 10.

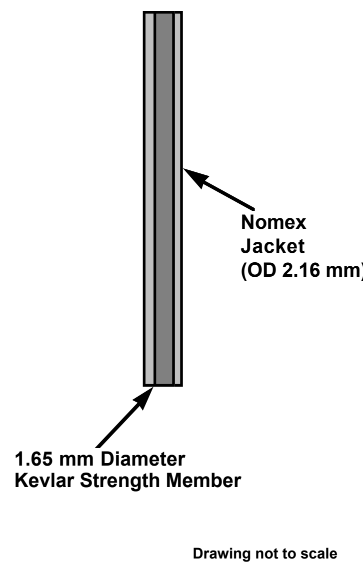

Fig. 9. A magnification of the baseline tether.

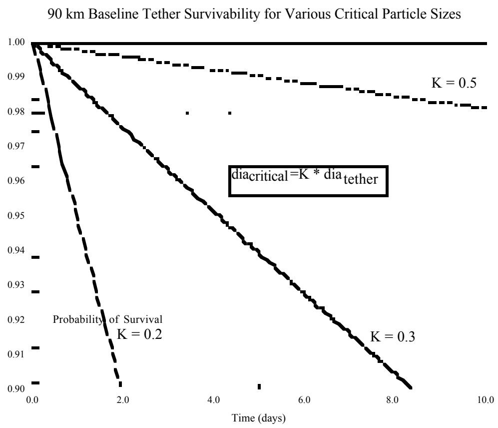

Fig. 10. Comparison of critical particle sizes and the probability of survival versus time.

Several alternate tether designs are being considered like the Hoytape (see *Failsafe Multiline Tethers for Long Tether Lifetimes* in the Application section). The survival probability using a particle size of 0.3 of the tether diameter jumps from 91 percent for a single line tether to 99.99 percent for the Hoytape. With a Hoytape type of tether, there is increased surface area increasing the overall drag on the tethered system. Other Hoytape designs using smaller diameter members will improve the drag concern while maintaining a near 100 percent survival.

Atmospheric Drag and Tether Dynamics

The atmospheric drag on the tether and endmass will induce libration oscillations of the tether. This is due to the fact that the atmospheric density is not constant thus affecting the in-plane libration of the tether.
Based on the current analysis, a libration and/or satellite pitch attitude control scenario may be required.

Deployment Dynamics

There are two types of deployers considered for the ATM mission. A modified Tethered Satellite System (TSS) deployer and a Small Expendable Deployer System (SEDS). The TSS deployer exists and has flown twice but must be modified for the ATM mission. The SEDS deployer is smaller but is not Orbiter qualified and would require extensive modification. The current baseline deployer of the ATM system is a modified TSS type deployer. Deployment dynamics are stable and have been demonstrated in earlier missions. The TSS deployment control strategy is proven and suitable for the expected endmass altitudes required in the ATM mission. The proposed ATM system will be mounted on a Spacelab Pallet in a designated location in the Orbiter payload bay.

Weight Statement

The total estimated weight (without contingency) of the endmass is 325.3 kg. The deployer reel, electronics, support structure and Spacelab pallet add an additional 2940 kg and the tether adds 500 kg. With a 30 percent contingency the total weight of the ATM system is 4895 kg. Table 2 details the ATM weight statement.

Table 2. ATM weight statement.

• Endmass	
– Science Instruments & Electronics Boxes	60.9 kg
– Structures	81.9 kg
– Electrical Power System	155.0 kg
– C&DH System	5.5 kg
– Thermal Control	7.0 kg
– Attitude Control System	15.0 kg
• Deployer	
– Reel, Electronics, Support Structure, SLPallet	2940.0 kg
– Tether (120 km)	500.0 kg
• Contingency (30%)	1129.6 kg
• Total	4894.9 kg

ATM Development Schedule

From Authority To Proceed (ATP), the development of the ATM is planned to take four years. A six month Phase A study for engineering design would begin immediately followed by a nine month Phase B definition. Parallel to the beginning of the Phase A, an Announcement of Opportunity (AO) would be released for the science instruments. The selection of the instruments would occur at the beginning of the Phase B and the science instrument design, development, fabrication and testing would begin. The development of the endmass and tether would begin parallel to the instrument development with the deployer development starting within the next quarter. All hardware would be delivered and integrated into the Orbiter in the beginning of the fourth year with a projected launch in the third quarter of the year.

Contacts:

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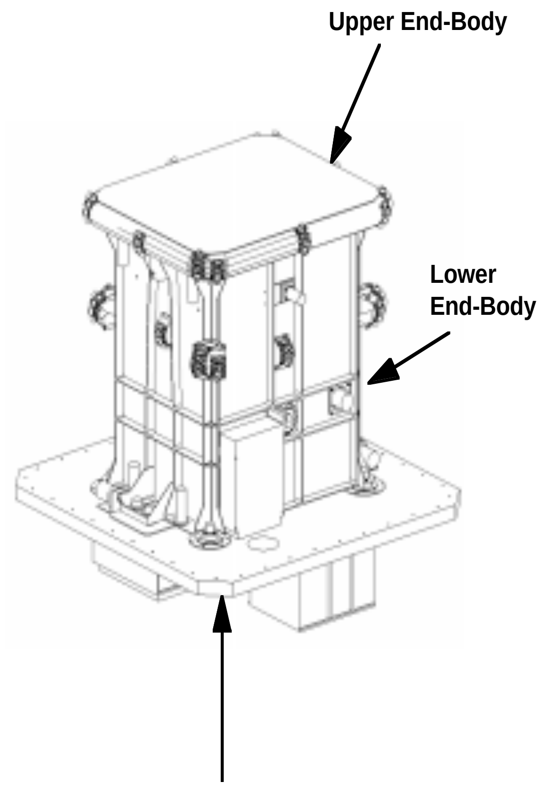
2.3 The Naval Research Laboratory's Advanced Tether Experiment

The Naval Research Laboratory (NRL) plans to fly its second tether experiment, called ATEx, in 1998. ATEx stands for Advanced Tether Experiment. The tether system is a simple gravity-gradient dynamics and survivability research experiment.

Major program objectives include adding to the tether community's understanding of deployment dynamics and control via a constant-speed motor, in- and out-of-orbit plane libration control via thrusters to excite and damp librations, and investigating the survivability of long-life tether materials.

Isometric Views of ATEx



Upper End-Body: 7.6 x 62.2 x 52.0 cm
Lower End-Body: 60.9 x 48.2 x 38.1 cm

Mechanical Overview

The 83 kg tether system will fly as a payload on a host satellite in a circular altitude of 425 NM. A passive upper end-body's mass of about 12 kg has no instrumentation other than green-filtered retroreflectors. A 6 km (12 kg) tether is composed of 0.004 inch thick by 1 inch wide low density polyethylene with 3 single strands of 215 denier Spectra® 1000 uniformly spaced across the width. The lower end-body, of 30 kg mass, remains attached to a 29 kg electronics deck for the 90-day attached phase of the mission. At the end of the 90-day tether experiment, the lower end-body is separated from the electronics deck, which remains with the satellite. The lower end-body and portions of the satellite are covered with IR-filtered retroreflectors.

To accomplish some of the mission's science objectives, the lower end-body is instrumented with a 3-axis tensiometer at the tether attach point, a 3-axis accelerometer, a reel turn-counter, and a sensor to detect some discrete angles of tether departure with respect to the lower end-body.

Deployment Scenario

After achieving a near-circular orbit, the 3-axis stabilized momentum-bias satellite will orient with ATEx radially away from Earth. ATEx's upper end-body will separate away from the lower end-body via a constant speed motor at 2 cm/s. The stepper-motor will drive a pair of pinch rollers pulling the tether off a level-wound reel; but, the motor and reel cannot reverse direction. The entire deployment sequence has been specified and includes satellite pitch motions to maintain a tether departure angle nearly perpendicular to the lower end-body.

Analysis showed the in-plane system libration angle will initially be fifty degrees and throughout the deployment oscillate at significantly lower angles to result in a final libration angle near zero degrees.

Libration Control Demonstrations

For the remaining 87 days of post-deployment activities, tether dynamics will focus on exciting and damping in- and out-of-plane librations. The satellite has thrusters located on all four sides of the vehicle to force the satellite and lower end-body (now acting as one large end-body) forward-and-back in the orbit plane and left-and-right out the orbit plane. Details of these activities have not been defined; however, a thruster would be fired and observations made of tension, acceleration, satellite attitude perturbations, and end-body positions. The results would be interpreted in a quick-look scheme via the dynamics simulations.

Satellite Laser Ranging (SLR) Tracking

Each end-body has 43 retroreflector optics or "corner cubes". A retroreflector returns light back to the source independent of retroreflector orientation thus permitting the end-bodies to be observed by the global SLR network. The different coating on each end-body is sensitive to a different laser frequency to assist in identifying the end-body. Early in the mission, telescope observations will guide the laser beam to the end-body.

Later in the mission, perhaps the tether motions will repeat regularly and orbit determination will be straightforward such that a laser can target the end-bodies even in local daylight.

The SLR ground stations require pointing information given by inter-range vectors (IRVs). NRL will enhance the tether system's orbit determination from USSPACECOMMAND by including end-body motions. Initially, the tether dynamics models of the in-plane and out-of-plane librations will be used to augment the IRV.

Later, as SLR data becomes routinely available, estimates of the orbit and refined tether dynamics models from the SLR data should substantially improve end-body position and rate estimates. The IRV can be fit to the observed tether dynamics to enhance the acquisition and tracking, perhaps the SLR sites can acquire (in daytime) without telescope assist. This will increase around the globe viewing opportunities.

The Goddard Space Flight Center coordinates SLR observations within their international network and distributes the IRVs to each site. We expect to collect tether data for approximately one year. After that, we plan to occasionally request a series of SLR tracks to confirm long-term tether motion and that the tether is still intact.

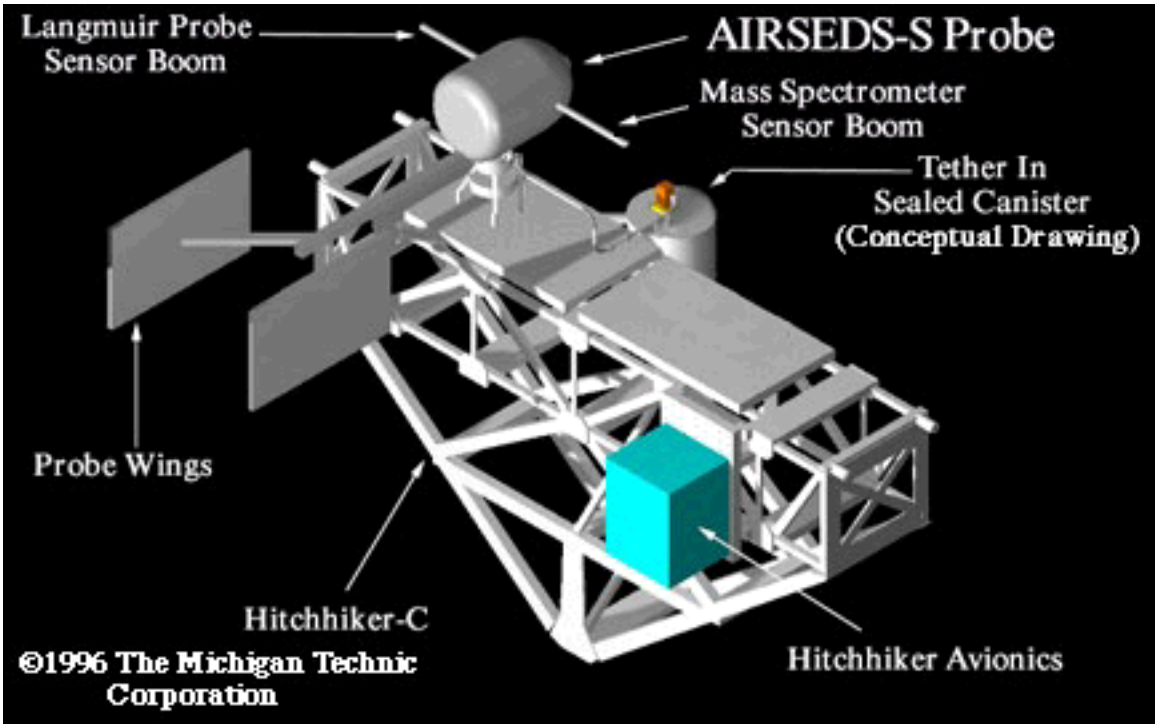
Tether Survivability

After the 87 days of libration control research, the lower end-body is separated from the satellite. At this time, ATEx is completely unpowered, passive, and can only be observed by the ground methods: SLR, radar, optical telescops. At this point, the ATEx mission is similar to the TiPS project described in chapter 1 of this handbook. Analyses indicate that ATEx will reenter into the atmosphere in 3-4 years. The model included the atmospheric heating effects of the solar cycle.

Contacts:

- D. Spencer, M. F. Zedd - NRL

2.4 The AIRSEDS-S Mission



Several organizations have expressed a need for low cost tether solutions for the space shuttle, International Space Station and unmanned launch vehicles. Furthermore, NASA and ASI have expressed interest in flying a tethered satellite system in a downward deployed mission called TSS-2.[1] The scientific and engineering information to be gained from such a mission would allow advances in our understanding and modeling capabilities of atmospheric and ionospheric phenomena including satellite drag, the energy deposition from magnetospheric currents and particle precipitation, and the spatial and temporal gradients in ionospheric properties. Moreover, the next generation of tethered satellites and hypersonic vehicles are being planned to fly through this atmospheric region. Before undertaking a mission of the size and complexity of TSS-2 it may be prudent to explore the possibility that a less complex mission might be performed, which utilizes many present tether technologies and options for commercial sponsorship, to achieve a limited set of science and engineering goals. In the fall of 1994 The Michigan Technic Corporation (TMTC) was awarded by NASA Headquarters and Marshall Space Flight Center Phase A funding to conduct a preliminary design of the AIRSEDS-S probe and mission plan. AIRSEDS-S, Atmospheric/Ionospheric Research Small Expendable Deployed Satellite, will test and demonstrate tether system dynamical interactions, flight qualify deployer systems and reusable components for application to the Space Shuttle and the International Space Station (ISS), verify models of tether and satellite aerothermodynamic behavior, and determine lower thermosphere chemistry and composition. Figure 1 shows the system conceptually integrated with the Hitchhiker-C Crossbay Structure. AIRSEDS-S, based on NASA's successful and proven SEDS program, is a 90 km tether mission designed to collect atmospheric information in the altitude range of 230-130 km via a tethered satellite lowered from the Space Shuttle Orbiter to altitudes which cannot currently be explored using balloons or aircraft. The AIRSEDS-S mission will provide the first horizontal in-situ sampling at low altitudes in the Earth's upper atmosphere. In addition, the successful flight demonstration of the AIRSEDS-S probe and deployer system could result in the future development of a low cost deployer to conduct further exploration of the Earth's upper atmosphere and ionosphere, and conduct payload return operations, ISS towing operations and microgravity experiments from the space shuttle and the International Space Station.

The specific objectives of the AIRSEDS-S Mission are to:

(a) Flight qualify tethered satellite hardware on the Space Shuttle Hitchhiker-C and for use, by inference, on the International Space Station.

(b) Conduct an investigation of the horizontal distribution of neutral atmosphere composition and dynamics in the lower thermosphere.

(c) Understand the local atmospheric environment of the tethered probe, and compare with current predictions.

(d) Test and demonstrate tether system dynamical interactions. This includes studying the behavior of a tethered satellite system and analyzing the flight characteristics of the probe in the Earth's upper atmosphere and comparing with current models.

(e) To provide educational opportunities to students in both pre-college and college level.

The long term goal of TMTC and the participants of the AIRSEDS-S mission including the University of Texas at Dallas, the University of Iowa, the University of New Hampshire, The AIRSEDS Institute, Tether Applications, Tethers Unlimited, The Smithsonian Astrophysical Observatory, and NASA Marshall and Goddard Space Flight Centers, is to provide a low-cost reusable modular tether facility for the International Space Station (ISS) and the Space Shuttle Hitchhiker-C programs. Such a facility may be further developed to support experiments conducting remote sensing, electrodynamic operations, microgravity studies and payload return. Most of the components for the AIRSEDS-S mission will have direct application on future ISS applications and shuttle based missions including the deployer system, the tether, avionics, payload ejection and payload support systems including data systems, end mass attitude control, communication and data collection.

For further information please refer to the *AIRSEDS Internet Central* web site at http://www.airseds.com/.

Contacts:

- A. Santangelo - The Michigan Technic Corporation

2.5 The RAPUNZEL Mission

The small tether project RAPUNZEL was started in 1991 by the Institute of Astronautics, Munich Technische Universitat (TU) and the Kayser-Threde Company to design a low cost tether experiment. In collaboration with the Samara State Aerospace University (SSAU), Russia, the initial mission intended to fly the German re-entry capsule MIRKA on a Russian Photon capsule. Later on, in collaboration with SSAU and the former NPO Energia, the project split into three different missions on Resurs, Photon, and Progress spacecraft, respectively.

The TU team designed and built a deployer based on textile technology, which would ensure both high reliability and low cost (Fig. 1). SSAU is building a small re-entry capsule to fly on Resurs.

Lately, the main effort has been the development and test of the deployer. In November 1995, a campaign of parabolic flights tested the deployer under microgravity conditions. The first tests have shown good results and proven the concept feasibility. The laboratory tests were followed by numerical simulations of the payload deployment and its re-entry in the atmosphere.

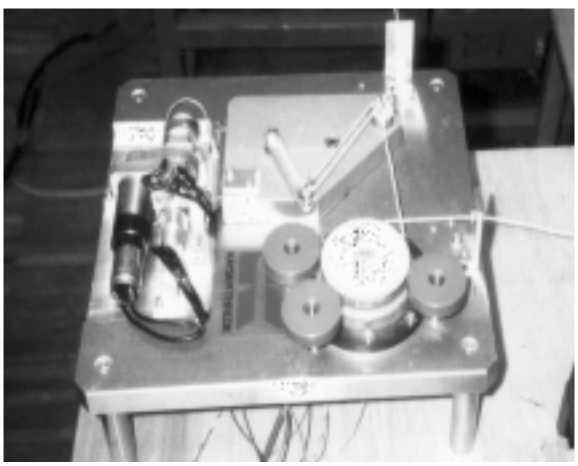


Figure 1. Breadboard model of tether deployer

Fig. 2 shows a schematic of the mission sequence. When the endmass is ejected by springs (1) the deployment starts (2). After reaching the full tether length of 52 km, the tether is cut (3) and the capsule reenters the earth atmosphere (4) and lands on parachute (5). Preliminary simulations have shown that even though the atmospheric drag induces small oscillations in the system, the endmass lands safely in the Kasakstan region.

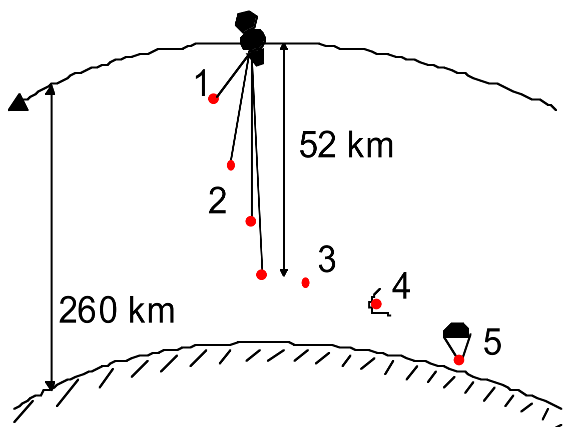


Figure 2. Schematic view of the deployment sequence

Contacts:

- Manfred Krischke, Kayser-Threde GmbH, Munich, Germany
- Dieter Sabath - Technische Universitat Munich, Germany

2.6 Tether Mechanism Materials and Manufacture Project

The ESA funded Tether Mechanism Materials and Manufacture (TMM&M) project has been performed by Alenia Spazio (Italy), as prime contractor, and SABCA (Belgium) and SENER (Spain) as subcontractors.

One important class of low-cost tether mechanisms and related space missions was identified in the development of expendable tether systems that did not require complex mechanism operations and the associated technology development. For the TMM&M ESA technology development activity, a EURECA-based tether initiated material or sample re-entry model mission, with a 150-kg mass capsule and a 20-km tether, was adopted for the expendable tether mechanism design and its breadboard model selected to be manufactured and tested.

A particular challenge in the expendable tether mechanism design, associated with a near-horizontal tether deployment operation, was represented by the deployment control, tension and rate ranges and accuracy requirements. Various simple tether mechanism design solutions were traded-off and a spool-reel configuration solution, in which no (passive) control is applied in the early tether spool deployment operation and active reel-brake (rate-feedback) actions are implemented to control the remaining part of deployment accurately, was adopted and bread-boarded. The TMM&M Project expendable tether mechanism bread-board model (fig. 1) was functionally tested on a suitably designed and manufactured test facility capable of performing tether deployment testing for a vast range of preselected length, rate and tension reference profiles.

Figure 1. Expendable tether mechanism breadboard model

Contacts:

- R. Licata, P. Merlina - Alenia
- J.M. Gavira - ESA/Estec

2.7 The Space Tether Experiment (STEX)

Description

The Space Tether Experiment (STEX) has been proposed by ISAS to fly onboard the Space Flight Unit (SFU) follow-on mission as one of the science and technology experiments.

SFU orbit is 500 km and circular and the spacecraft attitude is sun-oriented. SFU can carry 1000 kg of payload. The major objective of STEX is to assess the tether technology for future scientific missions.

Mission Scenario

In order to evaluate the performance of different control logics, a 40-kg subsatellite will be deployed up to 10 km and retrieved several times. During stationkeeping the susbatellite will be stabilzed along the vertical with impulsive thrusts.

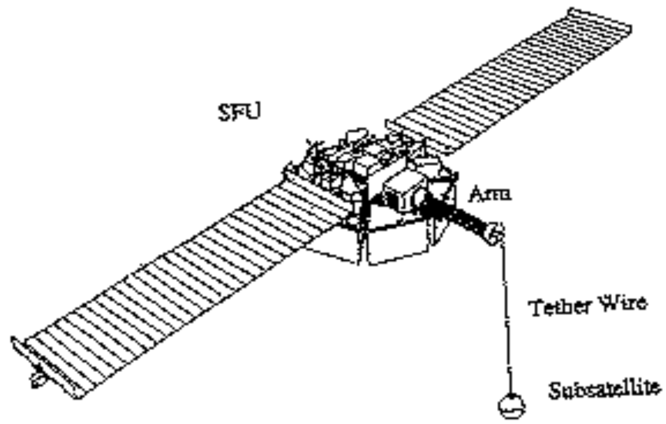


Figure 1. STEX on board SFU

Instrumentation

The subsatellite will be equipped with a vacuum gauge, plasma probes and wave receivers to study SFU electromagnetic environment. A tether deployment and retraction system has been developed for laboratory tests, a schematic is shown in figure 2. The deployment/retrieval speed, tether tension and reponse of the feedback system have been analyzed using this system.

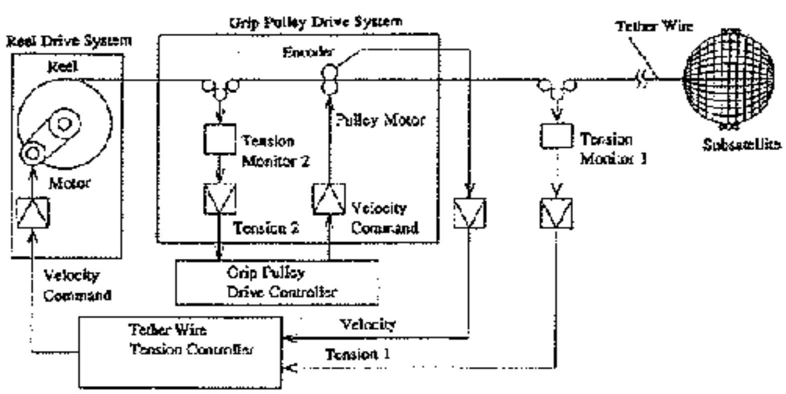


Figure 2. Schematic of STEX Deployment/Retrieval System

Contacts:

- K.I. Oyama, S.Sasaki, ISAS

SECTION 3.0 TETHER APPLICATIONS

3.1 General

This section provides a summary of various tether applications proposed thus far, concentrating on near-term, mid-term, and innovative applications. In some cases, these applications are general ideas, and in others, they are well-defined systems, based on detailed study and computational analysis. These applications have been divided into eight general categories. In cases where an application can be logically placed in more than one, it has been placed in the one considered most appropriate. To avoid redundancy, variations of a particular system concept are not described separately. Instead, Section 3.2 contains a listing of the applications by category, page number, and possible cross reference to other categories. Descriptions of proposed applications follow this listing. For these descriptions, a standardized format is used to allow quick and easy comparisons of different applications. This format is designed to effectively serve as wide a readership as possible, and to conveniently convey the pertinent details of each application. Readers with different interests and needs can find the information and level of detail they desire at a glance.

The Category and title of each application is presented at the top of the page. The "Application" subsection provides a brief statement of the application, and the "Description" subsection provides a brief description of the system design and operation. A picture is located in the upper right of the page to supplement the description, by providing a diagrammatic representation of the system and its operation. The "Characteristics" subsection exhibits the major system design and operation parameters in bullet form. The last characteristic is always a bullet entitled "Potential for Technology Demonstration". This entry attempts to classify both the conceptual maturity of an application, and the amount of technological development required to demonstrate the particular application. When applicable we have mentioned the availability of flight data that somehow may support the feasibility of the application. Three descriptors have been used to indicate the demonstration time-frame:

- Near-Term: 5 years or less,
- Mid-Term: 5-10 years, and
- Far-Term: 10 years or greater.

The date of this printing may be assumed to be the beginning of the Near-Term period. Together, these subsections present a brief and complete summary of the system's application, design, and operation.

The "Critical Issues" subsection, lists the developmental and operational questions and issues of critical importance to the application. The "Status" subsection indicates the status of studies, designs, development, and demonstrations related to the application. The "Discussion" subsection presents more detailed information about all aspects of the application. Following this, the "Contacts" subsection lists the names of investigators who are involved with work related to the application, and who may be contacted for further information. (See "Contacts" section, for addresses and telephone numbers.) Finally, the "References" subsection lists the reference used in the preparation of the application description.

Many of the applications that follow are subject to similar critical issues which are more or less "generic" to tethers. These are issues such as damage from micrometeoroids or other space debris, dynamic noise induced on platforms, high power control electronics technology, rendezvous guidance and control, tether material technology development, and system integration. Many of the figures presented in the "Tether Data" section address these critical issues.

3.2 Tether Applications Listing

Following is a list of abbreviations used to identify cross references to other categories. The application listing has been arranged in alphabetical order by category and application within each category.

AE	AERODYNAMICS
CN	CONCEPTS
CG	CONTROLLED GRAVITY
EL	ELECTRODYNAMICS
PL	PLANETARY
SC	SCIENCE
SS	SPACE STATION
TR	TRANSPORTATION

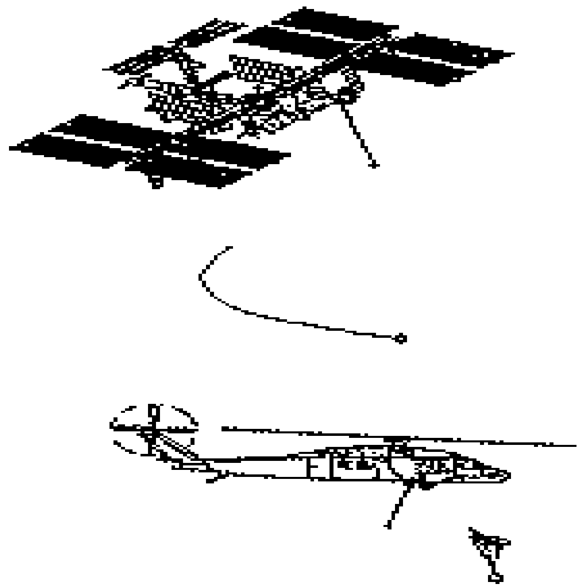
3.3 Tether Applications

-- AERODYNAMICS --

Station Tethered Express Payload System (STEPS)

APPLICATION: Provides a way to return small payloads from the International Space Station to earth between shuttle flights, without the safety hazards of handling rocket motors or propellants.

DESCRIPTION: Payloads are tied down inside a mini-Apollo capsule small enough to fit through the robotic airlock in the Japanese Experiment Module. The capsule is ejected downward and deploys using a SEDS-1 (deploy-swing) strategy. The tether is cut free at the station end, and it orients the capsule for reentry before burning off. (This "kite tail" effect was validated by SEDS-1.)



CHARACTERISTICS:

- Tether length: 30-33 km
- Payload: 30 kg, 100 liters
- Timescale: Near-Term

CRITICAL ISSUES:

- Tether deployment control for proper swing
- Implications of micrometeoroid cut (~0.7% risk)
- Accelerations of ~4 microgee on station during swing

STATUS:

- Tether Applications has contract to deliver protoflight capsule & deployer Feb 1998.
- Capsule can be tested as Delta or Progress secondary payload; both are under study.

DISCUSSION: The tether deployer is a smaller easily reloadable version of SEDS. It mounts in a reusable capsule balancer/ejector/deployer assembly that remains with the station.
For test flights, the deployer and flight computer mount inside the capsule. This simplifies integration on the host vehicle and maximizes hardware recovery for inspection and potential re-use. Baseline recovery scenario involves soft mid-air capture of gliding parachute by helicopter.

CONTACTS:

- Joe Carroll
- Chris Rupp
- Paul Kolodziej

REFERENCES:

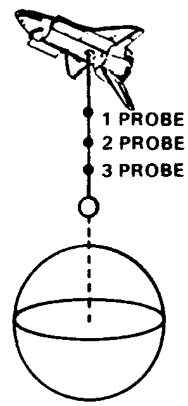
A Station Tethered Express Payload System (STEPS), available from Tether Applications

-- AERODYNAMICS --

Multiprobe for Atmospheric Studies

APPLICATION: Measurement of spatial geophysical gradients.

DESCRIPTION: A one-dimensional constella-tion of probes is lowered by the Shuttle or Space Station into the atmosphere in order to provide simultaneous data collection at different locations.



CHARACTERISTICS:

- Physical Characteristics:Mission related
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Crawling systems might be necessary
- Operational sequence for deployment and retrieval

STATUS:

- Configuration study performed by Smithsonian Astrophysical Observatory
- Analysis of scientific applications performed at University of Texas , Dallas

DISCUSSION: This constellation configuration could prove very valuable in low altitude measurements requiring simultaneous data collection at the various probe positions. Good time correlation of the measurements is one benefit of this system.

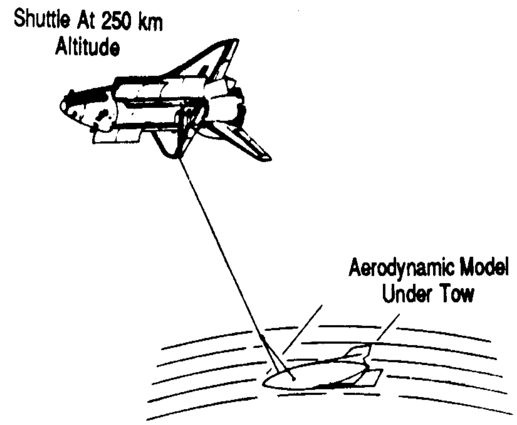
CONTACTS:

- Enrico Lorenzini
- Rod Heelis

REFERENCES:

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Shuttle Continuous Open Wind Tunnel



APPLICATION: Obtain steady-state aerothermo-dynamic research data under real gas conditions without experiencing limitating effects inherent in ground-based wind tunnels.

DESCRIPTION: A tethered aerodynamically shaped research vehicle is deployed downward form the Space Shuttle to obtain data in the free molecule, transition, and upper continuum flow regimes. Characterization of the free-stream, measurement of gas-surface interactions, flow field profiling, and determination of state vectors are to be accomplished.

CHARACTERISTICS:
- Length: 100-120 km
- Mass: Variable, dependent on mission requirements
- Power Required: TBD, for instruments and data handling only
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:
- Quantitative definition of data requirements
- Define method for flow-field profiling
- Quantitative analysis of orifice effects vs. altitude

STATUS:
- Prototype experiment and instrument package proposed for ATM mission

DISCUSSION: Unique measurements are possible due to low Reynold;s number and high Mach number regime. Measurements in real-gas will provide more dependable data regarding fluid flow, turbulence, and gas-surface interactions.

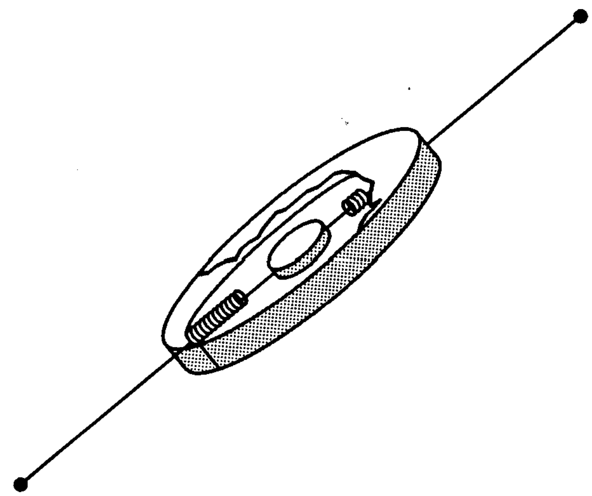
CONTACTS:
- Giovanni Carlomagno
- Franck Hurlbut
- George Wood

REFERENCES:

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- CONCEPTS --

Gravity Wave Detection Using Tethers



APPLICATION: To detect gravity waves from sources such as binary stars, pulsars, and supernovae.

DESCRIPTION: The system would consist of two masses on each end of a long tether with a spring at its center. As this tether system orbits the Earth, gravitational waves would cause the masses to oscillate. This motion would be transmitted to the spring, which would be monitored by a sensing device. Analysis of the spring displacement and frequency could then lead to the detection of gravity waves.

CHARACTERISTICS:

- Mass: 20 kg (Each End Mass)
- Tether Length:25 km
- Tether diameter: 0.6 mm
- Spring Constant: $K_S = 2.3 \times 10^3$ dyne/cm
- Orbital Altitude: ≥ 1000 km
- Potential For Technology Demonstration: Long-Term

CRITICAL ISSUES:

- Existence of gravity waves
- Gravity wave noise level from other bodies
- Excitation of oscillations from other sources

STATUS:

- Preliminary calculations have been performed at SAO, Caltech, and Moscow State University

DISCUSSION: This gravitational wave detector would operate in the 10 - 100 MHz frequency band that is inaccessible to Earth-based detectors because of seismic noise. If gravitational waves do exist in this region, a simple system such as a tether-spring detector would prove of great value.

CONTACTS:

- K. Thorne
- Marino Dobrowolny

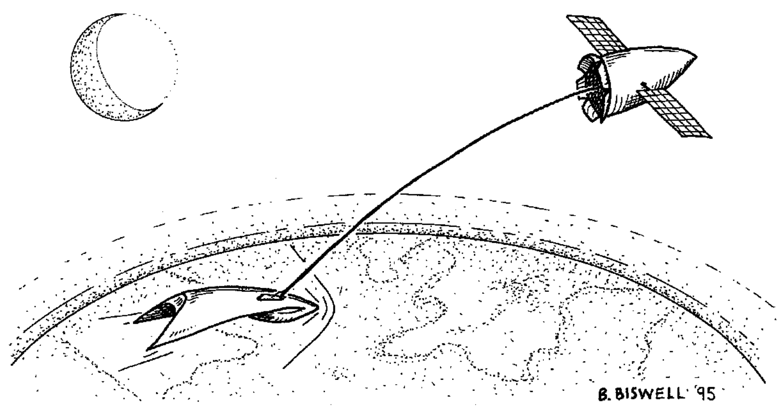
REFERENCES:

V.B. Braginski and K.S. Thorne, "Skyhook Gravitational Wave Detector," Moscow State University, Moscow, USSR, and Caltech, 1985.

B. Bertotti, R. Catenacci, M. Dobrowolny, "Resonant Detection of Gravitational Waves by Means of Long Tethers in Space," Technical Note (Progress Report), Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, March 1977.

-- CONCEPTS --

Tethered Lifting Probe



APPLICATION: The lifting body controls the altitude of the probe in atmospheric tether missions.

DESCRIPTION: A hypersonic lifting body is used for the probe in an atmospheric mission. Changes in lift forces on the probe can be used to control the probe altitude without changing the length of the tether. Required changes in probe attitude can be accomplished using a movable tether attachment point or aerodynamic control surfaces.

CHARACTERISTICS:
- Tether Length: 10-200 km
- Probe Area: 10-50 m^2
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:
- Development of control laws to maintain probe attitude.

STATUS:
- Preliminary results indicate the feasibility of using lift as a control mechanism for probe altitude.
- Current studies favor the use of a movable tether attachment point as a simple and highly effective attitude control mechanism.

DISCUSSION: The lifting probe provides an ideal control mechanism for the altitude of an atmospheric tether system. The alternative is to slowly change the tether length by using a reel mechanism. This may not be effective in situations where probe altitude must be maintained in the presence of atmospheric uncertainties. In addition, the use of a lifting body can increase the atmospheric penetration of the probe without increasing its mass. This concept can be applied to a wide range of tether atmospheric missions from upper atmosphere research to aerocapture.

CONTACTS:
- Jordi Puig-Suari
- Brian Biswell

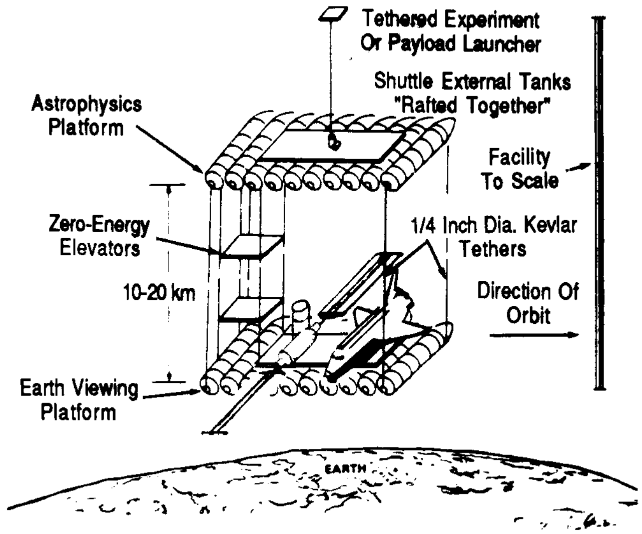
REFERENCES:

Biswell, B., and Puig-Suari, J. "Lifting Body Effects on the Equilibrium Orientation of Tethers in the Atmosphere,"AIAA-96-3597, *AIAA/AAS Astrodynamics Conference*, San Diego, CA, 1996.

Keshmiri, M., and Misra, A.K. "Effects of Aerodynamic Lift on the Stability of Tethered Subsatellite System," AAS-93-184, *AAS/AIAA Spaceflight Mechanics Meeting*, Pasadena, CA, 1993.

-- CONCEPTS --

External Tank Space Structures



APPLICATION: Utilize Shuttle external tanks in a raft format to form a structure in space.

DESCRIPTION: Tethers are used to separate rafts composed of external tanks. These can either be used as a "Space Station" or as structural elements in an evolving Space Station.

CHARACTERISTICS:

- Tether Length:10 - 20 km
- Potential For Technology Demonstration: Long-Term

CRITICAL ISSUES:

- Space operations required to adapt tanks to proposed applications
- External tank induced contamination environment
- Stability/controllability of proposed configuration
- Assembly/buildup operations
- Drag makeup requirements

STATUS:

- Preliminary analysis performed
- Further analyses effort deferred

DISCUSSION: Most likely use of this concept would be as a "space anchor" for tether deployment concepts.

CONTACTS:

- Joe Carroll

REFERENCES:

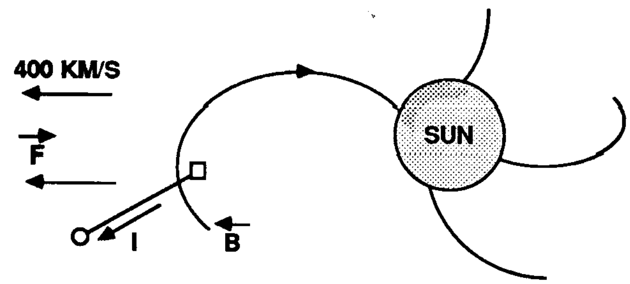
Carroll, J. A., "Tethers and External Tanks, Chapter 3 of Utilization of the External Tanks of the Space Transportation System," California Space Institute, La Jolla, California, Sept. 1982.

Carroll, J. A., "Tethers and External Tanks: Enhancing the capabilities of the Space Transportation System," Dec. 1982

-- CONCEPTS --

Heliocentric Alfven Engine for Interplanetary Transportation

APPLICATION: Generation of propulsion for interplanetary travel by using the electromagnetic interaction of a conducting tether and the interplanetary magnetic field.



DESCRIPTION: An insulated conducting tether, connected to a spacecraft and terminated at both ends by plasma contactors, provides interplanetary propulsion in two ways. The current induced in the tether by the solar wind magnetic field is used to power ion thrusters. The interaction between the tether current and the magnetic field can also be used to produce thrust or drag.

CHARACTERISTICS:

- Tether Length:1000 km
- Cooling: Helium (2°K)
- Current: 1000 A
- Power: 2 MW
- Materials: Superconducting Niobium-Tin
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- How does this system compare with others, such as nuclear or solar sail
- Feasibility and controllability have not been established

STATUS:

- TSS-1R flight to demonstrate electrodynamic interaction with surrounding plasma
- More detailed study and evaluation of this application are required

DISCUSSION: The solar wind is a magnetized plasma that spirals outward from the sun with a radial velocity of about 400 km/sec. The magnetic field of the solar wind is 5×10^{-5} Gauss, producing an electric field of 2 V/km, as seen by an interplanetary spacecraft. If a conducting tether, connected to the spacecraft and terminated at both ends by plasma contactors, were aligned with the electric field, the emf induced in it could yield an electric current. This current could be used to power ion thrusters for propulsion. The current could be maximized by using superconducting materials for the tether. (This system was proposed by Hannes Alfven in 1972). It has been calculated that a 1000 km superconducting wire of Niobium-tin could generate 1000 A (2 MW). To achieve superconduction temperatures, this wire could be housed in an aluminum tube with flowing supercooled (2° K) helium. The tube would be insulated and capped at each end with a refrigeration system.

In addition to the ion thrusters, the interaction of the tether current and solar wind magnetic field would produce thrust or drag. As current flowed in the tether, the magnetic field would exert an IL x B force on the tether. If the spacecraft were moving away from the sun (with the solar wind), a propulsive force would be exerted on the tether as its electrical power was dissipated. A drag would be exerted on the tether if current from an on-board power supply were fed into it against the induced emf. When moving toward the sun (against the solar wind), the opposite conditions would apply.

This system could be used to spiral away from or toward the sun, or to move out of the ecliptic. Theoretically, such a spacecraft could attain the solar wind velocity of 400 km/sec. Use of the electromagnetic interaction between a conducting tether system and the solar wind may allow much shorter transfer times and larger payloads for planetary missions.

CONTACTS:

- Mario Grossi
- Jim McCoy
- Nobie Stone

REFERENCES:

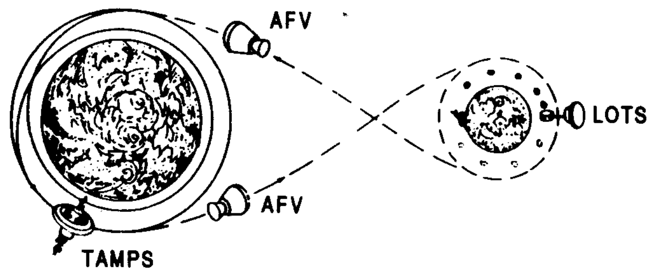
Applications of Tethers in Space, Vol. 1,2 Workshop Proceedings, NASA CP-2365, March 1985

H. Alfven, "Spacecraft Propulsion: New Methods," Science, Vol. 176, pp. 167-168, April 14, 1972.

-- CONCEPTS --

Earth-Moon Tether Transport System

APPLICATION:
Transportation of material from lunar to Earth orbit.



DESCRIPTION: Material (probably Moon rocks) in lunar orbit is collected by the LOTS (Lunar Orbiting Tether Station), half is transferred to an AFV (Aerobraking Ferry Vehicle) which transports it to LEO, where it is transferred to the TAMPS (Tether And Materials Processing Station). The AFV then returns to the Moon for more lunar material.

CHARACTERISTICS:
- Physical Characteristics: Undetermined
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:
- Undetermined

STATUS:
- No detailed study on this application has been performed

DISCUSSION: Material (probably Moon rocks) in lunar orbit could be transported to Earth orbit without the use of propellants with this tether transport system. (The material in lunar orbit could have been placed there by the Lunar Equator Surface Sling; Application "Lunar Equator Surface Sling"). It could be collected in orbit by a Lunar Orbiting Tether Station (LOTS). The LOTS would proceed as follows: (1) catch the rocks, spin-up, catch an Aerobraking Ferry Vehicle (AFV); (2) Load the AFV with half of the rocks; (3) spin-up, throw the AFV into trans-Earth injection; (4) de-spin, load the other rocks on a tether; and (5) spin-up and deboost the rocks for momentum recovery.
The AFV would proceed to Earth, where it would aerobrake into LEO for capture by the Tether And Materials Processing Station (TAMPS). The TAMPS would proceed as follows: (1) catch, retrieve, and unload the aerobraked AFV; (2) process moonrocks into LO_2, etc; (3) refuel and reboost the AFV toward the Moon; (4) recover momentum with an electromagnetic tether; and (5) also capture, refuel, and reboost AFV's going to GEO and deep space when required. The AFV returning to the Moon would be a rocket boosted into trans-lunar injection and final lunar orbit for recapture by the LOTS.

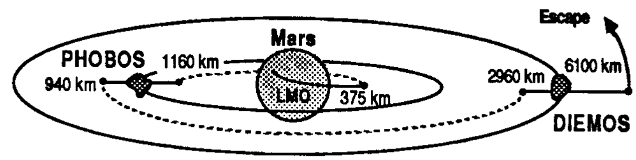
CONTACTS:
- Joe Carroll

REFERENCES:
Applications of Tethers in Space, NASA CP-2422, March 1986.

-- CONCEPTS --

Mars Moons Tether Transport System

APPLICATION: Transportation of manned vehicles and spacecraft from low Mars orbit out to escape, or from escape to low Mars orbit, using tethers attached to the Moons of Mars.



DESCRIPTION: Long tethers (Kevlar strength or better) are attached above and below both Phobos and Deimos to ferry vehicles and other payloads between low Mars orbit and Mars escape without the use of propulsion. For example, a vehicle is tethered upward from a low Mars orbit station, released, and then caught by a downward hanging tether on Phobos. The payload is then transferred to the upward deployed tether and released. The process is repeated at Deimos, and results in escape from Mars. The process is reversible.

CHARACTERISTICS:

- Length: 940 km (up), 1160 km (down) at Phobos; 6100 km (up), 2960 km (down) at Deimos
- Tether Mass: 5000 kg to 90,000 kg
- Tether Diameter: 2 mm (or greater)
- Power: TBD
- Materials: Kevlar, or higher strength material
- Payload Mass: 20,000 kg
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Tether dynamics analysis
- Comparison with other advanced propulsion methods
- Rendezvous feasibility
- Operations and cost
- Tether severing by micrometeoroids or debris

STATUS:

- A conceptual study defines the tether length and strength requirements, but does not address construction, placement, and operation of the tether station.

DISCUSSION: The two moons of Mars, Phobos and Deimos are near equatorial, and can function as momentum banks in the transfer of mass from Mars low orbit to Mars escape (or the reverse). The requirement is to place long tethers, upward and downward, on each of the two moons of Mars. Example uses might be to transfer Deimos or comet material to the Mars surface or to transfer astronauts from Mars surface to a waiting interplanetary low thrust vehicle at Deimos, or to support materials processing in Mars orbit.

Tether stations on Phobos and Deimos may have to be manned for construction, operation, and maintenance. Therefore, other human functions at these satellites would be necessary to make this concept viable. It is best suited to a high activity scenario with departures and arrivals at Mars daily or weekly. A station on Phobos alone would be sufficient for near Mars operations, and could even be used for escape with a sufficiently long upward tether. The mass of the two bodies is so great, ($>10^{15}$ kg) that their orbits would not be affected for decades or longer.

CONTACTS:

- Joe Carroll
- Paul Penzo

REFERENCES:

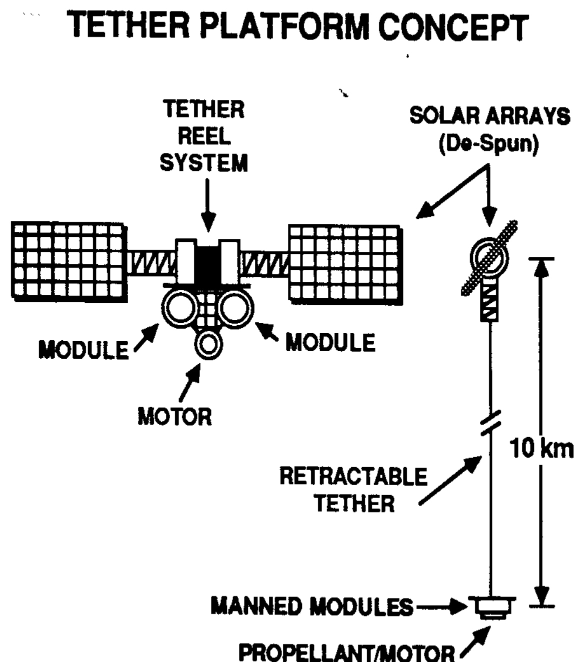
Penzo, P. A., "Tethers for Mars Space Operations," The Case for Mars II, Ed. C. P. McKay, Vol. 62, Science and Technology Series, p. 445-465, July 1984.

-- CONTROLLED GRAVITY --

Rotating Controlled-Gravity Laboratory (Tethered Platform)

APPLICATION: Provide a readily accessible variable/controlled gravity laboratory, capable of generating artificial gravity levels of up to 1 g and over, in Earth orbit.

DESCRIPTION: A tethered platform composed of two end structures, connected by a deployable/retractable 10 km tether. One end structure includes the solar arrays, related subsystems, and tether reel mechanism. The other includes two manned modules and a propellant motor. Artificial gravity is created in the manned modules by extending the tether and firing the motor, rotating the entire system about its center of mass (the solar panels are de-spun). Tether length is used to control the gravity level.



CHARACTERISTICS:

- Length: Up to 10 km
- g-Level: Up to 1.25
- Rotation Rate: Up to 0.75 rpm
- Potential for Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Susceptibility to micrometeoroid/debris damage

STATUS:

- A detailed dynamic analysis has been performed at SAO
- A System study has been performed at Stanford University

DISCUSSION: Access to an orbiting variable/controlled-gravity laboratory, capable of providing artificial gravity levels of up to 1 g and over, would allow vital experimentation in this important gravity range, and provide an appropriate facility, should artificial gravity be determined to be a physiological requirement for extended manned orbital missions. Artificial gravity (in the form of centrifugal acceleration) would be created by rotating the laboratory. The magnitude of the resulting centrifugal acceleration is equal to the square of the angular velocity times the radius of rotation.

Three basic rotating lab configurations are possible - a torus or cylinder (centrifuge), a rigid station, and a tethered platform. The centrifuge is the least attractive because of its relatively small volume, large Coriolis force, and large dynamic disturbance levels. Of the remaining two, the tethered system has several advantages over the rigid one. It would provide a larger radius of rotation, reducing the rotational rate required to produce a desired g-level. This, in turn, would reduce unwanted side effects, such as the Coriolis force. The variable tether length would also allow a large variety of artificial gravity environments. To spin the system, the tether would be extended to its full 10 km length, and the motor fired. (The minimum necessary Delta-V has been calculated to be 125 m/s.) The tether length would then be adjusted to provide the desired g-level. Assuming the end masses are equal and rotating about a common center, 0.08 g would result from a tether length of 10 km at a spin rate of 0.12 rpm, 0.16 g (lunar gravity) from a length of 8 km at 0.20 rpm, 0.38 g (Mars gravity) from a length of 6 km at 0.33 rpm, 1 g from a length of 4.3 km at 0.65 rpm, and 1.25 g from a length of 4 km at 0.75 rpm. The solar arrays would be de-spun and sun-oriented. However, a disadvantage is the high Delta-V required to start and stop this spin. Another is the fact that the rotation would probably have to be stopped to allow docking with a spacecraft.

This lab would allow experimentation at gravity levels ranging from low gravity, through Moon, Mars, and Earth gravities, to more than 1 g. The effects of gravity on plant and animal growth, and on human performance and medical processes (such as those related to the cardiovascular, skeletal, and vestibular systems) could be studied for prolonged periods of time. Gravity conditions on the Moon and Mars could be simulated, and the lab could be used to prepare for the possible use of artificial gravity on manned interplanetary missions. It could also provide Earth-like habitability at partial g. Such physical processes as crystal growth, fluid science, and chemical reactions could be studied at various gravity levels.

CONTACTS:

- Enrico Lorenzini
- Paul Penzo
- Chris Rupp

REFERENCES:

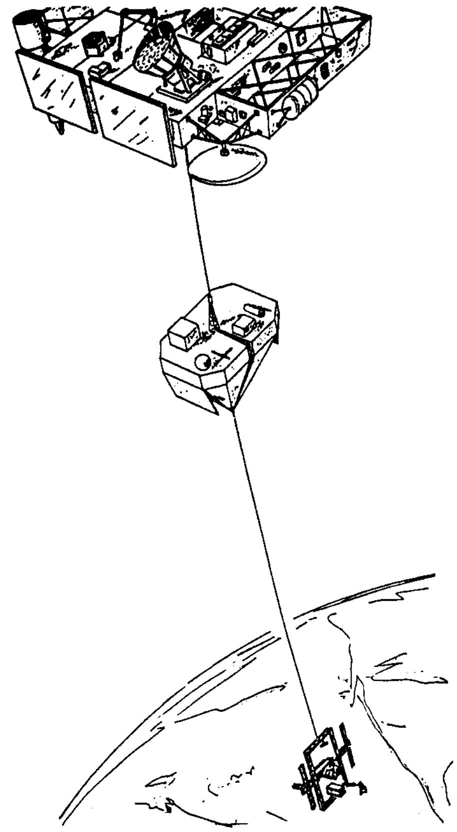
Applications of Tethers in Space, NASA CP-2422, March 1986

B.M.Quadrelli, E.C. Lorenzini, "Dynamics and Stability of a Tethered Centrifuge in Low Earth Orbit", The Journal of the Astronautical Sciences, Vol. 40, No. 1, 1992, pp.3-25

Powell, J. David, Systems Study of a Variable Gravity Research Facility, Final Report to NASA (Grant No. NCA2-208), April 1988.

-- CONTROLLED GRAVITY --

Tethered Space Elevator



APPLICATION: The Space Elevator may be used as a Space Station facility to tap different levels of residual gravity, and a transportation facility to easily access tethered platforms.

DESCRIPTION: The Space Elevator is an element able to move along the tether in a controlled way by means of a suitable drive mechanism. The primary objectives of the microgravity elevator mission are the achievement of a new controllable microgravity environment and the full utilization of the Space Station support while avoiding the microgravity disturbances on board the Space Station. A shorter and slack cable could be used as both a power and data link.

A ballast mass represents the terminal end of the tether system. It could be any mass (e.g., a Shuttle ET) or a tethered platform. The objective of the transportation elevator application is to access large tethered platforms for maintenance, supply of consumables, or module and experiment exchanges.

CHARACTERISTICS:

- Length: 10 km
- Elevator Mass: 5,000 kg
- Ballast Mass: Up to 50,000 kg
- g-Level: 10^{-7} to 10^{-3}
- Power Required: Up to 10 kW by Tether Power Line Link
- Link Data Rate: Up to 40 Mb/s by Tether Optical Fiber Link

- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Space Station impacts
- Dynamic noise induced on the tether drive mechanism
- Gravity-measuring instrumentation
- Power link technology
- Optical fibers link technology

STATUS:

- ASI/Aeritalia Elevator Definition Study in initial design assessment phase, Final Report issued in March 1988

- Analysis of dynamics during deployment, station-keeping, and transfer maneuvers carried out by the Smithsonian Astrophysical Observatory under contract to NASA/MSFC

DISCUSSION: The most promising feature offered by the Space Elevator is the unique capability to control with time the gravity acceleration level. In fact, since the radial acceleration changes with position along the tether, the Elevator would be able to attain a continuous range and a desired profile vs. time of residual gravity level by the control of the Elevator motion. Moreover, the Elevator is able to fully utilize the Space Station support (power, communications, logistics) and to avoid the Space Station contaminated environment, from a microgravity point of view, by tether mediation.
Another way to exploit the Space Elevator capabilities is its utilization as a transportation facility. The idea of using large tethered platforms connected to the Space Station by power line and communication link (via tether technology) makes unrealistic frequent operations of deployment and retrieval. On the other hand, the platform may require easy access for maintenance, supply of consumables, module and experiment exchange. The Space Elevator, as a transportation facility able to move along the tether to and from the platform, may be the key to tethered platform evolution.

CONTACTS:

- Franco Bevilacqua
- Enrico Lorenzini
- Pietro Merlina

REFERENCES:

Applications of Tethers in Space, NASA CP-2422, March 1986

F. Bevilacqua and P. Merlina, "The Tethered Space Elevator System," Second International Conference on Tethers In Space, Venice, Italy, 1987.

SATP Definition Study, Mid-Term Report, Aeritalia, TA-RP-AI-002, March 21, 1986.

Tethered Space Elevator Definition and Preliminary Design, Final Report, Aeritalia, TA-RP-AI-009, 1988.

L.G. Napolitano and F. Bevilacqua, "Tethered Constellations, Their Utilization as Microgravity Platforms and Relevant Features," IAF-84-439.

S. Bergamaschi, P. Merlina, "The Tethered Platform: A Tool for Space Science and Application," AIAA-86-0400, AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986.

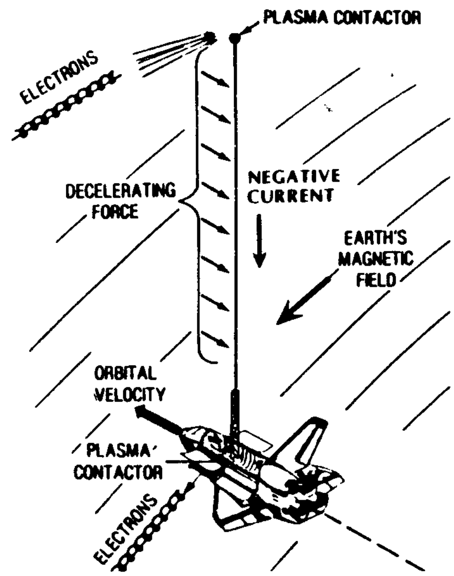
Lorenzini, E.C., M.D. Grossi, D.A. Arnold, and G.E. Gullahorn, "Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit (Phase II)," Smithsonian Astrophysical Observatory Reports for NASA/MSFC, Contract NAS8-36606. Quarterly Reports

Lorenzini, E.C., "A Three-Mass Tethered System for Micro-g/Variable-g Applications," Journal of Guidance, Control, and Dynamics, Vol. 10, No.3, May-June 1987. (pp. 242-249)

Applications "Microgravity Laboratory" and "Variable/Low Gravity Laboratory"

-- ELECTRODYNAMICS --

Electrodynamic Power Generation (Electrodynamic Brake)



APPLICATION: Generation of DC electrical power to supply primary power to on-board loads.

DESCRIPTION: An insulated conducting tether connected to a spacecraft and possibly terminated with a subsatellite. Plasma contactors are used at both tether ends or with the bare tether (see sect. 2). Motion through the geomagnetic field induces a voltage across the orbiting tether. DC electrical power is generated at the expense of spacecraft/tether orbital energy.

CHARACTERISTICS:

- Power Produced: 1 kW - 1 MW
- Length: 10 - 20 km
- Mass: 900 - 19,000 kg
- Efficiency: ~90%
- Materials: Aluminum
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Flight experiment validation of the current-voltage characteristics of plasma contactor devices and operating at currents of up to 50 A in the ionosphere are urgently needed to validate results from chamber tests and theoretical models in space
- Flight experiment validation of the current-voltage characteristics of the bare tether concept
- Flight experiment determination of the role played by ignited mode operation in the ionosphere
- Ground and flight experiment validation of the theoretically predicted role of plasma contactor cloud instabilities
- Characterization of the magnetosphere current closure path and its losses
- Characterization of the effects of large electromagnetic tether systems on the LEO environment and other space vehicles
- Assurance of long-term insulator life
- Characterization of massive tether dynamics
- Development of space compatible insulation methods and power processing electronics for multikilovolt operation
- Susceptibility to micrometeoroid/debris damage
- Understanding of current collection effects at resulting insulator defects and their impacts on system performance (as in TSS1R)

STATUS:

- TSS-1 and -1R, PMG flights
- A wide variety of work is actively underway in the areas of electrodynamic demonstrations, hollow cathodes, tether materials, and hardware technologies including a demo flight (see section 2 and “bare tether” concept)

DISCUSSION: An orbiting insulated tether, terminated at the ends either by plasma contactors or by a bare section of tether, can be used reversibly as an electrical power or thrust generator. Motion through the geomagnetic field induces a voltage in the tether, proportional to its length and derived from the v x B electric field and its force on charges in the tether. This voltage can be used to derive a DC electrical current in the tether. Electrical power is generated at a rate equal to the loss in spacecraft orbital energy due to a drag force of magnitude (ilB) where i is the tether current and l is the length. It has been shown that this drag force functions as an electrodynamic brake and can be used to perform orbit maneuvering in LEO or in the ionosphere of planets such as Jupiter or Saturn.

Three basic plasma contactor configurations have been considered in the studies performed to date: (1) a passive large-area conductor at both tether ends; (2) a passive large-area conductor at the upper (positive) end and an electron gun at the lower (negative) end and (3) a plasma-generating hollow cathode configuration. Hollow cathodes as flown on PMG are considered to be safer for spacecraft systems, since they establish a known vehicle ground reference potential with respect to the local plasma. They also allow simple reversibility of the tether current for switching between power and thrust generation.

CONTACTS:

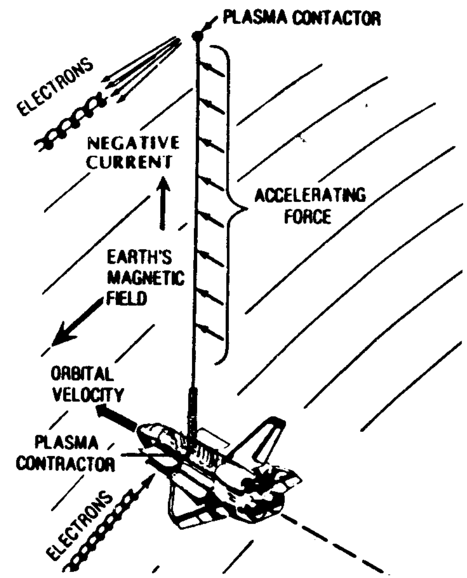
- Les Johnson
- Joseph Kolecki
- Jim McCoy
- Juan Sanmartin
- Nobie Stone

REFERENCES:

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- ELECTRODYNAMICS --

Electrodynamic Thrust Generation



APPLICATION: Generation of electro-magnetic propulsive thrust to boost the orbit of a spacecraft.

DESCRIPTION: An insulated conducting tether connected to a spacecraft and possibly terminated with a subsatellite. Plasma contactors are used at both tether ends. Current from an on-board power supply is fed into the tether against the emf induced by the geomagnetic field, producing a propulsive force on the spacecraft/tether system. The propulsive force is generated at the expense of primary on-board electric power.

CHARACTERISTICS:

- Thrust Produced: Up to 200 N
- Power Required: Up to 1.6 MW
- Length: 10-20 km
- Mass: 100-20,000 kg & power supply
- Efficiency: ~90%
- Materials: Aluminum
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- The same as listed in Electrodynamic Power Generation application

STATUS:

- The same as listed in Electrodynamic Power Generation application

DISCUSSION: An insulated conducting tether, terminated at the ends by plasma contactors, can be used reversibly as an electromagnetic thruster or electrical power generator. A propulsive force of IL x B is generated on the spacecraft/tether system when current from an on-board power supply is fed into the tether against the emf induced in it by the geomagnetic field.

Recommendations have been made through the years to use electrodynamic tethers to provide drag compensation and orbital maneuvering capability for the International Space Station, other solar array powered satellites, and to use higher power tethers (up to about 1 MW) for orbital maneuvering of the Space Station and other large space systems. Design tradeoffs were also recommended, including:

- Use of counterbalancing tethers deployed in opposite directions to provide center-of-mass-location control
- Use of shorter tethers operating at low voltage and high current versus longer tethers operating at high voltage and low current
- Definition of electrical/electronic interface between the tether and the user bus.

CONTACTS:

- Marino Dobrowolny
- Les Johnson
- Joseph Kolecki
- Jim McCoy
- Juan Sanmartin
- Nobie Stone

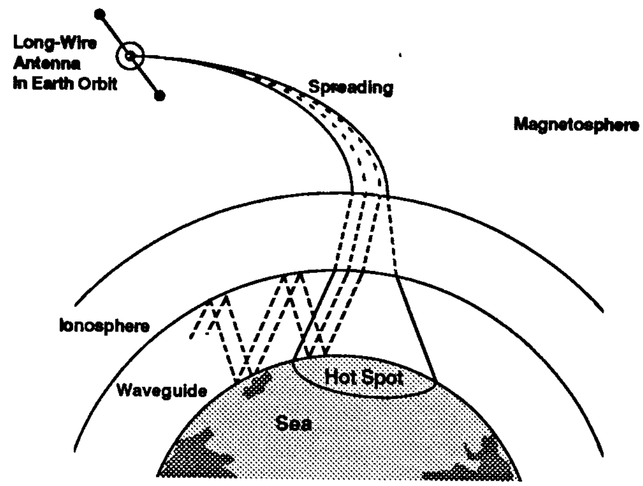
REFERENCES:

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- ELECTRODYNAMICS --

ULF/ELF/VLF Communications Antenna

APPLICATION: Generation of ULF / ELF / VLF waves by an orbiting electrodynamic tether for worldwide communications.



DESCRIPTION: An insulated conducting tether connected to a spacecraft, and terminated at both ends with plasma contactors. Variations in tether current can be produced to generate ULF/ELF/VLF waves for communications. This tether antenna can be self-powered (using the current induced in it by the geomagnetic field for primary power) or externally powered (fed by an on-board transmitter).

CHARACTERISTICS:

- Length: 20-100 km
- Tether Current: 10 A
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Characterization of the transmitter
- Characterization of the propagation media (including the ionosphere at LEO altitudes, the lower atmosphere, and ocean water)
- Analysis of the sources of background noise and the statistical structure of that noise at the receiver
- Characterization of the instabilities and wave due to large current densities in the Alfven wings
- More advanced mathematical models are required for an adequate understanding of tether antenna systems, including the need to supersede the present cold-plasma based models with more accurate warm-plasma based models
- Determination of optimum ground station locations, including the possibility of mobile receivers
- Correlation of signals received at different ground station locations to subtract out noise

STATUS:

- TSS-1 and TSS- 1R flights

DISCUSSION: When a current flows through the tether, electromagnetic waves are emitted, whether the current is constant or time-modulated. The tether current can be that induced by tether motion through the geomagnetic field, or one generated by an on-board transmitter. Modulation of the induced current can be obtained by varying a series impedance, or by turning an electron gun on the lower end on and off, at the desired frequency. Waves are emitted by a loop antenna composed of the tether, magnetic field lines, and the ionosphere.

ULF/ELF/VLF waves produced in the ionosphere will be injected into the magnetosphere more efficiently than those from present ground-based man-made sources. These waves may provide instant worldwide communications by spreading over most of the Earth via the process of ducting. With a 20-100 km tether and a wire current of the order of 10 A, it appears possible to inject into the Earth-ionosphere transmission line power levels of the order of 1 W by night and 0.1 W by day.

CONTACTS:

- Robert Estes
- Mario Grossi
- Giorgio Tacconi

REFERENCES:

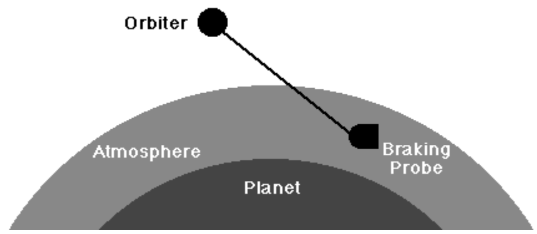
Grossi, M. D., "A ULF Dipole Antenna on a Spaceborne Platform of the PPEPL Class," Report for NASA contract NAS8-28203, May, 1973.

P.R.Bannister et al. “Orbiting Transmitter and Antenna for Spaceborne Communications at ELF/VLF to Submerged Submarines”, Agard Conference Proceedings 529, May 1993, pp. 33-1-33-14

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- PLANETARY --

Aerocapture with Tethers for Planetary Exploration



APPLICATION: May provide significant mass savings when used in the exploration of the atmosphere-bearing planets and satellites in the solar system.

DESCRIPTION: The basic concept involves an orbiter and a probe connected by a long, thin tether. The probe is deployed into the atmosphere of a planet where aerodynamic drag decelerates it from hyperbolic approach speed to capture speed. The tension on the tether provides the braking effect on the orbiter, thus eliminating the need for a retro-propulsion maneuver. During the maneuver the orbiter travels outside the atmosphere and does not require heat shielding.

CHARACTERISTICS:

- Tether Length: 10-100 km
- Tether Diameter: 0.5-1.5 mm
- Orbiter Mass: 1000 kg
- Probe Mass: 1000 kg
- Probe Area: 500-3000 m^2
- Potential for Technology Demonstration: Mid-term

CRITICAL ISSUES:

- Reducing the probe area without causing significant bending in the tether.
- Assessing the effect of parameter uncertainties (such as atmospheric density, target altitude, ballistic coefficient and spin rate) on tether and maneuver design.
- Developing guidance and control laws and mechanisms to handle these uncertainties.

STATUS:

- Preliminary analyses demonstrate the feasibility of the concept.
- Reentry of SEDS-1 provides insight into the dynamics of a tether in an atmosphere.

DISCUSSION: Analytical and numerical studies have considered the possibility of using the aerobraking tether for the exploration of Venus, Mars, Jupiter, Saturn, Uranus, Neptune and Titan as well as for returning to Earth from Mars. One study compares the propellant mass of a typical rocket propulsion system to the tether mass required for the aerobraking system. In every instance in this study, the tether mass turns out to be less than the propellant mass.
The feasibility of the design is supported by studies that include flexibility, out-of-plane effects and parameter uncertainties. As a passive system, the aerobraking tether is less sensitive to parameter uncertainties than the typical aerobraking configuration.
For precise guidance, the system seems well suited to feedback control by adjusting the tether length.

CONTACTS:

- James M. Longuski
- Jordi Puig-Suari
- Steven G. Tragesser

REFERENCES:

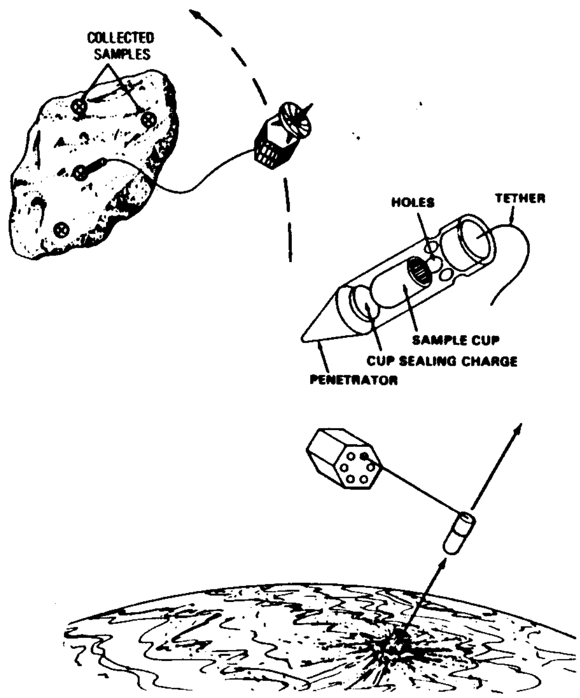
Puig-Suari, J., "Aerobraking Tethers for the Exploration of the Solar System," Ph.D. Thesis, School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, August 1993.

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Comet/Asteroid Sample Return

APPLICATION: Collection and return to Earth of comet or asteroid samples.

DESCRIPTION: Tethered penetrators are launched from a spacecraft during its rendezvous with a comet or asteroid. They penetrate the body's surface, collecting samples of surface material. They are then reeled aboard the spacecraft for return to Earth. Using several penetrators, samples could be collected from different spots on one body, or from more than one body.



CHARACTERISTICS:

- Tether Length: 50-100 m
- Tether System: Single Reel
- Penetrator System: Multiple Chambered Turret
- Penetrators: Core Drilling and Surface
- Deployment: Spring and Solid Rocket
- Potential for Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Long-range, remote-controlled maneuvering and rendezvous
- Design and development of the penetrators, tether-reel subsystem, and penetrator turret subsystem

STATUS:

- Preliminary definition of the mission and hardware has been performedat JPL
- Detailed Analysis and design performed by Alenia for ESA’s ROSETTA

DISCUSSION: The conventional approach to collecting samples from comets and asteroids would be for a spacecraft to rendezvous with them and release a lander. The lander would attach itself to the body in some way, drill for a core sample, and return to the spacecraft. The sample would then be returned to Earth. A typical scenario would require the following capabilities: (1) close range verification of a suitable landing and drilling site; (2) automated and highly accurate soft landing; (3) lander attachment to the body (since some would have very low gravity); (4) a drill unit with sufficient power to core a sample;

(5) lander separation from the body; (6) automated rendezvous with the orbiter; (7) sample transfer; (8) launch stage ejection; and (9) Earth return.

A tether approach would consist of the following sequence of events: (1) the spacecraft rendezvous with the comet or asteroid; (2) a tethered penetrator is shot at the target from a 50-100 m altitude; (3) on impact, sample material enters holes in the penetrator shell and fills the sample cup inside; (4) an explosive seals the cup and ejects it from the penetrator shell; (5) the cup velocity creates a tension in the tether as it rotates it; (6) spacecraft thrusters control the cup retrieval as it is reeled aboard; (7) other tethered penetrators retrieve samples from other areas or bodies; and (8) the spacecraft returns the samples to Earth.

In addition to the penetrator design described above, another type, in which the penetrator contains a core drill, could also be used. For this version, flanges would be extended upon impact, to secure the penetrator shell to the surface while the core sample is being drilled. The surfaces hardness would determine which type to use. Both types could be launched from the spacecraft by a spring and then propelled by attached solid rockets to the impact point. (This should impart sufficient momentum to permit a good surface penetration.) To allow a single tether reel subsystem to handle many penetrators, a rotatable turret with multiple, chambered penetrators could be used.

This tether system has the advantage of being simpler than a lander system (not requiring many of the capabilities listed for a lander system), and of allowing the collection of samples from more than one spot or body. The cost of such a tether mission has been estimated to be about $750 M, as opposed to about $1-2 B for a lander mission. However, the two methods are complementary in that the lander provides a single very deep sample and the penetrator provides smaller samples from different areas or bodies.

<u>CONTACTS:</u>

- Pietro Merlina
- Paul Penzo

<u>REFERENCES:</u>

"Tether Assisted Penetrators for Comet/Asteroid Sample Return," by Paul A. Penzo (JPL); paper presented at 1986 AIAA/AAS Astrodynamics Conference.

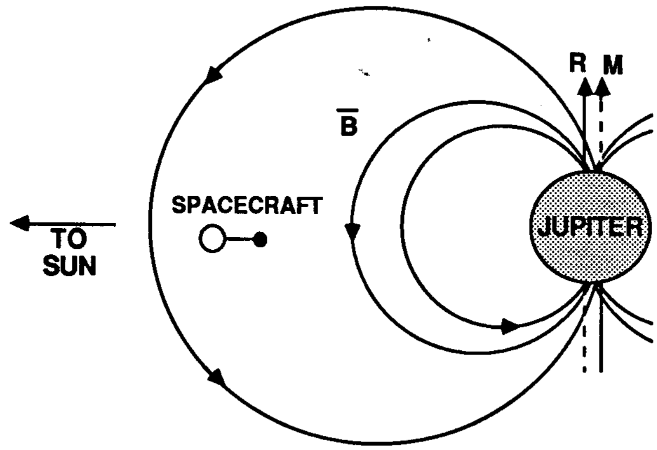
“Feasibility Assessment of a Tethered Harpoon for the ROSETTA backup Sampling”, Alenia Spazio, SD-RP-AI-040, January 1990

“CSNR, Mission and System Definition Document”, ESA SP-1125, June 1991

-- PLANETARY --

Jupiter Inner Magnetosphere Maneuvering Vehicle

APPLICATION: Generation of electro-magnetic thrust or drag for maneuvering within the inner Jovian magnetosphere.



DESCRIPTION: An insulated conducting tether connected to a spacecraft and possibly terminated with a subsatellite. Plasma contactors are used at both tether ends. When used selectively with an on-board power supply (probably nuclear) or a load, it interacts with the Jovian magnetic field to produce thrust, drag and electrical power as required to change orbital altitude or inclination.

CHARACTERISTICS:

- Physical Characteristics: Undetermined
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Successful operation of hollow cathodes or related active collectors as plasma contactors
- Assurance of long-term insulator life
- Susceptibility to micrometeoroid/debris damage
- Successful operation of a power supply (probably nuclear) with sufficient output power density
- Characterization of the performance of an electromagnetic tether in the Jovian Magnetosphere

STATUS:

- TSS-1, demonstrating electrodynamic applications, is scheduled for a 1991 launch
- No detailed system design study for this application has been performed

DISCUSSION: Since Jupiter's magnetic field is about twenty times that of Earth, an electromagnetic tether should work well there. Because of Jupiter's rapid rotation (period = 10 hrs), at distances greater than 2.2 Jovian radii from its center, the Jovian magnetic field rotates faster than would a satellite in a circular Jovian orbit. At these distances, the magnetic field would induce an emf across a conducting tether, and the dissipation of power from the tether would produce a thrust (not drag) on the spacecraft/tether system. At lesser distances, the satellite would rotate faster than the magnetic field, and dissipation of tether power would produce drag (not thrust). Examples of induced tether voltages are:
-10 kV/km (for drag) in LJO; and +108, 50, 21, and 7 v/km (for thrust) at Io, Europa, Ganymede, and Callisto, respectively.

Inside the Jovian magnetosphere, at distance > 2.2 Jovian radii, the spacecraft could decrease altitude (decelerate) by feeding power from an on-board power supply into the tether against the induced emf. Below 2.2 radii, power from the tether could be dissipated. To return to higher altitudes, the process could be reversed.

Since the gravitational attraction of Jupiter is so strong, the energy required to descend to (or climb from) a very low Jupiter orbit is prohibitive for any conventional propulsion system. To descend to the surface of Jupiter from a distance of, say, 100 Jovian radii, an energy density of a little over 200 kW-hr/kg would be required for propulsion. Using this as a conservative estimate of the required performance of a tether system, it should be well within the capability of a nuclear power supply.

Recommendations were made at the Tether Workshop in Venice (October 1985) for a Jupiter inner magnetosphere survey platform to operate in the range from one to six Jovian radii. The electromagnetic tether in this application would be used primarily for orbital maneuvering. It could also assist a Galileo-type satellite tour (all equatorial), sampling of the Jovian atmosphere, and rendezvous with a Galilean satellite.

CONTACTS:

- Paul Penzo
- James McCoy

REFERENCES:

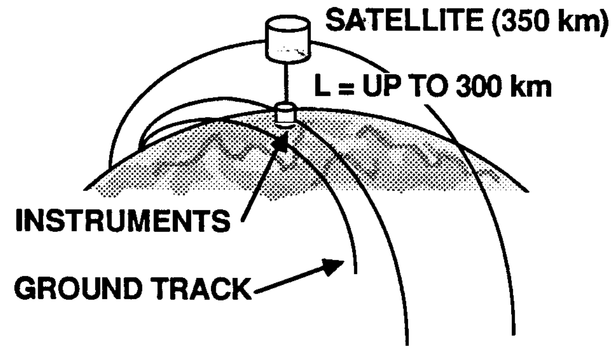
Applications of Tethers in Space, NASA CP-2422, March 1986.

Gabriel, S. B., Jones, R. M., and Garrett, H. B., "Alfven Propulsion at Jupiter," Tether Int. Conf. 1987.

Penzo, P. A., "A Survey of Tether Applications to Planetary Exploration," AAS 86-206, AAS Int. Conf. 1986.

-- PLANETARY --

Mars Tethered Observer



APPLICATION: Provide instrument access to low orbital altitudes for periodic *in-situ* analysis of the upper Martian atmosphere.

DESCRIPTION: An instrument package attached by a deployable tether (up to 300 km in length) to an orbiting Mars Observer spacecraft.

CHARACTERISTICS:
- Length: Up to 300 km (Tether is not vertical)
- Satellite Altitude: 350 km
- Instrument Altitude: Down to 90 km
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:
- Tether material (graphite is a potential candidate) and Orbiter fuel consumption

STATUS:
- System performance analysis for various altitudes and different mission scenarios of the probe performed by the Smithsonian Astrophysical Observatory

DISCUSSION: The purpose of the mission itself is to analyze the composition and chemistry of the Martian atmosphere for one Martian year. The tether would allow instruments to be lowered periodically for *in-situ* measurements at lower altitudes and collection martian dust during storms thus saving on landers's costs. A tether (Up to 300 km long) could be used with the observer as it orbits Mars at an altitude of 350 km. The instrument package would be deployed for a few hours at a time, perhaps every two months, or so. Additional propulsion capability would be required for the observer for altitude maintenance. Although addition of the tether system would increase the mission cost, it should greatly enhance its scientific value.

CONTACTS:
- Enrico Lorenzini
- Paul Penzo
- Monica Pasca

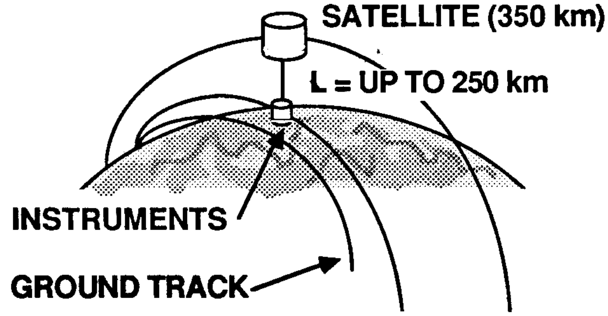
REFERENCES:

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Lorenzini, E.C., MD, Grossi, and M. Cosmo, " Low Altitude Tethered Mars Probe," Acta Astronautica, Vol 21, No.1, 1990, pp. 1-12.

Pasca M. and E. C. Lorenzini, "Optimization of a Low Alitude Tethered Probe for Martian Atmospheric Collection", The Journal of the Astronautical Sciences, Vol. 44, No.2, 1996, pp.191-205

Tethered Lunar Satellite for Remote Sensing



APPLICATION: Provide instrument access to low, unstable, lunar orbital altitudes.

DESCRIPTION: An instrument package at low altitude, suspended by a tether from a satellite in a higher, stable, polar orbit around the moon.

CHARACTERISTICS:
- Tether Length: 90 -250km
- Instrument Altitude: up to 50 km
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:
- Assurance of acceptable strength and flexibility for the tether material
- Susceptibility to micrometeoroid/debris damage

STATUS:
- PROTEUS (PRObe Tethered for Exploration of Uncovered Satellites) study performed by ALENIA Spazio. Analysis of mission scenarios and scientific objectives

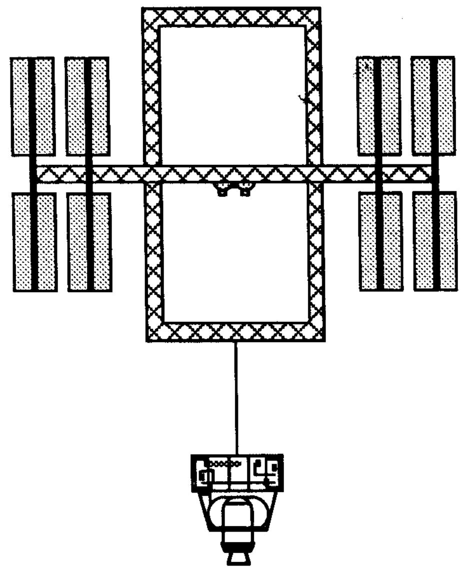
DISCUSSION: Due to Sun and Earth perturbations, close lunar satellites would be unstable and short lived (perhaps a few months). However, as proposed by Giuseppe Colombo, access to low lunar orbits could be achieved by tethering an instrument package to a satellite in a stable lunar orbit. The package could be lowered as close to the Moon as desired. One proposed configuration would tether an instrument package 50 km above the lunar surface from a satellite in a stable 300 km orbit. By using a polar orbit, complete coverage of the lunar surface could be obtained. Occasional adjustments to the tether length may be required to keep the package at a safe altitude. Sensitive measurements of lunar magnetic field and gravitational anomalies could be performed.

CONTACTS:
- Pietro Merlina
- Paul Penzo

REFERENCES:
Colombo G., et al., “Dumbbell Gravity Gradient Sensor: A New Application of Orbiting Long Tethers, SAO Report in Geoastronomy No. 2, June 1976

Merlina P, “PROTEUS-PRObe Tethered for Exploration of Uncovered Satellites: The Proteus Lunar Mission, ESA WPP-081, 1994, pp.512-527

Science Applications Tethered Platform



APPLICATION: Provides a remote platform to the Space Station for space and Earth observation purposes.

DESCRIPTION: A platform, attached to the Space Station by a multifunction tether (power link, data link), provides a new means to allow high precision pointing performance by the combination of disturbance attenuation via tether and active control of a movable attachment point.

CHARACTERISTICS:

- Length: 10 km
- Mass: 10,000 kg
- Power required: Up to 15 kW by Tether Power Line Link
- Link Data Rate: Up to 20 Mb/s by Tether Optical Fibers Link
- Pointing Accuracy: Up to 10 Arcseconds
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Space Station impacts
- Dynamic noise induced on tether
- Movable attachment point control
- Power link technology
- Optical fibers link technology
- Tether impact protection technology

STATUS:

- ASI/Aeritalia SATP Definition Study in initial design assessment phase, mid-term report issued in March 1986. Final report for the current study phase issued in May 1987
- Ball Aerospace, Selected Tether Applications Study Phase III

DISCUSSION: A tethered pointing platform would take advantage of the facilities of the station for maintenance and repair while being isolated from contamination and mechanical disturbances. As an initial step, a medium size pointing platform seems the most suitable facility for a class of observational applications. In fact, if ambitious astrophysical projects justify the design of a dedicated complex free-flyer, medium observational applications of relatively short duration could take advantage of a standard pointing facility able to arrange at different times several observational instruments. This pointing facility could allow reduction of costs, avoiding the cost of separate service functions for each application.

CONTACTS:

- Franco Bevilacqua
- Pietro Merlina
- James K. Harrison

REFERENCES:

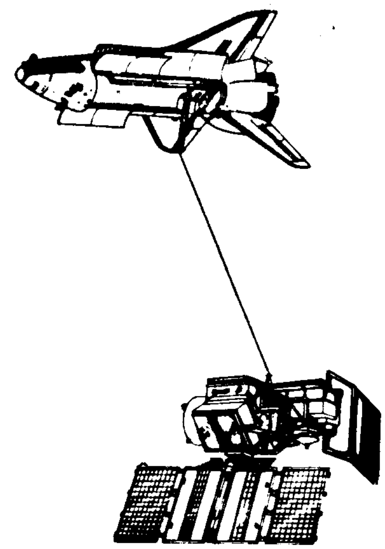
Applications of Tethers in Space, NASA CP-2422, March 1986.

SATP Definition Study, Mid-Term Report, Aeritalia, TA-RP-AI-002, March 21, 1986.

SATP Definition and Preliminary Design, Final Report, Aeritalia, TA-RP-AI-006, 1987.

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Shuttle Science Applications Platform



APPLICATION: Provides a remote platform to the Space Shuttle for various science and applications purposes.

DESCRIPTION: A platform, attached to the Space Shuttle by a tether, provides a unique means by which remote applications may be performed.

CHARACTERISTICS:

- Physical Characteristics: TBD
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Dynamic noise induced on tether
- Micrometeoroid damage

STATUS:

- Various investigators (listed below) have examined preliminary concepts

DISCUSSION: Possible uses for a remote platform include stereoscopic sensing, magnetometry, atmosphere science experiments, and chemical release experiments.

CONTACTS:

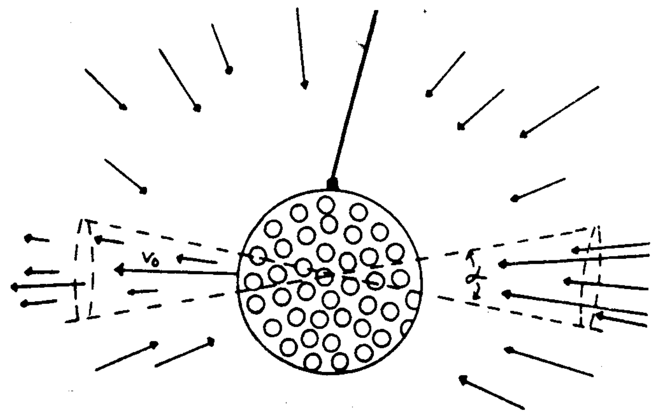
- Franco Angrilli
- Franco Bevilacqua
- Franco Mariani
- Antonio Moccia
- Sergio Vetrella

REFERENCES:

Applications of Tethers in Space, NASA CP-2422, March 1986.

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Tethered Satellite for Cosmic Dust Collection



APPLICATION: To collect micrometeoric material from the upper atmosphere.

DESCRIPTION: A satellite tethered to the Space Shuttle is lowered into the upper atmosphere. The surface of the satellite contains numerous small collecting elements which would document the impact of cosmic dust or actually retain the particles for analysis back on Earth.

CHARACTERISTICS:
- Tether Length: 100 km
- Operating Altitude: 120 km
- Tether Diameter: 1 meter
- Power Requirements: Minimal, enough to operate solenoid activated irises
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:
- Efficient analysis of large collector surface areas to detect micron-sized particles and impact craters

STATUS:
- Preliminary concept design investigated at Indiana University Northwest

DISCUSSION: This concept proposes to collect intact cosmic dust particles smaller than 2 microns which impact the collector surface at velocities less than 3 km/sec, and the study of impact craters and impact debris which result from impacts of all sized particles at velocities greater than 3 km/sec. It is estimated that at a 120 km altitude, between 1×10^3 and 1×10^4 particles will survice collection intact per square meter per day, and between 2×10^4 and 2×10^5 impact craters will be recorded per square meter per day. The figure in the illustration above represents the "survivable" impact cones for particles striking a tethered satellite. For a maximum impact velocity of 3 km/sec, a is approximately 22 degrees.

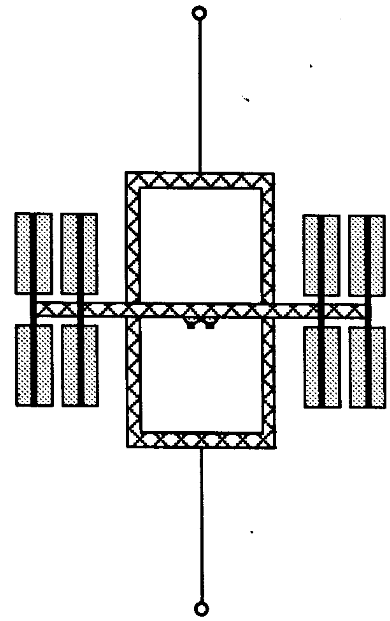
CONTACTS:
- George J. Corso

REFERENCES:

G.J. Corso, "A Proposal to Use an Upper Atmosphere Satellite Tethered to the Space Shuttle for the Collection of Micro-meteoric Material," Journal of the British Interplanetary Society, Vol. 36, pp. 403-408, 1983.

-- SPACE STATION --

Microgravity Laboratory



APPLICATION: Provide a readily accessible laboratory in Earth orbit with the minimum gravity level possible.

DESCRIPTION: A laboratory facility on board the Space Station at its vertical center of gravity. Two opposing tethers with end masses are deployed vertically from the Space Station (one above and one below). Their lengths are varied to control the Space Station center of gravity, placing it on the microgravity modules to minimize their gravity gradient acceleration (artificial gravity level).

CHARACTERISTICS:
- Physical Characteristics: TBD

CRITICAL ISSUES:
- Evaluation of the overall impacts to the Space Station
- Determination of just how good the lab's microgravity would be
- Identification of the process and technologies to be studied in microgravity, and the laboratory facilities and capabilities they will require
- Development of the necessary gravity-measuring instrumentation
- Evaluation of the tether system's cost effectiveness

STATUS:
- A JSC tethered gravity laboratory study (addressing the issues of active center-of-gravity control, identification of low-gravity processes to be studied, and evaluation of the laboratory g-level quality)
- SEDS-1 and -2 missions abd TSS-1 and TSS-1R have provided measurements of the acceleration fields and associated noise during tether and payload deployment

DISCUSSION: To allow the performance of experiments under microgravity conditions (10^{-4} g and less) for extended periods of time, a microgravity laboratory facility could be incorporated into the Space Station. The laboratory modules would be located on the Space Station proper, at its center of gravity. Two opposing TSS-type tethers with end masses would be deployed vertically from the Space Station (one above and one below), to assure that the station center of gravity is maintained within the lab modules. Its exact location would be controlled by varying the upper and lower tether lengths, allowing prolonged and careful control of the residual microgravity magnitude and direction inside the lab. A nearly constant microgravity could be maintained. These tethers would lower the gravity-gradient disturbances transmitted to the experiments being performed while enhancing station attitude control. Although people would be a major source of disturbances, human access to microgravity experiments is preferred (at least initially) over remote access. This configuration would easily accommodate this preference.

One candidate microgravity lab currently under study for the Space Station, is the Materials Technology Lab (MTL). It is projected to be a common module, equipped as a lab, to perform a variety of experiments related to materials technology. Biological experiments may also be performed in microgravity in another module.

Although this is the preferred microgravity lab configuration, two alternatives are also possible. One would be to have the lab connected by a crawler to a single tether from the Space Station. The crawler would position the lab on the station-tether system center of gravity. The other configuration would be to fix the lab to a single tether from the station. The lab would be positioned at the system center of gravity by varying the tether length. Both alternatives have the advantage of isolating the lab from disturbances, but they have the disadvantages of reducing human access and probably precluding the use of the microgravity modules planned for the initial Space Station.

CONTACTS:

- Franco Bevilacqua
- Mario Cosmo
- Pietro Merlina
- Enrico Lorenzini

REFERENCES:

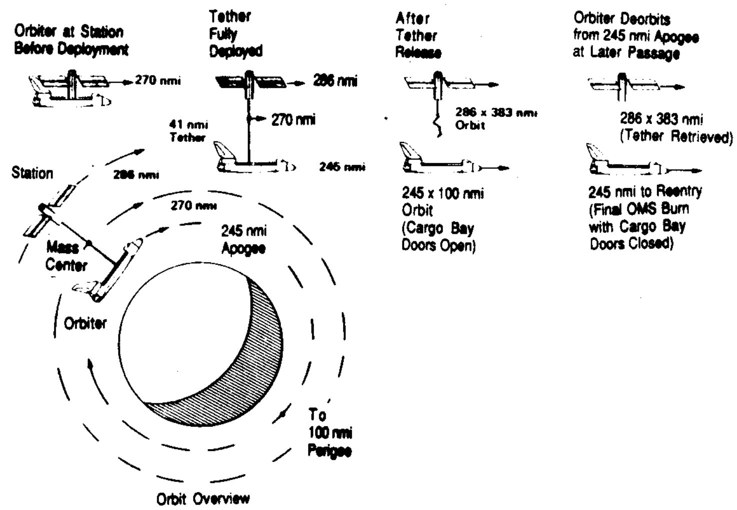
Applications of Tethers in Space, NASA CP-2422, March 1986. (pp. 223-238)

G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.

Lorenzini, E.C., "A Three-Mass Tethered System for Micro-g/Variable-g Applications," Journal of Guidance, Control, and Dynamics, Vol. 10, No.3, May-June 1987, pp. 242-249

-- SPACE STATION --

Shuttle Deorbit from Space Station



APPLICATION: Allows the Shuttle Orbiter to be deboosted to Earth while the Space Station is boosted to a higher orbit.

DESCRIPTION: Upon completion of a Shuttle re-supply operation to the Space Station, the Shuttle is deployed on a tether toward the Earth. The Space Station, accordingly, is raised into a higher orbit, causing excess momentum to be transferred from the Shuttle orbit to the Space Station orbit. After deployment, the Shuttle is released causing the Shuttle to deorbit.

CHARACTERISTICS:

- Initial Space Station/Shuttle Orbit: 500 km
- Tether Length: 65 km
- Final Space Station Orbit: 518 x 629 km
- Final Shuttle Orbit: 185 x 453 km
- Estimated Mass: 250,000 kg (Space Station) 100,000 kg (Shuttle)
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Excess angular momentum scavenged by Space Station must be used in order to beneficially use this application
- Dynamic noise induced by tether deployment and separation
- Alignment of tether to Space Station to eliminate torques

STATUS:

- Martin Marietta, Selected Tether Applications Study, Phase III
- NASA-MSFC System study

DISCUSSION: This application potentially could be one of the most cost effective uses of a tether. The main disadvantage is that the excess momentum transferred to the Space Station must be efficiently used, otherwise the station will be in an orbit too high for subsequent Shuttle re-supply missions. Several ideas on use of this excess momentum have been studied, such as altering STV boosts by the Space Station with Shuttle re-supply missions (see Application "Tethered STV Launch"). Another method is using an electrodynamic tether (see Application "Electrodynamic Power Generator") to generate power at the expense of orbital energy to deboost the Space Station.

CONTACTS:

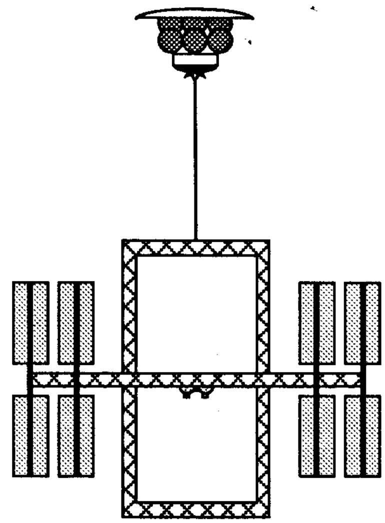
- James K. Harrison
- Les Johnson

REFERENCES:

G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.

-- SPACE STATION --

Tethered STV Launch



APPLICATION: Allows an STV to be boosted to a higher orbit at the expense of Space Station angular momentum.

DESCRIPTION: An STV would be deployed from the Space Station on a tether away from Earth, in preparation for launch. Upon separation from the tether, orbital angular momentum is transferred from the Space Station to the STV, causing the Space Station Altitude to be lowered while that of the STV is raised.

CHARACTERISTICS:

- Initial Space Station/ STV Orbit: 500 km
- Tether Length: 150 km
- Final Space Station Orbit: 377 x 483 km
- Final STV Orbit: 633 x 1482 km
- Estimated Masses: 250,000 kg (Space Station) 35,000 kg (STV)

- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Angular momentum taken away from the Space Station must be resupplied in order to beneficially use this application
- Dynamic noise induced by tether deployment and separation
- Alignment of tether to Space Station to eliminate torques

STATUS:

- Martin Marietta, Selected Tether Applications Study Phase III

DISCUSSION: Martin Marietta has studied the application of tethered deployment of the STV as well as Shuttle from the Space Station. Either of these applications alone would cause an unacceptable change in altitude of the Space Station. When combined, properly sequencing STV launches and Shuttle deorbits, the orbital angular momentum of the Space Station may be preserved while providing a large net propellant savings for the Shuttle, STV and Space Station.

CONTACTS:

- James K. Harrison
- Les Johnson

REFERENCES:

Applications of Tethers in Space, NASA CP-2422, March 1986.

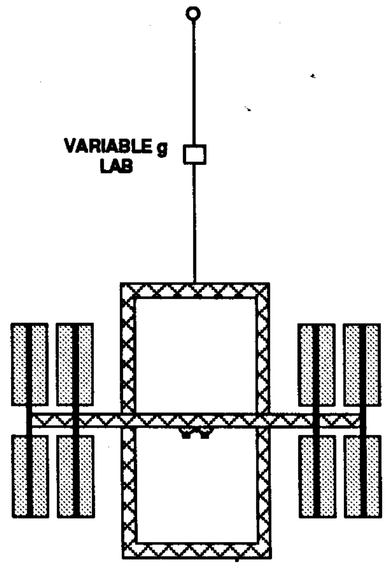
G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.

Application "Shuttle Deorbit From Space Station"

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- SPACE STATION --

Variable/Low Gravity Laboratory



APPLICATION: Provide a readily accessible laboratory in Earth orbit with a variable, low-gravity level.

DESCRIPTION: A laboratory facility, attached by a crawler to a tether deployed vertically from the Space Station. The gravity gradient between the station-tether system center of gravity and the laboratory produces an artificial-gravity force throughout the lab. The lab gravity level, with a constant vertical direction, is varied by changing the lab and crawler distance from the system's center of gravity. The lab can attain microgravity levels if it can move to the center of gravity.

CHARACTERISTICS:

- Physical Characteristics: TBD
- g-Level: Up to 10^{-1}
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Evaluation of the overall impacts to the Space Station
- Determination of just how good the lab's low gravity would be
- Identification of the processes and technologies to be studied in low gravity, and the laboratory facilities and capabilities they will require
- Development of the necessary gravity-measuring instrumentation
- Evaluation of the tether system's cost effectiveness
- Determination of how gravity-level medical experiments should be performed in a Space Station system
- Design of a tether crawler and lab module
- Development of systems for the remote control of the lab experiments

STATUS:

- A study by Alenia-SAO-Padua U. for NASA-JSC on tethered gravity laboratory study (addressing the issues of active center-of-gravity control, identification of low-gravity processes to be studied, and evaluation of the laboratory g-level quality)
- A study by SAO for NASA-MSFC on tethered variable gravity elevators.
- TSS-1 and -1R, SEDS-1 and -2 have provided measurements of the acceleration field change and associated noise during tether and payload deployment

DISCUSSION: To allow the performance of experiments under conditions of constant or variable low gravity (up to 10^{-1} g) for extended periods of time, a variable/low gravity lab could be attached to a crawler on a tether deployed vertically from the Space Station. The artificial gravity at any point along the tether is produced by the gravity gradient between that point and the station/tether system center of gravity, and is proportional to the distance between them. The lab could vary its gravity level, with a constant direction, by varying its distance from the system center of gravity. A constant gravity level could be maintained by adjusting the lab position to compensate for orbital variations in the system gravity level. The lab could also attain microgravity levels if it could move to the center of gravity. This lab could study processes with both gravity and time as variables. It has been calculated the the lab could attain g-levels of 10^{-6}, 10^{-4}, 10^{-2}, and 10^{-1} at distances above the center of gravity of about 2 m, 200 m, 20 km, and 200 km, respectively.

In addition to easy gravity control, the use of a tether system for a low gravity lab would have other advantages. It would reduce disturbances transmitted to the lab (to about 10^{-8} g), minimize the gravity gradient acceleration inside the lab, and enhance overall system attitude control. It would have the disadvantage of reducing human access to lab experiments, requiring the increased use of remote controls. Also, it could only provide a gravity level of up to 10^{-1} g.

This lab could be used to examine the effects of low gravity on both physical and biological processes. Some biological processes of interest would be plant and animal growth, and human performance and medical processes (such as those related to the cardiovascular, skeletal, and vestibular systems). Such physical processes as crystal growth, fluid science, and chemical reactions could be studied. Conditions on low gravity bodies (such as asteroids) could be simulated to examine natural processes (such as meteor impacts). Of particular interest would be the determination of the gravity threshold for various processes.

CONTACTS:

- Chris Rupp
- Silvio Bergamaschi
- Franco Bevilacqua
- Mario Cosmo
- Enrico Lorenzini
- Pietro Merlina

REFERENCES:

Applications of Tethers in Space, NASA CP-2422, March 1986.

G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.

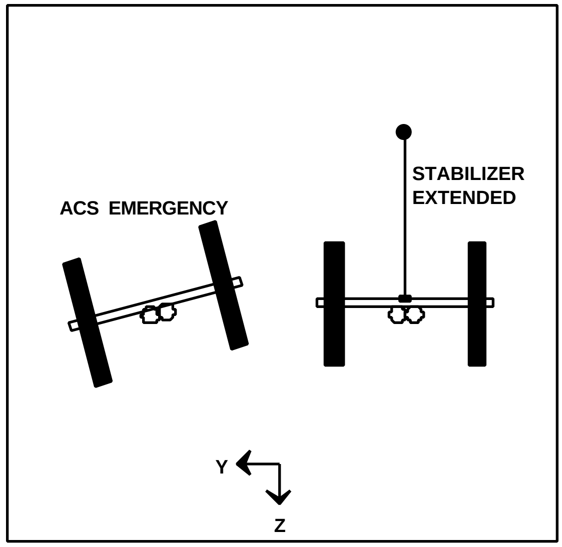
F. Bevilacqua and P. Merlina, "The Tethered Space Elevator System," Second International Conference on Tethers In Space, Venice, Italy, 1987.

E.C. Lorenzini et al., “Dynamics and Control of the Tether Elevator Crawler System”, Journal of Guidance, Control, and Dynamics, Vol. 12, No.3, pp. 404-411 1989

-- SPACE STATION --

Attitude Stabilization and Control

APPLICATION: Provides the Space Station with restoring torques around pitch and roll axes



DESCRIPTION: A tethered ballast could be deployed to serve as an attitude stabilizer. This feature could be used on a temporary basis during the construction of the Space Station or on a permanent basis to alleviate the CMG's requirements as well as function as a backup facility in case of ACS failure.

CHARACTERISTICS:
- Mission Duration: up to some days
- Masses: Deployer ~ 650 Kg; Tether ~ 400 Kg; Ballast ~ 1400 Kg
- Tether Length: 6000 m
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:
- Attitude dynamics of the tether-stabilized Station during -deployment of ballast.
- Assessment of mass, propellant, CMG's sizing, redundancy philosophy and contingencyreboost scenario.

STATUS:
- Feasibility analysis performed by Alenia and SAO for NASA/JSC

DISCUSSION: The typical configuration of the Space Station results in a spacecraft that requires a complex and careful design of the Attitude Control System. CMG's sizing and RCS propellant allocated depend on several nominal and emergency operations that need to be managed. The attitude tether stabilizer concept seems to have the potential for being an effective way of overcoming some of the above difficulties The advantages include: system simplicity, relatively low costs and reusability.

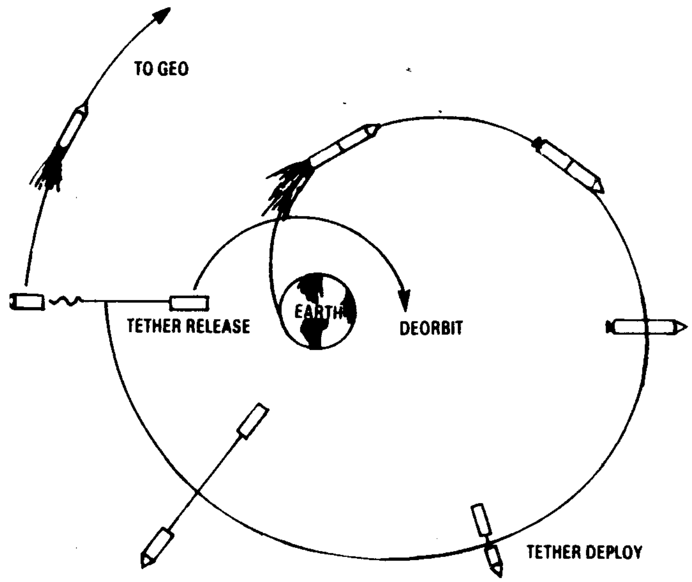
CONTACTS:
- Pietro Merlina
- Enrico Lorenzini

REFERENCES:

"Tethered Gravity Laboratories Study". Performed by ALENIA Spazio and SAO under NASA-JSC Contract NAS9-17877.

Generalized Momentum Scavenging from Spent Stages

APPLICATION: Scavenge angular momentum from a spent stage for the benefit of the payload.



DESCRIPTION: After the injection of an upper stage and its payload into an elliptical park orbit, the payload is tethered above the spent stage. At the proper time, the payload is released which causes a payload boost and spent stage deboost.

CHARACTERISTICS:
- Physical Characteristics : TBD
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:
- Mass of tether and reel equipment versus payload performance gain
- Integration impact on systems

STATUS:
- Preliminary evaluation completed by MIT , Michoud and Tether Applications
- Detailed analysis in progress at SAO in collaboration with Tether Unlimited

DISCUSSION: This concept appears to be impractical due to mass relationships and integration costs. The most immediate application is for newly developed upper stage/payload combinations and those having a high ratio of spent upper stage to payload mass.

CONTACTS:
- Manual Martinez-Sanchez
- Joe Carroll
- Les Johnson
- Enrico Lorenzini

REFERENCES:

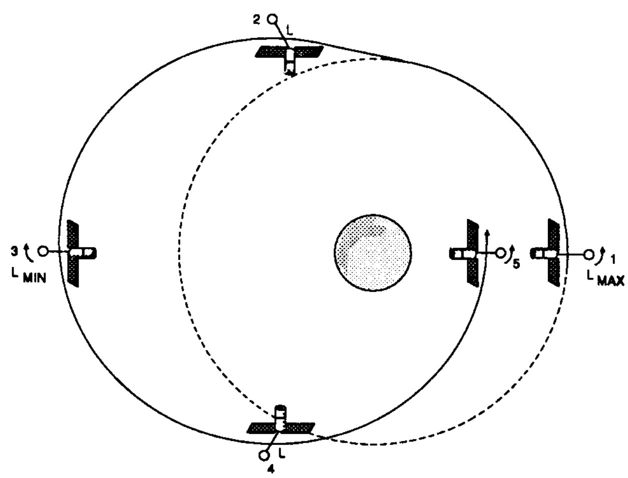
J.A. Carroll "Guidebook for Analysis of Tether Applications," Contract RH4-394049, Martin Marietta Corporation, March 1985. Available from the author

M. Martinez-Sanchez, "The Use of Large Tethers for Payload Orbital Transfer," Massachusetts Institute of Technology, 1983.

G. Colombo, "The Use of Tethers for Payload Orbital Transfer," NASA Contract NAS8-33691, SAO, Vol. II, March 1982.

Internal Forces for Orbital Modification (Orbital Pumping)

APPLICATION: To change the orbital eccentricity of a Space Station or platform without the use of propulsion systems.



DESCRIPTION: The internal mechanical energy of a Space Station (in the form of excess electrical energy transferred to a motor) is used to vary the length of a tether attached to an end mass. The length is changed in phase with the natural libration of the tether, which is known as libration pumping. Proper timing of tether deployment and retrieval done in this fashion can be used to change the orbital eccentricity.

CHARACTERISTICS:

- Physical Characteristics: Undetermined
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Internal vs. external energy trade-off
- Power required and heat generated by the operation
- Change in orbits is relatively slow

STATUS:

- Preliminary feasibility shown by Martin Marietta Denver

DISCUSSION: Orbit eccentricity can be increased by libration pumping as is shown in the illustration. At (1) the mass is fully extended, and libration starts. At (2), with the mass in a prograde swing, the retrieval motor pulls the spacecraft toward the mass, adding energy to the orbit. At (3), which is the new apogee of the orbit, the tether length is at a minimum. At (4), with the mass in a retrograde swing, the tether is re-deployed and the retrieval brakes are used to dissipate orbital energy in the form of excess heat. At (5), the new perigee, the mass is again fully deployed. This procedure is repeated until the desired eccentricity is reached.

CONTACTS:

- Manual Martinez-Sanchez
- Joe Carroll

REFERENCES:

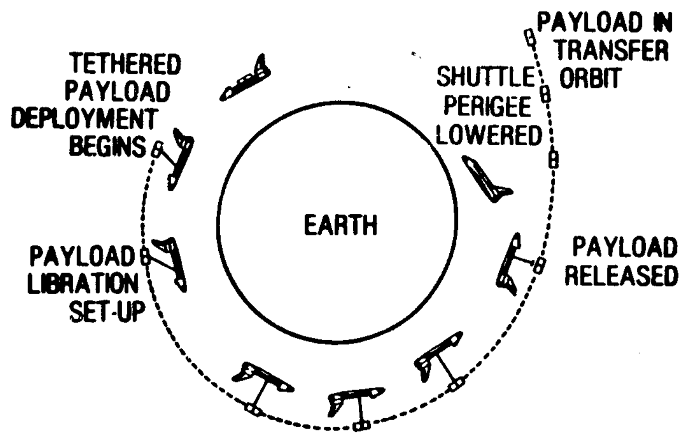
G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.

Breakwell, J. V., Gearhart, J. W., "Pumping a Tethered Configuration to Boost its Orbit Around an Oblate Planet," AAS 86-217, Int. Conf. 1986.

-- TRANSPORTATION --

Satellite Boost from Orbiter

APPLICATION: Boost a satellite payload into a circular or elliptical orbit higher than the Orbiter orbit.



DESCRIPTION: A satellite is deployed along a tether "upward" (away from the Earth) from the Shuttle Orbiter. Libration begins and momentum is transferred from the Shuttle orbit to the satellite. The satellite is released and placed into a higher orbit while at the same time giving the Shuttle a deboost to return to Earth. Less fuel is required for both the satellite and the Orbiter. A TSS-derived deployer could be used.

CHARACTERISTICS:
- Length: Dependent on desired orbit (see "Discussion" below)
- Tether System: Either permanent or removable from Orbiter
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:
- Release mechanism for payload
- Airborne support equipment for Orbiter
- Micrometeorite damage

STATUS:
- Energy Science Lab development contract completed March 1987
- MIT, Martin Marietta-Denver have completed preliminary assessment
- Ball Aerospace, Selected Tether Applications Study, Phase III
- SAO analysis for “SEDSAT” mission

DISCUSSION: This application has been studied in various forms by several contractors as noted above. One example studied is the tethered deployment of the AXAF (Advanced X-Ray Astrophysics Facility) into its operational orbit. For this example, the AXAF is assumed to have a mass of 9,070 kg and the Shuttle (after deployment) a mass of 93,000 kg. With the Shuttle and AXAF at an initial elliptical orbit of 537 x 219 km, the AXAF is deployed along a 61 km tether. As momentum is transferred from Shuttle to AXAF, the Shuttle orbit descends to a new 531 x 213 km and the AXAF orbit ascends to a new 593 x 274 km orbit. After tether separation, the AXAF is directly inserted into a 593 km circular orbit. Simultaneously, the Shuttle takes on an elliptical 531 x 185 km orbit, from which it will make a final OMS burn before its reentry.

CONTACTS:

- James K. Harrison
- Joe Carroll
- Les Johnson
- Enrico Lorenzini
- Manual Martinez-Sanchez

REFERENCES:

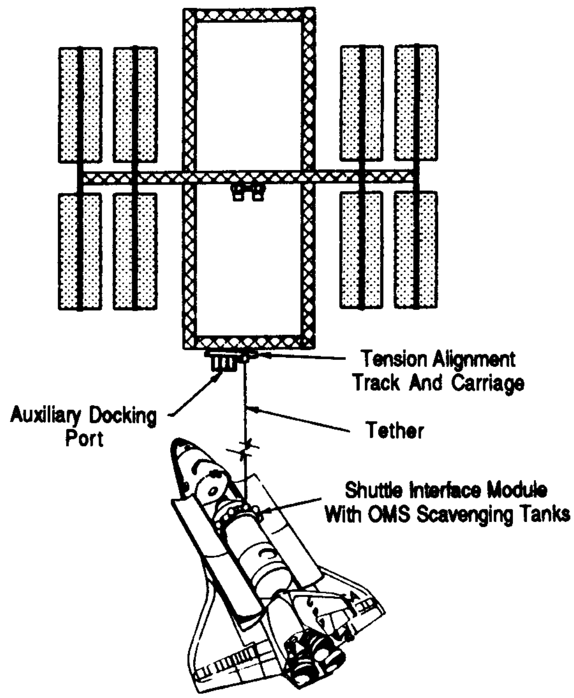
Applications "Upper Stage Boost from Orbiter" and "Small Expendable Deployer System"

Carroll, J. A., "Guidebook for Analysis of Tether Applications," Contract RH4-394049, Martin Marietta Corporation, Feb. 1985.

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

-- TRANSPORTATION --

Shuttle Docking by Tether



APPLICATION: Enables Shuttle Orbiter to dock to other structures such as the Space Station.

DESCRIPTION: A tether deployed by the Space Station is attached to a docking module. This module would capture and retrieve the Shuttle, allowing a remote rendezvous.

CHARACTERISTICS:

- Tether Length: 40-100 Km
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Accurate guidance system, such as GPS needed
- Rendezvous and capture technique definition required
- Post-rendezvous tether dynamics
- Alignment of tethertension with Station center of mass

STATUS:

- Martin Marietta, Selected Tether Applications Study, Phase III

DISCUSSION: A tether, attached to a docking module, would be deployed toward the Earth from the Space Station. The length of deployment is adjusted so that the velocity of the docking module matches the velocity at apogee of an elliptical orbit of the Shuttle. This would cause increased OMS propellant available to the Shuttle. This application would probably be combined with Application "Shuttle Deorbit from Space Station".

CONTACTS:

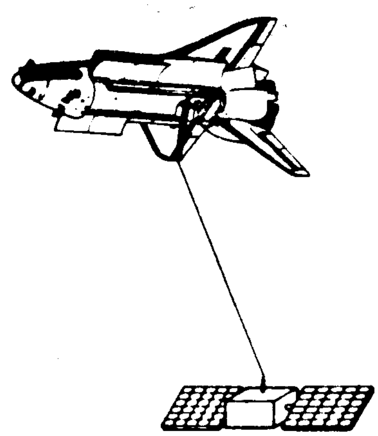
- James K. Harrison
- Chris Rupp

REFERENCES:

Applications of Tethers in Space, NASA CP-2422, March 1986.

-- TRANSPORTATION --

Tether Reboosting of Decaying Satellites



APPLICATION: To retrieve, repair, and reboost a defective or decaying satellite.

DESCRIPTION: A permanent tether attached to the Space Shuttle is used to rendezvous with a decaying satellite. It can then either be repaired by Shuttle crewmen and/or reboosted into a higher orbit. This would eliminate the need to launch a replacement for the defective or decaying satellite.

CHARACTERISTICS:

- Physical Characteristics: Undetermined
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Mechanisms and rendezvous techniques to capture satellite
- Compatibility with existing satellite systems
- Trade-off of the mission and reboost requirements

STATUS:

- Preliminary analysis indicates feasible concept
- No defined mission requirement

DISCUSSION: Integration of this system may be costly. The concept appears to be feasible, but the practicality has not been established. No mission drivers have yet been determined.

CONTACTS:

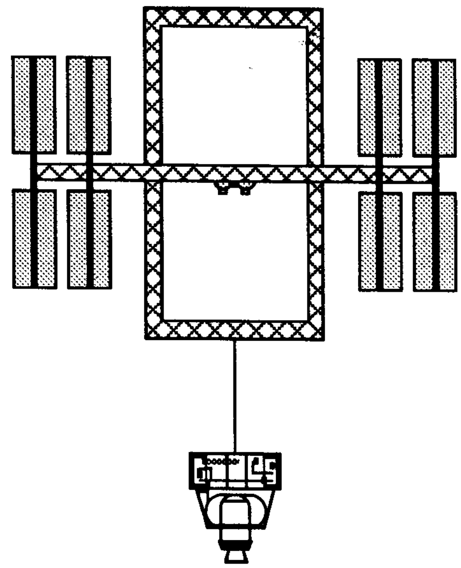
- Joe Carroll

REFERENCES:

G. Von Tiesenhausen, ed., Tether Applications Concept Sheets, June 28, 1984.

-- TRANSPORTATION --

Tether Rendezvous System



APPLICATION: Used to supplement the operations of the Space Station and OMV.

DESCRIPTION: The Tether Rendezvous System would be used to capture and retrieve payloads, OTVs or the Space Shuttle to the Space Station. The system would consist of a "smart" hook which would be able to rendezvous and attach to a payload with or without human intervention.

CHARACTERISTICS:
- Physical Characteristics: Undetermined
- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:
- Extent of system capabilities needs to be determined
- Dynamics in the tether and on the Space Station after rendezvous
- System design
- Rendezvous and capture techniques
- Hardware required

STATUS:
- Concept under study by Aeritalia
- Preliminary evaluations have been positive

DISCUSSION: The Tether Rendezvous System can supplement the operations of the Space Station or any space platform by accomplishing remote rendezvous, increasing flexibility, decreasing risk and saving a great amount of propellant for incoming vehicles (STV, OMV, or the Shuttle Orbiter).

CONTACTS:
- Chris Rupp
- Joe Carroll
- Franco Bevilacqua

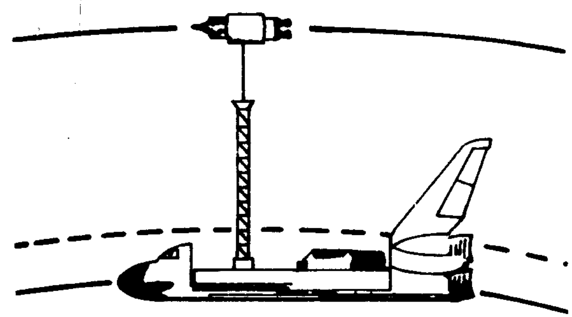
REFERENCES:

G. Von Tiesenhausen, ed., Tether Applications Concept Sheets, June 28, 1984.

Stuart, D. G., "Guidance and Control for Cooperative Tether-Mediated Orbital Rendezvous," Journal of Spacecraft and Rockets, 1988.

-- TRANSPORTATION --

Upper Stage Boost from Orbiter



APPLICATION: Boost an upper stage payload into a higher orbit.

DESCRIPTION: An upper stage is deployed along a tether "upward" (away from the Earth) from the Shuttle Orbiter. Libration begins and momentum is transferred from the Shuttle to the upper stage, enhancing the performance envelope of the upper stage motor. A SEDS-derived (e.g. no retrieval capability) deployer system could be used. The Orbiter could be deboosted along with the upper stage boost. Spinup capability for some upper stages may be required.

CHARACTERISTICS:

- Length: Dependent on desired final orbit
- Tether Deployment System: Permanent or removable from Orbiter, TSS-derived
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Requirement for spinup capability may be difficult

STATUS:

- Ball Brothers, Selected Tether Applications Study, Phase III
- SEDSAT project at University of Alabama in Huntsville
- SEDSAT deployment study at SAO

DISCUSSION: This application could be tailored to the Space Transfer Vehicle (STV). An expendable tether system or TSS-derived system could eliminate a major portion of the STV propellant required and increase payload capability for a specific mission with a fixed STV. The SEDSAT project (currently cancelled) was supposed to be the first space mission to boost a satellite into higher orbit with a tether . The boosting effect was observed at TSS-1R tether breakup

CONTACTS:

- James K. Harrison
- Les Johnson
- Enrico Lorenzini
- Mauro Pecchioli

REFERENCES:

"Study of Orbiting Constellations in Space," Contract RH4-394019, Martin Marietta, Smithsonian Astrophysical Observatory, December 1984.

Pecchioli, M., and Graziani, F., "A Thrusted Sling in Space: A Tether-assist Maneuver for Orbit Transfer," Second International Conference on Tethers In Space, Venice, Italy, 1987.

Proc. of Fourth International Conference on Tethers in Space, Washington DC, 10-14 April 1995

Applications "Satellite Boost from Orbiter" and "Small Expendable Deployer System"

Tether Assisted Transportation System (TATS)

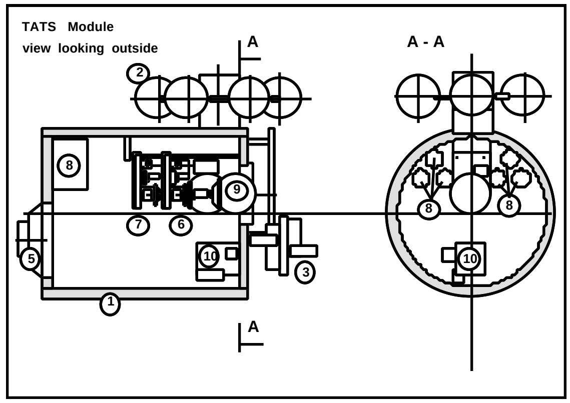
APPLICATION: TATS is a tether-based system that provides the Space Station Alpha with transport capability not dependant on conventional propulsion

DESCRIPTION: The need and the feasibility of the additional Tether Assisted Transportation System have been evaluated in the context of the International Space Station Alpha. A preliminary cargo's traffic analysis indicated that large benefits in terms of mass and cost saving are expected by tether deorbit of disposable cargoes. The tether use was discovered to present also additional benefits increasing the safety of the Station and simplifying the execution of some operations.

CHARACTERISTICS:

- Mission Duration : up to some hours
- Altitude : 400-450 Km
- Active phase : < 1 day
- Return to ground : Re-entry Capsules
- Accommodation : Space Station
- Mass Deployer : 300 Kg (typical)
- Tether Mass : 40 Kg (typical))
- Capsule Mass: 150 Kg (typical)
- Tether length : about 37 Km

- Potential For Technology Demonstration: Near-Term



1 Structure of the TATS-module
2 Storage system for the re-entry capsules
3 Manipulator on rails
4 Air lock to the space
5 Docking mechanism and air lock to station
6 Tether system in operating position
7 Tether system in position during preparation
8 Storage system for replaceable tether units
9 Re-entry capsule in start position
10 Path tracking system

CRITICAL ISSUES:
- System configuration analysis,trade-off and design
- Re-entry capsule architecture definition
- Space Station-based Operations definition
- Station storage system for capsules and waste containers design
- Station robotic for TATS elements handling definition
- Tether system deployment timing for proper prograde swing
- Dynamics of tether after payload release

DISCUSSION: A potential utilization scenario of an additional Tether Assisted Transportation System has been devised to show the extent of its capabilities. As an example, the following evolution could be considered:

Initial Capability

- Frequent Sample Return
- Raduga-type Capsule Deorbit

Waste Disposal

Small Payloads Disposal

Full Capability

- Frequent Sample Return
- Raduga-type Capsule Deorbit
- Waste Disposal
- Cargoes Deorbit (PROGRESS, ATV)
- Large Modules and Payloads Disposal

TATS consists of a set of re-entry capsules in a storage compartment, tools to allow the loading of the processed samples, a separation system (springs), and a tether deployer to perform properly capsule deployment and release. The analysis of possible ways to accommodate the TATS system on the Station has been focused on the two main options for accommodation: External and Internal Accommodation. Several possible options have been envisaged for possible accommodation of the system both at the ISSA US section and at the ISSA RS section.

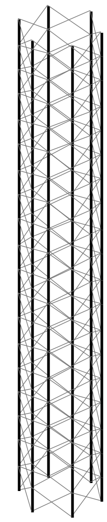
CONTACTS:

- Pietro Merlina

REFERENCES:

"Tether Assisted Transportation System (TATS)", ESA/ESTEC contract No. 11439/95/NL/VK, Alenia Spazio/RSC Energia/DASA, 1995.

Failsafe Multiline Tethers for Long Tether Lifetimes (Hoytether)



Hoytether Section

APPLICATION: Long-life, damage resistant tether system for extended-duration, high-value, and crew-rated missions. Applications include low-drag, long life tethers for atmospheric and ionospheric science, electrodynamic tethers for in-orbit power and propulsion, and high-strength tethers for LEO-GEO-Lunar transport systems.

DESCRIPTION: The lifetimes of conventional single-line tethers are limited by damage due to meteorite and orbital debris impactors to periods on the order of weeks. Although single-line tether lifetimes can be improved by increasing the diameter of the tether, this incurs a prohibitive mass penalty. The Hoytether, shown in the figure, is a tether structure composed of multiple lines with redundant interlinking that is able to withstand many impacts.

CHARACTERISTICS:

- Can be designed to have survival probabilities of >99% for periods of months to years.

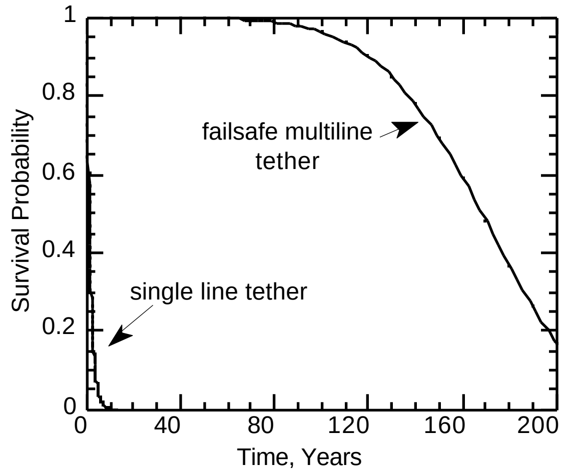
CRITICAL ISSUES:

Development of methods to fabricate and deploy many-kilometer long multiline tethers.

STATUS:

- 1/2 km long samples of bi- and tri- line Hoytethers were fabricated during a Phase I SBIR effort.
- A 1/2 km bi-line Hoytether was successfully deployed from a SEDS deployer ground tests.
- Development of methods for fabricating and deploying multi-kilometer conducting and non-conducting Hoytethers continues under a Phase II SBIR contract.

DISCUSSION: Analytical modeling, numerical simulation, and ground-based experimental testing of this design indicate that this tether structure can achieve lifetimes of tens of years without incurring a mass penalty. Moreover, while single-line tether survival probability drops exponentially with time, redundant linkage in failsafe multiline tethers keeps the tether survival probability very high until the tether lifetime is reached. The survival probability of a failsafe multiline tether is compared to that of an equal-mass single line tether in next figure.



Lifetime comparison of equal-weight single line and failsafe multiline tethers for a low-load mission.

CONTACTS:

- Robert P. Hoyt
- Robert L. Forward

REFERENCES:

Proceeding of the Fourth International Conference on Tethers in Space, Washington, DC, 10-14 April 1995.

R.L. Forward, R.P. Hoyt, Failsafe Multistrand Tether SEDS Technology Demonstration, Final Report on NAS8-40545 SBIR 94-1 Phase I Research Study.

R.L. Forward, Failsafe Multistrand Tethers for Space Propulsion, Forward Unlimited, Final Report on NAS8-39318 SBIR 91-1 Phase I Research Study.

SECTION 4.0 TETHER FUNDAMENTALS

4.1 GRAVITY GRADIENT

4.1.1 General

Gravity-gradient forces are fundamental to the general tether applications of controlled gravity, and the stabilization of tethered platforms and constellations. The basic physical principles behind gravity-gradient forces will be described in this section. This description will be in three parts. The first will discuss the principles behind the general concept of gravity-gradient forces. The second will continue the discussion, addressing the specific role of these forces in controlled-gravity applications. The third will address their role in the stabilization of tethered platforms and constellations.

For the purposes of this discussion, it will be sufficient to describe the motion of the simple "dumbbell" configuration, composed of two masses connected by a tether. Figure 4.1 shows the forces acting on this system at orbital velocity. When it is oriented such that there is a vertical separation between the two masses, the upper mass experiences a larger centrifugal than gravitational force, and the lower mass experiences a larger gravitational than centrifugal force. (The reason for this is described later in the discussion.) The result of this is a force couple applied to the system, forcing it into a vertical orientation. This orientation is stable with equal masses, and with unequal masses either above or below the center of gravity. Displacing the system from the local vertical produces restoring forces at each mass, which act to return the system to a vertical orientation. The restoring forces acting on the system are shown in Figure 4.2 (see Ref. 1).

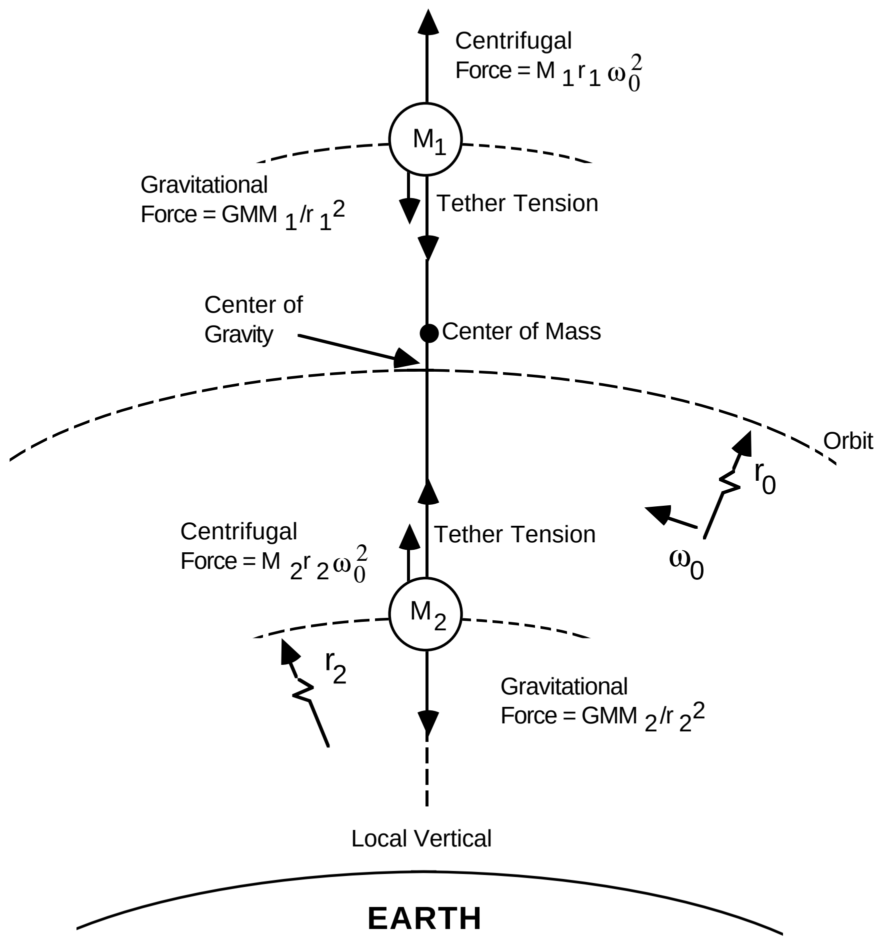


Figure 4.1 Forces on Tethered Satellites

Since the gravitational acceleration changes nonlinearly with distance from the center of the Earth, the center of gravity of the tethered system will not coincide exactly with its center of mass. The separation becomes more pronounced as the tether length increases. However, the separation is not dramatic for systems using less than very large long lengths. Therefore, for the purpose of this discussion it will be assumed that the center of mass coincides with the center of gravity. Furthermore, to facilitate an "uncluttered" discussion, the two masses will be assumed to be equal, and the tether mass will be ignored.

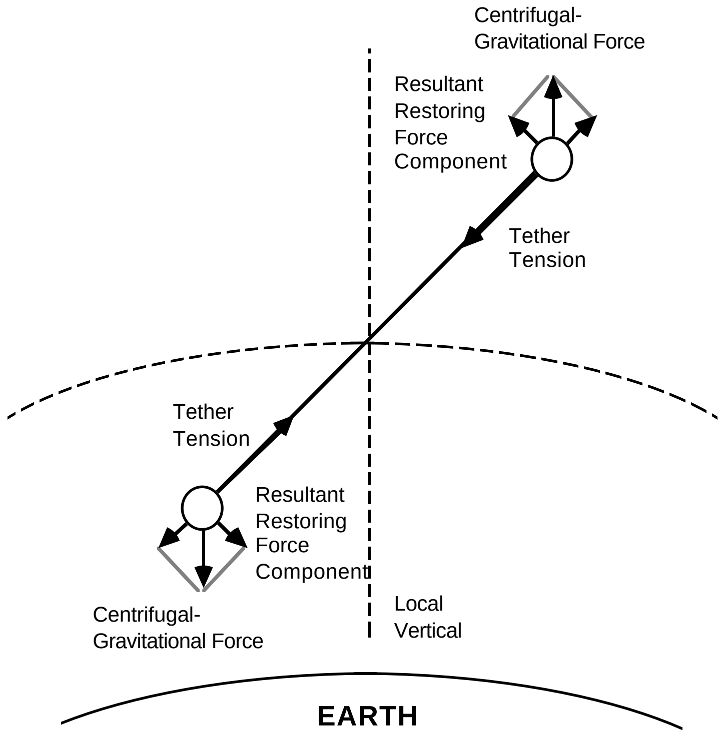


Figure 4.2 Restoring Forces on Tethered Satellites

The gravitational and centrifugal forces (accelerations) are equal and balanced at only one place: the system's center of gravity (C.G.). The center of gravity (or mass), located at the midpoint of the tether when the end masses are equal, is in free fall as it orbits the Earth, but the two end masses are not. They are constrained by the tether to orbit with the same angular velocity as the center of gravity. For the center of gravity in a Keplerian circular orbit, equating the gravitational and centrifugal force,

$$\frac{GMM_o}{r_o^2} = M_o r_o \omega_o^2 \qquad \text{and}$$

$$\omega_o^2 = \frac{GM}{r_o^3} \qquad ; \text{ where}$$

G = universal gravitational constant (6.673 x 10^{-11} Nm^2/kg^2),

M = mass of the Earth (5.979 x 10^{24} kg),

M_o = total tether system mass (kg),

r = radius of the system's center of gravity from the center of the Earth (m), and

ω_o = orbital angular velocity of the center of gravity (s^{-1}).

Since

$$\omega_o = \frac{V_o}{r_o} \quad \text{and}$$

$$\omega_o = \frac{2\pi}{T_o} \quad , \text{ where}$$

V_o = orbital speed of the center of gravity, (m/s), and
T_o = orbital period of the center of gravity (s),

$$V_o^2 = \frac{GM}{r_o} \quad \text{and}$$

$$T_o^2 = \frac{4\pi^2 r_o^3}{GM}$$

Note that the orbital speed, period, and angular velocity depend on the orbital radius, and are independent of the tether system mass.

If the two end masses were in Keplerian circular orbits at their respective altitudes and were not connected by a tether, their orbital speeds would be different from the tethered configuration. For the upper mass, applying equations (1) and (2),

$$\omega_1^2 = \frac{GM}{(r_o + L)^3} \quad \text{and}$$

$$V_1^2 = \frac{GM}{(r_o + L)} \quad ; \text{ where}$$

L = tether length from the center of gravity to the mass (m).

Similarly, for the lower mass,

$$\omega_2^2 = \frac{GM}{(r_o - L)^3} \quad \text{and}$$

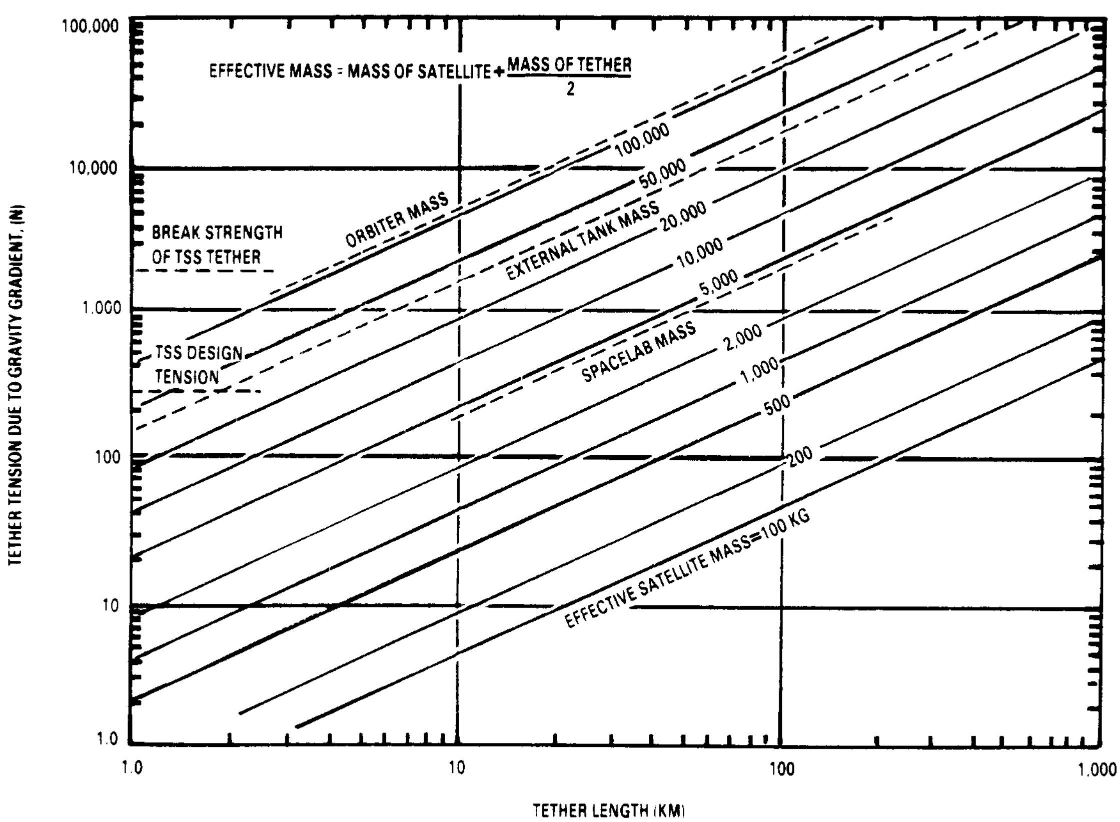
$$V_2^2 = \frac{GM}{(r_o - L)}$$

It can be seen that without the tether, the upper mass would move at a slower speed and the lower mass would move at a higher speed. The tether, therefore, speeds up the upper mass and slows down the lower mass. This is why the upper mass experiences a larger centrifugal than gravitational acceleration, and why the lower mass experiences a larger gravitational than centrifugal acceleration. The resulting upward acceleration of the upper mass and downward acceleration of the lower mass give rise to the balancing tether tension. They also produce the restoring forces when the system is deflected from a vertical orientation. The masses experience this tension as artificial gravity.

The artificial-gravity force and tether tension are equal to the gravity-gradient force. The gravity-gradient force on a mass, m, attached to the tether at a distance, L, from the system's center of gravity is equal to the difference between the centrifugal and gravitational forces on it. An approximate value for this force is given by,

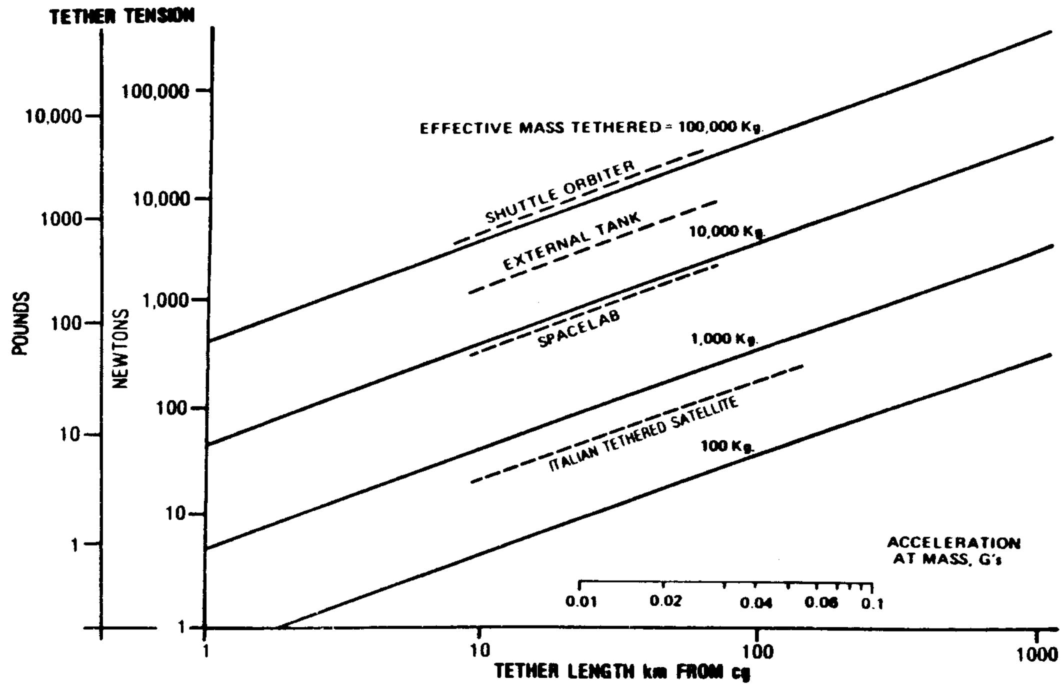
$$F_{GG} \approx 3L\ m\ \omega_o^2$$

For mass m below the center of gravity, the gravity-gradient force is simply



$$F_{GG} \approx -\ 3L\ m\ \omega_o^2\ ,$$

indicating that the gravity-gradient force acts upward above the center of gravity and downward below it. The force acts along the tether and away from the center of gravity. Furthermore, the gravity-gradient acceleration and force increase as the distance from the center of gravity increases and as the orbital radius

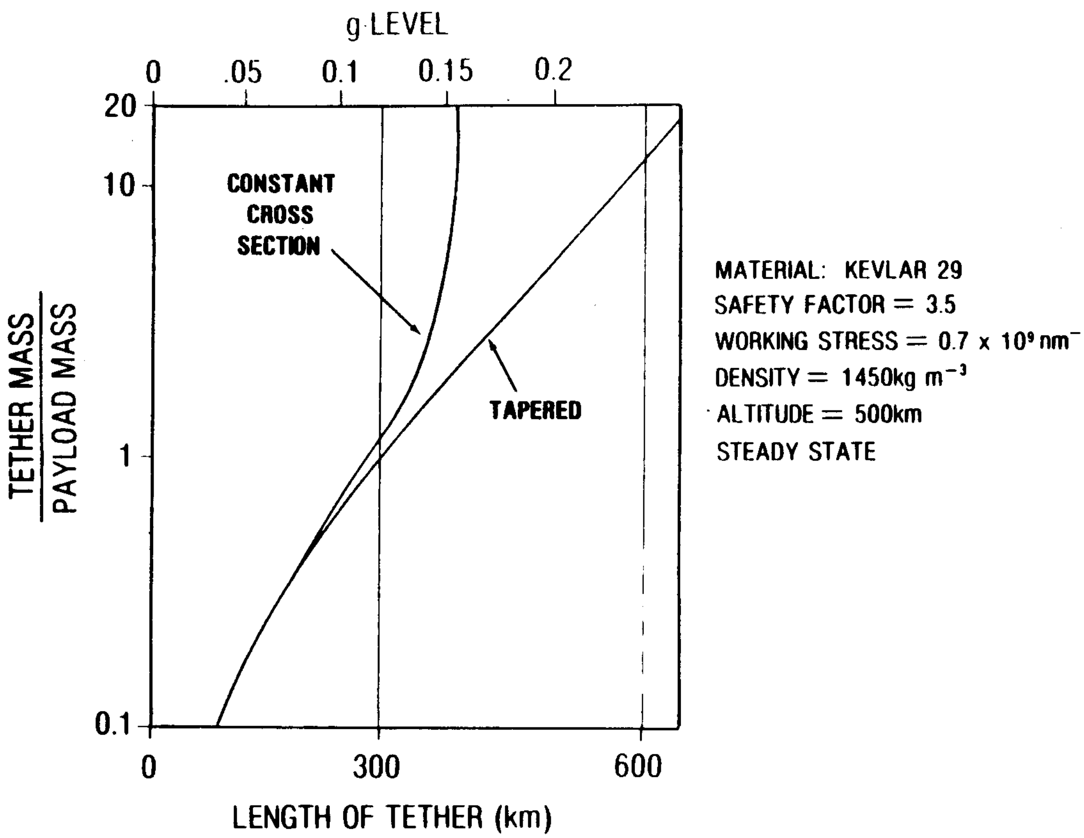


of the center of gravity decreases. (A more rigorous derivation of this equation is presented in Ref. 2, and also in Ref. 3). Figures 4.3 and 4.4 show the tether tension (artificial-gravity force) and artificial-gravity acceleration as a function of tether length from the center of gravity for various system masses in LEO (see Ref. 4). Figure 4.5 shows the tether mass and g-level as a function of tether length for a tether made of Kevlar 29. This figure includes tapered tethers which are discussed below.

Figure 4.3 Tether Tension Due to Gravity Gradient Versus Tether Length From Center of Gravity and Effective Satellite Mass In LEO

Figure 4.4 "Artificial Gravity" at Tethered Masses in LEO

Figure 4.5 Tether Mass and g-Level Versus Tether Length for Kevlar 29 Tethers



Since the gravity-gradient force and acceleration in orbit vary with GM/r_o^3 (where M is the planetary mass), they are independent of the planet's size, and linearly dependent on its density. The acceleration is largest around the inner planets and the Moon (0.3-0.4 x 10^{-3}g/km for low orbits, where g is Earth gravity), and about 60-80% less around the outer planets. The gravity-gradient acceleration decreases rapidly as the orbital radius increases (to 1.6 x 10^{-6} g/km in GEO).

Although the vertical orientation of the tether system is a stable one, there are forces which cause it to librate (oscillate) about the vertical. These weak but persistent forces include atmospheric drag due to the different air densities encountered in the northward and southward passes of non-equatorial orbits and due to solar heating and electrodynamic forces (for conducting tethers). Station-keeping and other rocket maneuvers would also contribute to driving (or damping) libration. The natural frequency for in-plane (in the orbit plane) librations is $\sqrt{3}\ \omega_o = 1.732\ \omega_o$, and $2\ \omega_o$ for out-of-plane librations (a detailed derivation is contained in Ref. 2).

Since both the displacement and restoring forces increase linearly with tether length, libration frequencies are independent of tether length. Therefore, the tether system will librate as a solid dumbbell (except for very long tethers, where the gravity gradient itself varies). Libration periods, however, do increase at large amplitudes. Since the tether constrains the motion of the masses, the sensed acceleration is always along the tether. Furthermore, the tether can go slack if the in-plane libration angle exceeds 65°, or if the out-of-plane libration angle exceeds 60°. The slackness can be overcome by reeling or unreeling the tether at an appropriate rate. Additional information on tether libration is presented in Ref. 5 and also Section 5.0.

Libration can be damped out by varying the tether length. It would be deployed when the tension was too high and retracted when the tension was too low. Since the in-plane and out-of-plane librations have different periods, they could be damped simultaneously. Shorter-period, higher-order tether vibrations could also be damped in this way.

Since the portion of the tether at the center of gravity must support the tether as well as the masses, the mass of long tethers must be taken into account. To minimize the tether's mass while maintaining its required strength, its cross-sectional area could be sized for a constant stress at all points along its length. The optimum design for very high tether tensions would be an exponentially tapered tether with a maximum area at the center of gravity and minima at the end masses. Tethers of constant cross-section have limited length, as indicated in Figure 4.5, whereas tapered tethers can have unlimited length; but then, its mass will increase exponentially along with its cross-section. A detailed discussion of tapered tether design is provided in Ref. 6.

In addition to the general areas of controlled gravity and tethered-platform and constellation stabilization, gravity-gradient effects play a fundamental role in applications related to momentum exchange and tethered-satellite deployment. These aspects are discussed in Section 4.3, entitled "Momentum Exchange."

4.1.2 Controlled Gravity

As a first step in discussing the role of gravity-gradient effects in controlled-gravity applications, a few definitions will be established. The definitions used in this book will be those recommended by the controlled gravity panel at the tether applications conference in Venice, Italy in October 1985 (Ref. 4). The term "controlled gravity" means the intentional establishment and control of the magnitude, vector properties, time dependence, and associated "noise" (uncertainty) of the acceleration field within a designated volume of space. In addition, the following definitions are also provided:

g = the acceleration on the equator at mean sea level on the Earth's surface (9.81 m/s^2);
microgravity = 10^{-4} g and smaller;
low gravity = 10^{-1} g to 10^{-4} g;
Earth gravity = 1 g;
hypergravity = greater than 1 g;
reduced gravity = microgravity and low gravity; and
enhanced gravity = hypergravity.

There are two basic tether configurations which can be used to provide controlled-acceleration fields: gravity-gradient-stabilized configurations (rotating once per orbit in an inertial frame), and rotating configurations (rotating more rapidly than once per orbit). This section will cover gravity-gradient-stabilized configurations. Rotating configurations are discussed later in Section 4.2.

In an orbiting, vertically-oriented, gravity-gradient-stabilized tether system composed of two end masses connected by a tether, all portions of each end mass experience the same acceleration, caused by the tether tension pulling on the end mass. This force is perceived as artificial gravity. As described before, its magnitude is proportional to the tether length from the system's center of gravity, and may be held constant or varied by deploying and retracting the tether. (For LEO, the gravity gradient is about 4 x 10^{-4} g/km.) Its direction is along the tether and away from the center of gravity.

This same principle can be used in more complex configurations (constellations) of three or more bodies. For example, consider a three-body system stabilized along the gravity gradient. In this system, a third body is attached to a crawler mechanism ("elevator") on the tether between the two primary end masses. The crawler mechanism allows the third body to be moved easily to any point along the tether between the end masses. The acceleration field (artificial gravity) in the third body can be controlled easily by moving it up or down the tether. Its distance from the system's center of gravity determines the magnitude of the artificial gravity within it. This artificial gravity acts in the direction along the tether and away from the center of gravity. The two end masses experience the artificial gravity determined by their distances from the center of gravity, as in the two-body system. The artificial gravity that they experience can also be held constant or varied by increasing or decreasing the tether length.

When positioned at the center of gravity, the third body could experience an acceleration field as low as about 10^{-8} g at the center of gravity, and 10^{-7} g and 10^{-6} g at distances from the center of gravity of

20 cm and 2 m, respectively. Using appropriate control laws, the third body's position could be automatically adjusted to produce a desired g-level time profile or to minimize transient disturbing effects.

Gravity-gradient effects can also be used to control the location of the system's center of gravity. This would be a very useful capability for the Space Station if microgravity experiments were to be performed on-board. Two tethered masses would be deployed vertically from the Space Station - one above and one below. By controlling the tether lengths, the position of the center of gravity could be maintained at a particular point in the system or moved to the other points as desired. This means that the artificial gravity at all points in the system would be correspondingly controlled to a fine degree of resolution. For example, the center of gravity could be adjusted to coincide with the minimum possible acceleration field.

All of these system configurations allow the generation and fine control of a wide range of g-levels. Using appropriate control laws, tether lengths and the relative positions of system components can be varied to produce desired gravity fields and their time profiles, to minimize transient disturbances to the gravity field, and to carefully control the location of the system's center of gravity. In addition to all of this, tethers also provide two-axis stabilization of the system.

Gravity-gradient systems have several advantages over rotating systems. They can provide artificial gravity for large-volume structures more easily. Also, the gravity gradient and Coriolis accelerations within these volumes are much less than those produced in rotating systems. One result of this is a lower occurrence of motion sickness. However, one disadvantage of gravity-gradient systems is that they would require very long tethers to achieve g-levels approaching 1 g or more. In fact, current tether materials are not strong enough to support their own weight at such tether lengths. However, by using moderate lengths and a relatively small rotation rate about the C.G, g-levels of 1 g or more can be achieved, with some increase in the Coriolis acceleration and gravity gradient. Figure 4.6 provides additional information concerning the acceptable values of artificial-gravity parameters (Ref. 4).

ARTIFICIAL GRAVITY PARAMETERS

- UNAIDED TRACTION REQUIRES 0.1 G
- ANGULAR VELOCITY SHOULD BE LESS THAN 3.0 RPM TO AVOID MOTION SICKNESS
- MAXIMAL CENTRIPETAL ACCELERATION NEED NOT EXCEED EARTH GRAVITY
- CORIOLIS ACCELERATION SHOULD NOT EXCEED 0.25 CENTRIPETAL ACCELERATION FOR A LINEAR VELOCITY OF 3 FEET/SECOND IN A RADIAL DIRECTION
- GRADIENT SHOULD NOT EXCEED 0.01 G/FOOT IN RADIAL DIRECTION
- TETHER MASS MIGHT BE LIMITED TO 10,000 TO 20,000 POUNDS

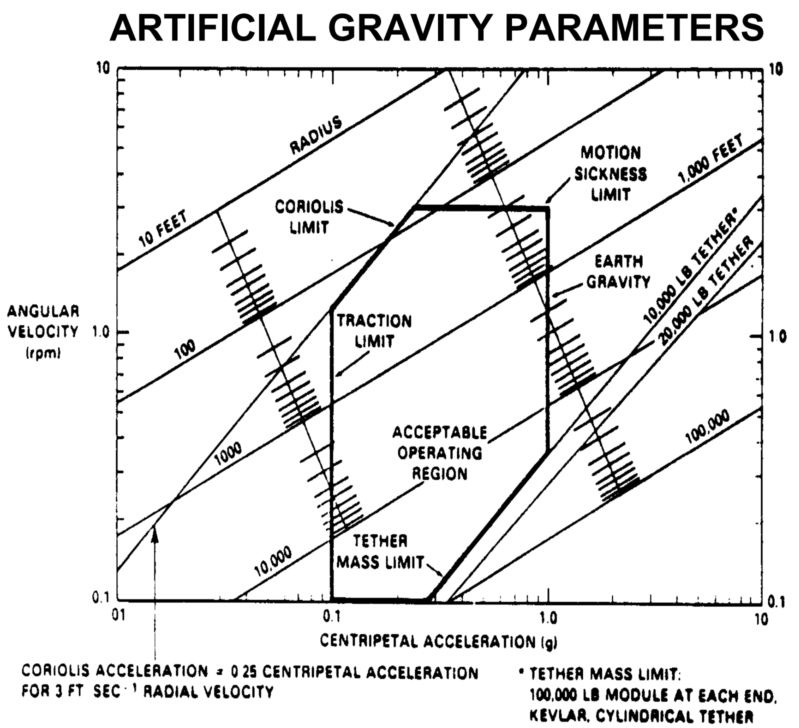


Figure 4.6 Acceptable Values of Artificial-Gravity Parameters

Tether technology suggests a number of exciting application possibilities. For example, since a tether can be used to attain a gravity field simply by deploying a counterweight along the gravity gradient, the establishment of a desirable low-level gravity on-board the Space Station appears practical. The use of 0.01 - 0.1 g on-board the Space Station might permit simpler and more reliable crew-support systems (such as eating aids, showers, toilets, etc.), operational advantages (no floating objects, easier tool usage, and panels and controls which are operated as in ground training), and perhaps some long-term biological advantages. The tether mass would be a significant part of the station mass to produce 0.1 g (using a tapered 450 km tether), but would be relatively small for 0.05 g or less. However, careful consideration will have to be given to the disadvantages of tether system mass and complexity, and to assurance of survival in case of tether severing by meteoroid or debris impact. Such a system would also affect a microgravity laboratory, requiring it to be moved from the Space Station to the C.G. location.

A variable/low gravity laboratory module could be attached by a crawler mechanism to a tether deployed along the gravity gradient from the Space Station. A microgravity laboratory could also be built as part of the Space Station at its center of gravity. These labs could be used to examine the effects of microgravity and low gravity on both physical and biological processes. Some biological processes of interest would be plant and animal growth, and human performance and medical processes (such as those related to the cardiovascular, skeletal, and vestibular systems). The gravity-threshold values for various biological phenomena could also be studied. Such physical processes as crystal growth, fluid science, and chemical reactions could be studied. Many experiments in materials science and manufacturing could be performed in these gravity ranges. Liquid propellant storage and refueling facilities could be tethered to the Space Station. The artificial gravity produced by the tether would assist in propellant handling and transfer. Figure 4.7 shows the tether lengths necessary to allow propellant settling for the proper transfer of various propellants.

These are but a few of the possible applications of the artificial-gravity environments produced by gravity-gradient effects. Detailed descriptions of applications utilizing these gravity-gradient effects are contained in the "Tether Applications" (Section 3.0) of this handbook. Note that, due to the wide variety of possible system configurations, all of these applications are contained in one category. There are applications which overlap two or more categories and which could be logically listed under any one of them. In these cases, a judgment has been made as to which category is the most appropriate for the particular application and it is listed in that category. The applications related to the artificial gravity produced by gravity-gradient effects appears in the "Controlled Gravity" and "Space Station" categories of the "Applications" section, as appropriate.

Fluid Settling

- **SETTLING REQUIREMENT**
  - **GRAVITY DOMINATE SURFACE TENSION**
- **FLUID SETTLING PARAMETER IS BOND NUMBER (B_O)**

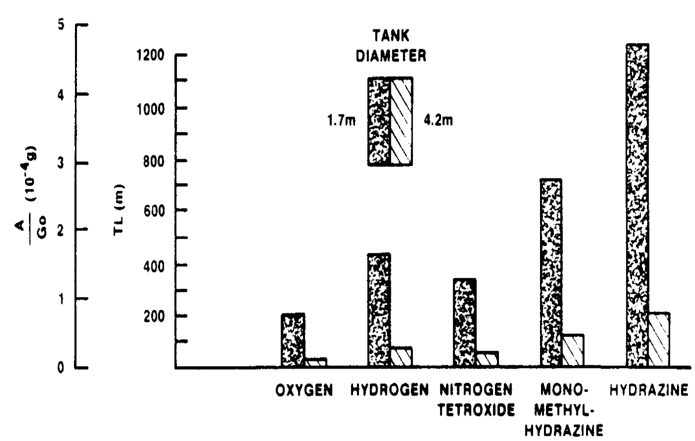
$$B_O = \frac{\rho A D^2}{4\sigma}$$

ρ = **FLUID DENSITY**
σ = **SURFACE TENSION COEFFICIENT**
D = TANK DIAMETER

- **FLUID SETTLES IF $B_O > 10$**
  - **$B_O = 50$ CHOSEN TO BE CONSERVATIVE**

PROPELLANT SETTLING ON A STATIC TETHER (Bo = 50)

Figure 4.7 Fluid Settling Properties of Various Liquid Propellants Under Conditions of Artificial Gravity - Required Tether Length Versus Propellant

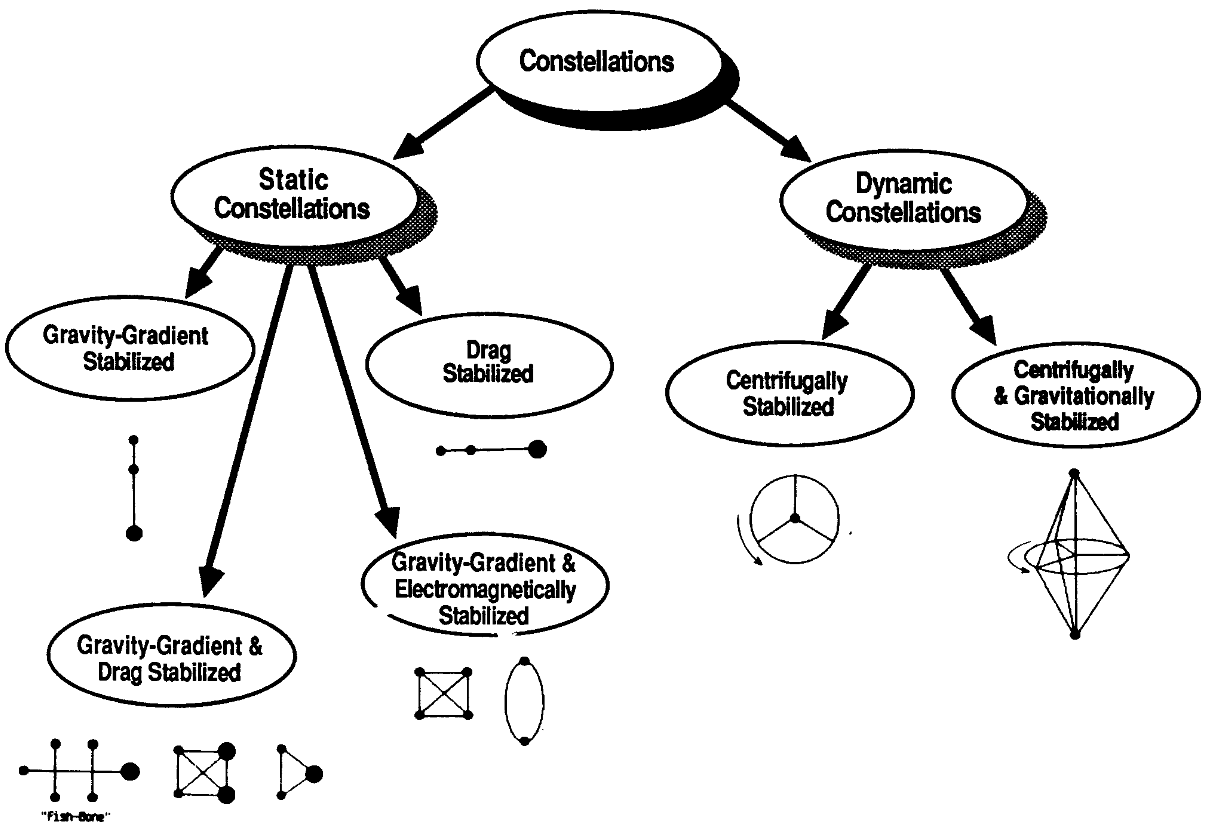


4.1.3 Constellations

Gravity-gradient forces also play a critical role in the stabilization of tethered constellations. A tethered constellation is defined as a generic distribution of more than two masses in space connected by tethers in a stable configuration. They can be configured in either one, two, or three dimensions. All of the non-negligible forces or gradients available in low orbit come into play to stabilize these various configurations. The vertical gravity gradient has the strongest influences, but differential air drag, electrodynamic forces, the J_{22} gravity component (an harmonic of the Earth's gravitational potential), and centrifugal forces also contribute. Different configurations utilize different combinations: 1-D vertical and horizontal, drag-and gravity-gradient-stabilized and electromagnetically stabilized (2-D).

Tethered constellations are divided into the two basic categories shown in Figure 4.8 (Ref. 4, p. 296). These are "static" and "dynamic" constellations. Static constellations are defined as constellations which do not rotate relative to the orbiting reference frame (they do rotate at the orbital rate when referred to an inertial frame). Dynamic constellations, on the other hand, are defined as constellations which do rotate with respect to the orbiting reference frame. These two basic categories are subdivided further. Static constellations include gravity-gradient-stabilized (one-dimensional, vertical), drag-stabilized (one- and gravity-gradient-stabilized (two-dimensional) constellations. Dynamic constellations include centrifugally stabilized two dimensional and three-dimensional constellations. This section will address only the static constellations.

Figure 4.8 Types of Tethered Constellations



From the standpoint of stability and complexity, a gravity-gradient-stabilized, one-dimensional, vertical constellation is the most desirable configuration. A diagram showing three bodies tethered in this configuration is shown in Figure 4.9. Examples included the three-body configurations used for variable/low gravity and microgravity labs, and for the position control of the system center of gravity. Earlier discussion of vertical configurations included descriptions of their dynamics (including libration). The dominant influence on these constellations is the vertical gravity gradient.

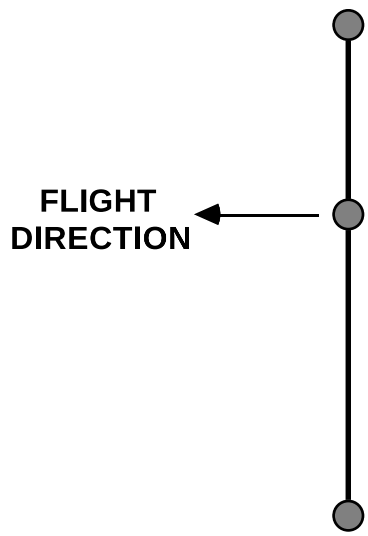


Figure 4.9 Example Configuration of 1-D, Gravity-Gradient-Stabilized, Vertical Constellation

Stability in one-dimensional, horizontal constellations is provided by tensioning the tethers. (Such a constellation is depicted in Figure 4.10.) By designing such a constellation so that the ballistic coefficient of each of its elements is lower than that of the element leading it and higher than that of the element trailing it, a tension is maintained in the tethers connecting them along the velocity vector. The resulting differential drag on its elements prevents the constellation from compressing, and the tension in its tethers prevents it from drifting apart. In principle, there is no limit to the number of platforms which can be connected in this manner. However, it should be noted that drag takes orbital energy out of the constellation, shortening its orbital lifetime unless compensated by some form of propulsion.

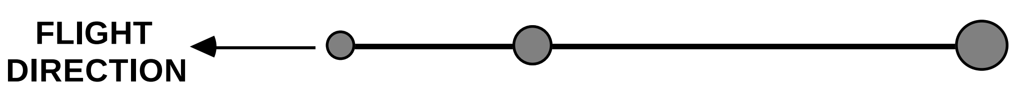


Figure 4.10 Example Configuration of 1-D, Drag-Stabilized, Horizontal Constellation

The fundamental parameter for one-dimensional, horizontal constellations is the differential ballistic coefficient of the two end bodies. In the case of a massive front body and a voluminous rear body (balloon), it is equal to the ballistic coefficient of the latter. Tether lengths and orbital lifetimes are competing requirements and are never sufficiently satisfied in the altitude range of interest. Since the vertical gravity gradient dominates over the differential air drag at the Space Station altitude and above, the maximum horizontal tether length must be short for stability. At lower altitudes (150-200 km) where the differential air drag becomes relatively strong, tether length may be longer, but the orbital lifetime will be limited.

The "fish-bone" configuration was the first proposed two-dimensional constellation and it utilizes both gravity-gradient and air-drag forces in order to attain its stability. A simple "fish-bone" constellation is depicted in Figure 4.11. For analytical purposes, this constellation can be reduced to an equivalent one-dimensional, horizontal constellation by lumping the overall ballistic coefficient of the rear leg (balloons plus tethers) and the front leg at the ends of the horizontal tether. Additional information on the stability analysis of the original "fish-bone" configuration shown in Figure 4.11 is presented in Ref. 4 (p.171-172) and contains calculated values of its stability limits versus altitude. Analysis has revealed that this configuration is less stable than a comparable one-dimensional, horizontal constellation. The necessity of a massive deployer at the center of the downstream vertical tether subsystem greatly reduces the area-to-mass ratio of that subsystem.

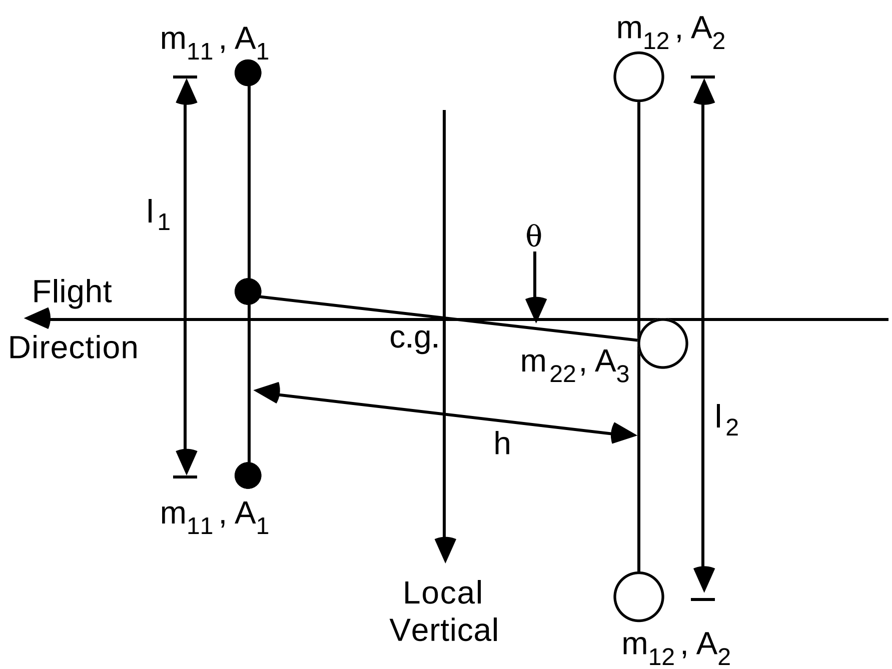
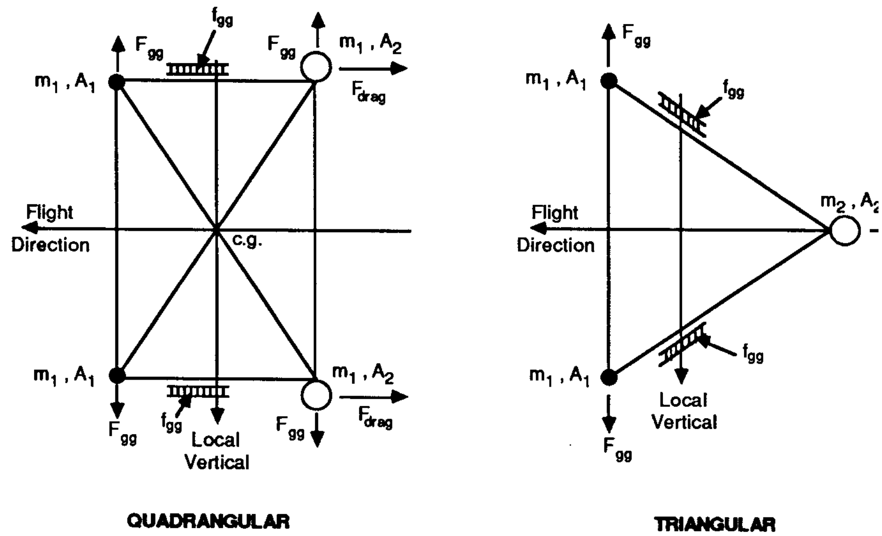


Figure 4.11 Example Configuration of 2-D, "Fish-Bone"



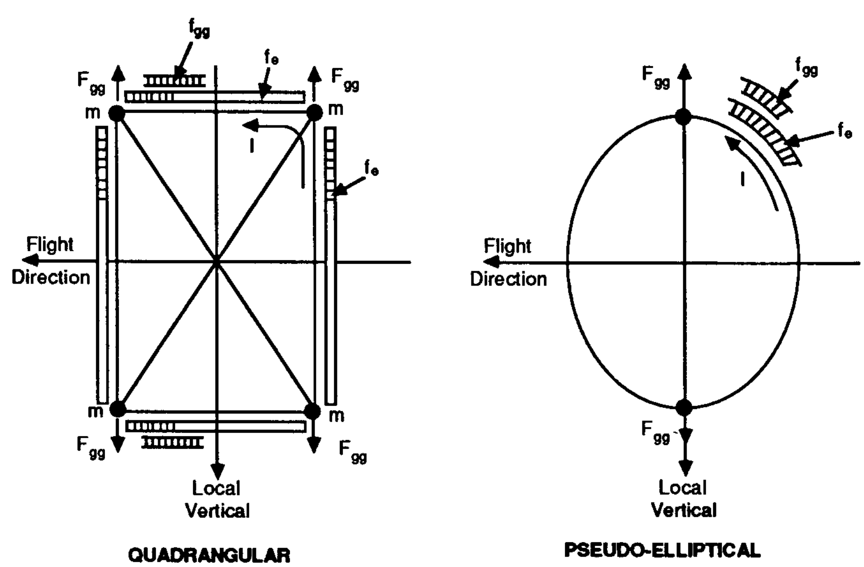
Two additional designs for a two-dimensional constellation, utilizing gravity-gradient and air-drag forces for stability, have been proposed. These drag-stabilized constellation (DSC) designs are depicted in Figure 4.12. With this type of configuration, the gravity gradient is exploited for overall attitude stability (the constellation's minimum axis of inertia must be along the local vertical), and differential air-drag forces are used to stretch the constellation horizontally for shape stability. The drag force is fully exploited to assure the minimum tension in the horizontal tethers, and not to counteract the gravity-gradient force as it does in the "fish-bone" configuration. Design parameters for DSC systems are presented in Ref. 4 (p. 175-178).

Two designs for a two-dimensional constellation utilizing gravity-gradient and electromagnetic forces for stability have been proposed. These electromagnetically stabilized constellation (ESC) designs are shown in Figure 4.13. In these configurations, the gravity gradient is again used for overall attitude stability (the minimum axis of inertia is vertical) and electromagnetic forces are used to stretch the constellation horizontally for shape stability. (These electromagnetic forces are discussed in detail in Ref. 7 and section 4.4).

Figure 4.12 Two Designs of 2-D DSC Constellations Horizontally

In the quadrangular configuration, current flows in the outer-loop tethers, interacting with the Earth's magnetic field, to generate electromagnetic forces in the outer loop. The current direction is chosen such that these forces push the tethers outward, tensioning them (like air inside a balloon). Although the shape is different in the pseudo-elliptical constellation (PEC) design, the same principle of electromagnetic tensioning of the outer-loop tethers is applied. The two lumped masses provide extra attitude stability without affecting the constellation shape. Moreover, since the resultant force is zero, the orbital decay rate is provided by air drag only. Design parameters for ESC systems are presented in Ref. 4 (p. 176-177).

Figure 4.13 Two Designs of ESC 2-D Constellations Where Shape Stability is Provided by Electromagnetic forces



Preliminary conclusions on the design of two-dimensional constellations have been reached. The "fish-bone" constellations are less stable than the one-dimensional, horizontal constellations. "Fish-bone" constellations are stable with very short horizontal tethers (less than 100 m at 500 km altitude). The alternative quadrangular DSC and ESC constellations (and PECs for special applications) exhibit a better static stability. Suitable design parameters can provide good stability with a reasonably low power requirement for ESCs and feasible balloons for DSCs.

Typical dimensions for these constellations are 10 km (horizontal) by 20 km (vertical) with balloon diameters of about 100 m for DSCs, a power consumption of about 5.5 kW for ESCs and 2 kW for PECs. The ESC constellations have greater tension in the horizontal tethers than the DSC constellations and an orbital decay which is smaller by an order of magnitude. ESCs are suitable for low inclination orbits. Moreover, since they tend to orient their longitudinal plane perpendicular to the Earth's magnetic field (B vector), a small oscillation about the vertical axis at the orbital frequency is unavoidable even at low orbital inclinations. DSCs, on the other hand, are suitable for any orbital inclination. In the DSCs, the yaw oscillation occurs at high inclinations only due to the Earth's rotating atmosphere.

There are several proposed applications for one-dimensional, vertical constellations. A three-body configuration could be used for microgravity/variable-gravity laboratories attached to the Space Station or the Shuttle. A three-body system could be used on the Space Station to control the location of the center of gravity. A system of 3 or more bodies attached to the Shuttle or Space Station could be used as a multi-probe lab for the measurement of the gradients of geophysical quantities. A 3-body system could also function as an ELF/ULF antenna by allowing a current to flow alternatively in the upper and lower tether to inject an electromagnetic wave with a square waveform into the ionosphere. A space elevator (or crawler) for the Space Station is yet another application.

There are several proposed applications for two-dimensional constellations. An electromagnetically stabilized constellation could provide an external stable frame for giant orbiting reflectors. Multi-mass constellations in general allow a separation of different activities while keeping them physically connected, such as for power distribution, etc. Detailed analysis of these two-dimensional structures may be found in Ref. 7.

4.2 ROTATION OF TETHER SYSTEMS

4.2.1 General

Tethers will almost always be involved in some form of rotational configuration. Any planet-orbiting tether system, by nature, will rotate about the planet at the orbit angular velocity. The combination of the centrifugal forces due to rotation and gravity gradient acting on the tether end masses causes it to be stabilized in a vertical position about the planet center of mass. In many interplanetary applications, rotation will be desired to cause an artificial-gravity environment or to create a centrifugally stabilized configuration.

4.2.2 Controlled Gravity

A tether-mass system may desire controlled gravity for a number of applications. These may range from an artificial-gravity environment for manned interplanetary missions to a controlled-gravity platform for industrial space applications. The calculation of the acceleration at a point for purely circular motion is presented here. With reference to Figure 4.14, we assume that point P (which would represent the mass) is at a constant radius, r (the tether), from the center of our rotation system.

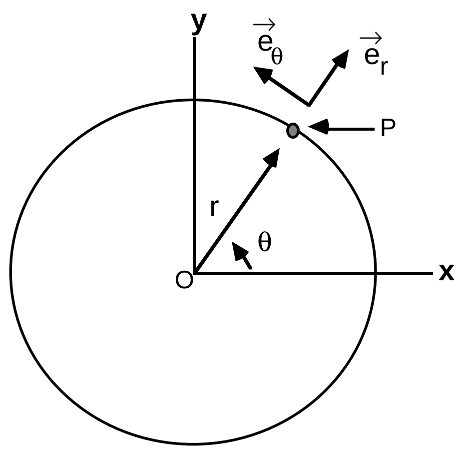


Figure 4.14 Circular Motion of a Point.

The acceleration can then be found by the expression:

$$\vec{a} = (-r\,\omega^2)\,\vec{e}_r + (r\,\dot{\omega})\,\vec{e}_\theta \quad ;$$

where,

$\vec{a}$ = acceleration at the point P (m/s^2),

$\vec{e}_r$ = unit vector in radial direction,

$\vec{e}_\theta$ = unit vector in tangential (velocity) direction,

r = radius (length of tether) (m),

ω = angular velocity (rad/s),

$\dot{\omega}$ = angular acceleration (rad/s^2).

Notice that if the angular velocity is constant the acceleration simplifies to

$$\vec{a} = (-r\,\omega^2)\,\vec{e}_r \quad ;$$

where the negative sign indicates that the acceleration acts toward the center of rotation (see Ref. 8).

As an example, suppose it is desired to calculate the gravity level at a manned module rotating about another similar module with angular velocity of 2.0 rpm, attached by a tether of length 200 meters. The center of mass will be exactly between them, and, with this as the origin, the distance to each module is 100 meters. Then, the calculation is,

$$
\begin{aligned}
a &= r\,\omega^2 \\
&= (100\ \text{m}) \left[\left(\frac{2\ \text{rev}}{\text{min}}\right) \left(\frac{1\ \text{min}}{60\ \text{sec}}\right) \left(\frac{2\,\pi\ \text{rad}}{\text{rev}}\right) \right]^2 \\
&= 4.38\ \text{m/s}^2
\end{aligned}
$$

To calculate the gravity level (as compared to Earth's):

$$a = \frac{4.38 \text{ m/s}^2}{9.8 \text{ m/s}^2}$$

$$= 0.45 \text{ g} .$$

4.3 MOMENTUM EXCHANGE

4.3.1 General-Conservation of Angular Momentum

Tethers can have useful space applications by redistributing the orbital angular momentum of a system. A tether can neither create nor destroy system angular momentum, only transfer it from one body to another. Angular momentum is defined (for a rotating system, Figure 4.15) as,

$$\vec{h} = m \vec{r} \times \vec{v} = mr^2 \vec{\omega} ;$$

where

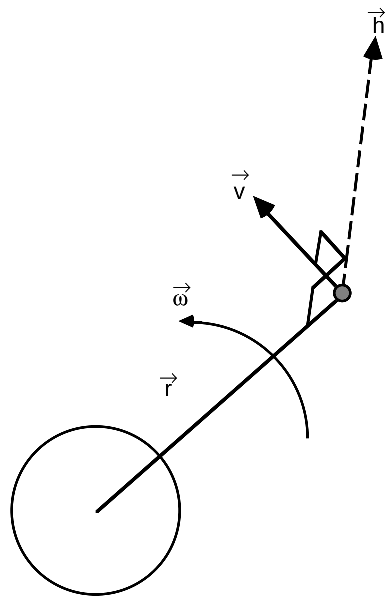
$\vec{h}$ = angular momentum of system ($kgm^2 s^{-1}$),

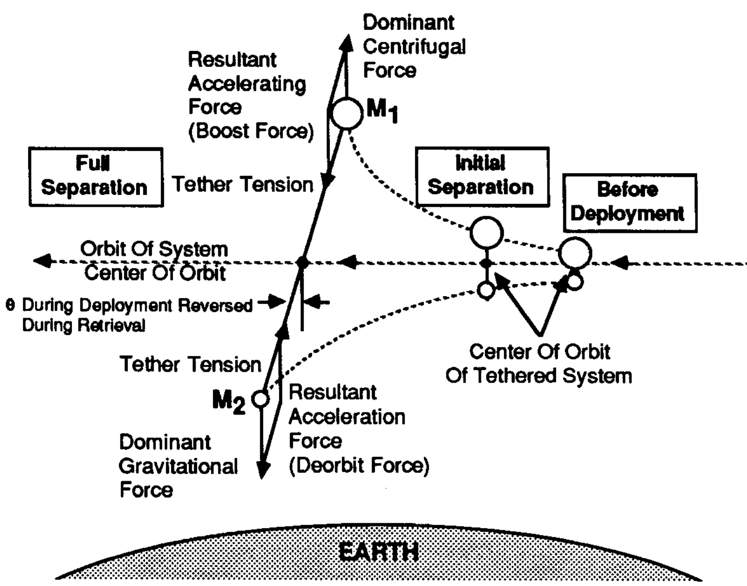
m = mass of system (kg)

$\vec{r}$ = radius vector from center of rotating coordinate system (usually the Earth) to system center of mass (m),

$\vec{v}$ = velocity of system center of mass normal to r (ms^{-1}), and

$\vec{\omega}$ = system angular velocity (s^{-1}).





In genera ... ions using different momentum excha ... by examples of their application. A us ... ata".

4.3.2 Tether P...

Consider ... er as in Figure 4.16 (see Ref. 9).

In order t ... downward from the Shuttle (M_1), it i ... t separation. After a certain length of ... bits so that gravity-gradient and cent ... nstrained by a tether, mass M_1 would ... igher orbital circular velocity in ther n ... 's gravitational field, its potential energy is raised and its kinetic energy is lowered. For M_2 the exact opposite is true. Since the masses are constrained by a tether, they also must move at the same orbital velocity. Mass M_2, therefore, will "drag" mass M_1 along until libration occurs. Libration (pendulum motion) will continue due to the centrifugal, gravitational, and tether tension restoring forces.

Figure 4.16 Tethered Deployment

In this case, mass M_1 gained angular momentum equal to an identical amount lost by M_2. This amount of angular momentum transferred is equal to:

$$\Delta h = M_1 V \Delta R_1 = M_2 V \Delta R_2 .$$

The momentum is transferred from M_1 to M_2 through the horizontal component of the tether tension. This tension is caused by the Coriolis term of the acceleration expression of the librating masses.

If the tether is now cut, the upper mass, M_1, is boosted into an elliptical orbit having higher energy than it would have had due to its greater velocity. The point in the orbit where the tether is severed will correspond to the perigee of M_1. The situation is exactly reversed for M_2, which will be at its apogee at this point.

The preceding discussion explains the basic mechanics of momentum transfer in tethers. There are many variations of tethered deployment, many of which are beyond the scope of this text. Only some of the more basic ones will be described here.

Static and dynamic tether deployment are basically the same, except that static deployment occurs with the tether remaining under small angular displacements from the vertical, and dynamic deployments utilize large angular displacements. For certain dynamic deployments, it is possible to impart additional energy to one mass at the expense of the other. In order to implement this exchange, the deployment begins with a large angular displacement, tether tension is purposely kept low until a desired length is reached. When brakes are applied, a large angle prograde swing occurs. When the upper mass (payload) leads the lower mass, the tether is severed. In this way, an added boost due to the additional velocity of the prograde swing is accomplished.

Another method of tethered deployment is libration pumping. The tether is initially deployed then alternately extended and retrieved in resonance with tether tension variations during libration. (In-plane libration causes these tension variations due to Coriolis effects.) Spin pumping is yet another method, whereby libration pumping is carried further to the point that the tether system is caused to spin. In both cases, the added energy increases the departure velocity of the payload, just as in the dynamic tethered deployment case.

4.3.3 Orbit Variations

If the payload deployment described previously is carefully done, the orbits of both masses can be changed for one or both of their benefits. The Shuttle, for example, can boost a payload into a higher orbit and at the same time deboost itself back to Earth. Conversely, the Shuttle could perform a tethered deployment of its external tanks, whereby the tanks are deboosted back to Earth and the Shuttle is boosted to a higher orbit. Applications such as these are termed "momentum scavenging" since excess momentum is utilized for a beneficial purpose. The trick with this approach is that excess momentum must be available. One major application which is described in the applications section of the handbook is the Space Station-Shuttle deboost operation. This is an excellent example where both masses benefit. Resupply missions of the Space Station by the Shuttle are finalized by a tethered deployment of the Shuttle. In this way, the Space Station is boosted to a higher orbit and the Shuttle is de-boosted back to Earth. In order to utilize the additional momentum of the Space Station, tethered deployments of an STV are alternated with those of the Shuttle. Fuel savings can be obtained by both Shuttle and STV in this example. Tethers can also be used to change orbit eccentricity. This is done by libration pumping of tethered mass, phased as in Figure 4.17 (Ref. 9).

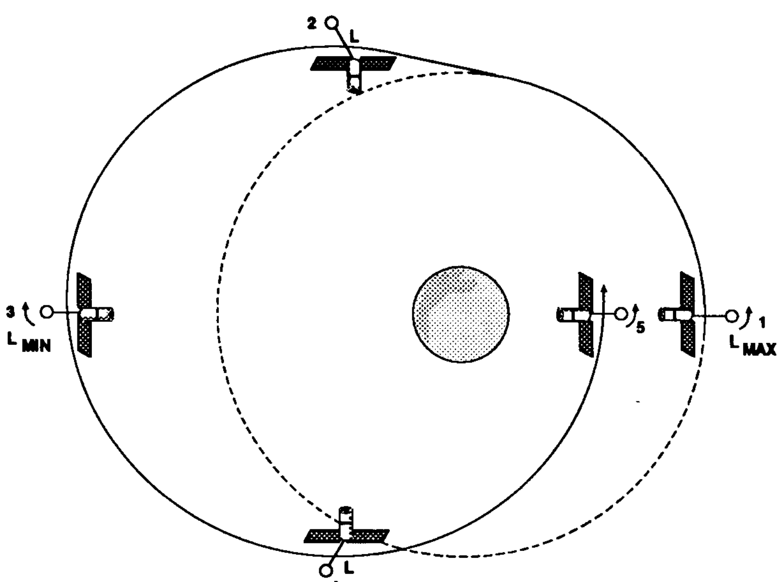


Figure 4.17 Orbit Eccentricity Change

At (1) the mass is fully extended, and libration commences. At (2), with the mass in a prograde swing, the retrieval motor pulls the spacecraft toward the mass, adding energy to the orbit (through the use of excess electrical energy transferred to the motor). At (3), which is the new apogee of the orbit, the tether length is at a minimum. At (4), with the mass in a retrograde swing, the tether is re-deployed and the retrieval brakes are used to dissipate orbital energy in the form of excess heat. At (5), the new perigee, the mass is again fully deployed.

4.4 ELECTRODYNAMICS

4.4.1 General

Electrodynamic tether systems can be designed to produce several useful effects by interacting with magnetic fields. They can be designed to produce either electrical power or thrust (either a propulsive thrust or a drag). They can also be designed to alternately produce electrical power and thrust. In addition, they can be designed to produce ULF/ELF/VLF electromagnetic signals in the upper atmosphere, and shape-stability for orbiting satellite constellations. Electrodynamic systems can be designed to produce electrical power.

4.4.2 Electric Power Generators

The discussion of electric power generation by tether systems will begin with electrodynamic systems in low Earth orbit. Consider a vertical, gravity-gradient-stabilized, insulated, conducting tether, which is terminated at both ends by plasma contactors. A typical configuration is shown in Figure 4.18 (Ref. 9, 10). As this system orbits the Earth, it cuts across the geomagnetic field from west to east at about 8 km/s. An electromotive force (emf) is induced across the length of the tether. This emf is given by the equation:

$$V = \int_{\text{along length of tether}} (\vec{v} \times \vec{B}) \cdot \vec{dl}$$

where

V = induced emf across the tether length (volts),

$\vec{v}$ = tether velocity relative to the geomagnetic field (m/s)

$\vec{B}$ = magnetic field strength (webers/m^2), and

$\vec{dl}$ = differential element of tether length - a vector pointing in the direction of positive current flow (m).

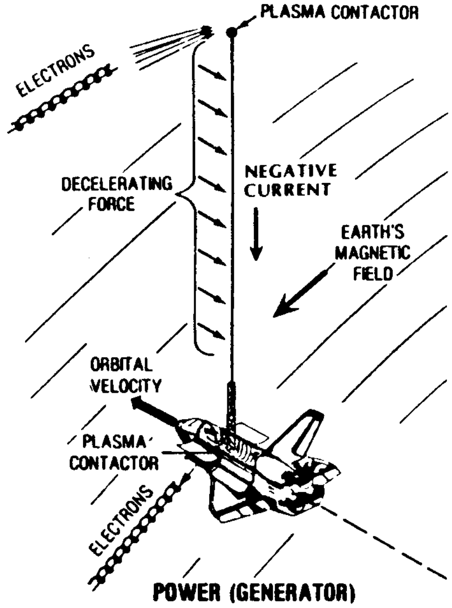
For the special case where the tether is straight and perpendicular to the magnetic field lines everywhere along its length, the equation for the emf simplifies to:

$$V = (\vec{v} \times \vec{B}) \cdot \vec{L} \quad ;$$

where

$\vec{L}$ = tether length - a vector pointing in the direction of positive current flow (m).

The equation for the induced emf across the tether in this special case can also be written as:



$$V = L \, v \, B \sin\theta \quad ;$$

where

θ = angle between

(From these equations, it can be seen that equatorial and low-inclination orbits will produce the largest emfs, since the maximum emf is produced when the tether velocity and the magnetic field are perpendicular to each other.)

Figure 4.18 Power Generation With an Electrodynamic Tether

The emf acts to create a potential difference across the tether by making the upper end of the tether positive with respect to the lower end. In order to produce a current from this potential difference, the tether ends must make electrical contact with the Earth's plasma environment. Plasma contactors at the tether ends provide this contact, establishing a current loop (a so-called "phantom loop") through the tether, external plasma, and ionosphere. Although processes in the plasma and ionosphere are not clearly understood at this time, it is believed that the current path is like that shown in Figure 4.19. The collection of electrons from the plasma at the top end of the tether and their emission from the bottom end creates a net-positive charge cloud (or region) at the top end, and a net-negative charge cloud at the bottom. The excess free charges are constrained to move along the geomagnetic field lines intercepted by the tether ends until they reach the vicinity of the E region of the lower ionosphere where there are sufficient collisions with neutral particles to allow the electrons to migrate across the field lines and complete the circuit.

To optimize the ionosphere's ability to sustain a tether current, the tether current density at each end must not exceed the external ionospheric current density. Plasma contactors must effectively spread the tether current over a large enough area to reduce the current densities to the necessary levels. Three basic tether system configurations, using three types of plasma contactors, have been considered. They are: (1) a passive large-area conductor at both tether ends; (2) a passive large-area conductor at the upper end and an electron gun at the lower end; and, (3) a plasma-generating hollow cathode at both ends.

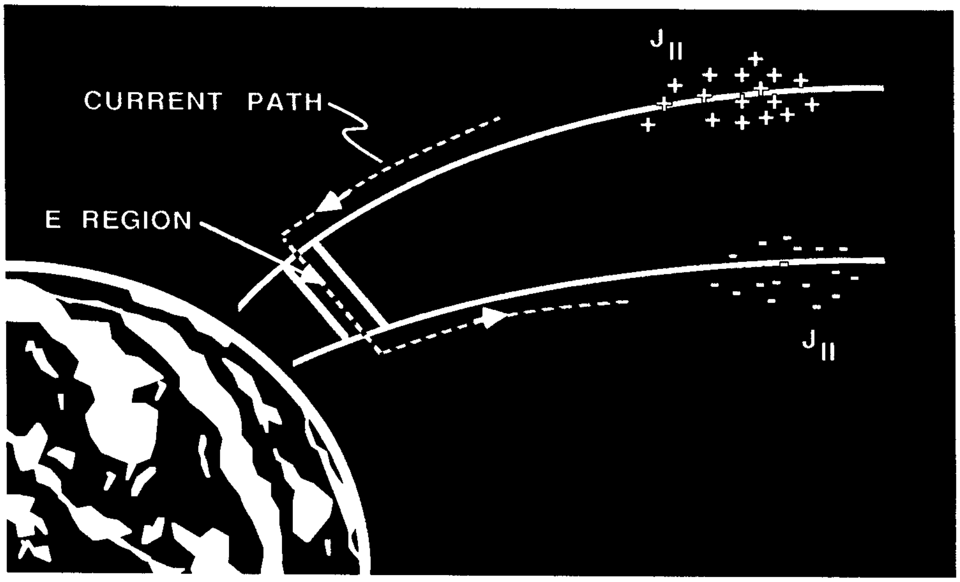
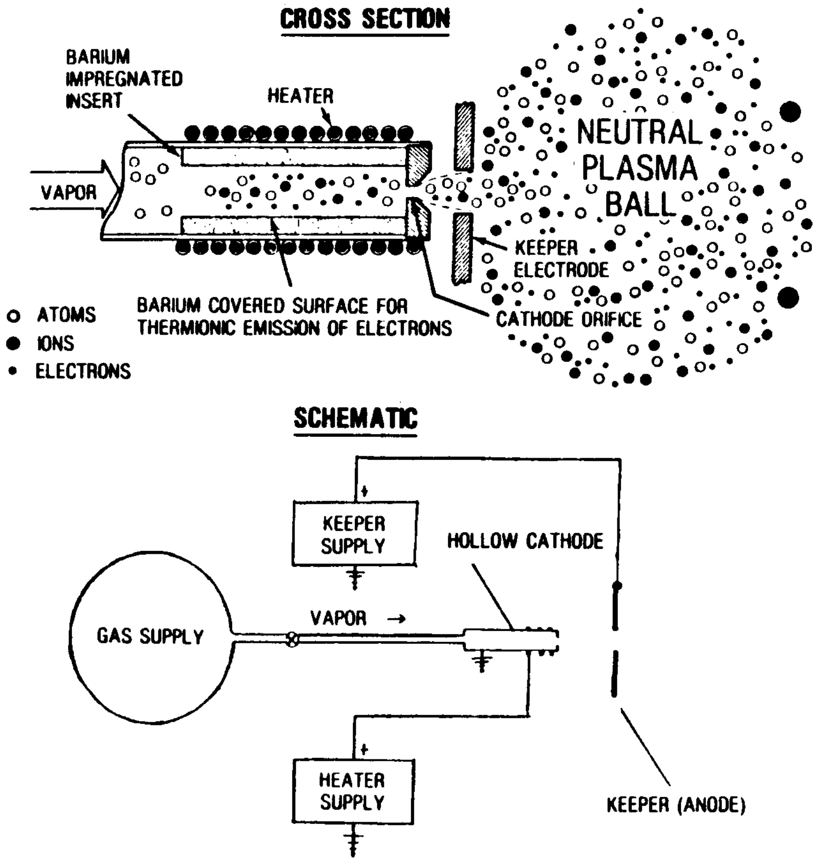


Figure 4.19 The Current Path External To An Orbiting Electrodynamic Tether System

In the first configuration, the upper conductor (probably a conducting balloon) collects electrons. The lower plasma contactor in this configuration (perhaps a conductive surface of the attached spacecraft) utilizes its large surface area in a similar way to collect ions.

To achieve higher currents, it is possible to replace the passive large-area conductor at the lower end with an electron gun, providing the equivalent of collecting a positive ion current by ejecting a negative electron current. Ejecting these electrons at a high energy distributes them over an effectively large contact region. Unfortunately, electron guns are active plasma contactors, requiring on-board electrical power to drive them.

The third configuration is quite different from the first two. Based upon research results and performance modeling up to this point, it is projected to be the most promising of the three systems. Instead of relying on a passive and physically large conducting surface to collect currents, a hollow cathode at each tether end generates an expanding cloud of highly conductive plasma. The plasma density is very high at the tip of the tether and falls off to ionospheric densities at a large distance from the tip. This plasma provides a sufficient thermal electron density to carry the full tether current in either direction at any distance from the tether end, until it is merged into the ambient ionospheric plasma currents. This case of current reversibility allows the system to function alternately as either a generator or a thruster, with greater ease than either of the other two configurations (as will be discussed in more detail in the next section). Hollow cathodes are also active plasma contactors, requiring on-board electrical power and a gas supply to operate. However, they require much less power than an electron gun, and the gas supply should not impose a severe weight penalty. Two diagrams of a hollow cathode plasma source are shown in Figure 4.20. Additional diagrams and information relating to the construction and operation of the PMG hollow cathode plasma contactor are given in Figures 4.21, 4.22 and 4.23. Typical characteristics of a hollow cathode and an electron gun are compared in Figures 4.24 and 4.25. More information on the TSS and PMG flights results are given in Section 1.



TSS-1R flight showed that larger tether currents can be generated and at much lower satellite potentials than were theoretically predicted. A final assessment on the performance of hollow cathodes flown on PMG compared to other configurations cannot be given as long as TSS-1R data analysis is completed and more flights test are verified. In addition, there may be particular applications for which passive contactors or electron guns are desirable. On the other hand, using hollow cathode plasma contactors should also be safer for spacecraft systems, since they establish a known vehicle ground reference potential with respect to the local plasma.

Figure 4.20 Diagrams of a Hollow Cathode Plasma Contactor

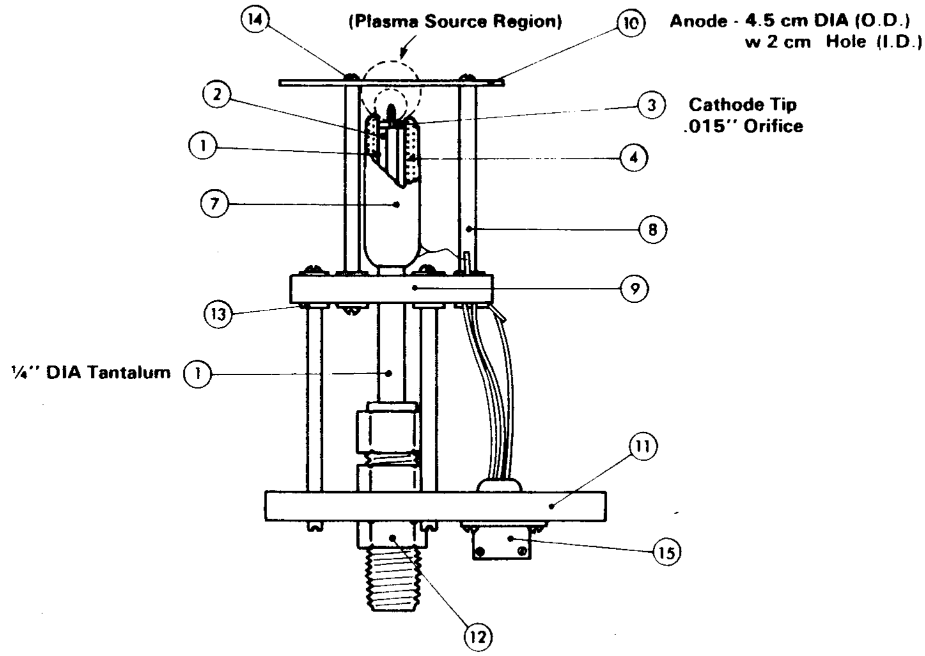


Figure 4.21 Diagram of the Plasma Motor/Generator (PMG) Hollow Cathode Assembly

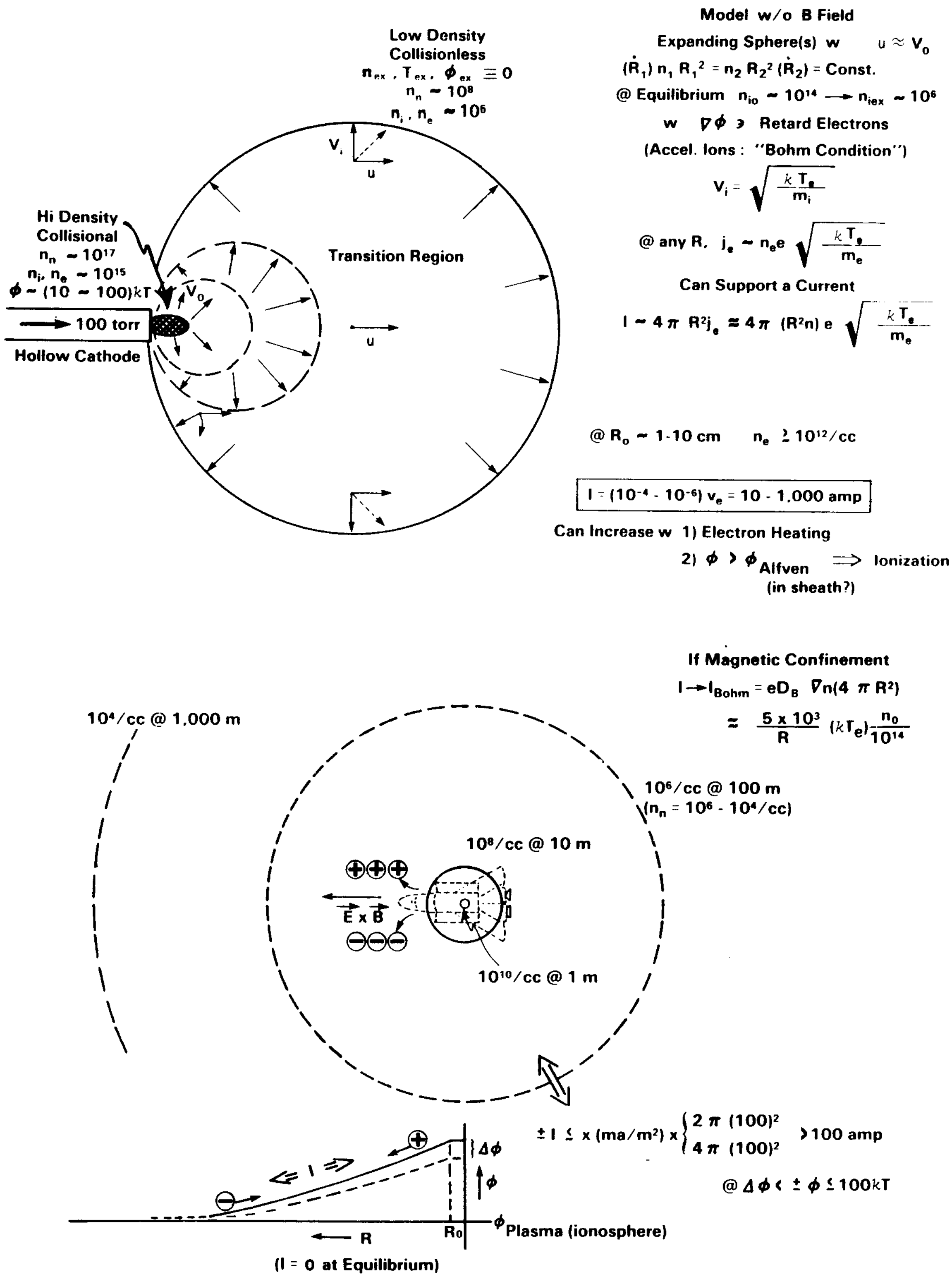


Figure 4.22 Plasma Cloud Expansion for PMG Hollow Cathode Plasma Contactor

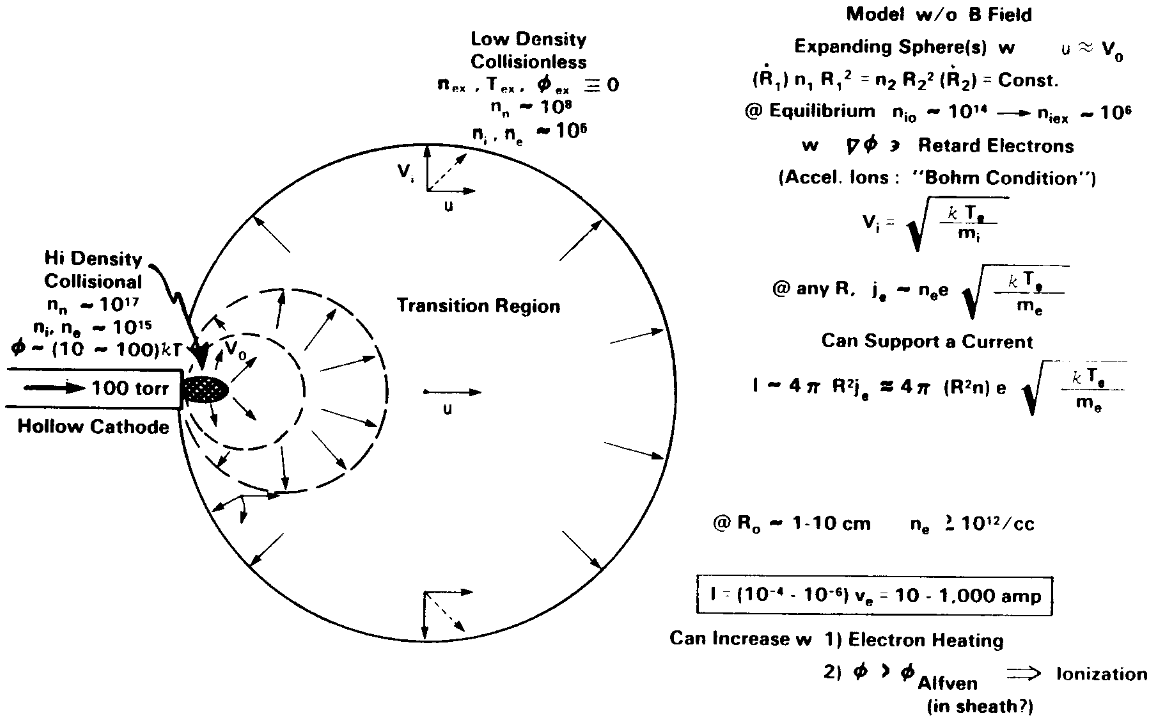


Figure 4.23 Electron Current Flow To/From the Ionosphere for PMG Hollow Cathode Plasma Contactor

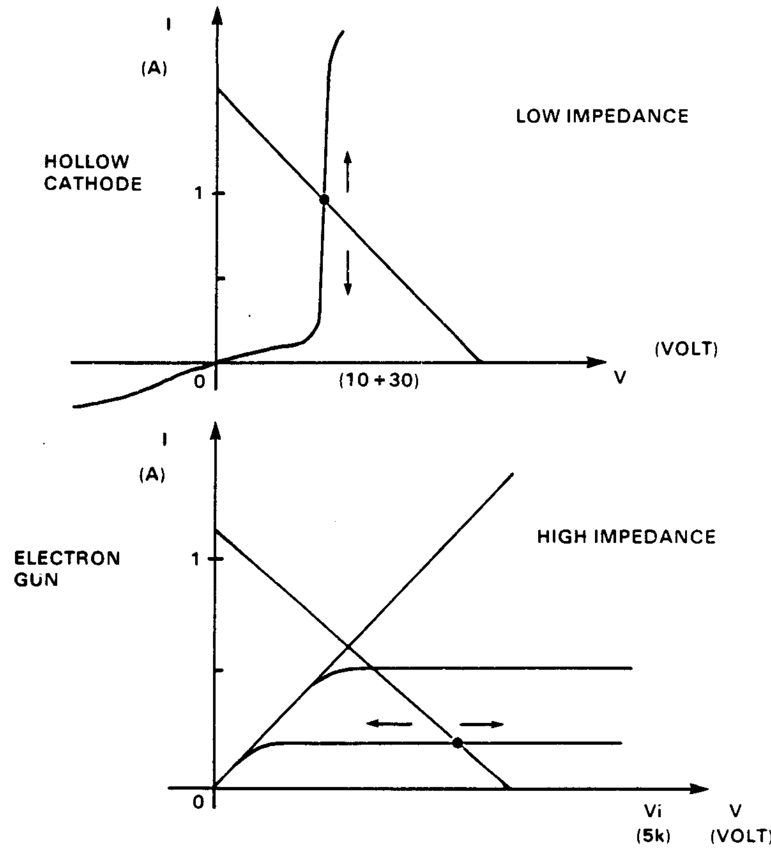


Figure 4.24 Comparison of the IV Characteristics of a Hollow Cathode and Electron Gun

	Electron Gun	Hollow Cathode
• **Current Range**	**$I_e \leq$ 1A**	**$I_e \geq$ 10 A (Nominal)**
• **Power Consumption**	**~ 1 KW**	**~ 10 KW**
• **Life Time**	**Similar**	**Similar**
• **Automatic Switching**	**No**	**Yes**
• **Main Applications**	**Basic Science Exp. and Power**	**Low Impedance Coupling**

Dissipation **Thrusting and Power Generation**

Figure 4.25 Comparative Characteristics of an Electron Gun and a Hollow Cathode

The current passing through the tether can be controlled by any one of several methods, depending upon the type of plasma contactors used. For systems with passive conductors at both ends, control is by variable resistance, inserted between the tether and one of the plasma contactors. For systems using an electron gun as a plasma contactor, tether current is controlled by the current emitted by the electron gun. Unfortunately, these methods are very inefficient. They not only waste all of the I^2R power lost in the resistors, plasma sheaths (around the plasma contactors), and electron gun impedance, but they also transfer most of it as heat back into the spacecraft, where it may cause significant thermal control and heat rejection problems.

The basic equation of the current loop (circuit) is:

$$V_{IND} = IR + \Delta V_{LOW} + \Delta V_{UP} + \Delta V_{ION} + \Delta V_{LOAD} \; ;$$

where

V_{IND}	=	emf induced across the tether (volts),
I	=	tether current (amps),
R	=	resistance of the tether (ohms),
ΔV_{LOW}	=	voltage drop across the space charge region around the lower plasma contactor (volts),
ΔV_{UP}	=	voltage drop across the space charge region around the upper plasma contactor (volts),
ΔV_{ION}	=	voltage drop across the ionosphere (volts), and
ΔV_{LOAD}	=	voltage drop across a load (volts),

This equation simply states that the emf induced across the tether by its motion through the magnetic field is equal to the sum of all of the voltage drops in the circuit. The IR term in the equation is the voltage drop across the tether due to its resistance (according to Ohm's Law).

To provide an expression for the working voltage available to drive a load, this equation can be rewritten as:

$$\Delta V_{LOAD} = V_{IND} - IR - \Delta V_{LOW} - \Delta V_{UP} - \Delta V_{ION} \; .$$

The voltage drop across the space charge region (sheath, electron gun, or plasma cloud) at each tether end is caused by the impedance of that region. The voltage drop across the ionosphere is likewise due to its impedance. The problem with these equations is that the impedances of the charge regions around the tether ends are complex, nonlinear, and unknown functions of the tether current. The impedance of the ionosphere has not been clearly determined. Although some laboratory studies have been performed, and estimates made, detailed flight test measurements will have to be performed before these quantities can be clearly determined.

It has been calculated that the ionospheric impedance should be on the order of 1-20 ohms (Ref. 11). The highest impedance of the tether system are encountered at the space charge sheath regions around the upper and lower plasma contactors. Reducing these impedances will greatly increase the efficiency of the tether system in providing large currents. PMG data indicate that plasmas released from hollow cathode plasma contactors greatly reduce the sheath impedance between the contactors and the ambient plasma surrounding them. Although processes in these plasmas and in the ionosphere are not well understood and require continued study and evaluation through testing, preliminary indications are that feasible tether and plasma-contactor systems should be able to provide large induced currents.

As indicated earlier, the electric currents induced in such tether systems can be used to power loads on board the spacecraft equipped with them. They can also be used as primary power for the spacecraft. It has been calculated that electrodynamic tether systems should be capable of producing electrical power in the multikilowatt to possibly the megawatt range (Ref. 4, p. 161-184). Calculations a 200 KW system is given in figure 4.26.

There is a price to be paid for this electrical power, however. It is generated at the expense of spacecraft/tether orbital energy. This effect is described in detail in the next section .

In principle, electrodynamic tether systems can generate electrical power not only in Earth orbit, but also when they move through the magnetic fields of other planets and interplanetary space. The magnetic field in interplanetary space is provided by the solar wind, which is a magnetized plasma spiralling outward from the sun.

References 1 (p. 1-22 through 1-24, 3-49 through 3-65), 2, 4 (p. 153-184, 547-594), 10,11, and data from Dr. James McCoy (NASA/Johnson Space Center) are the primary references for this section.

TETHER LENGTH	20 KM (10 UP+10 DN)	WORKING TENSION	42 N
NOMINAL VOLTAGE	4 KV	WORKING ANGLE	17 DEG
RATED POWER	200 KW	RATED THRUST	25 N
PEAK POWER	500 KW	PEAK THRUST	>100 N

CONDUCTOR	#00 AWG ALUMINUM WIRE DIAMETER 9.3 MM @ 20°C RESISTANCE 8.4 OHNS @ 20°C 7.7 OHMS @ 0°C 7.1 OHMS @ -20°C	3640 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)	278 KG
FAR END MASS	50 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)	25 KG
TETHER CONTROLLER ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% =2 KW)		94 KG
ARGON SUPPLY & CONTINGENCY RESERVE		163 KG
TOTAL		4,200 KG

TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING	
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING	
TETHER OUTSIDE DIAMETER	10.3 MM	
TETHER BALLISTIC DRAG AREA	206 SQ METERS	
DRAG FORCE @ 10^{-11} KG/M^3 (300 KM 1976 USSA-400 KM SOLAR MAX)	12 N	.96 KW
I^2R LOSSES @ 200 KW		19.25 KW
HOLLOW CATHODE POWER		2.50 KW
IONOSPHERIC LOSS @ 50 AMP		1.25 KW
TOTAL PRIMARY LOSSES		23.96 KW

EFFICIENCY ELECTRIC (177 KW NET @ 50 AMP/200KW) 88.5%
OVERALL (201 MECH. TO 177 ELEC. KW) 88.1%

INCLUDING CONTROLLER/POWER PROCESSOR LOSSES @ 1%	2.00 KW
TOTAL (NET POWER OUT 175.0 KW)	25.96 KW

FINAL EFFICIENCY ELECTRIC = 87.5% OVERALL = 87.1%

Figure 4.26 Calculated Performance of an Electromagnetic Tether System

4.4.3 Thrusters

As mentioned in the previous two sections, electrodynamic tether systems can be used to generate thrust or drag. Consider the gravity-gradient-stabilized system in Earth orbit, for example. Its motion through the geomagnetic field induces an emf across the tether. When the current generated by this emf is allowed to flow through the tether, a force is exerted on the current (on the tether) by the geomagnetic field (see Figure 4.27). This force is given by:

$$\vec{F} = \int_{\text{along length of tether}} (I\ \vec{dl}) \times \vec{B} \qquad = I \int_{\text{along length of tether}} \vec{dl} \times \vec{B} \quad ;$$

where

$\vec{F}$ = force exerted on the tethe

I = tether current (amps),

$\vec{dl}$ = differential element of tet
of positive current flow (

$\vec{B}$ = magnetic field strength (v

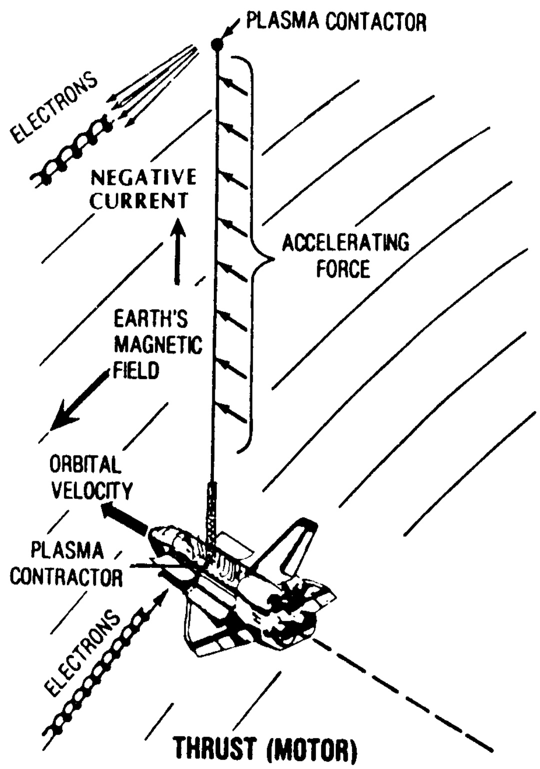


Figure 4.27 Thrust Generation With An Electrodynamic Tether System

For the special case of a straight tether, this equation simplifies to:

$$\vec{F} = I\vec{L} \times \vec{B} \quad ;$$

where

$\vec{L}$ = tether length - a vector pointing in the direction of positive current flow (m).

This equation for the electromagnetic force on a straight tether can also be written as:

$$F = ILB \sin\theta \quad ;$$

where

θ = angle between $\vec{L}$ and $\vec{B}$.

Its maximum value occurs when the tether is perpendicular to the magnetic field.

Depending on the relative orientation of the magnetic field to the tether velocity, this force can have a component parallel to the velocity and one perpendicular to the velocity. Considering the parallel (inplane) component, whenever the current induced in the tether by the magnetic field is allowed to flow, this component of the force always acts to reduce the relative velocity between the tether system. In low Earth orbit, where the orbital velocity of the tether is greater than the rotational velocity of the geomagnetic field and they are rotating in the same direction, this force is a drag on the tether. This means that when electric power is generated by the system for on-board use, it is generated at the expense of orbital energy. If the system is to maintain its altitude, this loss must be compensated by rockets or other propulsive means.

When current from an on-board power supply is fed into the tether against the induced emf, the direction of this force is reversed. This force follows the same equation as before, but now the sign of the cross product is reversed, and the force becomes propulsive. In this way, the tether can be used as a thruster. Therefore, the same tether system can be used reversibly, as either an electric generator or as a thruster (motor). As always, however, there is a price to be paid. The propulsive force is generated at the expense of on-board electrical power.

It is necessary to distinguish between tether systems orbiting at subsynchronous altitudes, and those orbiting at altitudes greater than the synchronous altitude, where the sense of the relative velocity between the satellite and the magnetic field rest frame is reversed (often thought of in terms of a concept known as the "co-rotating field"). An analogous situation exists in orbits around Jupiter for altitudes greater than 2.2 Jovian radii from its center (the Jovian synchronous altitude: i.e., the altitude at which the rotational angular velocity of an orbiting satellite equals the rotational velocity of Jupiter and its magnetic field). Another analogous situation exists in interplanetary space if a spacecraft moves outward at a speed of 400 km/s). In such cases, dissipation of the induced electrical current would produce a thrust (not a drag) on the tether. Again, the force acts to bring the relative velocity between the tether and the magnetic field rest frame to zero. In such cases, feeding current into the tether against the induced emf would produce a drag. When moving in a direction opposite to the direction of motion of the magnetic field, the effects would be reversed.

Systems have been proposed to operate reversibly as power and thrust generators (Ref. 4 and 10). Such systems could provide a number of capabilities. Calculations of the performance of a 200 KW system is given in figure 4.26.

In addition to the in-plane component, the electromagnetic force on the tether current generally also has an out-of-plane component (perpendicular to the tether velocity). For an orbiting tether system, the out-of-plane force component acts to change the orbital inclination, while doing no in-plane mechanical work on the tether and inducing no emf to oppose the flow of current in the tether. This makes electrodynamic tethers potentially ideal for orbital plane changes. Unlike rockets, they conserve energy during orbital plane changes. If the current is constant over a complete orbit, the net effect of this force is zero (since reversals in the force direction during the orbit cancel each other out). On the other hand, if a net orbital inclination change is desired, it can be produced by simply reversing the tether current at points in the orbit where the out-of-plane force reverses its direction, or by allowing a tether current to flow for only part of an orbit. Attention must be paid to this out-of-plane force when operating a tether alternately as a generator and thruster, and when operating a tether system which alternately generates and stores electrical energy. Strategies for using electrodynamic tethers to change orbits are shown in Section 5.0.

Electromagnetic forces also cause the tether to bow and produce torques on the tether system. These torques cause the system to tilt away from the vertical until the torques are balanced by gravity-gradient restoring torques. These torques produce in-plane and out-of-plane librations. The natural frequencies of in-plane and out-of-plane librations are $\sqrt{3}$ times the orbital frequency and twice the orbital frequency, respectively. Selective time phasing of the IL x B loading, or modulation of the tether current, will damp these librations. The out-of-plane librations are more difficult to damp because their frequency is twice the orbital frequency. Unless care is taken, day/night power generation/storage cycles (50/50 power cycles) can actively stimulate these librations. Careful timing of tether activities will be required to control all tether librations. Additional information on electromagnetic libration control issues is shown also in Section 5.0.

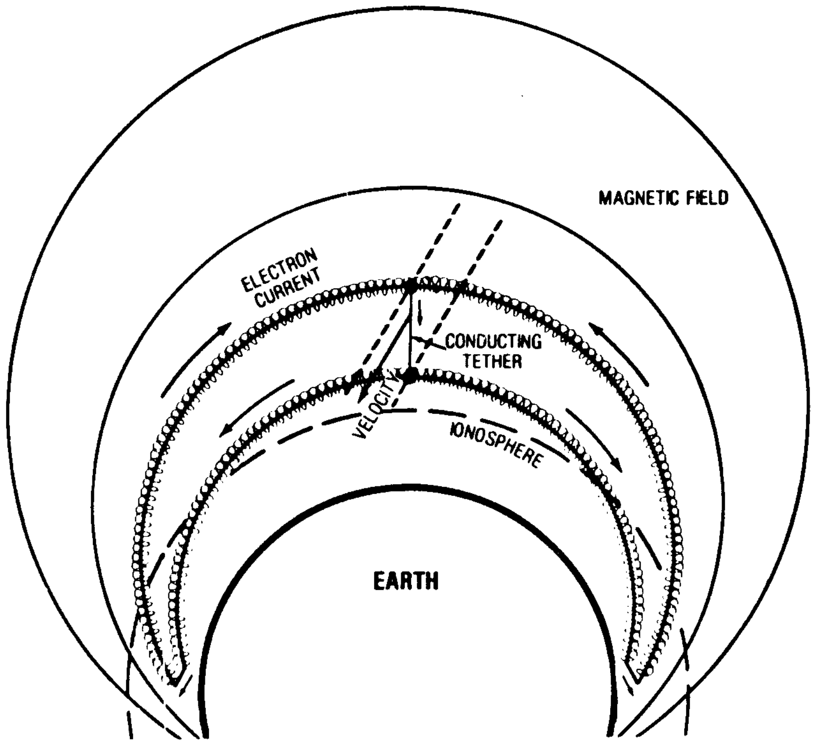
4.4.4 ULF/ELF/VLF Antennas

As discussed in Section 4.4.2, the movement of an Earth-orbiting electrodynamic tether system through the geomagnetic field gives rise to an induced current in the tether. One side effect of this current is that as the electrons are emitted from the tether back into the plasma, ULF, ELF, VLF electromagnetic waves are produced in the ionosphere (see Ref. 11).

In the current loop external to the tether, electrons spiral along the geomagnetic field lines and close at a lower layer of the ionosphere (see Figure 4.28). This current loop (or so-called "phantom loop") acts as a large ULF, ELF, and VLF antenna. (The phantom loop is shown in Figure 4.29). The electromagnetic waves generated by this loop should propagate to the Earth's surface, as shown in Figure 4.30. The current flow generating these waves can be that induced by the geomagnetic field or can be provided by a transmitter on board the spacecraft so that the tether is in part an antenna.

Messages can be transmitted from the tether (antenna) by modulating the waves generated by the current loop. If the induced current is used to generate these waves, it is modulated by varying a series impedance or by turning an electron gun or hollow cathode on the lower tether end on and off at the desired frequency. If a transmitter is used, current is injected into the tether at the desired frequency.

The ULF, ELF, VLF waves produced in the ionosphere will be injected into the magnetosphere more efficiently than those from existing ground-based, man-made sources. It is believed that the ionospheric boundary may act as a waveguide, extending the area of effective signal reception far beyond the "hot spot" (area of highest intensity reception, with an estimated diameter of about 5000 km) shown in Figure 4.30. If this turns out to be the case, these waves may provide essentially instant worldwide communications, spreading over the Earth by ducting. Calculations have been performed, predicting that power levels of the order of 1 W by night and 0.1 W by day can be injected into the Earth-ionosphere transmission line by a 20-10 km tether with a current of the order of 10 A. Such tether systems would produce wave frequencies throughout the ULF (3-30 Hz) and ELF bands (30-300 Hz), and even into the VLF band (about 3000 Hz).



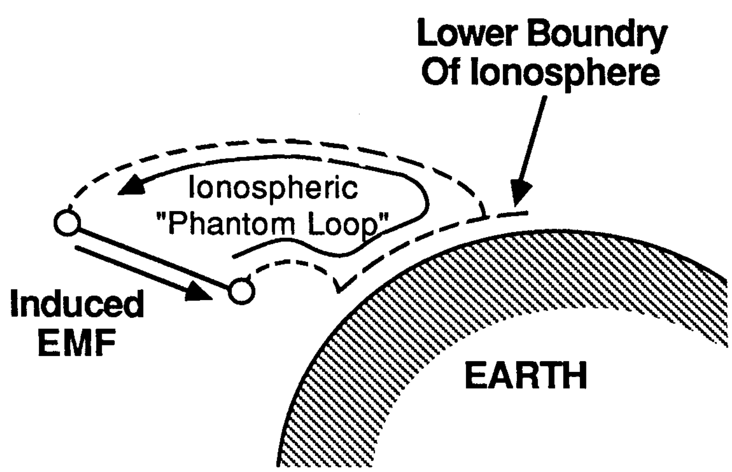


Figure 4.28
Electron Paths in
the Electrodynamic
Tether Generator

Figure 4.29 The "Phantom Loop" of the ULF/ELF Tether Antenna

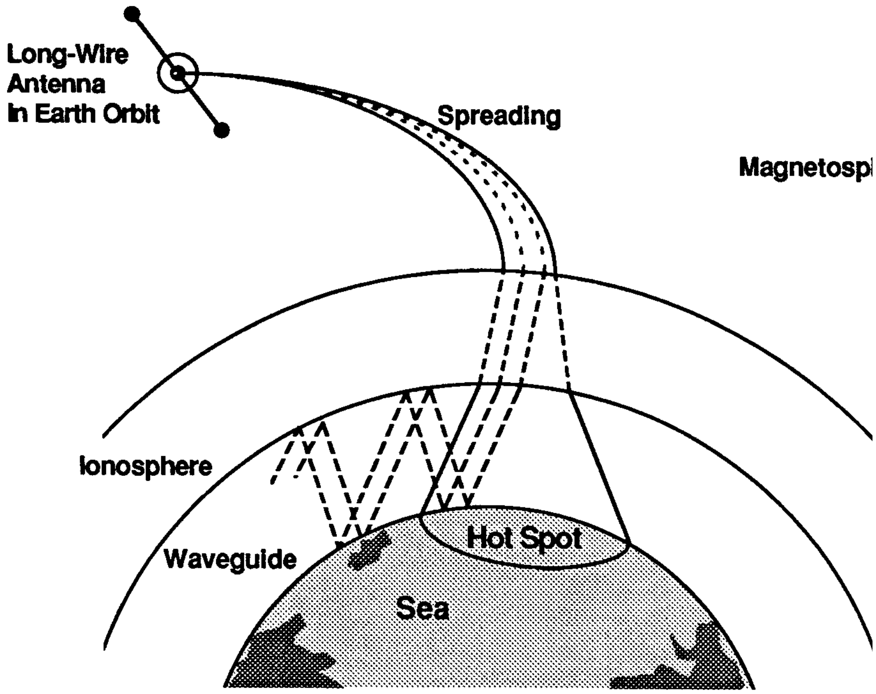


Figure 4.30 Propagation of ULF/ELF/VLF Waves To The Earth's Surface From An Orbiting Tether Antenna

It should be noted that if the induced tether current is used to power the antenna, orbital energy will be correspondingly decreased. A means of restoring this orbital energy (such as rocket thrust) will be required for long missions.

4.4.5 Constellations

As mentioned earlier, electromagnetic forces exerted by the geomagnetic field on the current in orbiting tethers can be used in conjunction with gravity-gradient forces to stabilize two-dimensional constellations (see Figure 4.13). The force exerted on a current in a tether is exactly the force described in Section 4.4.3. The tether currents used in these constellations can be those induced by the geomagnetic field or those provided by on-board power supplies.

The basic concept is that gravity-gradient forces will provide vertical and overall attitude stability for the constellation, and electromagnetic forces will provide horizontal and shape stability (see Ref. 1, p.1-29, and 4, p. 150-203). This is accomplished in the quadrangular configuration by establishing the current direction in each of the vertical tethers such that the electromagnetic forces on them push the side arcs horizontally away from each other. Each side arc may be composed of a number of satellites connected in series by tethers. The current directions for the tethers on each side arc will be the same, providing a consistent outward force. Large masses are placed at the top and bottom juncture points where the two sides join together. This provides additional stability for the constellation.

4.5 REFERENCES

1. Applications of Tethers in Space, Workshop, Williamsburg, Virginia, 15-17 June 1983, Workshop Proceedings, NASA CP-2364 (Vol. 1), NASA CP-2365 (Vol. 2), March 1985.

2. Beletskii, V. V. and Levin, E. M., "Dynamics of Space Tether Systems," Advances in the Astronautical Sciences, Vol. 83.

3. Arnold, D. A., "The Behavior of Long Tethers in Space," Journal of the Astronuatical Sciences, Vol. 35, No. 1, p. 3-18, January-March, 1987.

4. Applications of Tethers in Space, Workshop, Venice, Italy, 15-17 October 1985, Workshop Proceedings, NASA CP-2422 (Executive Summary, Vol. 1, Vol. 2), 1986.

5. Carroll, J. A., Guidebook for Analysis of Tether Applications, Contract RH4-394049, Martin Marietta Corporation, Feb. 1985.

6. Pearson, J., "Anchored Lunar Satellites for Cislunar Transportation and Communication," Journal of the Astronautical Sciences, Vol. 27, No. 1, p. 39-62, Jan.-Mar. 1979.

7. Lorenzini, E. C., "Novel Tether-Connected Two-Dimensional Structures for Low Earth Orbits," Journal of the Astronautical Sciences, Vol. 36, No. 4, p. 389-405, Oct.-Dec. 1988.

8. Greenwood, D. T., Principles of Dynamics, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1965.

9. Tiesenhausen, G. von, ed., "The Roles of Tethers on Space Station," NASA-TM-86519, NASA/MSFC, Oct. 1985.

10. McCoy, J. E., "Plasma Motor/Generator Reference System Designs for Power and Propulsion," AAS 86-229, Int. Conf. 1986.

11. Grossi, M. D., "Spaceborne Long Vertical Wire as a Self-Powered ULF/ELF Radiator," IEEE Journal of Oceanic Engineering, Vol. OE-9, No. 3, p. 211-213, July 1984.