

Tethers In Space Handbook - Second Edition -



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**Tether
Programs**

Tethers In Space Handbook - Second Edition -

**Tether
Applications**

**Tether
Fundamentals**

May 1989

Tether Data

**Conference
Summaries**

Prepared For:

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FOREWORD

The Tethers in Space Handbook Second Edition represents an update to the initial volume issued in September 1986. As originally intended, this handbook is designed to serve as a reference manual for policy makers, program managers, educators, engineers, and scientists alike. It contains information for the uninitiated, providing insight into the fundamental behavior of tethers in space. For those familiar with space tethers, it summarizes past and ongoing studies and programs, a complete bibliography of tether publications, and names, addresses, and phone numbers of workers in the field. Perhaps its most valuable asset is the brief description of nearly 50 tether applications which have been proposed and analyzed over the past 10 years. The great variety of these applications, from energy generation to boosting satellites to gravity wave detection is an indication that tethers will play a significant part in the future of space development.

This edition of the handbook preserves the major characteristics of the original; however, some significant rearrangements and additions have been made. The first section on Tether Programs has been brought up to date, and now includes a description of TSS-2, the aerodynamic NASA/Italian Space Agency (ASI) mission. Tether Applications follows, and this section has been substantially rearranged. First, the index and cross-reference for the applications have been simplified. Also, the categories have changed slightly, with Technology and Test changed to Aerodynamics, and the Constellations category removed. In reality, tether constellations may be applicable to many of the other categories, since it is simply a different way of using tethers. Finally, to separate out those applications which are obviously in the future, a Concepts category has been added.

The section on Tether Fundamentals now appears after the Tether Applications, and just before the section on Tether Data. These two sections go well together, and provide the user with the technical background necessary to understand the requirements and limitations of the applications, and perhaps to develop ideas of his own.

A new section included here on Conference Summaries recognizes the fact that the tether community is growing internationally, and that meetings provide a means of rapid communication and interaction. There have been three international conferences, and several major workshops, both here and in Italy, and simply reproducing the programs can provide the reader with a quick reference of the literature and active participants in specific tether areas. All of these meetings are well documented elsewhere.

Finally, the Bibliography section has been considerably updated to include all known references. These are listed by author and by subject and include the papers to be presented at the Third International Conference in May 1989.

This second edition expands on the efforts of W. A. Baracat, and C. L. Butner of the General Research Corporation, who issued the first edition in 1986, and the authors are appreciative of their efforts. None of this, of course, would have been possible without the enthusiasm, dedication, and hard work of many tether advocates: in NASA, industry, the university, and certainly those in Italy.

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LIST OF ACRONYMS/ABBREVIATIONS

AFB	Air Force Base	NEP	Near End Package
AFV	Aerobraking Ferry Vehicle	OMV	Orbital Maneuvering Vehicle
AIAA	American Institute of Aeronautics and Astronautics	OTV	Orbital Transfer Vehicle
ARC	Ames Research Center	PEC	Pseudo Elliptical Constellation
ASI	Italian Space Agency	PEP	Power Extension Package
AWG	American Wire Gauge	PMG	Plasma Motor/Generator
AXAF	Advanced X-ray Astrophysics Facility	POF	Proof-Of-Flight
C.G.	Center-of-Gravity	RCS	Reaction Control System
DC	Direct Current	RMS	Remote Manipulator System
DSC	Drag Stabilized Constellation	SAO	Smithsonian Astrophysics Observatory
emf	Electromotive Force	SATP	Scientific and Applications Tethered Platform
EMP	Enhanced Multiplexer Demultiplexer Pallet	SBIR	Small Business Innovative Research
ESC	Electromagnetically Stabilized Constellation	SCOWT	Shuttle Continuous Open Wind Tunnel
EVA	Extra Vehicular Activity	SEDS	Small Expendable Deployer System
FEP	Far End Package	SRV	Satellite Reentry Vehicle
GAS	Get-Away Special	STARFAC	Shuttle Tethered Aerothermodynamic Research Facility
GATE	Get-Away Tether Experiment	STS	Space Transportation System
GEO	Geosynchronous Earth Orbit	STV	Space Transfer Vehicle
GPS	Global Positioning System	TAMPS	Tether and Materials Processing Station
GSFC	Goddard Space Flight Center	TECS	Tether Elevator/Crawler System
HHG	Hitchhiker-G	TEMAG	Tethered Magnetometer
HOCAT	Hollow Cathode Sounding Rocket Experiment	TIRE	Tether Inspection and Repair Experiment
HQ	Headquarters	TISRS	Tether Initiated Space Recovery System
I	Current	TORF	Tethered Orbital Refueling Facility
IFSI	Interplanetary Space Physics Institute	TSS	Tethered Satellite System
JPL	Jet Propulsion Laboratory	V	Volts
JSC	Johnson Space Center	VGRF	Variable Gravity Research Facility
KITE	Kinetic Isolation Tether Experiment	Z	Impedance
kV	Kilovolts		
LaRC	Langley Research Center		
LEO	Low Earth Orbit		
LeRC	Lewis Research Center		
LJO	Low Jupiter Orbit		
LOTS	Lunar Orbiting Tether Station		
MAO	Mars Aeronomy Observer		
MIT	Massachusetts Institute of Technology		
MMPF	Microgravity Materials Processing Facility		
MMU	Mass Memory Unit		
MPES	Mission Peculiar Equipment Support Structure		
MSFC	Marshall Space Flight Center		
MTL	Materials Technology Laboratory		

SECTION 1.0 TETHER PROGRAMS

1.1 Tethered Satellite System

1.1.1 TSS-1

The Tethered Satellite System (TSS) is a joint undertaking between the United States and Italy. Presently, only the first mission, TSS-1, is approved and scheduled for a 1991 launch with planning authorized for TSS-2 and TSS-3. The system consists of a U.S.-built deployer and an Italian-built satellite, both of which are reusable. The prime contractors for the TSS deployer and satellite are Martin Marietta Denver Aerospace and Aeritalia, respectively. The TSS deployer system is mounted on a Spacelab Enhanced/Multiplexer Demultiplexer Pallet (EMP), science equipment is mounted on a Mission Peculiar Equipment Support Structure (MPESS) located in the Orbiter cargo bay, and a satellite is attached to the deployer by a conducting tether. The total integrated TSS is installed in the Space Shuttle Orbiter as shown in Figure 1.1. Overall system characteristics for the TSS are presented in Table 1.1.

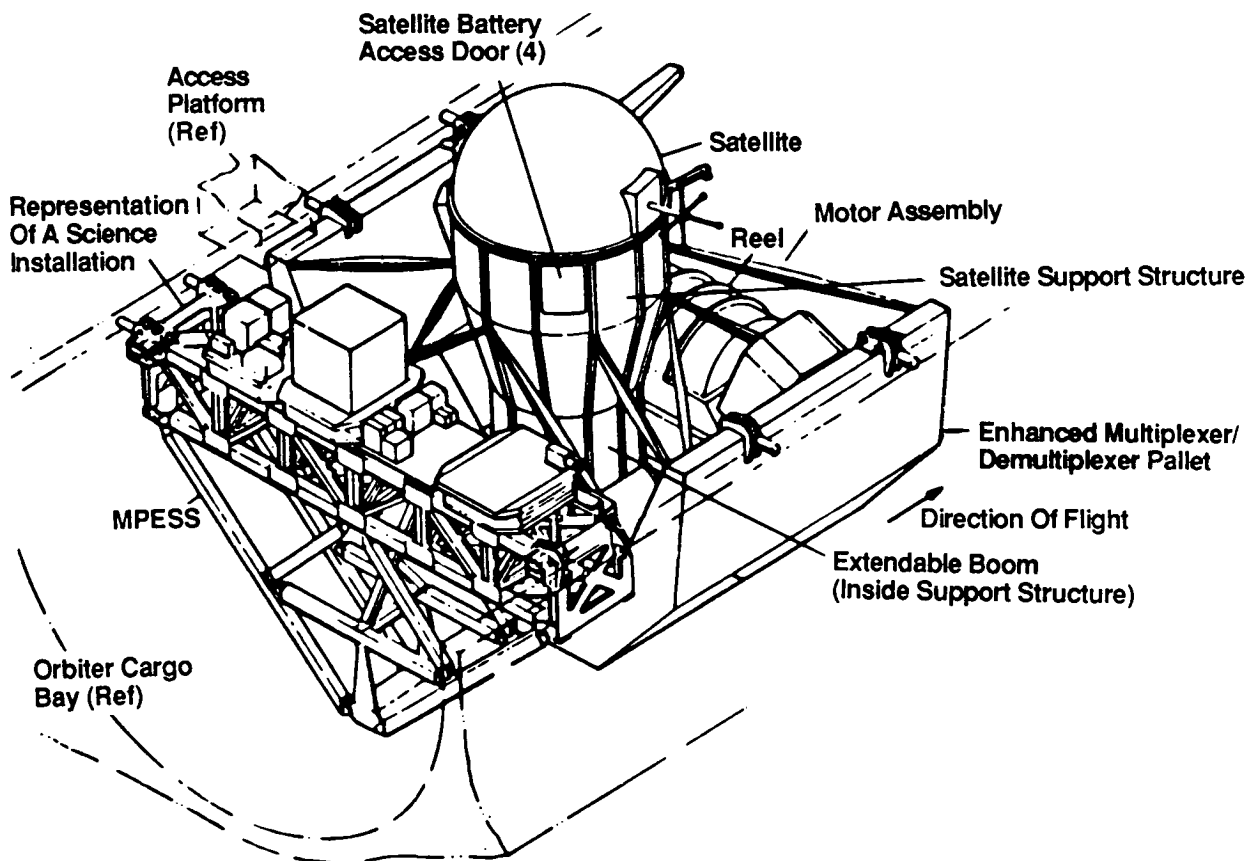


Figure 1.1 TSS-1 Configuration on Orbiter

The deployer system is capable of performing two types of reference missions: Electrodynamic and Atmospheric. A unique feature of the deployer is the capability to stop and reinstate satellite deployment and retrieval such that the satellite can be maintained at intermediate altitudes before achieving the final fully-deployed tether length. The deployer provides the capability to accommodate a 500 kg satellite. The satellite is deployed from a 12 meter extendable boom which is mounted on the deployer (Figure 1.2). Prior to satellite deployment, the deployer provides an electrical interface with the satellite via two umbilicals. The satellite itself is multi-purpose with the capability of accommodating various payloads with different mission characteristics.

Table 1.1 Tethered Satellite System Characteristics

<u>PARAMETER</u>	<u>SATELLITE</u>	<u>DEPLOYER</u>
Maximum Total Mass (kg)	500	6120 (Total TSS-1 Payload)
Scientific Payload Mass (kg)	60 to 80	500
Payload Volume	Negotiable (1.6 m Dia.)	Negotiable (Spacelab MDM Pallet)
Temperature (°C)	Negotiable	Negotiable
Thermal Control To Science Payload (Watts)	50 (Passive)	5 Coldplates @ 1500
Power @ 28 ± 4 VDC:		
Average (Watts)	50	1750
Peak (Watts)	100	3000
Energy (Whs)	900 to 2000	Negotiable
Data:		
Telemetry (kbps)	16	32
Commands (kbps)	2	2
Operational Altitudes (km)	130 and Above	Up to 100 km Tether
Orbital Inclination	28.5°	28.5°
Mission Duration (Hrs Deployed)	Nominally 38 Hours	

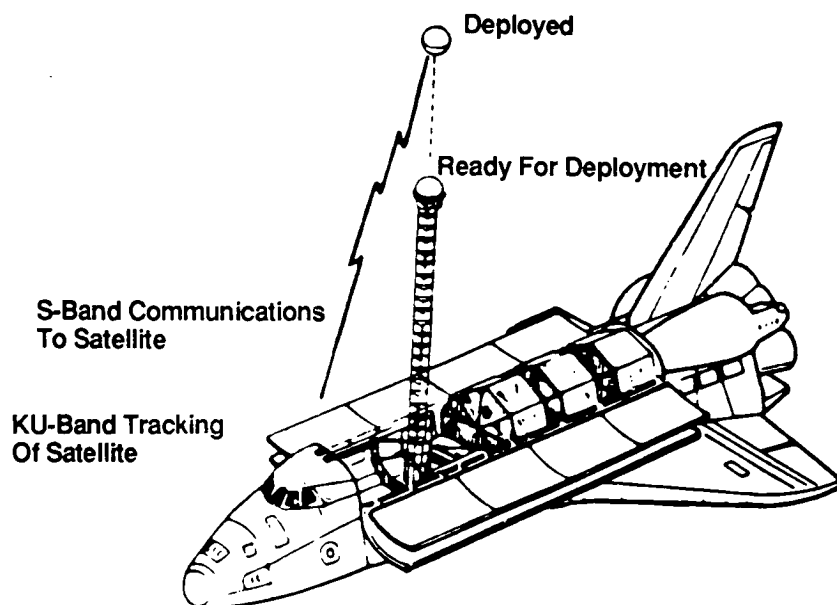


Figure 1.2 TSS-1 Satellite and Tether Attached to 12 Meter Extendable Boom

The satellite consists of a service module, a propulsion module, and a payload module. The service module contains the support structure and tether attachment, thermal control, attitude measurement and control, telemetry, on-board data handling, electrical power distribution, and engineering instrumentation. Science experiments on board TSS-1 will include electrical and magnetic field measurements, charged particle energy and spectra determinations, and DC magnetometry. Tether dynamics and plasma coupling mechanisms are also planned, as well as a series of ground-based observations of electromagnetic emissions from the tether. A list of these experiments along with their principal investigators appears as Table 1.2.

The 20 km conducting tether is comprised of five separate layers (Figure 1.3). The satellite will be electrically positive, collecting electrons from the ionosphere, and passing them to the Shuttle, which will emit the electrons with the help of an electron emitter. Potential measuring and controlling instruments are located at the Shuttle end of the tether. The tether will be conducting and will demonstrate the electromagnetic capabilities of tethers, producing up to 5 kV as it cuts through the Earth's magnetic field.

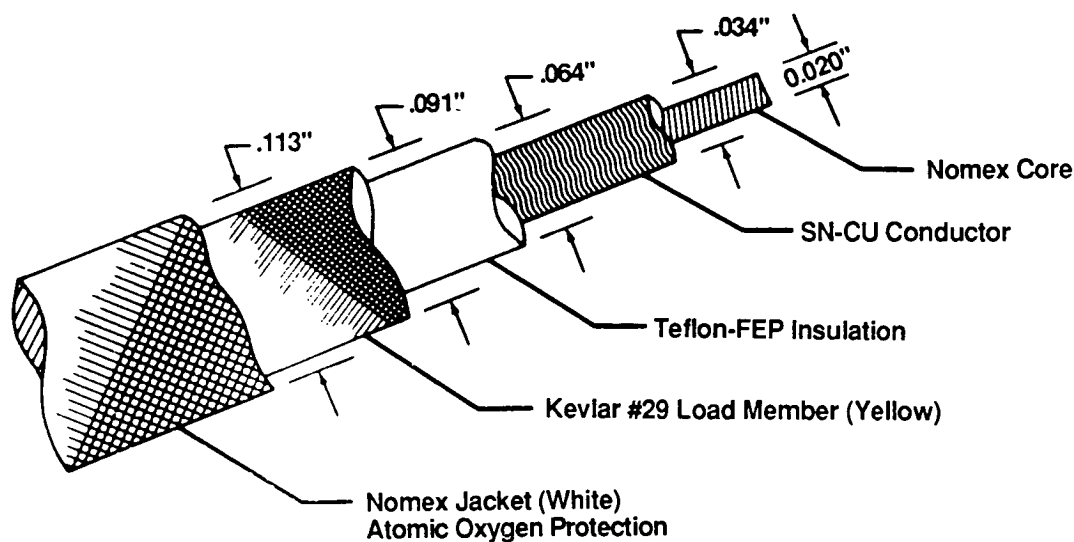


Figure 1.3 TSS-1 Conducting Tether Configuration

The TSS is designed to be compatible with the nominal STS orbit inclinations of both the eastern and western launch sites. Although the nominal TSS mission for deploying the satellite is 38 hours, the TSS is also compatible with an STS mission of up to 10 days. For the first TSS electrodynamic mission (TSS-1), the satellite will maintain control and stability during operations through the use of an active thruster control subsystem together with the deployer. This first mission will be an engineering verification flight performing limited electrodynamic science. The Orbiter will achieve a 160 nmi altitude, perform other payload operations, and then begin the TSS operation cycle. The 500 kg satellite will be deployed upward, away from the Earth on a 20 km tether during its approximate 36 hour mission (Figure 1.4).

Table 1.2 Tethered Satellite System Principal Investigation Science and Principal Investigators

TSS PROGRAMS

Thomas D. Stuart (NASA Headquarters)
Giafranco Manarini (Italian Space Agency - ASI)

TSS PROJECT MANAGER

John M. Price (NASA Marshall Space Flight Center)

SATELLITE INSTRUMENTATION

Research On Electrodynamic Tether Effects – Marino Dobrowolny (ASI)

- 3 Axis Dipoles
- 2 Axis Search Coils
- (2) Langmuir Probes
- A.C. Electric Fields & Electrostatic Waves
- A.C. Magnetic Fields
- e⁻ Density, e⁻ Energy, Potential Distribution

Research On Orbital Flight Plasma Electrodynamics – Nobie Stone (NASA Marshall Space Flight Center)

- Differential Ion Flux Probe
- (8) Soft Particle Energy Spectrometer
- Ion Energy Temperature & Density vs. Incidence Angle
- Charged Particle Energy Distribution & Space Potential

Magnetic Field Experiments For The TSS Missions – Franco Mariani (University of Rome)

- Triaxial Fluxgate Magnetometer
- Vector Magnetic Fields

ORBITER INSTRUMENTATION

Shuttle Electrodynamic Tether System – Peter Banks (Stanford)

- (2) Spot Charge & Current Probes
- Spherical Langmuir Probe
- Fast Pulse Electron Gun
- Local Current and Potential
- Vehicle Potential, Ion Density, and Temperature

ELECTRODYNAMIC THEORY

Theory And Modelling Of The Tether – Adam Drobot (SAI)

TETHER DYNAMICS

Investigation And Measurement Of Dynamic Noise In The Tether – Gordon Gullahorn (SAO)
Theoretical And Experimental Investigation Of Tether Dynamics – Silvio Bergamaschi (University of Padua)

GROUND BASED OBSERVATIONS

Investigation Of Electrodynamic Emissions By The Tether – Robert Estes (SAO)
– Giorgio Tacconi (University Of Genoa)

- ELF Receivers
- Magnetometers
- Detect Tether Generated Emissions at ELF
- Detect Tether Generated Emissions at ULF

CORE EQUIPMENT: INSTRUMENTS USEFUL TO ALL INVESTIGATIONS

DCORE Electron Generator – Carlo Bonifazi (ASI)
Shuttle Potential And Return Electron Experiment – David Hardy (AFGL)
Hollow Cathode Plasma Bridge – James McCoy (NASA Johnson Space Center)
Tether Optical Phenomena – Stephen Mende (Lockheed)

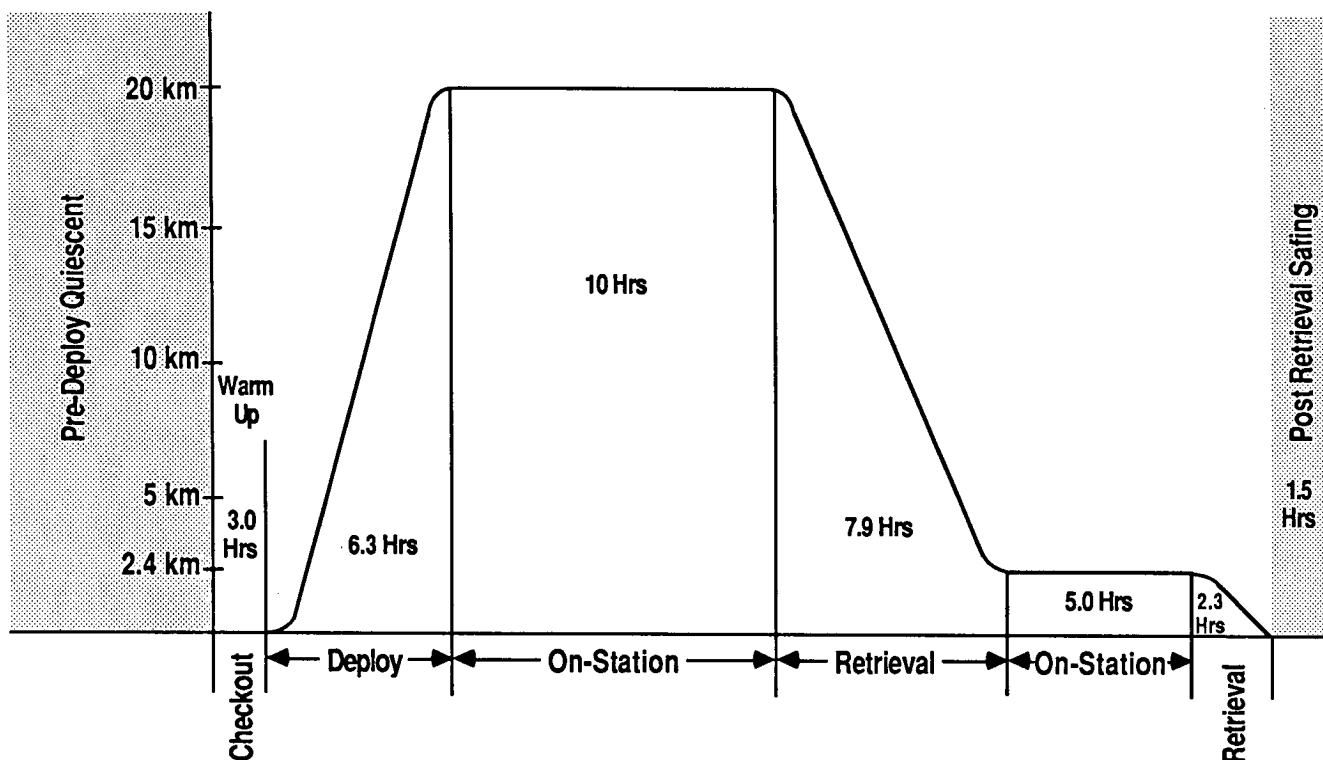


Figure 1.4 TSS-1 Planning Mission Timeline

The satellite is deployed over a 6 to 7 hour period after initial checkout. The satellite is then maintained at a 20 km altitude (from the Orbiter) for 10 hrs and is retrieved over a 15 hour period with a stop at 2.4 km. Note that the deployment is limited to a 20 km tether length for this first mission which limits the induced tether voltage to approximately 5 kV.

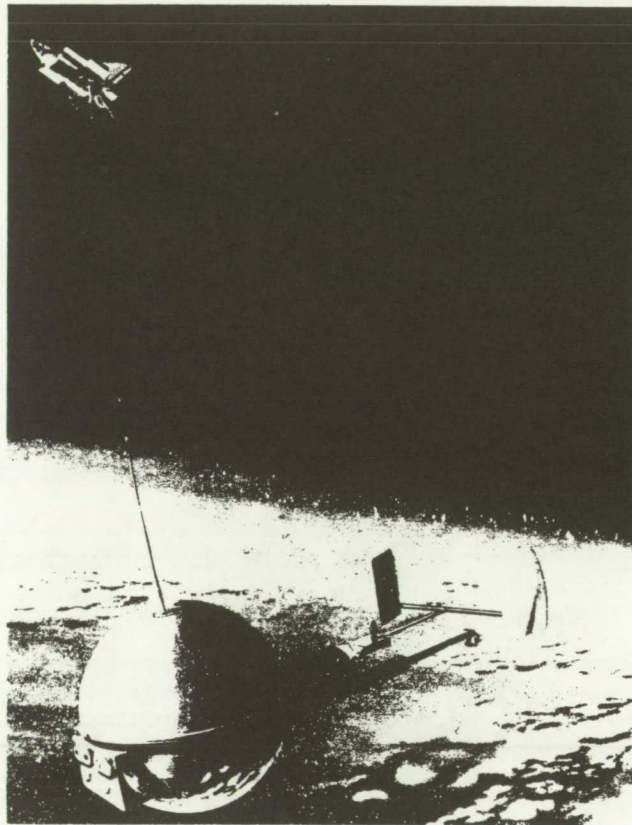
After the satellite has been released from the support structure and is extended upward along the 12 meter boom, checkout is completed and the satellite is released from the boom by a combination of gravity gradient tension and tether in-line thrusters. The flight crew initiates deployment and control and monitors the satellite during deployment, on-station operations, and retrieval. During operations of the TSS, the Orbiter attitude is adjusted to minimize RCS consumption. A "TSS dedicated" computer will automatically control deployment, on-station operations, and retrieval. The final 2 km of retrieval and docking of the satellite will be performed with "man-in-the-loop."

One example of a specific experiment which has been selected for TSS-1 is the Tether Magnetometer (TEMAG). The scientific objectives of the TEMAG experiment include measurement of the local magnetic field with a precision of the order of a few Gammas. These precision measurements will be possible only if careful "magnetic cleanliness" procedures are followed. All subsystems must be designed and manufactured in such a way as to minimize the satellite DC magnetic residual field and its low frequency variations. Procedures have been established between ASI, the experimenters, and the contractor to insure integrity of all systems and subsystems.

1.1.2 TSS-2

The second Tethered Satellite System Mission (TSS-2) is a joint NASA/Italian Space Agency (ASI) mission to demonstrate the deployment and retrieval of a large satellite from the Space Shuttle, and concurrently, obtain data to validate the deployment dynamics and control models, verify instrumentation performance, and obtain steady-state atmospheric and aerothermodynamic data under real gas conditions in free molecular flow.

The satellite is deployed downward from the Shuttle on a 100 km, non-conductive Nomex® coated Kevlar® tether. Although the satellite and tether will be in the free molecular flow regime during the entire deployment, other factors are expected to limit the achievable altitude to approximately 130 km (Figure 1.5).



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Figure 1.5 TSS-2 Aerothermodynamic Mission

The objectives of the TSS-2 are threefold: 1) to validate the computer models of the flow-fields, the deployment and retrieval dynamics, and the control laws that will be necessary to support the subsequent development and deployment of more advanced tethered research platforms; 2) to carry out measurements of free-stream composition and density between 220 and 130 km altitude; and, 3) to investigate the interaction of the satellite with the rarified atmosphere. Critical issues which remain to be addressed include re-use of the first (TSS-1) satellite vs. fabrication of a new satellite, determination of the actual configuration of the TSS-2 satellite, and experiment selection.

Planning for the deployment of the TSS-2 flight in late 1994 or early 1995 has been initiated with the formation of NASA/ASI Planning, Experiment Definition, and Facility Definition Teams, and with a NASA workshop to define research priorities for the mission. As of this printing, the experiment and instrumentation selection for the mission has not been finalized.

1.2 Approved Tether Experiments

1.2.1 Small Expendable Deployer System

The Small Expendable Deployer System (SEDS) is a lightweight spinning-reel system designed to deploy a payload attached to a 20 km long tether that is cut and discarded after use. The primary objectives are to study the dynamics of tether deployment and to validate the SEDS design concept. The deployer system weighs about 16 kg including the 2 kg electronic package and the 6 kg tether and is approximately 25 cm in diameter and 33 cm in length. The tether is made from a new high-strength, low-density polyethylene fiber called SPECTRA. The hardware development should be completed in 1989 allowing SEDS to fly on a Delta II launch vehicle in 1990 or 1991, if the decision is made to proceed with a flight experiment. Later SEDS versions may fly on the Shuttle. On the first flight, a passive end-mass weighing 23 kg will be deployed toward the Earth at the end of a 20 km tether. The experiment will last about 1-1/2 hours, ending when the full 20 km tether length is deployed and has swung to a vertical position, i.e., the tether is pointing directly toward the Earth. The tether is then cut, allowing it and the end-mass to reenter the Earth's atmosphere. The SEDS concept is shown schematically in Figure 1.6.

One proposed application of SEDS is the periodic deorbiting of Space Station waste materials packaged in lightweight containers that can be folded for easy storage during Shuttle trips to the Station. A study of this application concluded that a 200 kg SEDS-type deployer using a 100 km length tether can deorbit 2,000 kg of Space Station waste.

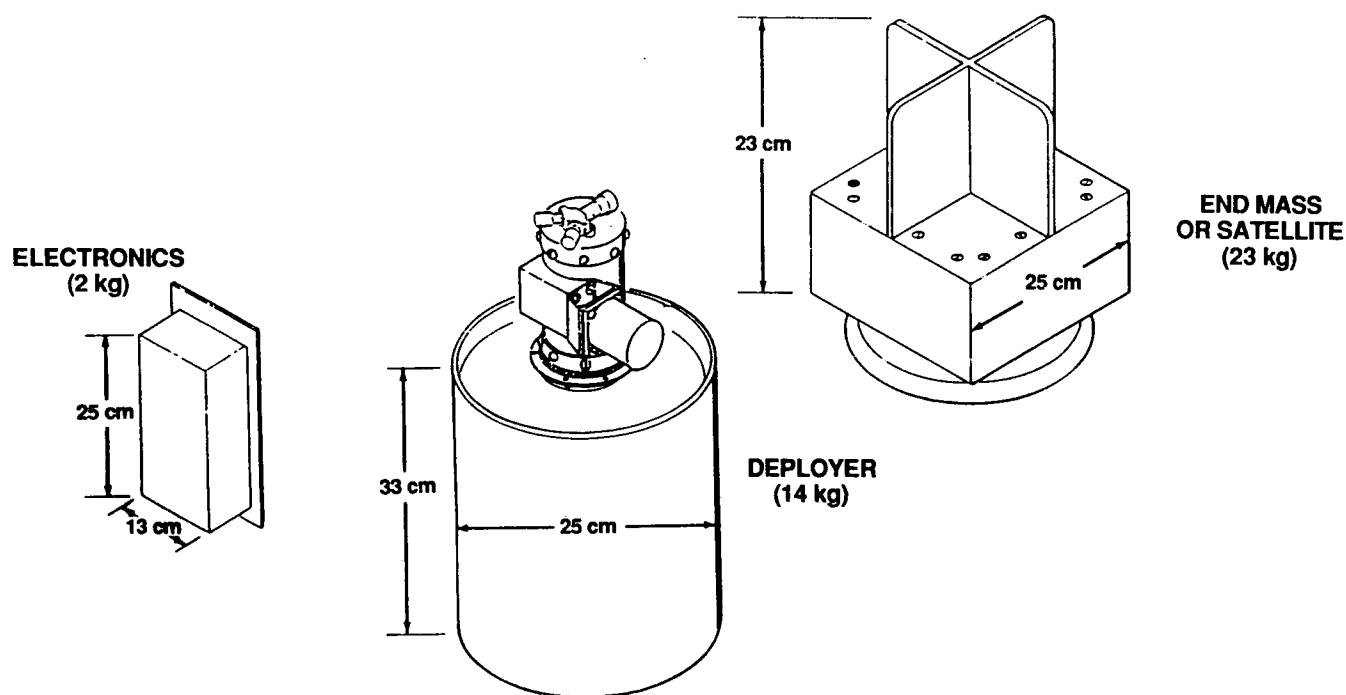


Figure 1.6 Small Expendable Deployer System (SEDS)

1.2.2 Plasma Motor/Generator

The Plasma Motor/Generator Proof of Flight (PMG/POF) Experiment is a low cost "Payload of Opportunity" for flight on the Shuttle Orbiter using the Hitchhiker-G (HHG) carrier. The objective of this experiment is to provide engineering verification of key physical processes involved in the operation of proposed PMG systems. A summary chart of the PMG/POF characteristics appears as Table 1.3.

Table 1.3 Plasma Motor/Generator POF Characteristics

PMG/POF Characteristics	
<u>60 Kg Total Mass</u>	
Far End Package (FEP):	25 kg, 15" dia x 10' high
<ul style="list-style-type: none"> • 0.5 M² Passive Collection Area • 1 A Hollow Cathode Plasma Neutralizer (Battery) • Power Supply & Controller for Hollow Cathode • Spool with 200 M #32 AWG Copper Wire • Argon Gas Supply & Controller 	
200 Meter Wire:	0.4 kg, Teflon Insulation, 2 lb. "Test" with 4 lb. Breakaway
Near End Package (NEP)	30 kg, 16" dia x 28" high
<ul style="list-style-type: none"> • Retains FEP Until Release for Deployment • 1 A Hollow Cathode Plasma Neutralizer • Power Supply & Controller for Hollow Cathode • Variable Load & Precision Ammeter • Power Supply to Drive Motor Mode Current • Programmable Micro-Processor Controller • Wire Cutter for Jettison • Xenon/Argon Gas Supply & Controller • Ground Test Plug • Interface & Control Plug: (HHG Standard) • Deployment Ejection System (Fixture Mounted on NEP) 	
<u>Deployable By Spring Ejection</u>	
(Could Use RMS or EVA/MMU If Easier)	
Centrifugally Stabilized @ 1 Degree/Sec = 1.5 N Tension	
Via STS Orbiter:	
<ul style="list-style-type: none"> • Station-Keeping 200 M (-Z) • (OMS) Delta-V 3.5 M/Sec • Roll 1 Degree/Sec to Keep FEP @ + Z ± 30 Degree 	
<u>Deployment Simulated Successfully At NASA/JSC Tested In Zero-g Airplane</u>	
Tension During Swinging (Max)	3.0 N
Tension During Swinging (Avg)	1.5 N
Tension During Ejection	< 0.1 N
<u>Jettison At End Of Experiment (Into Non-Recontacting Orbit)</u>	
From 25 km Orbit, Rapid Decay of Jettisoned Package	
Decays 1 km Below Orbiter By First Crossing	
Reenters in 25 Hrs	
NEP With All Data Recorded Returned to Landing by STS Orbiter	

Early verification of the performance of hollow cathodes (the provision of adequate conduction of large currents between the ionosphere and each end of an electrodynamic tether wire) is needed to guide tether application studies of 20 kW to 200 kW PMG systems. The primary unknown in the operation of a PMG system is the ability of the hollow cathode "brushes" to connect the tether "armature" to the ionospheric current path. The numerous variables involved in the theoretical computations of the relevant plasma physics processes result in considerable uncertainty. Only direct measurements in orbit of the induced $V \times B$ voltage, current coupling, and ionospheric circuit impedance can provide adequate verification of the calculated effects.

Initial verification of these critical issues can be obtained prior to the availability of the Tethered Satellite System (TSS) by flying the 100 kg/200 meter/10 watt PMG/POF "non-tether" experiment. In this experiment, a 25 kg Far End Package (FEP), containing a hollow cathode system, is deployed at the end of an insulated #32 AWG umbilical wire. This wire connects the FEP hollow cathode system to another hollow cathode system at the Orbiter. The 200 meter wire length is long enough to provide an adequate induced voltage and separation from the spacecraft wake effects, while still being short enough to avoid complex tether deployment, stabilization, and retrieval systems. The deployed wire and FEP are jettisoned at the completion of the experiment.

The results obtained from initial flights (now scheduled for HHG-2 and HHG-3) will also provide a basis for planning larger scale investigations using the TSS and expanded PMG/POF type experiments. These growth experiments could be flown at 6-month intervals using the HHG carrier to provide a low cost sequence of data points.

1.3 Proposed Tether Experiments

1.3.1 Tether Initiated Space Recovery System (TISRS)

The TISRS is a joint flight demonstration between NASA and the Italian Space Agency (ASI), designed to demonstrate deployment of a reentry package from the Shuttle or Delta II. Primary objectives include demonstrating: 1) Small Expendable Deployer System (SEDS) plus Satellite Reentry Vehicle (SRV) Deployment/Braking/Release, 2) SRV ExoAtmospheric Performance, and 3) SRV Recovery. The secondary objective is to demonstrate EndoAtmospheric performance.

The system utilizes a 20 km tether attached to the SEDS, coupled with a modified version of the General Electric-built Satellite Reentry Vehicle (SRV). The TISRS mission baseline includes flying the system at a 250 km, 27.5° inclination, circular orbit. Using the SEDS deployment control, the SRV is released from the tether at 25.7° N Latitude, 138.1° W Longitude. Reentry will occur approximately 20 minutes later at 12.65° N Latitude, 56.2° W Longitude with recovery (by parachute) at Ascension Island 32 minutes after the SRV is released from the tether. The total weight of the system is approximately 450 lbs, with a 200 lbs payload capacity.

Major hardware remaining to be developed includes a modified thermal cover, parachute, capsule cover, heatshield forebody, flight instrumentation, and communication/command links to the Shuttle. Concept definitions scheduled for 1989 are being performed by General Electric (Space Recovery Vehicle) and Aeritalia (TISRS Experiment Definition). Hardware assembly and qualification tests are scheduled for 1991, with an initial flight on a Delta II in 1992.

1.3.2 Get-Away Tether Experiment (GATE)

The Get-Away Tether Experiment (GATE) encompasses a small free-flying tether system deployed from a Get-Away Special (GAS) canister. The primary objectives of this system are to 1) demonstrate electric power generation and orbital reboost using tether electrodynamics, 2) measure micrometeoroid hazards to the tether, 3) perform radio propagation experiments, and 4) measure long wire radar cross section.

The free-flying payload tether system is deployed from the orbiter via the GAS deployment system. Upon deployment, the payload separates into two parts connected by a 1 km electrically conductive tether. Orientation along the local vertical is achieved by deploying the tether from a small reel system. Once stabilized, the orbit of the system may be boosted by a magnetomotive force produced by forcing electrical energy from on-board batteries into the tether. This process is then reversed to demonstrate power generation by recharging the batteries. While the tether is deployed, micrometeoroid impacts on the tether are measured by vibration detectors and analyzed by a data system. Prior to reentry, the Orbiter rendezvous radar is used to measure the radar cross section of the tether at various aspect angles.

The four experiment objectives all demonstrate or develop technology of interest to both NASA and ASI. Moreover, the results of the GATE will complement the work of TSS-1 and may help plan the second TSS electrodynamic mission. In addition, the GATE will provide new insight into the study of micrometeoroid hazards to space tethers.

1.3.3 Kinetic Isolation Tether Experiment (KITE)

The Kinetic Isolation Tether Experiment is a proposed Space Shuttle flight experiment intended to demonstrate the feasibility of providing attitude control to a space platform by changing the attachment point of a tether with respect to the platform center-of-mass. Offsetting this point causes the tether tension force to be offset from the platform center of mass, thus producing a torque about the platform center-of-mass. The KITE envisions a small (approximately 1000 kg) subsatellite deployed either upward or downward from the Shuttle at the end of a gravity gradient stabilized tether. The tether length will be in the range of 1 to 1.5 km. The positioning of the tether attachment point on the subsatellite will be performed by a microprocessor-based closed loop control system and will provide attitude control about two orthogonal axes. The third axis will be controlled by a conventional momentum wheel. This KITE project is currently in the laboratory definition and demonstration phase with laboratory modelling and prototype testing being conducted at Stanford University.

1.3.4 Tether Elevator/Crawler System (TECS)

The Tether Elevator/Crawler System consists of two tethers attached to the Space Station. Attached to the end of the upper tether is the "Sky's Observation Platform," and the "Earth's Observation Platform" at the end of the lower tether. An elevator can crawl along the upper tether carrying variable-g experiments while the acceleration level on board the Space Station is controlled to better than 10^{-5} g. The upper tether length is approximately 10 km, with lower tether lengths ranging between 10 and 15 km, depending on the elevator's position. The length of the lower tether is adjusted to compensate for the motion of the elevator. Consequently, variable-g experiments can be performed on the elevator without any interference with the micro-g experiments on-board the Station.

1.3.5 Tether Inspection and Repair Experiment (TIRE)

The Tether Inspection and Repair Experiment originated from the prospect of long duration missions for tethered systems. The TIRE (currently in Phase I) will investigate tether survivability in the space environment. The prime contractor for the TIRE is Aeritalia, performing system requirements definition, impact damage testing and analysis, and global demonstration characterization. Currently planned tether tests for the TIRE demonstration-Phase I include:

- Conducting, insulating, armoring and jacketing material performance degradation after prolonged exposure to LEO environment
- Transmissive and mechanical performances of candidate optical fibers in LEO environment
- Damage to external coat under simulated radiation, ions and atomic oxygen LEO environment
- Damage of tether simulacra due to high kinetic energy particle impact

Phase I study outputs are expected to yield a system requirement definition, selection of candidate material components on the basis of functional performance, inspectability and repairability, selection of applicable non-destructive inspection strategies, trade-offs among the suitable repair methods and technologies, and planning, scheduling and cost assessments of the subsequent ground demonstration phase.

1.3.6 Potential New Start Programs

Potential new start programs which require a considerable amount of definition for future flight demonstrations include concepts such as the Scientific and Applications Tethered Platform (SATP). This system would consist of a fixed or highly-accurate pointing platform attached to the end of a tether which would provide accommodation and support to a wide range of space science and technology activities. The Italian Space Agency (ASI) has completed an initial study of the SATP, producing a preliminary SATP configuration and subsystem analysis. The SATP study has created new interest in the scientific community for an ASTRO-SATP (possible use of the SATP as a facility for astrophysical payloads). This ASTRO-SATP study will include analysis of the SATP high-precision attitude pointing capability through a simulation of SATP dynamics. Assessment of technological requirements will be performed, coupled with the ASTRO-SATP concept evaluation.

Another application currently being studied is the Variable Gravity Research Facility (VGRF). This application would provide a facility in Earth orbit that will operate at gravity levels between 0 and 2g at rotation rates between 1 and 10 rpm for the purpose of studying the long term effects of various gravity levels on humans. This facility would allow scientific investigation into the question of human performance and health at gravity levels other than Earth gravity for periods of up to 90 days. In particular, long-term exposure to Martian or Lunar gravity can be studied. The relationship of gravity level and rotation rate can also be studied in such a facility, since both are independently controllable. The facility also address engineering questions concerning generation of artificial gravity as might be required for manned missions to other planets. The current study is examining several options in the configuration and operation of the facility. Some of these trades include the use of a dead weight on the counterweight end of the tethered system thus allowing an inertially oriented spin axis and refurbishment without despin.

Additional new start programs include the Shuttle Tethered Aerodynamic Research Facility (STARFAC) and an Orbital Electrodynamic Platform. STARFAC would perform steady-state aerothermodynamic and atmospheric measurements below an altitude of 200 km. The Electrodynamic Platform would be used for long-term (6-12 months) test and demonstration of power (25-50 kW) and thrust generation.

1.4 Joint U.S./Italian Tether Task Groups

1.4.1 Tether Applications In Space Planning Group

The Tether Applications in Space Planning Group (TASPG) was first established by the Director of Advanced Planning (Code MT, Office of Space Flight) in 1983. The groups main charter was "...to extend our knowledge and understanding of the theoretical and operational feasibility of the behavior, technical and operational risks, technology requirements and overall costs and benefits of tether applications as compared to alternate conventional approaches." The current group consists of representatives from NASA Headquarters, field centers, and the Italian Space Agency (ASI) as shown in Table 1.4. Some of the original objectives of the group were:

- To research and determine the feasibility of applications of tethers in space to such areas as transportation, electrodynamics, gravity utilization, space platforms, science and applications, and technology
- To match technological solutions with theoretical systems requirements
- To establish the state-of-the-art and required technology advancements
- To provide responsive designs based on the assessed technology requirements
- To derive cost/benefits as a function of comparing alternate equivalent mission options with tether applications
- To establish proof-of-concept demonstration candidate missions to verify performance in preparation for specific tether mission applications

Table 1.4 Tether Applications In Space Planning Group Members

<u>NAME</u>	<u>ORGANIZATION</u>	<u>ADDRESS/MAIL CODE</u>	<u>PHONE</u>	<u>REMARKS</u>
Charles C. Rupp	MSFC	PS04	(205) 544-0627	Chairman
Dr. John W. Alred	JSC	ED2	(713) 483-6615	
John L. Anderson	NASA-HQ	RS	(202) 453-2756	
Edward Brazill	NASA-HQ	MD	(202) 453-1155	
Dale Ferguson	LeRC	302-1	(216) 433-2298	
Joel Galafaro	LeRC	302-1	(216) 433-2294	
James K. Harrison	MSFC	PS04	(205) 544-0629	
Joseph C. Kolecki	LeRC	302-1	(216) 433-2296	
Lawrence G. Lemke	NASA-HQ	Z	(202) 453-8928	
Dr. Alberto Loria	ASI	00198 Roma, Italy Viale Regina Margherita 202	39-6-4767250	
Dr. James E. McCoy	JSC	SN3	(713) 483-5068	
Dr. Paul A. Penzo	JPL	301-170U	(818) 354-6162	
Marcie Smith	AMES	244-14	(415) 694-4833	
Dr. William J. Webster, Jr.	GSFC	662	(301) 286-7166	
Dr. George M. Wood	LaRC	234	(804) 865-2466	

The TASPGE developed the Tether Applications in Space Plan (a five year plan), with the purpose of being utilized for initiating and proceeding with studies and advanced development activities. This Program Plan has been updated annually since 1983 and used by NASA Headquarters as an administrative and technical tool for managing and directing tether applications in space activities at the field centers.

Over the past three years, however, the TASPGE has concentrated more on advancing those applications which are near-term candidates for flight demonstrations. This new thrust expanded and a complementary joint NASA/ASI task group was formed (Tether Flight Demonstrations Task Group, Section 1.4.2). The TASPGE reviews and recommends tether applications for further development. Over the years they have guided the development of the Plasma Motor/Generator (PMG) and the approval of the Small Expendable Deployer System (SEDS) for flight demonstrations. Another significant accomplishment has been the NASA Agency-wide approval to begin planning the second Tethered Satellite System mission (TSS-2). The TASPGE serves as an overall guidance mechanism for the research, technology development, and funding of tether applications.

1.4.2 Tether Flight Demonstrations Task Group

The Task Group for Tether Flight Demonstrations was established in July 1986 by the Italian National Space Plan (PSN/CNR) and NASA with the purpose of identifying and establishing areas for joint cooperation and complementary activities in tether applications leading to flight demonstration experiments. A letter of agreement was then written and signed by the two organizations for conduct of tether applications in space studies. The letter states: "NASA and the Italian National Space Plan (PSN/CNR) under the authority of the National Research Council of Italy confirm their mutual interest in carrying out complementary focused definition studies of potential application of tethers in space that could lead to cooperative flight demonstrations or experiments in the future...and...It is understood that the respective complementary and parallel studies by NASA and PSN/CNR will be conducted with no exchange of funds between NASA and PSN/CNR."

In July 1988 the Italian Space Agency (ASI) was established and took over all duties and international relations of PSN/CNR, henceforth referred to as ASI.

The Joint Task Group identified initial areas of study including: tether electrodynamics, tethered platforms, tether crawlers (elevators), deboost of materials from the Space Station, and tethered reentry systems. The Task Group also plans to review proposals for flight demonstrations or experiments on a case-by-case basis, and no commitment or obligation is assumed for funding or proceeding into development with any program, unless specifically approved by both agencies. Presented below in Table 1.5 are the current members of the Joint ASI/NASA Task Group for Tether Flight Demonstrations.

Table 1.5 Tether Flight Demonstrations Task Group Members

<u>NAME</u>	<u>ORGANIZATION</u>	<u>ADDRESS/MAIL CODE</u>	<u>PHONE</u>	<u>REMARKS</u>
James K. Harrison	MSFC	PS04	(205) 544-0629	Co-Chairman
Dr. Alberto Loria	ASI	00198 Roma (Italia) Viale Regina Margherita 202	39-6-4767250	Co-Chairman
Dr. Silvio Bergamaschi	Padua Univ./ ASI	35131 Padova (Italia)	39-49-8071033	
Charles C. Rupp	MSFC	PS04	(205) 544-0627	
Larry G. Lemke	ARC	244-14	(415) 694-6531	
William Djinis	NASA-HQ	MD	(202) 453-1157	
Dr. William J. Webster, Jr.	GSFC	622	(301) 286-4506	
Dr. Paul A. Penzo	JPL	301-170U	(818) 354-6162	
Dr. George M. Wood	LaRC	234	(804) 865-2466	
Dr. James E. McCoy	JSC	SN3	(713) 483-5068	
Dr. Carlo Bonifazi	ASI	00198 Roma (Italia) Viale Regina Margherita 202	39-6-4767246	
Edward J. Brazill	NASA-HQ	MD	(202) 453-1155	
Joseph Kolecki	LeRC	302-1	(216) 433-2296	

Since the creation of the Task Group in 1986, there have been a number of meetings in which work has begun toward proposing joint flight demonstration experiments. Following is a summary of the Task Groups activities over the past two years:

- July 1986 - Task Group established
- Sept. 1986 - NASA proposed various tasks associated with six prospective flight demonstration projects
- Work began on NASA/ASI Letter Of Agreement
- Oct. 1986 - PSN response to NASA proposals led to revisions in tasks and flight projects
- Jan. 1987 - Summary presentation and critical review of each joint endeavor plan
- Presentation and review of Letter Of Agreement Final Draft
- Sept. 1987 - Confirmation of agreements
- Outline of implementation steps
- Brief program review of each project
- Agreed to establish and recommend a priority for flight projects
- Oct. 1988 - Agreed to propose TISRS as a joint flight demonstration experiment

To date, the Joint Task Group has assembled a list of proposed tether flight demonstration projects which have been divided into three groups. Group 1 consists of those joint flight demonstrations which have had substantial definition and are capable of being flown in the next 4 to 7 years. Group 2 consists of projects which still require a considerable amount of concept definition, and Group 3 contains future applications that are potential "new starts." Listed below are these three groups, the proposed joint flight demonstration projects, and the main features of each experiment. A more detailed description of each project is presented in Section 1.3 "Proposed Tether Experiments."

GROUP 1 (Capable of being flown in the next 4 to 7 years)

1. Tether Initiated Space Recovery System (TISRS)
 - Orbital deboost and recovery of a reentry vehicle
 - Waste removal from the Space Station
 - Possible launch in 1992
2. Get-Away Tether Experiment (GATE)
 - Tether dynamics studies
 - Measure particle impacts on tether; determine radar cross section
 - Provide data on ULF radio propagation
 - Possible launch in 1993
3. Kinetic Isolation Tether Experiment (KITE)
 - Spacecraft attitude control and stability by tether tension
 - Attitude and stability control of small instrument platform tethered to the Space Station
 - Possible launch in 1994
4. Tether Elevator/Crawler System (TECS)
 - Provide variable microgravity environment
 - Tether inspection and repair operations
 - Space Station center of mass management
 - Possible launch in 1995

GROUP 2 (Requires a considerable amount of definition)

1. Tether Inspection and Repair Experiment (TIRE)
 - Tether damage detection and repair

GROUP 3 (Future programs that are potential "New Starts")

1. Scientific and Applications Tethered Platform (SATP)
 - A 10-ton platform attached to the Space Station via a 10 km tether to serve as a base for scientific experiments
2. Shuttle Tethered Aerothermodynamic Research Facility (STARFAC)
 - Steady-state aerothermodynamic and atmospheric measurements below an altitude of 200 km
3. Orbital Electrodynamic Platform
 - Multikilowatt electrodynamic tether (50 km) platform for long-term (6 to 12 months) test and demonstration of power (25-50 kW) and thrust generation
4. Variable Gravity Research Facility (VGRF)
 - Facility in Earth orbit capable of producing gravity levels between 0 and 2g for the purpose of studying the long-term effects of various gravity levels on humans

1.5 United States Tether Studies

Following is a summary of tether studies being conducted by various organizations in the United States under contract to NASA. The list is grouped by NASA field center location.

- | | |
|---------------------------|---|
| Title: | Kinetic Isolation Tether Experiment |
| NASA Center: | Ames Research Center (ARC) |
| Contract Number: | NCC2-389 |
| Contract Monitor: | Larry Lemke |
| Contractor: | Stanford University, J. David Powell |
| Contract Duration: | 1/85 - On going to end of FY '89 |
| Abstract: | To develop an instrumented tethered platform with variable orientation and to measure force limits. |
-
- | | |
|---------------------------|--|
| Title: | Tether Science and Applications User Requirements |
| NASA Center: | Goddard Space Flight Center (GSFC) |
| Contract Number: | N/A (In-house) |
| Contract Monitor: | William J. Webster, Jr. |
| Contractor: | In-House Study |
| Contract Duration: | 10/88 - 10/94 |
| Abstract: | Establish the limitations imposed by the dynamics and other physical properties of tethers as transportation tools for science data in Earth orbit. Quantify the performance problems expected. Investigate means for the suppression of the problems. |
-
- | | |
|---------------------------|---|
| Title: | Tether Applications In the Space Station Era |
| NASA Center: | Jet Propulsion Laboratory (JPL) |
| Contract Number: | NAS7-100 |
| Contract Monitor: | Paul Penzo |
| Contractor: | In-House Study |
| Contract Duration: | 10/84 - 9/86 |
| Abstract: | Assess system and technology needs to support tether applications, Earth orbital and planetary, in the Space Station Era. |
-
- | | |
|---------------------------|--|
| Title: | Tether Applications for Transportation and Science |
| NASA Center: | Jet Propulsion Laboratory (JPL) |
| Contract Number: | NAS7-100 |
| Contract Monitor: | Paul Penzo |
| Contractor: | In-House Study |
| Contract Duration: | 10/86 - On going |
| Abstract: | To develop concepts and perform preliminary analyses of tether applications to transportation (Earth orbital, lunar, and planetary), and to investigate the mission possibilities of using tethers for scientific use. Current studies include a lunar orbit transportation node, tethered telescopes for deep space interferometry, and a tethered lunar sounder/SAR mission. |
-
- | | |
|---------------------------|---|
| Title: | Tethered Propellant Resupply Depot Study |
| NASA Center: | Johnson Space Center (JSC) |
| Contract Number: | NAS9-17422, NAS9-17059 |
| Contract Monitor: | Kenneth Kroll |
| Contractor: | Martin Marietta Denver Aerospace, Dale Fester |
| Contract Duration: | 10/84 - 4/86 |
| Abstract: | This study examined the use of a tether to simplify fluid transfer for OTV propellant resupply. |

Title: Hollow Cathode Plasma Coupling
NASA Center: Johnson Space Center (JSC)
Contract Number: NAG9-120
Contract Monitor: Jim McCoy
Contractor: Colorado State University
Contract Duration: 8/85 - 10/88
Abstract: Plasma chamber experimental studies of current coupling between two hollow cathode sources.

Title: Hollow Cathode Plasma Turbulence
NASA Center: Johnson Space Center (JSC)
Contract Number: NAS9-17900
Contract Monitor: Jim McCoy
Contractor: Lockheed; SAIC subcontractor
Contract Duration: 7/87 - 3/89
Abstract: Study of plasma turbulence and electrostatic wave generation by operation of a hollow cathode in a surrounding plasma.

Title: 8 kW Orbit Reboost System
NASA Center: Johnson Space Center (JSC)
Contract Number: NAS9-17751
Contract Monitor: Jim McCoy
Contractor: TRW
Contract Duration: 1/87 - 7/88
Abstract: Preliminary design study of a light version of the PMG for orbit maintenance of low altitude solar array powered or other high drag spacecraft. Primary emphasis on integration and operation with existing or planned s/c concepts, Space Station, free-flying platforms.

Title: 200 kW Plasma Motor Generator
NASA Center: Johnson Space Center (JSC)
Contract Number: NAS9-17666
Contract Monitor: Jim McCoy
Contractor: Ball Brothers, Cal Rybak
Contract Duration: 8/86 - 9/88
Abstract: Engineering design study of the plasma motor generator concept for both power and thrust generation, including reversible power operation for power storage.

Title: Analysis of Aerothermodynamic Experiments that may be Conducted with Tethered Satellites
NASA Center: Langley Research Center (LaRC)
Contract Number: NAG1-878
Contract Monitor: George Wood
Contractor: Vanderbilt University, Dr. Leith J. Potter
Contract Duration:
Abstract: Identify and quantitatively evaluate specific aerothermodynamic and free stream measurements that should be conducted with tethered satellites. Develop research strategy for TSS-2 and succeeding tethered systems.

- Title:** Analysis of Sampling Techniques to Determine Atmospheric Composition
NASA Center: Langley Research Center (LaRC)
Contract Number: NAS1-18584-9
Contract Monitor: George Wood
Contractor: Old Dominion University, Dr. Kenneth G. Brown
Contract Duration:
Abstract: Assess methodology for determining concentration profiles from the vehicle surface outward to the termination of the shock or boundary layer.
- Title:** Application of Receiver Operating Characteristics to Resolution Enhancement
NASA Center: Langley Research Center (LaRC)
Contract Number: NAG1-800
Contract Monitor: George Wood
Contractor: University of Southern Mississippi, Dr. Grayson H. Rayborn
Contract Duration:
Abstract: Develop the computational methodology necessary to determine and enhance efficiencies of electronic detectors to be used in obtaining atmospheric and aerothermodynamic data at orbital velocities with tethered satellites.
- Title:** Atmospheric Investigation Related to Aerothermodynamic Research in the 90 to 130 Km Region by Means of Tethered Probes
NASA Center: Langley Research Center (LaRC)
Contract Number: NAG1-876
Contract Monitor: George Wood
Contractor: Smithsonian Astrophysical Observatory, Jack W. Slowey
Contract Duration:
Abstract: Investigate ambient and induced atmospheric environment related to a vehicle moving at orbital velocity between 90 and 130 km and develop an observational strategy to support aerothermodynamic research in the region.
- Title:** Determination of Design and Operation Parameters for Upper Atmospheric Research Instrumentation
NASA Center: Langley Research Center (LaRC)
Contract Number: NAG1-804
Contract Monitor: George Wood
Contractor: University of New Orleans, Dr. George E. Ioup; Dr. Juliette W. Ioup
Contract Duration:
Abstract: Analyze and develop a systematic mathematical methodology to extract information obtained in noisy signals generated on tethered research vehicles moving at orbital velocities.
- Title:** Effects of the Interaction of Polymeric Materials with the Space Environment
NASA Center: Langley Research Center (LaRC)
Contract Number:
Contract Monitor: Shiela T. Long
Contractor: College of William and Mary, Dr. Richard Keifer; Dr. Robert Orwoll
Contract Duration:
Abstract: Determine the effects on the molecular structure of the surface of Kevlar[®] and Nomex[®] exposed to atomic oxygen and UV radiation.

Title: Requirements of Wall/Gas Interaction Studies to be Supported by Tethered Satellites
NASA Center: Langley Research Center (LaRC)
Contract Number: NAG1-879
Contract Monitor: George Wood
Contractor: University of California, Berkeley, Dr. Franklin C. Hurlbut
Contract Duration:
Abstract: Identify and quantitatively evaluate requirements for studies of wall/gas interactions between characteristic vehicle surfaces and atmospheric gases. Develop research strategy for TSS-2 and succeeding tethered systems.

Title: Shuttle Tethered Aerothermodynamic Facility
NASA Center: Langley Research Center (LaRC)
Contract Number: NAS1-17511
Contract Monitor: Paul Siemers
Contractor: In-House Study and Analytic Mechanics, Henry Wolf
Contract Duration: 1/84 - 12/88
Abstract: Develop algorithms and models of the deployment, control and retrieval of a tethered satellite to low (90 km) altitudes. Model specific mission profiles for the TSS-2, STARFAC, and other proposed systems.

Title: Beam Plasma Interaction Data Base
NASA Center: Lewis Research Center (LeRC)
Contract Number: NAG3-620
Contract Monitor: Joe Kolecki
Contractor: University of Alabama, Huntsville, AL, Chris Olsen
Contract Duration: 1/84 - 12/86
Abstract: Interaction of electron and ion beams with the ambient plasma at GEO and LEO.

Title: Electrodynamic Tether Device Characterizations
NASA Center: Lewis Research Center (LeRC)
Contract Number: NGR-06-002-112
Contract Monitor: Joe Kolecki
Contractor: Colorado State University, Dr. P. J. Wilbur
Contract Duration: 1/84 - On going
Abstract: Investigation of VI characteristics of plasma contactors as electron collectors in ground-based vacuum facilities.

Title: Electrodynamic Tether Device Characterizations
NASA Center: Lewis Research Center (LeRC)
Contract Number: N/A (In-house study)
Contract Monitor: Joe Kolecki
Contractor: LeRC In-House Study, Dr. M. Patterson
Contract Duration: 1/84 - 12/88
Abstract: Investigation of VI characteristics of plasma contactors as electron collectors in ground-based vacuum facilities.

Title: Plasma Turbulence Generated by Tether Current Flow
NASA Center: Lewis Research Center (LeRC)
Contract Number: NAG3-681
Contract Monitor: Joe Kolecki
Contractor: MIT, Dr. D. Hastings
Contract Duration: 1/85 - 12/88
Abstract: A theoretical study of turbulence effects in a contactor plasma cloud.

Title: Tether Plasma Interactions and Power Plant Feasibility
NASA Center: Lewis Research Center (LeRC)
Contract Number: NAS3-23881
Contract Monitor: Joe Kolecki
Contractor: S-Cubed, Dr. I. Katz
Contract Duration: 1/84 - On going
Abstract: Improve and validate the existing physics model of electron collection by a plasma contactor. Predict operational parameters for high power tether systems with plasma contactors. Both objectives use the NASCAP-LEO computer code.

Title: Tether Power System Study
NASA Center: Lewis Research Center (LeRC)
Contract Number: NAS3-24649
Contract Monitor: Joe Kolecki
Contractor: MIT, Dr. M. Martinez-Sanchez
Contract Duration: 1/84 - 12/85
Abstract: A conceptual design of a high power electrodynamic tether system.

Title: Hollow Cathode Sounding Rocket Experiment (HOCAT)
NASA Center: Lewis Research Center (LeRC)
Contract Number: Inter-Agency Number: C-0007-J (Transfer of funds)
Contract Monitor: Joe Kolecki
Contractor: Naval Postgraduate School, Chris Olsen
Contract Duration: 1/87 - 12/89
Abstract: Definition study of mother/daughter sounding rocket payload to study plasma coupling of hollow cathode plasma contactors in space.

Title: Constellation Dynamics
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-3666
Contract Monitor: Charles C. Rupp
Contractor: Center for Astrophysics Harvard-Smithsonian, E. Lorenzini
Contract Duration: 2/85 - On going
Abstract: To define the dynamic behavior of three body tethered constellations.

Title: Damage Inspection and Verification of Tethers
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-37618
Contract Monitor: Charles C. Rupp
Contractor: ANCO Engineers, Inc.
Contract Duration: 2/88 - 9/88
Abstract: To develop a concept using an optical device for inspection and detection of damaged tethers.

Title: Getaway Tether Experiment
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAG8-586
Contract Monitor: Charles C. Rupp
Contractor: Auburn University, Auburn, Alabama, M. Greene
Contract Duration: 1/87 - On going
Abstract: To deploy twin satellites that separate after deployment by a conducting tether.

Title: Small Expendable Deployer System
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-37885
Contract Monitor: James K. Harrison
Contractor: Energy Science Laboratories, J. Carroll
Contract Duration: 9/88 - 9/89
Abstract: To develop and fly on a Delta II launch a tether deployment system without tether retrieval capability.

Title: Small Expendable Deployer Measurement Analysis
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NGT 01-002-099
Contract Monitor: Charles C. Rupp
Contractor: University of Alabama; University of Southern California, Connie Carrington
Contract Duration: 1/89 - 1/90
Abstract: To plan the techniques for reducing dynamic experimental flight data on the first SEDS mission.

Title: Tether Deployment Monitoring Systems
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-36268
Contract Monitor: James K. Harrison
Contractor: ANCO Engineers, Inc., P. Ibanez, A. Levi
Contract Duration: 6/87 - 6/89
Abstract: To build and ground-test a concept of attaching small radar detectable modules to a tether during deployment to verify tether shape.

Title: Tether Elevator Crawler System
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAG8-620
Contract Monitor: James K. Harrison
Contractor: Tri-State University, Professor F. R. Swenson
Contract Duration: 2/87 - 2/88
Abstract: To develop a breadboard lab model of a tether crawler used to position experiment modules at various tether locations.

Title: Tether Released Recovery System
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-35096
Contract Monitor: Charles C. Rupp
Contractor: General Electric Company, Dwight Florence
Contract Duration: 3/85 - On going
Abstract: To study modification of an available reentry vehicle to be deployed by tether.

Title: Tethered Satellite Monitoring System
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-38051
Contract Monitor: Charles C. Rupp
Contractor: Applied Research, Inc., Scott Davis
Contract Duration: 12/88 - 5/89
Abstract: Development of an automated monitoring system for measuring tether damage.

Title: Tether Simulations
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAS8-36673
Contract Monitor: Charles C. Rupp
Contractor: Control Dynamics Company, John Glaese
Contract Duration: 6/84 - On going
Abstract: To develop simulation programs for dynamic behavior of tethers in various specific tether missions.

Title: ULF/ELF Tether Antenna
NASA Center: Marshall Space Flight Center (MSFC)
Contract Number: NAG8-551
Contract Monitor: Charles C. Rupp
Contractor: Smithsonian Astrophysical Observatory, R. Estes
Contract Duration: 9/85 - 11/86
Abstract: To analyze and develop an ultra-low and extremely low frequency electrodynamic tether antenna system.

1.6 Italian Tether Studies

The Italian studies of tether systems and applications are performed under contracts to Aeritalia, with some support by other companies for specific items. Also, many universities and research institutions have made significant contributions in some areas of investigation; these are described in paragraph 1.6.8.

The first phase of the Italian study on tether applications in space has examined a large number of concepts. In order for these concepts to be viable, many dynamical and technological aspects have been studied and the possibility of laboratory and flight demonstration has been investigated.

The following applications are presently under study:

1. Science and Application Tethered Platform
2. Small Tethered Pointing Platform
3. Tethered Space Elevator
4. Complex Tether Technology
5. Payload Orbital Transfer and Reentry, Rendezvous and Docking Facility
6. Space Station Gravity Gradient Stabilization by Tethers

1.6.1 Science and Application Tethered Platform (SATP)

The problems related to the dynamics of a tethered system attached to the Space Station have been investigated. The limited mobility of the Space Station does not allow application of the dynamic techniques developed for the deployment and retrieval of a tethered satellite released from the Shuttle. The deployer can be placed in an area of the Space Station where the gravity gradient is different from zero thus making the operations of deployment and retrieval easier due to a sufficiently high value of tension in the tether.

The main goal of the study was to assess the feasibility and to define the technical features of SATP:

- Acquisition, technical analysis and evaluation of the users requirements
- Definition of the technical requirements
- Analysis, trade-off, and definition of the SATP configuration
- Evaluation and definition of the preliminary design characteristics

1.6.2 Small Tethered Pointing Platform

The concept of a small tethered platform that would be released from the Shuttle to demonstrate the technological and scientific performance of a large-scale platform has been investigated. This pointing platform would use the displacement of the tether attachment point from the center of mass of the platform as a means of attitude control. This technique might also be used to allow attitude stabilization of a medium-size pointing platform tethered to the Space Station and to stabilize the Space Station itself. The demonstration of the concept would prove the feasibility of high-precision pointing performance where complex dynamics are involved.

The primary engineering objective of this mission is to demonstrate the ability to perform high-precision control of the pointing platform attitude. During the Shuttle mission, several engineering

parameters would be measured to assess the attainable performance with reference to pointing platform concept applications. At least five experiments goals can be accomplished:

- Measurement of attitude dynamics in the absence of attitude control
- Measurement of attitude dynamics in response to high-precision control
- Evaluation of attitude stabilization in response to induced dynamic disturbances
- Measurement of tether tension and tether angle as a function of time with respect to the scaled platform
- Measurement of displacement mechanism and control system performance

1.6.3 Tethered Space Elevator

Under contract to Italy's National Space Plan (now ASI), Aeritalia conducted a study of applications of tethers to the Space Station. A resultant intriguing concept selected as a candidate for a demonstration flight by the Space Shuttle is the Tethered Space Elevator. This element has the ability to move between both ends of a tether and can be used for microgravity studies as well as transportation.

The most promising feature offered by the Space Elevator when used as a microgravity facility is the unique capability to control the gravity acceleration level as a function of time. This possibility has provoked great interest in the microgravity science community. Moreover, the utilization of the Space Elevator as a transportation facility, able to move along the tether and providing easy access between the two tethered bodies, could be the fundamental tool used in the evolution of tethered systems.

The proposed demonstration would be a proof-of-concept scaled-down configuration, rather than a full test of the elevator. An STS flight test would be significant as a means of validating the mathematical models which describe the dynamics and control of the key component designs. The system proposed for a Shuttle flight test of the elevator concept is made up of three major elements: the TSS-deployer, the TSS-satellite, and the scaled proof-of-concept elevator.

Once the satellite is far away from the deployer, the scaled elevator would be mounted on the tether, by means of the Shuttle RMS, and recovered before satellite retrieval. The primary engineering objective of this mission is to demonstrate the ability to control the elevator motion and the overall system dynamics.

Engineering data would be measured during the mission to assess the attainable performance with reference to elevator concept applications. At least four engineering experiment goals should be realized:

1. Measurement of the residual acceleration behavior as a function of time for several elevator positions along the tether
2. Measurement of the residual acceleration profile vs. time as a response to a commanded profile by elevator motion control
3. Measurement of the system dynamics response to the elevator motion from the Shuttle to the satellite for a commanded velocity control profile
4. Measurement of technical performance parameters of the elevator drive mechanism

1.6.4 Complex Tether Technology

Achievement of the full potential of permanent tethered facilities in space is dependent on the development of complex tethers which will be able to perform several functions (i.e., power transmission, data communication) and be resistant to long exposures to the space environment.

Conventional cable technology suitable for performing several functions is well developed but does not apply directly to space activities. In addition, the impact protection technology developed for the usual space structures are relevant but must be adapted to the peculiar characteristics of long cables. The demonstration of complex tether technology, including impact protection, is a prerequisite to effective implementation of advanced tether applications in space.

The major requirement of this demonstration is simulation of the space environment. Specifically, such effects as pressure, temperature, radiation, and meteoroid debris flux must be modelled. These effects can be satisfactorily simulated in existing laboratories, hence the objective of this demonstration can be pursued by ground-based activities. The following steps outline the proposed demonstration procedure:

- a. Requirements identification and current technology assessment
- b. Materials testing, functional elements testing and technologies development
- c. Multifunction tether technology and configuration analysis
- d. Sample fabrication and development tests
- e. Verification of the tether's ability to satisfy its major functional requirements when subjected to the simulated space environment conditions
- f. Cost and performance trade-off studies
- g. Tether configuration definition

1.6.5 Payload Orbital Transfer and Reentry, Rendezvous and Docking Facility

The use of launching systems, such as the OMV, connected to the Space Station or a platform by means of very long tethers can improve their operational capability. In fact, a payload can be transferred to a variety of orbits by changing the length of an upward or downward tether, and by using a static or oscillating release maneuver. After release, the tether and the tip mechanism may be retrieved to the Space Station or platform and used for repeated launches.

It is also possible to capture suborbital payloads using a docking probe tethered to the Space Station. The major problem for this application is the limited rendezvous window due to the differences in speed between the probe and the object to be docked. The maneuverability of the docking probe appears to be very important for successful docking.

1.6.6 Space Station Gravity Gradient Stabilization by Tethers

There exists the possibility of obtaining attitude control of large space structures (e.g., the Space Station) by means of tethered masses. This technique can be used during the operational life of the Station, but it is of particular help during the assembly phases. The Italian studies have investigated a number of different attitude control configurations and have identified the most suitable ones.

1.6.7 Future Italian Tether Studies

The past Italian tether studies, reported above, were developed between 1985 and 1988. Quite a few of the concepts studied will be considered in the future, e.g., much work will be devoted to the Tethered Space Elevator. Nevertheless, on the basis of national interest and taking into account the recommendations of the ASI/NASA Task Group for Flight Demonstrations, effort will be concentrated on the following three subjects:

1. Tether Initiated Space Recovery System (TISRS)
2. Tether Inspection and Repair Experiment (TIRE)
3. Astrophysical Sciences Tethered Retrievable Observatory SATP (ASTROSATP)

The possibility of reentering payloads from orbit to ground by means of retro-rocket propulsion is well established. The Tether Initiated Space Recovery System (TISRS) provides the capability of deorbiting capsules from the Space Station or LEO without propulsion. A Shuttle flight is the baseline for this experiment utilizing the Small Expendable Deployer System (SEDS) under development in the U.S. and a capsule of the Satellite Reentry Vehicle (SRV) developed by General Electric. The hardware of the capsule will, however, be modified for this demonstration, i.e., the deorbit motor will be eliminated and a grappling fixture, together with the tether attachment system, will be added.

The Tether Inspection and Repair Experiment (TIRE) arises from an Aeritalia feasibility study performed on a tethered scientific platform (SATP) where the need for a deeper investigation of the tether was envisaged and addressed. It was shown that at least two major characteristics differentiate the present tether design with respect to potential future designs: the tether can perform several functions in addition to the structural ones, but the possibility of using it for long duration missions is strongly dependent on its capability to counteract or sustain the damaging environmental effects. A protective shield becomes necessary in order to prevent unacceptable damaging or the complete cutting of the tether. If suitable technological solutions are not found, it is likely a number of future tether applications will vanish.

A substantial effort, must be applied toward the design of a proper tether configuration and component material selection. A more important requirement will be the development of techniques to inspect, detect and repair the damage. A Tethered Space Elevator may be used for this purpose.

The SATP is a large multimission platform designed to support a wide range of scientific and application payloads tethered to the Space Station. SATP has been studied and the result was a preliminary configuration and subsystem analysis.

In the ASTROSATP study, the possible use of a SATP as a facility for astrophysical payloads will be performed. The major advantages of a tethered platform for scientific applications are the freedom from Space Station pollution (thermal, mechanical, chemical, and electromagnetic) and the possibility of lower costs of the experiments to be flown due to the close proximity of the platform to the Space Station.

The ASTROSATP study also affords the opportunity to further investigate high-precision pointing and attitude control by tether tension, since a marked interest has been shown by scientists for the installation of a Schmidt telescope on-board the platform.

1.6.8 Italian Universities and Research Institutions Tether Studies

Many universities and research institutions contribute to the Italian tether programs. Mention is made here of the work carried on in Padua and Frascati. At the Institute of Applied Mechanics of Padua University, two research areas are being investigated:

1. Dynamics of Tethered Systems and Other Applications
2. Tether Technology

In the first research area, the word "dynamics" covers all aspects of the motion, including momentum exchange and orbit transfer, tether elastic vibrations, response to orbital perturbations, attitude control and stability. The work done to date was related to TSS-1, but after the signing of the letter of agreement between NASA and PSN (now ASI) on tether applications, attention has also been focused on systems or demonstrations considerably different from TSS.

The Institute is providing an experiment on TSS-1 to evaluate the dynamical noise level on the satellite resulting from tether elasticity. As a result of the sequence of experiments to be performed, the effects of perturbations transmitted to the satellite will be determined by means of linear accelerometers and gyros mounted on it as part of the Core Equipment. The data obtained will be compared to the expectations of the mathematical models developed to simulate system dynamics.

For other applications, dynamics and control studies on future missions of tethers in space have been undertaken independently and in cooperation with Aeritalia. Among these are:

- a. Science and Application Tethered Platform (SATP) and Tethered Elevator: This is a multifunction system that would be tethered to the Space Station. Some functions are in the scientific area, such as use of the platform for sky or Earth observations. Others functions beneficial to Space Station operations, include storage of dangerous fluids on a tethered platform. The dynamics of this system, and the control laws of the motion of an attached elevator, have been studied by Aeritalia. Also, the vibration induced by the motion of the elevator has been investigated.
- b. Tether Initiated Space Recovery System (TISRS) and Trash Disposal from the Space Station: Here, the tether is used to deorbit a reentry capsule from the Shuttle orbit or to release a container filled with Space Station waste products and have it burned in the upper atmosphere. In the first case, the tether would be severed at both ends so that one of the problems is to evaluate the orbital lifetime of a free tether in space, and consequently, the probability of impact with another spacecraft in LEO. In the second, system parameters must be optimized in order to achieve waste destruction.
- c. Tether Assisted Space Station Attitude Stabilization: Since the Space Station is inherently unstable in attitude against the gravity gradient, a large expenditure of propellant will have to be dedicated to active control. Therefore, the possibility of utilizing one or two ballast masses properly tethered to the Space Station in order to generate stabilizing gravity gradient torques and save propellant has been studied. This study, as well as the next, has been carried out in cooperation with Aeritalia.
- d. Tether Assisted Space Station C. G. Control: The dual keel configuration of the Space Station permits the micro-g labs to be located as close as possible to the center of mass of the system. In this way, lower acceleration levels are expected. However, the location of the C.G. can change during the initial and the early operational phase due to mass and moment of inertia variations, Shuttle docking or other causes. The possibility of using masses connected to the Station by means of tethers of suitable length, to control the position of the C.G. with respect to the scientific laboratories, has been studied .
- e. Tethers and Aerobraking: Another potential application of tethers is in increasing the A/M ratio of a spacecraft to achieve an orbital maneuvering capability using aeroassisted braking. In this way, energy could be saved in unmanned missions requiring transfers from high altitude, or hyperbolic orbits down to LEO, such as for telecommunications platforms to be refurbished on board the Space Station, or for vehicles returning from the Moon.

In the second research area of tether technology, laboratory investigations on the physical parameters of the tether and the development of mathematical models for simulations have been conducted. For TSS-1 and TSS-2, for example, tests have been performed for the determination of the mechanical characteristics of tethers such as: (1) longitudinal wave propagation velocity, (2) stiffness and non-linear elasticity, and (3) hysteresis and loss factor. Also, the theoretical investigations performed include: (1) development of numerical models which represent the multilayer behavior of the tether with friction and shear between adjoining layers, and (2) development and implementation of simple programs which allow the checking of laboratory experiments and the simulation of maneuvers.

The Interplanetary Space Physics Institute (IFSI) at Frascati is involved in plasma experiments to be carried out in the Tethered Satellite System (TSS) electrodynamic missions. In support of these missions, an ionospheric plasma chamber of 9 m^3 , called SIMPLEX, has been designed in order to investigate the fundamental principles of plasma and TSS interactions. This chamber is equipped with hollow cathode sources and will provide simulations of the TSS orbiting at ionospheric altitudes. A Kaufman plasma source will be added to provide an adjustable ionic stream velocity and therefore perform a simulation of the relative velocity between the satellite and the ionospheric plasma. This would permit study of the current collection disturbance due to the ram and wake effect in the vicinity of the charged body. Since these phenomena are strongly dependent on the environmental magnetic field, the SIMPLEX facility is provided with a 3-D magnetic Helmholtz coil system in order to simulate the Earth magnetic field effects.

**Tether
Applications**

**SECTION 2.0
TETHER APPLICATIONS**

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2.1 General

This section provides a summary of various tether applications proposed up to this printing, 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 2.2 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. 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 Section 7.0, "Contacts", for addresses and telephone numbers.) Finally, the "References" subsection lists the reference and page numbers of the references 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 Section 4.0 "Tether Data" address these critical issues.

2.2 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

Category/Title	Page	Cross Reference
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AERODYNAMICS

Tether Initiated Space Recovery System	35	SC SS TR
Multiprobe for Atmospheric Studies	36	SC SS
Shuttle Tethered Aerothermodynamic Research Facility	37	SC
Shuttle Continuous Open Wind Tunnel	38	SC

CONCEPTS

Gravity Wave Detection Using Tethers	39	SC
Tethered Sail (Hypersonic Rudder)	40	AE TR
External Tank Space Structures	41	CG SS
Alfven Engine for Interplanetary Transportation	42	EL PL TR
Earth Moon Tether Transport System	44	PL TR
Mars Moons Tether Transport System	45	PL TR

CONTROLLED GRAVITY

Rotating Controlled-Gravity Laboratory (Tethered Platform)	47	SC PL
Rotating Controlled-Gravity Laboratory (Tether-Enhanced Station)	49	SC PL
Variable Gravity Research Facility (VGRF)	51	SC

ELECTRODYNAMICS

Electrodynamic Power Generation (Electrodynamic Brake)	53	PL SS TR
Electrodynamic Thrust Generation	55	PL SS TR
Electromagnetic Motor/Generator for Power Storage	57	PL SS
Electromagnetic Thruster to Offset Drag	59	PL SS TR
ULF/ELF/VLF Communications Antenna	61	SC SS

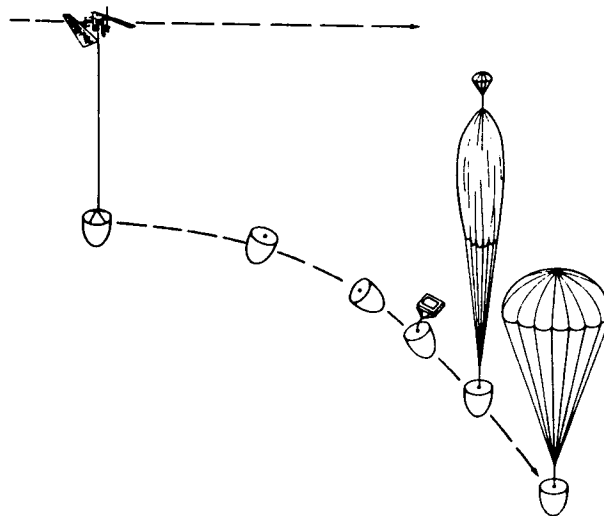
<u>Category/Title</u>	<u>Page</u>	<u>Cross Reference</u>
<u>PLANETARY</u>		
Comet/Asteroid Sample Return	63	SC
Electromagnetic Deceleration for Planetary Capture	65	EL TR
Jupiter Inner Magnetosphere Maneuvering Vehicle	66	EL TR
Mars Tethered Aeronomy Observer	68	AE SC
Multipass Aerobraking of Planetary Probe	69	AE TR
Tethered Lunar Satellite for Remote Sensing	71	SC
<u>SCIENCE</u>		
Science Applications Tethered Platform	72	CG EL SS
Shuttle Science Applications Platform	74	CG EL
Tethered Satellite for Cosmic Dust Collection	75	PL
<u>SPACE STATION</u>		
Microgravity Laboratory	76	CG SC
Shuttle Deorbit from Space Station	78	TR
Tethered Orbital Refueling Facility	80	CG
Tethered STV Hangar/Depot	82	CG
Tethered STV Launch	84	TR
Tethered Space Elevator	86	CG SC
Variable/Low Gravity Laboratory	88	CG SC
<u>TRANSPORTATION</u>		
Generalized Momentum Scavenging from Spent Stages	90	SS
Internal Forces for Orbital Modification (Orbital Pumping)	91	PL
Satellite Boost from Orbiter	93	SC
Shuttle Docking by Tether	95	SS
Shuttle External Tank Deorbit	96	AE
Small Expendable Deployer System	97	AE SC
Tether Reboosting of Decaying Satellites	98	SS
Tether Rendezvous System	99	PL SS
Upper Stage Boost from Orbiter	100	PL

2.3 Tether Applications

-- AERODYNAMICS --**Tether Initiated Space Recovery System**

APPLICATION: Provides a means of transferring a small payload from the Space Station to the Earth without the use of the Shuttle Orbiter.

DESCRIPTION: A payload (such as processed chemicals, engineering data, etc.) would be deployed along a tether from the Space Station. The tethered payload would be released into a reentry trajectory such that it would enter the upper atmosphere within one-half orbit. Upon reentry, a guided parachute would open, slowing its reentry speed to permit a soft landing.

**CHARACTERISTICS:**

- Tether Length: 20-40 km
- Payload Mass: 100 kg
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Tether system deployment timing for proper prograde swing
- Dynamics of tether after payload release

STATUS:

- Preliminary analysis completed by General Electric
- Demonstration mission for Shuttle - to be proposed October 1989

DISCUSSION: The time required for the tethered deployment of the payload is approximately 3 hours. An additional 1 hour and 15 minutes is required for the reentry phase after tether (or payload) is released. The benefits of using a tether for a payload recovery system are reduced sensitivity to payload mass and elimination of the retro-rocket as a safety issue.

CONTACTS:

- Chris Rupp
- Dwight Florence
- Alberto Loria
- Franco Bevilacqua

REFERENCES:

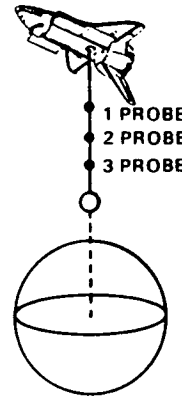
Tether Released Recovery, Final Report, NASA Contract NAS8-35096.

-- AERODYNAMICS --

Multiprobe for Atmospheric Studies

APPLICATION: Measurement of spatial geophysical gradients.

DESCRIPTION: A one-dimensional constellation 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: Undetermined
- 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

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

REFERENCES:

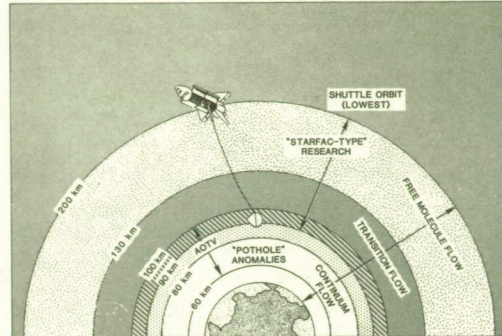
Applications of Tethers in Space, Workshop Proceedings, Volume 2, Venice, Italy, NASA CP2422, March 1986. (pp. 150-204)

-- AERODYNAMICS --

Shuttle Tethered Aerothermodynamic Research Facility

APPLICATION: Obtain aerothermodynamic data on various aerodynamically shaped vehicles at altitudes as low as 90 km.

DESCRIPTION: A tethered subsatellite in combination with the Shuttle Continuous Open Wind Tunnel (SCOWT) based instrument package will be deployed from the STS downward to the upper continuum flow regime. The satellite may be retrieved, or if properly configured, released and recovered.



CHARACTERISTICS:

- Length: 100-125 km
- Mass: TBD, nominally 500 kg depending on configuration
- Power Required: TBD
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- High temperature materials for tethers required below 120 km altitude
- Precision locating and tracking method
- TPS probably required

STATUS:

- STARFAC feasibility/definition results completed
- SCOWT study ongoing in support of STARFAC and TSS-2
- TSS-2 mission planning which will incorporate same objectives

DISCUSSION: STARFAC will enable aerothermodynamic research to be performed in a region of the Earth's atmosphere which is presently unattainable for extended periods of time. This region is 90 to 125 km above the Earth's surface. Presently, atmospheric measurements in this region of the atmosphere can only be made with sounding rockets over small regions of area and time. Since the STS will provide station keeping during the deployment, steady-state data which include diurnal variations can be obtained for an extended period encompassing several or more orbits.

CONTACTS:

- Paul Siemers
- George Wood
- Giovanni Carlomagno
- Luigi de Luca

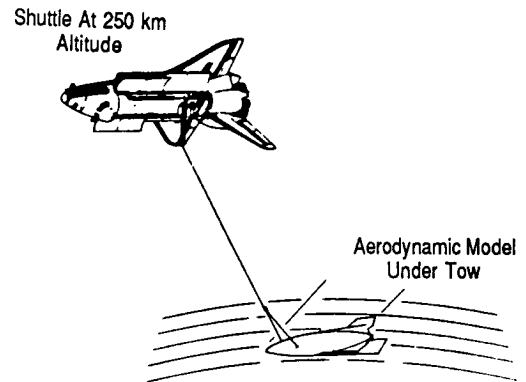
REFERENCES:

Applications of Tethers in Space, Workshop Proceedings, Volume 2, Venice, Italy, NASA CP2422, March 1986. (pp. 251-286)

-- AERODYNAMICS --**Shuttle Continuous Open Wind Tunnel**

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

DESCRIPTION: A tethered aerodynamically shaped research vehicle is deployed downward from 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 TSS-2
- Precursor for STARFAC

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

CONTACTS:

- Franco Mariani
- Paul Siemers
- Giovanni Carlomagno
- George Wood
- Luigi de Luca

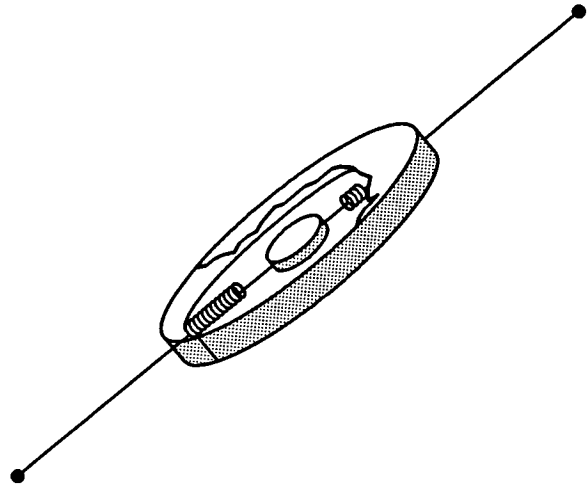
REFERENCES:

Applications of Tethers in Space, Workshop Proceedings, Volume 2, Venice, Italy, NASA CP2422, March 1986. (pp. 225-250)

-- 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: Near-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

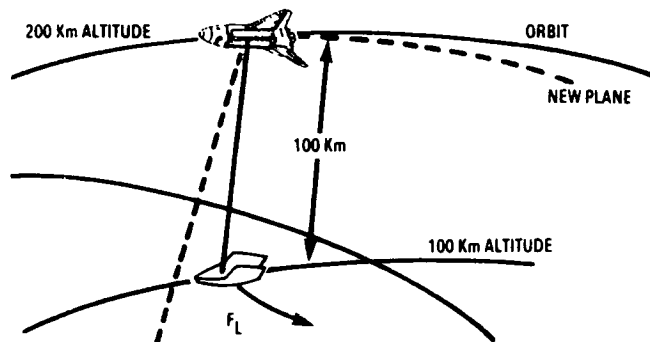
REFERENCES:

- 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 Sail (Hypersonic Rudder)**

APPLICATION: Used to change the orbital inclination of a body such as the Space Shuttle or a satellite.

DESCRIPTION: A hypersonic lifting body tethered below the Shuttle Orbiter is used to generate side forces in order to modify the inclination of the system's orbit. The body must be shifted from one side to the other during the orbit and reeled in and out in order to accomplish this.

**CHARACTERISTICS:**

- Tether Length: Approximately 100 km
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Performance
- RCS to counteract drag forces
- Tether heating
- Diagnostic instrumentation

STATUS:

- This concept is currently believed to be infeasible
- Preliminary evaluation completed by Wright-Patterson AFB
- No further work planned

DISCUSSION: This concept can also be used to test tether materials, tether control techniques and aerodynamic control structures if used as a high altitude test bed.

CONTACTS:

- James Walker
- Jerome Pearson
- Joe Carroll

REFERENCES:

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

-- CONCEPTS --

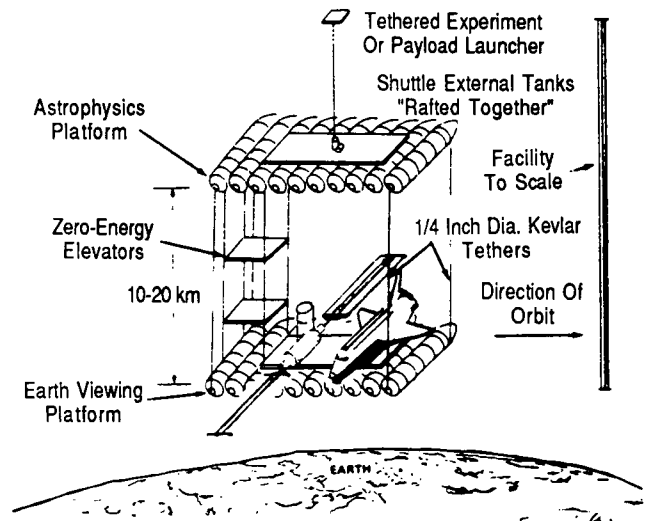
External Tank Space Structures

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: Mid-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:

- James Walker
- Joe Carroll

REFERENCES:

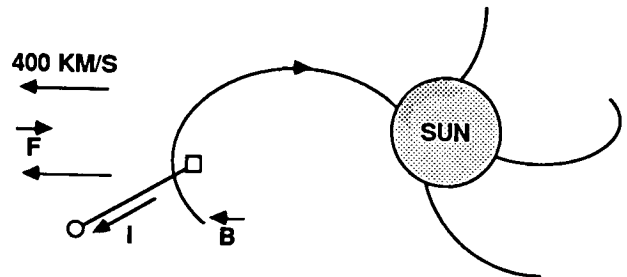
Carroll, J. A., "Tethers and External Tanks, Chapter 3 of Utilization of the External Tanks of the Space Transportation System," California Space Institute, La Jolla, California, Sept. 1982.

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-- CONCEPTS --**Heliocentric Alfvén 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 | • Potential For | Technology |
| • Power: | 2 MW | Demonstration: | Far-Term |
| • Materials: | Superconducting
Niobium-Tin | | |

CRITICAL ISSUES:

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

STATUS:

- TSS-1, demonstrating electrodynamic applications, is scheduled for a 1991 launch
- 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 Alfvén 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 $IL \times B$ 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:

- Jim McCoy
- Nobie Stone
- Richard Taylor

REFERENCES:

Applications of Tethers in Space, Vol. 1, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 4-11 through 4-22)

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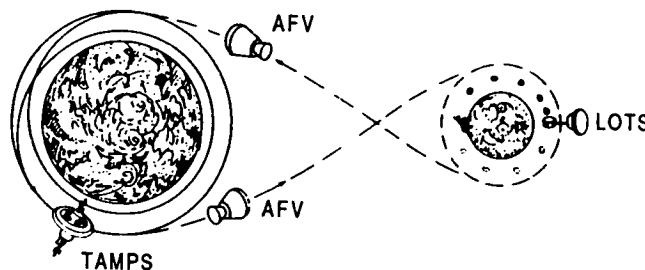
H. Alfven, "Spacecraft Propulsion: New Methods," Science, Vol. 176, pp. 167-168, April 14, 1972.

-- 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 aerobreak 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 LO₂, 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:

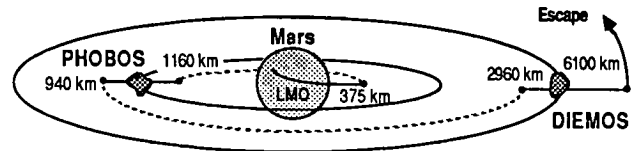
Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 127-151)

-- 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:

- Paul Penzo

REFERENCES:

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

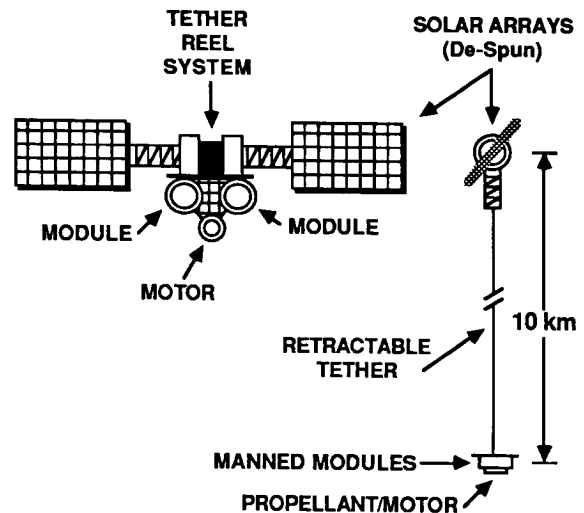
-- CONTROLLED GRAVITY --

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.

TETHER PLATFORM CONCEPT



CHARACTERISTICS:

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

CRITICAL ISSUES:

- Susceptibility to micrometeoroid/debris damage

STATUS:

- No detailed system design study for this application has been performed

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:

- Paul Penzo

REFERENCES:

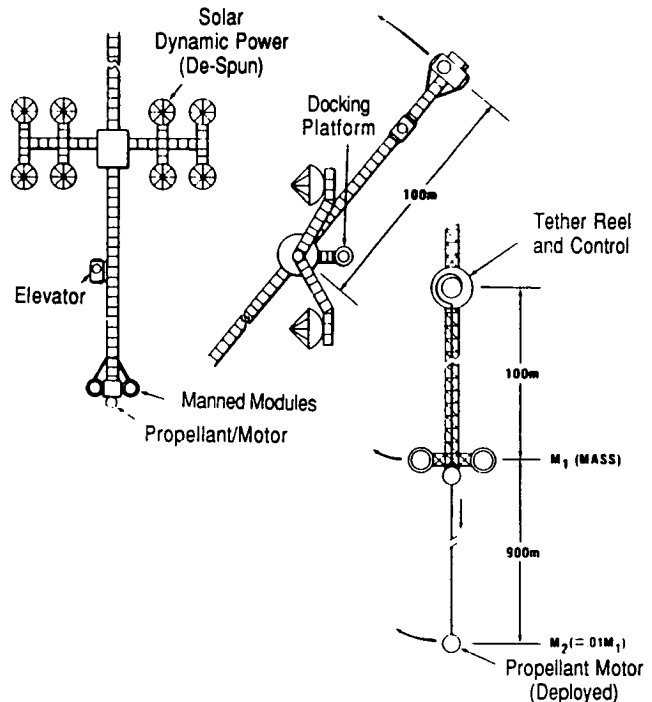
Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 125-135)

-- CONTROLLED GRAVITY --

Rotating Controlled-Gravity Laboratory (Tethered-Enhanced Station)

APPLICATION: Provide a readily accessible variable/controlled gravity laboratory, capable of generating artificial gravity levels of up to about one-half g, in Earth orbit.

DESCRIPTION: A rigid station with two manned lab modules and a tethered, deployable propellant motor at each end of a rotating beam. A hub structure at the center of the beam contains two tether reel and control systems for the motors, and a de-spun solar power system and docking platform. An elevator transfers men and supplies along the beam, to and from the ends. Artificial gravity is created in the lab modules by extending the tethers symmetrically and firing the two motors, rotating the entire system about its center of mass. Tether length is used to control the gravity level.



CHARACTERISTICS:

- | | | | |
|---------------------------|------------|---|-------------|
| • Module Rotation Radius: | 100 m | • Rotation Rate: | Up to 2 rpm |
| • Motor Rotation Radius: | 100 m | • Potential for Technology Demonstration: | Far-Term |
| • g-Level: | Up to 0.45 | | |

CRITICAL ISSUES:

- Susceptibility to micrometeoroid/debris damage

STATUS:

- No detailed system design study for this application has been performed

DISCUSSION: Access to an orbiting variable/controlled-gravity laboratory, capable of providing artificial gravity levels of up to about one-half g, 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 lab station. 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. The tether-enhanced rigid station combines the best features of the tethered platform and rigid station. It has a shorter radius of rotation than the tethered platform, while using deployable/retractable tethers with the propellant motors to control the station rotation and lab gravity more efficiently than a rigid station alone. The docking platform, which could be de-spun for docking with a spacecraft and then spun to allow the transfer of men and supplies to the lab modules, would allow easy access to the lab modules, without stopping their rotation. A disadvantage of this system is that its spin rate (and associated Coriolis force) would be greater than that of the tethered platform system, for a given gravity level.

The lab modules would be located 100 m from the center of the station, and the propellant motors could be deployed outward from that distance, up to 1000 m from the center. To spin the system, the tethers would be fully and symmetrically deployed, and the motors fired. It has been calculated that a g-level of 0.11 g would result from a tether length (from the end of the rigid beam) of 900 m at a spin rate of 1.0 rpm, 0.16 g (lunar gravity) from a length of 700 m at 1.2 rpm, 0.30 g from a length of 400 m at 1.6 rpm, and 0.45 g from a length of 0.0 m at 2.0 rpm.

With this lab, 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:

- Paul Penzo

REFERENCES:

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 125-135)

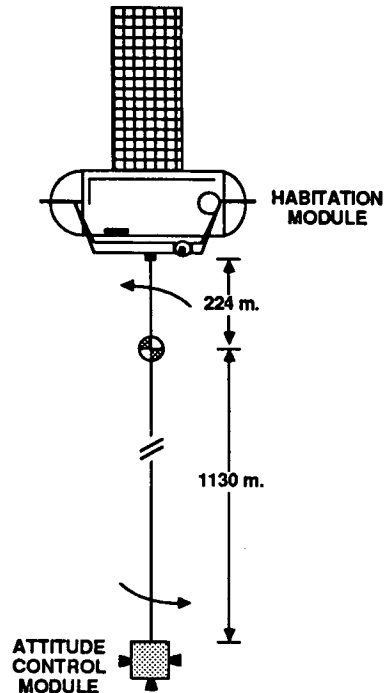
-- CONTROLLED GRAVITY --**Variable Gravity Research Facility (VGRF)**

APPLICATION: Provide a facility in Earth orbit that will operate at gravity levels between 0 and 2g at rotation rates between 1 and 10 rpm for the purpose of studying the long term effects of various gravity levels on humans.

DESCRIPTION: A habitation module with supporting structure, power and life support systems, connected to a propulsion module by a tether. The tether is deployable/retractable with a maximum length of about 2 km. Artificial gravity is created by extending the tether and using propulsion to spin the system about its center of mass. Both gravity levels and rotation rates are controllable by changing tether length and firing the propulsion motor.

CHARACTERISTICS:

- Tether Length: 0 to 2 km
- g-Level: 0 to 2g
- Rotation Rate: 0 to 10 rpm
- Crew Size: 2 to 3 persons



- Potential For Technology Demonstration: Mid-Term

CRITICAL ISSUES:

- Tether and Module dynamics and controls
- Mission operations development
- Engineering of subsystems that work in both zero and finite gravity

STATUS:

- Preliminary studies have been completed indicating feasibility
- Current studies are generating more detailed subsystem design
- Study underway of dynamics and controls of tethered configuration at Stanford University

DISCUSSION: This facility would allow scientific investigation into the question of human performance and health at gravity levels other than Earth gravity for periods of up to 90 days. In particular, long-term exposure to Martian or Lunar gravity can be studied. The relation with gravity level and rotation rate can also be studied in such a facility, since both are independently controllable. The facility also will answer the engineering questions concerning generation of artificial gravity required for manned missions to other planets. Engineering design of such systems that operate under variable gravity levels and with controllable forces will be required for this facility.

Operations of the facility might be as follows. The facility is initially docked and not rotating with the tether completely retracted. The tether is deployed in the gravity gradient configuration to the desired tether length, and then the propulsion motor is fired to create the desired rotation rate. Selection of tether length is determined by desired rotation rate and gravity level. The facility is spun so that the spin axis of

the system is solar pointing, for maximum solar panel output. To maintain such a configuration, however, requires precession of the spin axis to follow the Sun as the Earth orbits. Every 90 days, the facility is despun and the tether retracted for rendezvous with the Shuttle or the Space Station for crew change and resupply. Besides studying the effects of such rotation rates and gravity levels on humans, the facility will provide facilities for animal and plant research.

The current study is examining several options in the configuration and operation of the facility. Some of these trades include the use of a dead weight on the counterweight end of the tethered system; allowing an inertially oriented spin axis; and refurbishment without despin.

CONTACTS:

- Marcie Smith
- Larry Lemke
- Franco Bevilacqua

REFERENCES:

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

Wercinski, P. F., Searby, N. D., Tillman, B. W., "Space Artificial Gravity Facilities: An Approach to Their Construction", Engineering, Construction and Operations in Space: Proceedings of Space '88, Albuquerque, New Mexico, August 29-31, 1988.

Lemke, Larry G., "An Artificial Gravity Research Facility for Life Sciences", presented at the 18th Intersociety Conference on Environmental Systems, San Francisco, CA, July 11-13, 1988.

-- ELECTRODYNAMICS --

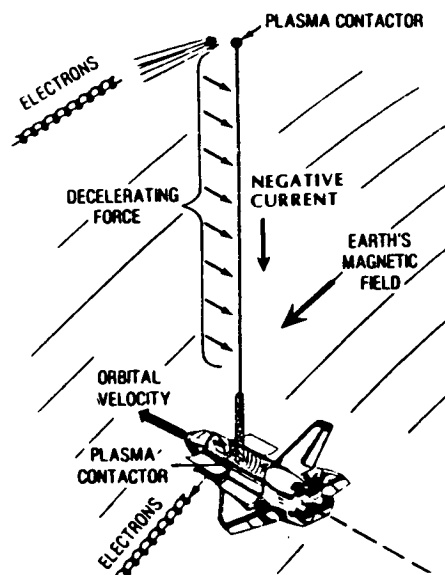
Electrodynamic Power Generation (Electrodynamic Brake)

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. 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/
Teflon



- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Flight experiment validation of the current-voltage characteristics of plasma contactor devices 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 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

STATUS:

- TSS-1, demonstrating dynamic and electrodynamic applications, is scheduled for a 1991 launch
- A demonstration of basic electrodynamic tether operation, using a small PMG system (a 200 m wire with plasma contactors), is expected to fly aboard the Shuttle as a GAS canister for James McCoy at the earliest practical date
- A wide variety of work is actively underway in the areas of electrodynamic demonstrations, hollow cathodes, tether materials, and hardware technologies including two proposed sounding rocket flight experiments

DISCUSSION: An orbiting insulated tether, terminated at the ends by plasma contactors, 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 $v \times B$ 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. Although not yet confirmed by flight testing, PMG systems appear superior for primary power applications operating at much lower voltages and higher currents. Hollow cathodes are 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. If flight tests show that the PMG design is not feasible, one or both of the other two system configurations would be alternatives. Moreover, there may be specific missions which would be best served by the characteristics of one of these two alternative configurations.

Calculations have been made of the performance of four PMG reference systems. A 2 kW system (designed with minimum mass and size for disposable tether applications) uses 10 km of #12 wire, has a mass of 200 kg, and has an efficiency of 80% (efficiency is traded for low mass and greater flexibility). A 20 kW PMG (normally operating at 2 kV and 10 A, and capable of a peak power of 125 kW) uses 10 km of #2 wire, has a mass of 1,200 kg, and has an overall efficiency of about 90%. A 200 kW PMG (normally operating at 4 kV and 50 A, and capable of a peak power of 500 kW) uses 20 km of #00 wire, has a mass of 4,200 kg, and has an overall efficiency of about 87%. A Megawatt Reference System (normally operating at 500 kW, 4 kV and 125 A; capable of a peak power of over 2 MW) uses a wire 2 cm in diameter, has a mass of 19,000 kg, and has an overall efficiency exceeding 90%. All of these reference systems use aluminum wire and Teflon insulation. Aluminum is used because its conductivity per mass is about twice that of copper, and Teflon because it provides good resistance to atomic oxygen erosion. Both are mature technologies with extensive experience and standards from use on aircraft.

CONTACTS:

- James McCoy
- Marino Dobrowolny
- Joseph Kolecki
- Paul Siemers

REFERENCES:

Applications of Tethers in Space, Vol. 1, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 1-17 through 1-30, 3-49 through 3-65, 4-11 through 4-22)

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James E. McCoy, "PMG Reference System Designs for Power & Propulsion," abstract.

-- ELECTRODYNAMICS --

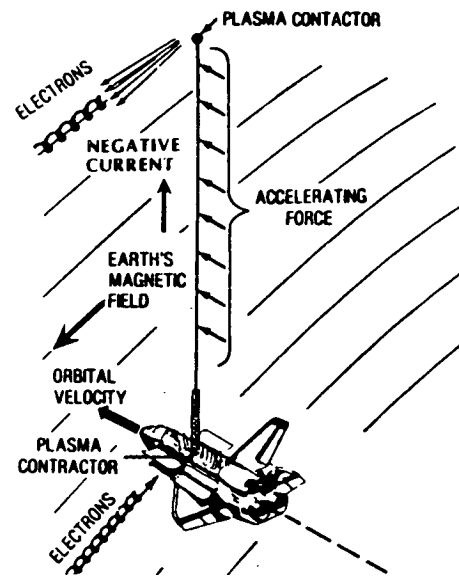
Electrodynamic Thrust Generation

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/Teflon
- 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 $IL \times B$ 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.

The Plasma Motor/Generator (PMG) configuration, previously discussed in the Electrodynamic Power Generation application, appears to be the most suitable design currently available for electrodynamic thrusters. Although projections of their performance have not yet been confirmed by flight testing, their projected high current capacity and ease of current reversibility make them good candidates for electrodynamic thruster systems. However, if flight tests show that the PMG design is not feasible, one or both of the other two system configurations discussed previously would be alternatives. Moreover, there may be specific missions which would be best served by the characteristics of one of these two alternative configurations.

Calculations have been made of the thruster performance available from the four PMG reference systems described previously. The 2 kW, 20 kW, 200 kW, Megawatt PMG systems have nominal thrust ratings of 0.25 N, 2.5 N, 25 N, and 125 N, respectively. When operated at their peak powers, the 20 kW, 200 kW, and 1 MW PMG's operate at 125 kW, 500 kW, and greater than 2 MW, producing thrusts of greater than 40 N, 100 N, and 400 N, respectively.

A major application of electromagnetic propulsion would be orbital maneuvering. A 2,000 kg PMG system, using a 20 km tether of #2 AWG aluminum wire, has been calculated to produce 10 N of thrust from an 80 kW power supply. Continuous application of this thrust could produce altitude changes of 7, 30, and 150 km/day for the Space Station (200,000 kg), a space platform (50,000 kg), and a free-flyer (10,000 kg), respectively. A PMG the size of the Megawatt Reference System could produce 200 N of thrust from a 1.6 MW power supply.

Recommendations were made at the Venice Tether Workshop (October 1985) to use electrodynamic tethers in the 1-20 kW range to provide drag compensation and orbital maneuvering capability for the Space Station, other solar array powered satellites, and the power extension package (PEP), 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 multiple parallel tethers instead of long single tethers
- 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:

- James McCoy
- Marino Dobrowolny
- Joseph Kolecki
- Paul Siemers

REFERENCES:

Applications of Tethers in Space, Vol. 1, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 1-17 through 1-30, 3-49 through 3-65, 4-11 through 4-22)

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G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985. (pp. 44-50)

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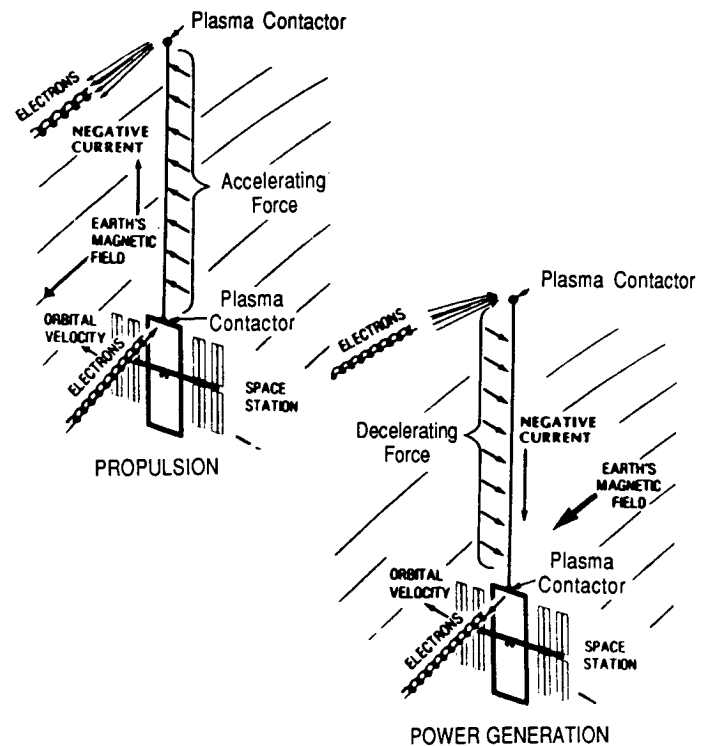
James E. McCoy, "PMG Reference System Designs for Power & Propulsion," abstract.

Application "Electrodynamic Power Generation"

-- ELECTRODYNAMICS --**Electromagnetic Motor/Generator for Power Storage**

APPLICATION: Reduction in battery use for energy storage by generating thrust during the daytime and DC electricity at night with a reversible conducting tether system.

DESCRIPTION: An insulated conducting tether connected to a spacecraft equipped with a solar array. Plasma contactors are used at both tether ends. During illumination, current from the solar array is fed into the tether against the emf induced in it by the geomagnetic field, producing a propulsive force on the spacecraft/tether system. During periods of darkness, DC electrical current (induced in the tether by the geomagnetic field) is tapped for on-board use. This system stores some of the electrical energy, generated by the solar array during illumination, as orbital mechanical energy, and converts it back from orbital to electrical energy when the array is in darkness.

**CHARACTERISTICS:**

- | | | | |
|-----------------------------|--|---|----------|
| • Thrust Produced: | 7.5 N | • Reduction In Solar Array Size: | 10% |
| • Power Required: | 60 kW | • Reduction in Heat Rejection: | 60% |
| • Power Generated: | 100 kW | • Potential for Technology Demonstration: | Mid-Term |
| • Length: | 10 km | | |
| • Mass: | 2,000 kg | | |
| • Efficiency: | ~80% (Full Cycle) | | |
| • System Weight Comparison: | 40% of Conventional Array with Batteries | | |

CRITICAL ISSUES:

- The same as listed in Application "Electrodynamic Power Generation"

STATUS:

- The same as listed in Application "Electrodynamic Power Generation"

DISCUSSION: A propulsive force of $IL \times B$ is generated on the spacecraft/tether system when current from the on-board solar array power system is fed into the tether against the emf induced in it by the geomagnetic field. This thrust boosts the orbital altitude during array illumination. During periods of darkness, the orbital altitude is reduced as the geomagnetic field induces a voltage in the tether (proportional to its length and derived from the $v \times B$ electric field and its force on charges in the tether), providing useful DC electrical power.

Such a reversible energy storage system has a higher theoretical efficiency than a system employing the charging and discharging of batteries. A system comprised of a 100 kW solar array and a 2,000 kg reversible Plasma Motor/Generator (PMG) tether system could produce thrust from 60 kW during the

day, and 100 kW of electrical power during the night. This system would have 40% of the weight of a conventional array with batteries. It would also provide a reduction of 10% in array size, and 60% in power-processing heat rejection.

At the Venice Tether Workshop (October 1985), high-power tethers (up to about 1 MW) were recommended for a Space Station power storage system. This concept could also be applied to any other spacecraft using a solar array power system.

CONTACTS:

- James McCoy

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 161-184, 369-377)

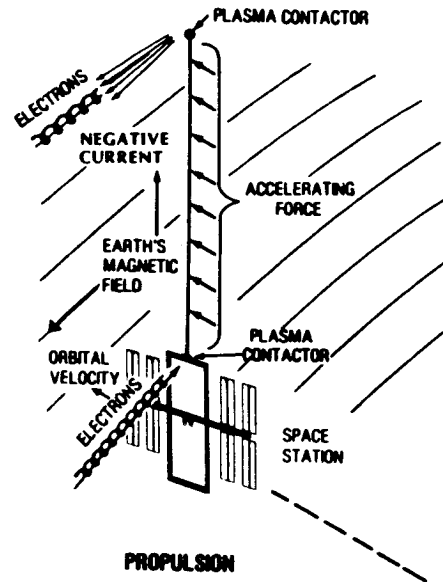
Applications "Electrodynamic Power Generation" and "Electrodynamic Thrust Generation"

-- ELECTRODYNAMICS --

Electromagnetic Thruster to Offset Drag

APPLICATION: Generation of sufficient electromagnetic thrust to offset the orbital drag of a spacecraft.

DESCRIPTION: An insulated conducting tether connected to a spacecraft and powered by an on-board solar array. Plasma contactors are used at both tether ends. During illumination, current from the solar array is fed into the tether against the emf induced in it by the geomagnetic field, producing a propulsive force on the spacecraft/tether system. This force, sufficient to offset the orbital drag, is generated at the expense of on-board electrical power from the solar array power system.



CHARACTERISTICS:

- | | | | |
|--------------------|------------|-----------------|-----------------|
| • Thrust Produced: | 0.1-2 N | • Fuel Savings: | >1,000 kg/yr |
| • Power Required: | 0.8-15 kW | • per kW | |
| • Length: | 10 km | • Materials: | Aluminum/Teflon |
| • Mass: | 100-200 kg | • Potential for | |
| • Efficiency: | ~90% | Technology | |
| | | Demonstration: | Mid-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

STATUS:

- TSS-1, demonstrating electrodynamic applications, is scheduled for a 1991 launch

DISCUSSION: A propulsive force of $IL \times B$ is generated on the spacecraft/tether system when current from the on-board solar array power system is fed into the tether against the emf induced in it by the geomagnetic field. A thrust sufficient to offset orbital drag can be generated by a small tether system. The advantage of such an arrangement is the savings in fuel no longer required to keep the spacecraft in orbit. The savings is especially significant for low Earth orbits and large spacecraft with high drag. A kilowatt of power thusly used is roughly equivalent to a ton per year of fuel expended for orbit maintenance. A 100 kg Plasma Motor/Generator (PMG) system, producing 0.1 N thrust from 0.8 kW, is calculated to save >1,000 kg/yr of fuel and keep a 100 kW solar array at the Space Station Altitude. A 200 kg PMG system, using 10-15 kW of electrical power, is calculated to produce 1-2 N of thrust -- enough to keep the Space Station and a 100 kW solar array in an orbit less than 300 km in altitude, using less than 60 kg/yr of argon for the hollow cathodes.

As recommended at the Venice Tether Workshop (October 1985), such a system could be applied to the Space Station, other solar array powered satellites, and the power extension package (PEP), which could then be left in LEO between successive Shuttle flights.

CONTACTS:

- James McCoy
- Neal Hulkower

REFERENCES:

Applications of Tethers in Space, Vol. 1, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 1-17 through 1-30, 3-49 through 3-65, 4-11 through 4-22)

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Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 161-184, 369-377)

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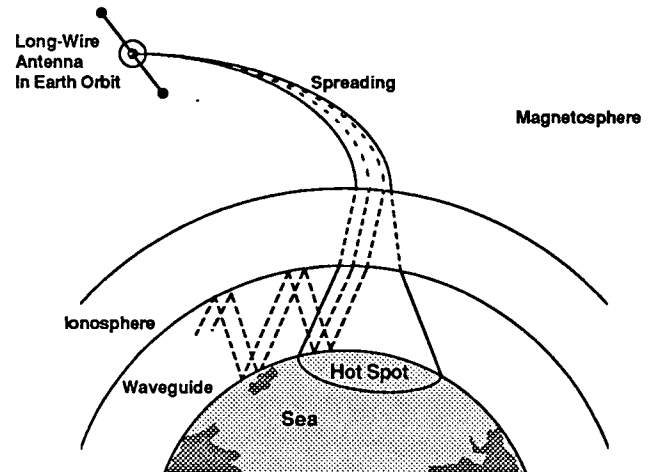
Hulkower, N. D., Rusch, R. J., "Plasma Motor Generator Tether System for Orbit Reboost," Int. Conf. 1987.

Application "Electrodynamic Thrust Generation"

-- 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 Alfvén 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, demonstrating electrodynamic applications, is scheduled for a 1991 launch

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:

- Joseph Kolecki
- Marino Dobrowolny
- Charles C. Rupp
- Mario Grossi
- Giorgio Tacconi

REFERENCES:

Applications of Tethers in Space, Vol. 1, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 4-11 through 4-22)

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

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

-- PLANETARY --

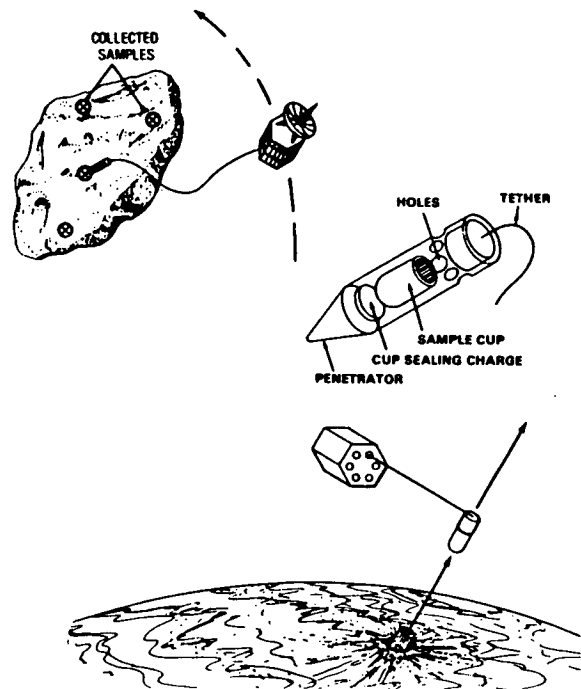
Comet/Asteroid Sample Return

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:

- Although preliminary definition of the mission and hardware has been performed, detailed study and design remain to be done

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 surface 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.

CONTACTS:

- Paul Penzo

REFERENCES:

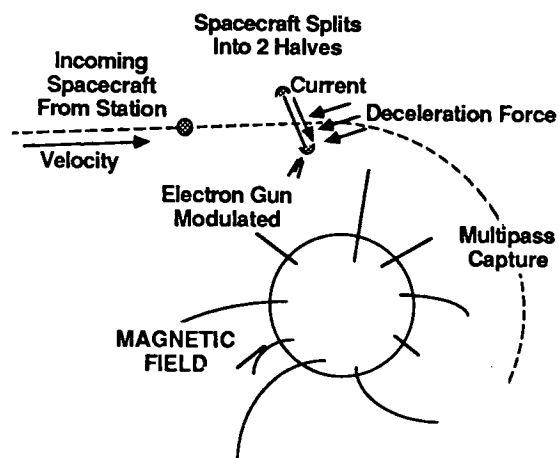
Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 127-151)

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

-- PLANETARY --**Electromagnetic Deceleration for Planetary Capture**

APPLICATION: Generation of a decelerating force on a spacecraft to allow planetary capture.

DESCRIPTION: A spacecraft constructed as two halves connected by an insulated conducting tether. Plasma contactors are used at both tether ends. Upon entering the magnetosphere of a planet with a strong magnetic field, the halves separate and deploy the tether, which conducts a large current between them. This produces a decelerating force on the spacecraft, slowing it for planetary capture. Upon capture, the halves rejoin for orbital operations.

**CHARACTERISTICS:**

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

CRITICAL ISSUES:

- Further study is required to determine if sufficient braking thrust can be generated to allow capture during one encounter

STATUS:

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

DISCUSSION: Such a system has the advantage of a lower weight than the rockets and fuel required for braking. However, if the tether cannot produce all of the required deceleration, assistance would be required from another propulsion source. This system would also require a lower insertion accuracy than an aerobraking process. If the system uses a modulative electron gun, super-power radio transmission would be available during capture. The energy from braking could be dissipated as heat in the plasma or tether, as well as being radiated as RF waves. The major disadvantage is that such a system would only be applicable to the outer planets with magnetic fields. This technology may provide a valuable tool for the exploration of these planets.

CONTACTS:

- Nobie Stone
- Richard Taylor

REFERENCES:

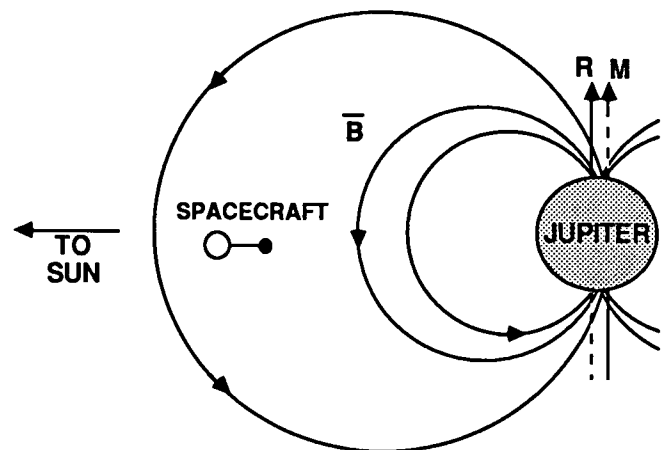
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Applications of Tethers in Space, Vol. 2, Workshop Proceedings, Williamsburg, Virginia, June 15-17, 1983, NASA CP-2365, March 1985. (pp. 5-11 through 5-29)

-- 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
- Steve Gabriel

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 127-151, 161-184, 369-377)

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

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

-- PLANETARY --

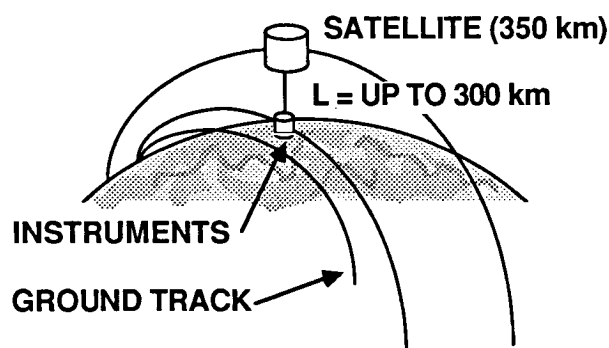
Mars Tethered Aeronomy Observer

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 | • Potential For Technology Demonstration: Mid-Term |
| • Instrument Altitude: | Down to 90 km | |



CRITICAL ISSUES:

- Tether material (graphite is a potential candidate)

STATUS:

- System performance analysis for various altitudes of the probe performed by the Smithsonian Astrophysical Observatory

DISCUSSION: The Mars Aeronomy Observer (MAO) is included in NASA's Solar System Exploration Committee (SSEC) core program, and is planned to be launched in 1994 or 1996. This application of tether technology would serve to enhance the presently planned observer. 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. 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:

- Paul Penzo
- Enrico Lorenzini

REFERENCES:

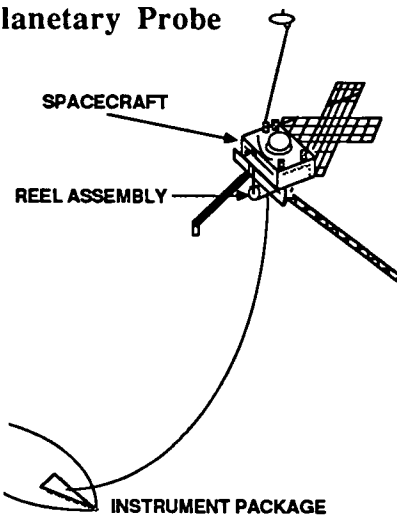
Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 127-151)

Lorenzini, E.C., MD, Grossi, and M. Cosmo, " Low Altitude Tethered Mars Probe," Proceedings of the 39th Congress of the International Astronautical Federation, Oct. 8-15, 1988, Bangalore, India. Also to appear in *Acta Astronautica*.

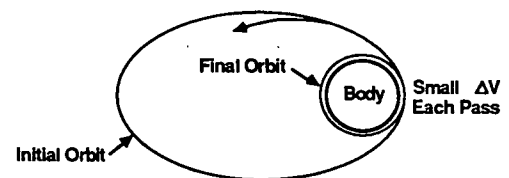
-- PLANETARY --**Multipass Aerobraking of Planetary Probe**

APPLICATION: Effecting propellant savings through gradual orbit contraction by means of the drag of a lightweight tether.

DESCRIPTION: A small diameter tether is deployed to the local vertical from a probe in a highly elliptical orbit about a planet possessing an atmosphere. At each successive periapsis pass the lower most region of the tether experiences rarefied flow, thus creating drag on the probe-tether system and gradually reducing the orbit's apoapsis. An instrument package at the tether tip could enhance mission science by taking data during the atmospheric passes.

**CHARACTERISTICS:**

- Tether Length: 100-300 km
- Tether Diameter: ~2 mm
- Tether System: Single reversible reel/brake
- Spacecraft: Conventionally designed for the space environment
- Potential For Technology Demonstration: Mid-Term

**CRITICAL ISSUES:**

- Possible severance due to prolonged exposure to micrometeoroid hazard
- Tether stability and control during aerobraking passes in highly elliptical orbits

STATUS:

- Preliminary study of the shapes, tensions, and drag of a flexible, massive tether in static, circular aerobraking have been performed
- Further study is required to determine open and closed-loop dynamical behavior of such a tether during aerobraking from highly elliptical orbits
- TSS-2 will demonstrate the behavior of a tether subjected to aerodynamic forces

DISCUSSION: Conventional planetary probes carry substantial propellant to establish low orbits about a body of interest. An alternative method uses only enough propellant to achieve a highly elliptical "capture" orbit. The spacecraft, now modified to avoid contamination and protected by a large circular shield, then effects a gradual reduction in the height of apoapsis through successive, drag-producing passes in rarefied flow at periapsis. This method requires the following: (1) A large, heat-resistant shield (or "aerobrake") in front of the spacecraft; (2) an unconventional spacecraft design protected from flow effects in the aerobrake's wake; (3) careful adjustment of the angle-of-attack during each atmospheric pass; and (4) orbit trim maneuvers at apoapsis to insure proper altitude at periapsis.

The tether approach would allow a conventional, unprotected spacecraft to use a bare tether to circularize an elliptical orbit in times comparable to those of a typical hard-shield aerobrake. The creation of the necessary drag could be shared between the lowest portion of tether equivalent in length to one or

two atmospheric scale heights and a suspended body at the tether tip. In addition, this end mass could give added control. Varying the tether length allows adjustment of the total drag on the spacecraft-tether system in order to account for unforeseen atmospheric variations and navigation uncertainties encountered during previous atmospheric passes.

CONTACTS:

- J.W. Flower
- Paul Penzo
- Silvio Bergamaschi

REFERENCES:

Flower, J. W., "Space Tethers: Comments on Their Scope and on the Possibility of Their Use with Aerodynamic Forces," Int. Conf. 1987.

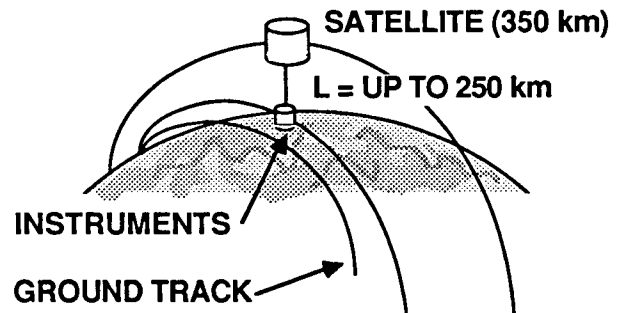
-- PLANETARY --**Tethered Lunar Satellite for Remote Sensing**

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:

- Instrument Length: 250 km
- Instrument Altitude: 50 km
- Satellite Altitude: 300 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:

- No detailed study on this application has been performed

DISCUSSION: Due to Sun and Earth perturbations, close lunar satellites would be unstable and short lived (perhaps a few months). However, as proposed by Guiseppe 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 such things as the Moon's magnetic field and gravitational anomalies could be made.

CONTACTS:

- Paul Penzo

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 127-151)

-- SCIENCE --**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

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

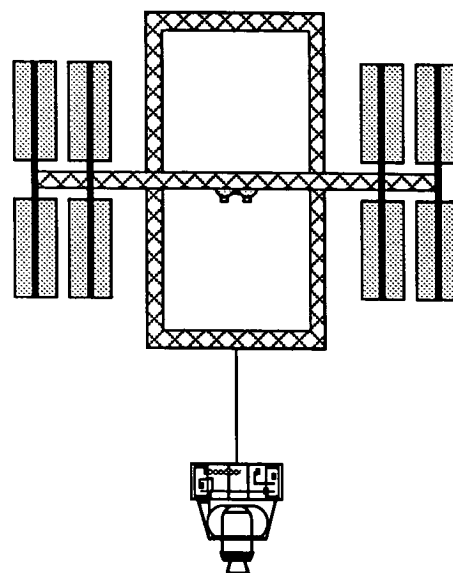
STATUS:

- 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
- Alberto Loria
- James K. Harrison
- James Walker



- Potential For Technology Demonstration: Mid-Term

REFERENCES:

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986.

F. Bevilacqua, P. Merlina, and A. Anselmi, "The Science and Applications Tethered Platform (SATP) Project," Aeritalia Space Systems Group, Torino, Italy, Tether Applications in Space Workshop, Venice, Italy, October 15-17, 1985.

J. Laue and F. Manarini, "The Tethered Retrievable Platform Concept and Utilization," #IAF-82-13, 33rd IAF Congress, Paris, France, September-October 1982.

S. Vetrella and A. Moccia, "A Tethered Satellite System as a New Remote Sensing Platform," University of Naples, Italy, Undated.

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.

Selected Tether Applications in Space, Phase III," NASA Contract NAS8-36617.

Walker, J. D., "Tether Applications Scenarios for Space Station/Platforms Systems," Int. Conf. 1987.

-- SCIENCE --

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: Undetermined
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Dynamic noise induced on tether
- Micrometeoroid damage

STATUS:

- Various investigators (listed below) have examined preliminary concepts

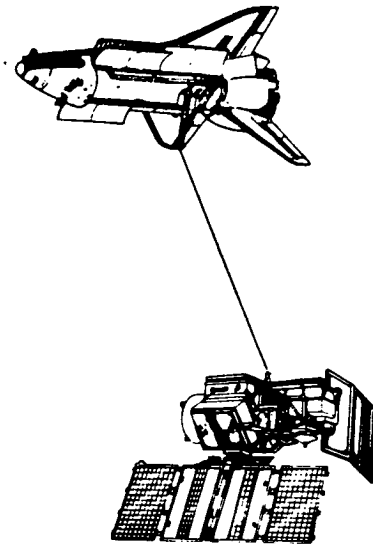
DISCUSSION: Possible uses for a remote platform include stereoscopic sensing, magnetometry, atmosphere science experiments, and chemical release experiments.

CONTACTS:

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

REFERENCES:

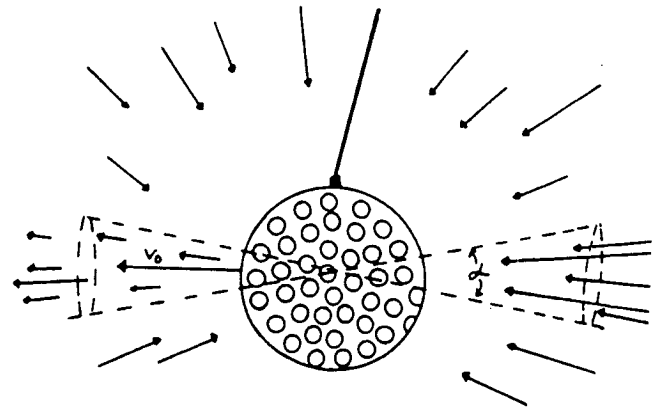
Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986.



-- SCIENCE --**Tethered Satellite for Cosmic Dust Collection**

APPLICATION: To collect micrometeoritic 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 over collectors

- 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 survive 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, α is approximately 22 degrees.

CONTACTS:

- George J. Corso

REFERENCES:

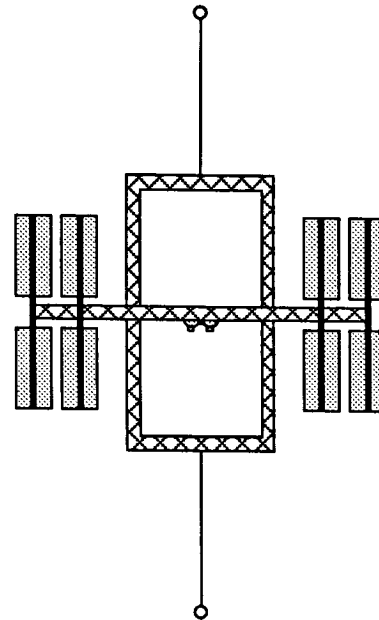
- G.J. Corso, "A Proposal to Use an Upper Atmosphere Satellite Tethered to the Space Shuttle for the Collection of Micro-meteoritic Material," Journal of the British Interplanetary Society, Vol. 36, pp. 403-408, 1983.

-- 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: Undetermined

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)
- MSFC study for definition of the Microgravity Materials Processing Facility (MMPF) for the Space Station
- The Small Expendable Deployer System (SEDS) mission (scheduled for a 1992 launch) may provide measurements of the acceleration field change and associated noise throughout the Shuttle, during tether and payload deployment
- TSS-1 will demonstrate and analyze the acceleration field and associated noise during all phases of tether operations

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:

- Kenneth Kroll
- Franco Bevilacqua

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 223-238)

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 53-77, 97, 137-147)

G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985. (pp. 64-66, 70-75, 78-80)

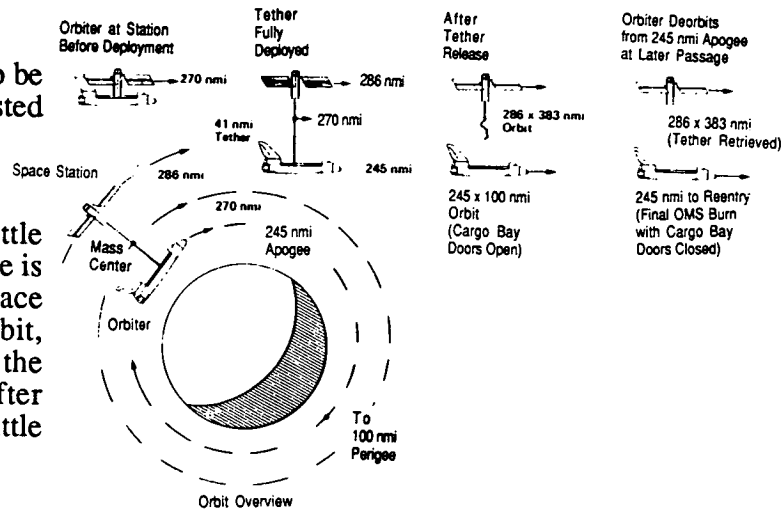
K. Kroll, Presentation Package for the NASA Tether Working Group Meeting at Marshall Space Flight Center, February 1986.

-- 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: Far-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

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
- Bill Woodis

REFERENCES:

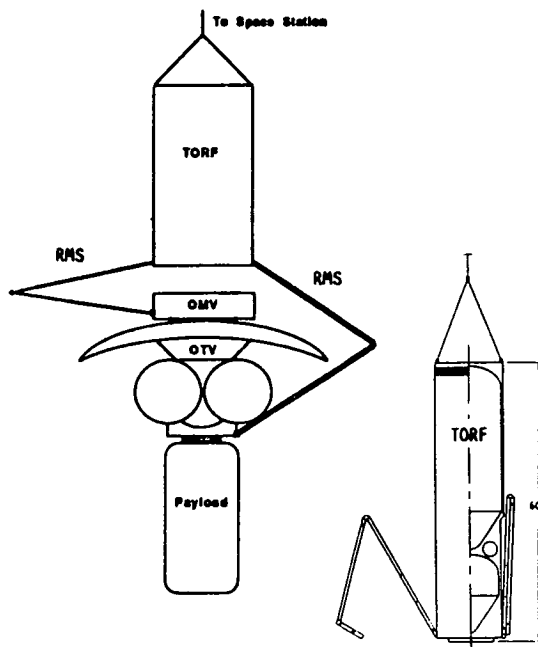
- Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 185-220, 239-268, 401-412)
- G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985.
- G. Von Tiesenhausen, ed., Tether Applications Concept Sheets, June 28, 1984.

-- SPACE STATION --

Tethered Orbital Refueling Facility

APPLICATION: Utilization of artificial gravity to assist in the transfer of liquid propellants to and from a tethered storage and refueling platform.

DESCRIPTION: A platform (depot) with liquid propellant storage tanks and remote manipulators, tethered a short distance above or below the Space Station. The gravity gradient between the Space Station and the depot produces a tension in the tether, resulting in an equal and opposite artificial-gravity force throughout the depot. The artificial gravity allows fluid settling in the tanks (liquid settles over an outlet and gas over a vent), facilitating propellant handling. The depot can be refilled by the Shuttle, providing a long-term remote refueling capability.



CHARACTERISTICS:

- Propellants: Cryogenic and Storable
- Tether Length: 1 km (Cryogens)
- Fuel Capacity: 100,000 lbs (Cryogens)
- Potential For Technology Demonstration: Far-Term

CRITICAL ISSUES:

- Design of the vapor return line to assure that it will not be blocked by trapped liquids during transfer
- Design of tank baffling to prevent the inflow jet from covering the gas vent with liquid while also controlling liquid slosh
- Prevention of propellant contamination of sensitive Space Station surfaces
- Evaluation of the overall impacts to the Space Station
- Evaluation of the tether system's cost effectiveness
- Determination of human access and control requirements

STATUS:

- The TORF is the first design proposed for a tethered STV refueling facility - it is now considered too small for currently projected requirements and has been superseded by the Tethered STV Hangar/Depot; however, the TORF design may prove to be useful in the future for other types of refueling
- The final report for the current JSC Tethered Orbital Refueling Study (including a cost/benefits comparison of tether and zero-g refueling systems) completed in June 1986
- The main emphasis is on cryogenic propellants
- Detailed design of the propellant depot has not been performed
- The Spinning Shuttle Experiment is the planned demonstration for this concept

DISCUSSION: In this stable vertical system, the level of artificial gravity at the Tethered Orbital Facility (TORF) is proportional to the tether length between the center of mass of the entire Space

Station/TORF system and the TORF. To determine the minimum gravity level (and tether length) required to overcome surface tension and allow fluid settling, a nondimensional number, the bond number (Bo), can be calculated for each liquid propellant. It is a fluid settling parameter, equal to the product of the fluid density, acceleration, and square of the tank diameter, divided by 4 times the fluid surface tension coefficient. (Although a fluid will settle if $Bo \geq 10$, a value of $Bo = 50$ is used to be conservative.) Using this value, the minimum required tether length has been calculated for each of the following propellants: 32.3 m for oxygen; 71.3 m for hydrogen; 342.0 m for nitrogen tetroxide; 719.0 m for monomethylhydrazine; and 1235.0 m for hydrazine. (Assuming that cryogenic propellants use a tank diameter of 4.2 m to fit in the Shuttle cargo bay, and storable propellants use a tank diameter of 1.7 m to fit side-by-side in the Shuttle bay.) Fluid slosh, from single and multiple disturbances, would be controlled by using tethers of at least 1 km in length, and by using tanks with a conical bottom and ring-type internal baffle.

Fluid settling would allow the use of a vapor return line from the receiver tank to the supply tank. This would permit receiver tank venting without dumping the gas overboard (where it would pose a contamination hazard), eliminate the need to resupply pressurant for the liquid transfer, and provide an equalizing supply tank pressure. Due to the availability of extra gas and limited pressure at a pump, a compressor in the vapor return line has been recommended to transfer cryogenic propellants. Due to the opposite conditions, a pump in the liquid transfer line has been recommended to transfer storable propellants. The gravity feed method could be used as a backup for either; however, it would be considerably slower. Calculations have also shown that a tether long enough for settling would overcome the acceleration due to the initial fluid transfer impulse.

The TORF would separate hazardous liquid storage and transfer from the Space Station; thus reducing the hazards related to propellant contamination, tank explosion, and spacecraft docking. Remote manipulators would provide remote maneuvering of the spacecraft during refueling, and the tether could be released if a catastrophic problem were imminent. (The fluid settling technique could also be applied to liquids other than propellants, if desired). A possible disadvantage of the TORF would be the vertical shift in the center of gravity to a point off of the Space Station, produced unless another tethered system balanced the TORF. Currently, an intermittent deployment is preferred because it would minimize the impact to microgravity experiments, and require no sustained counterbalancing.

The latest cryogenic propellant depot design would hold 100,000 lbs of fuel (equal to two Centaur loads), and could be launched in a single Shuttle flight. Auxiliary propulsion would be needed to overcome the drag produced by atmospheric drag, and spacecraft berthing. For continuous drag make-up, using only H₂ boiloff in cold gas thrusters, a specific impulse of 200 s would be adequate for TORF auxiliary propulsion (570 s for both the TORF and the Space Station).

CONTACTS:

- Kenneth Kroll

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 223-238)

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 89-123)

G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985. (pp. 64-72, 78-80)

-- SPACE STATION --**Tethered STV Hangar/Depot**

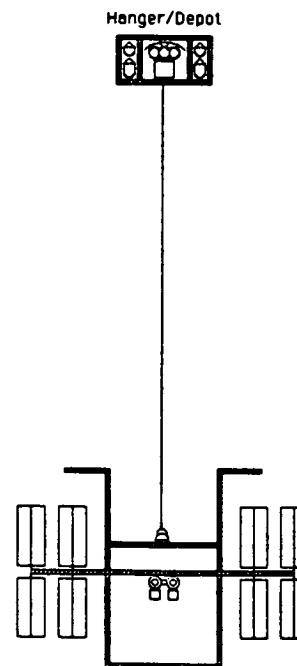
APPLICATION: Provide an STV facility for the Space Station, combining a hangar with a propellant depot which utilizes artificial gravity to assist in liquid propellant transfers.

DESCRIPTION: A combined STV hangar/depot facility with liquid propellant storage tanks and remote manipulators, tethered a short distance above or below the Space Station. The gravity gradient between the Space Station and this facility produces a tension in the tether resulting in an equal and opposite artificial-gravity force throughout the facility. The artificial gravity allows fluid settling in the tanks, facilitating propellant handling. The tanks can be refilled by the Shuttle, providing a long-term remote STV refueling capability.

CHARACTERISTICS:

- Propellants: Cryogenic and Storable
- Tether Length: 1 km (Cryogens)
- Fuel Capacity: 100,000 lbs (Cryogens)

- Potential For Technology Demonstration: Far-Term

**CRITICAL ISSUES:**

- Design of the vapor return line to assure that it will not be blocked by trapped liquids during transfer
- Design of tank baffling to prevent the inflow jet from covering the gas vent with liquid, while also controlling liquid slosh
- Prevention of propellant contamination of sensitive Space Station surfaces
- Evaluation of the overall impacts to the Space Station
- Evaluation of the tether system's cost effectiveness
- Determination of human access and control requirements

STATUS:

- This is the latest design for a tethered STV hangar/refueling facility on the Space Station
- The main emphasis is currently on cryogenic propellants
- The final report for the current JSC Tethered Orbital Refueling Study (including a cost/benefits comparison of tether and zero-g refueling systems) completed in June 1986
- Detailed design of the hangar/propellant depot and STV remains to be done
- The Spinning Shuttle Experiment is the planned demonstration for this concept

DISCUSSION: Current planning has determined a preferred STV design requiring twice the depot propellant quantities provided by the "Tethered Orbital Refueling Facility". (Detailed descriptions of liquid propellant settling and transfer are presented in that application). It has also been determined that basing an STV on the Space Station would require the addition of a large hangar, significantly shifting the

Space Station center of gravity laterally. These problems could be overcome by combining a hangar with two tethered propellant depots, of the type described in Application "Tethered Orbital Refueling Facility". Such a hangar/depot facility would eliminate the need to ferry the STV and its attached payload from the Space Station to a tethered depot for refueling, simplify STV refueling, and would allow the attachment of another tether to the bottom of the facility. It could also service other spacecraft as desired. A possible disadvantage would be the vertical shift in the center of gravity to a point off of the Space Station, produced unless another tethered system balanced this facility. Currently, an intermittent deployment is preferred because it would minimize the impact to microgravity experiments, and require no sustained counterbalancing. The STV could be launched from the deployed depot, minimizing its effects on the Space Station.

CONTACTS:

- Kenneth Kroll

REFERENCES:

Applications of Tethers in Space, Volume 1, Workshop Proceedings, Venice, Italy, 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. (pp. 64-72, 78-80)

K. Kroll, Presentation Package for the NASA Tether Working Group Meeting at Marshall Space Flight Center, February 1986.

Application "Tethered Orbital Refueling Facility"

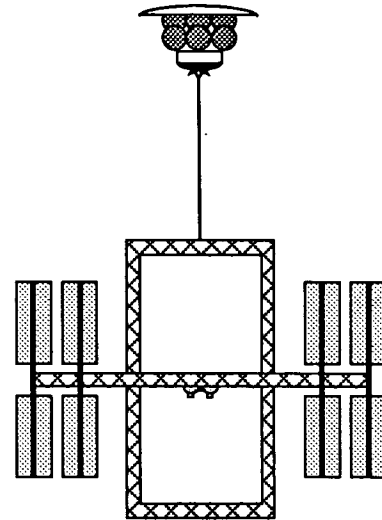
-- SPACE STATION --**Tethered STV Launch**

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
- Bill Woodis

REFERENCES:

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 185-220, 239-268, 401-412)

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

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

Application "Shuttle Deorbit From Space Station"

-- SPACE STATION --**Tethered Space Elevator**

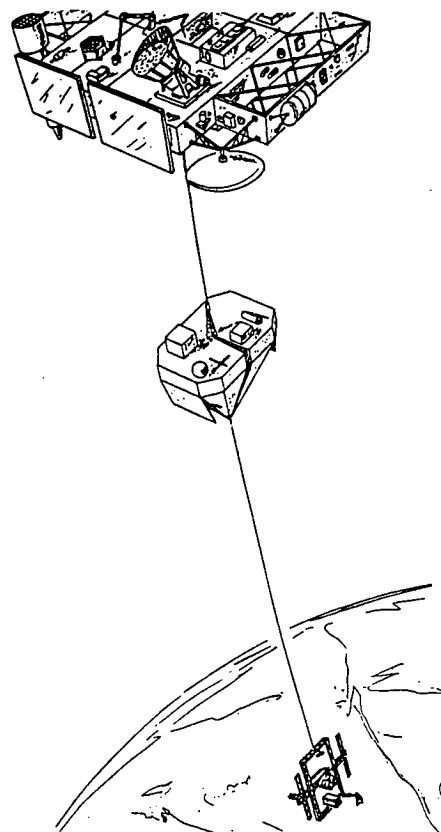
APPLICATION: The Space Elevator may be used as a Space Station facility to tap different levels of residual gravity, and a transportation facility to easily access tethered platforms.

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
- Alberto Loria

REFERENCES:

Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 413-456)

F. Bevilacqua, P. Merlina, and A. Anselmi, "The Science and Applications Tethered Platform (SATP) Project," Aeritalia Space Systems Group, Torino, Italy, Tether Applications in Space Workshop, Venice, Italy, October 15-17, 1985.

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

F. Bevilacqua, P. Merlina, and S. Ciardo, Aeritalia Space Systems Group, "Tethered Space Elevator: Possible Applications and Demonstrative Experiments," 38th I.A.F. Congress, Brighton, UK, IAF-87-049, 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: No.1, July 1985; No.2, October 1985; No.3, February 1986; and No.4, March 1986.

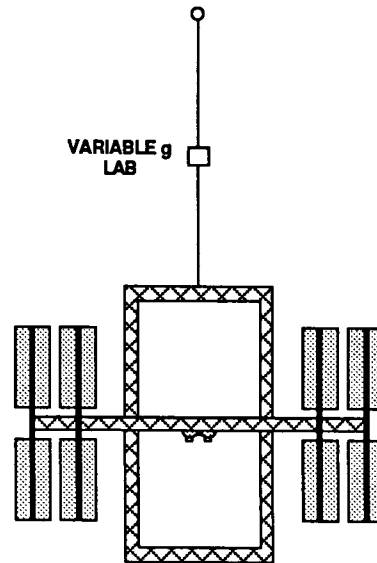
Lorenzini, E.C., "A Three-Mass Tethered System for Micro-g/Variable-g Applications," Journal of Guidance, Control, and Dynamics, Vol. 10, No.3, May-June 1987. (pp. 242-249)

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

-- 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: | Undetermined | • Potential For | |
| • g-Level: | Up to 10^{-1} | 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 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) will begin this year (procurement beginning in March, and the study in September)
- An MSFC study for definition of the Microgravity Materials Processing Facility (MMPF) for the Space Station is in progress
- The Small Expendable Deployer System (SEDS) mission (scheduled for a 1992 launch) may provide measurements of the acceleration field change and associated noise throughout the Shuttle, during tether and payload deployment
- The Spinning Shuttle Mission should provide initial investigations of controlled-gravity and threshold phenomena in the 10^{-1} g to 10^{-4} range
- TSS-1 will demonstrate and analyze the acceleration field and associated noise, during all phases of tether operations

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:

- Kenneth Kroll
- Paul Penzo
- Franco Bevilacqua

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Bevilacqua, F., Ciardo, S., and Loria, A., "Space Station Gravity Gradient Stabilization by Tethers," Int. Conf. 1987.

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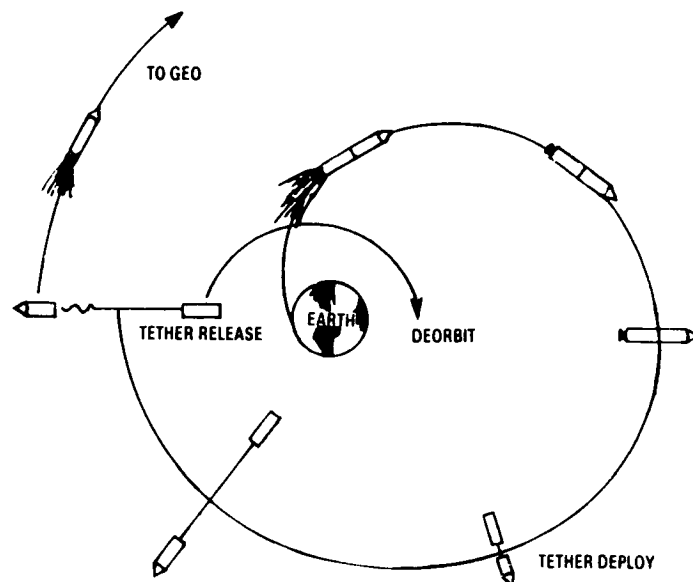
-- TRANSPORTATION --**Generalized Momentum Scavenging from Spent Stages**

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: | Undetermined |
| • 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 and Michoud
- No further analysis in process

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:

- James Walker
- Manuel Martinez-Sanchez
- Joe Carroll

REFERENCES:

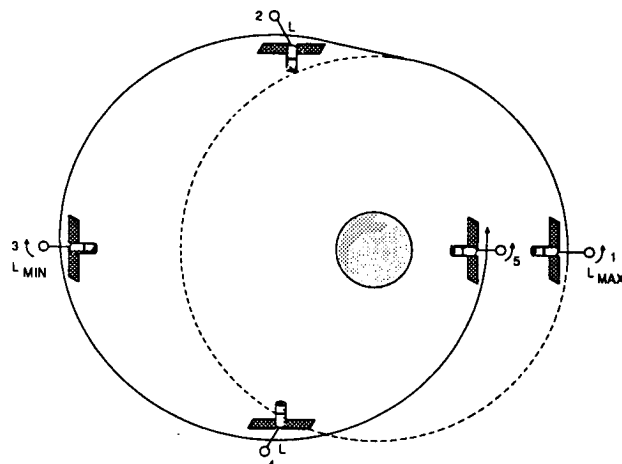
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- M. Martinez-Sanchez and S.A. Gavit, "Four Classes of Transportation Applications Using Space Tethers," Space Systems Laboratory, Massachusetts Institute of Technology in Contract with Martin Marietta, March 1984.
- M. Martinez-Sanchez, "The Use of 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, Vol. II, March 1982.

-- TRANSPORTATION --

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:

- James Walker
- Manual Martinez-Sanchez
- Joe Carrol
- John Breakwell

REFERENCES:

- G. Von Tiesenhausen, ed., "The Roles of Tethers on Space Station," NASA TM-86519, Marshall Space Flight Center, October 1985. (pp. 16-17)

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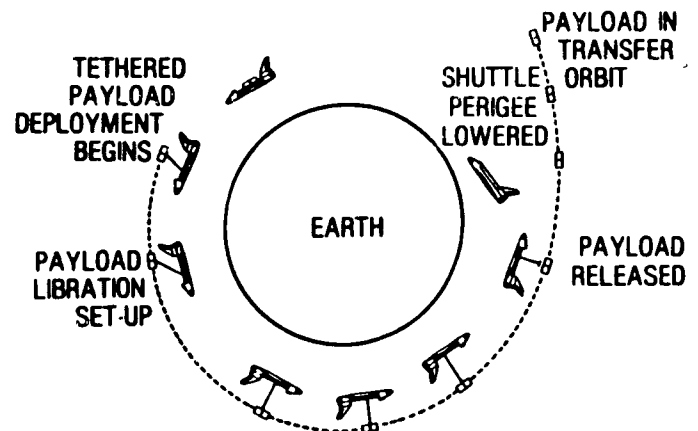
Breakwell, J. V., Gearhart, J. W., "Pumping a Tethered Configuration to Boost its Orbit Around an Oblate Planet," AAS 86-217, Int. Conf. 1986.

-- 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

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
- Manual Martinez-Sanchez

REFERENCES:

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

"Selected Tether Applications in Space, Phase III," NASA Contract NAS8-36617.

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.

-- TRANSPORTATION --**Shuttle Docking by Tether**

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

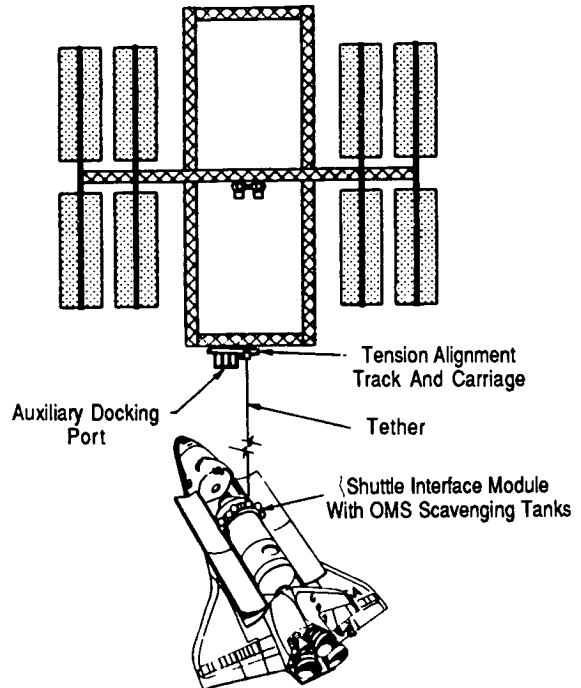
DESCRIPTION: A tether deployed by the Space Station is attached to a docking module. This module would capture and retrieve the Shuttle, allowing a remote rendezvous.

CHARACTERISTICS:

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

CRITICAL ISSUES:

- Accurate guidance system needed (such as GPS) to effect rendezvous
- Rendezvous and capture technique definition required
- Post-rendezvous tether dynamics
- Alignment of tether tension 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
- Bill Woodis

REFERENCES:

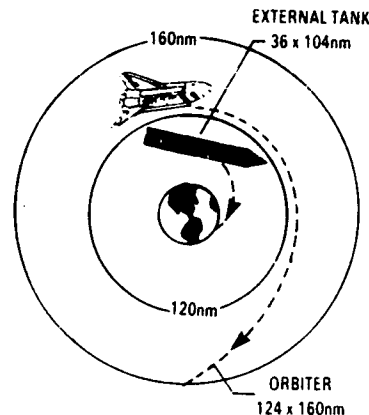
Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986.

"Selected Tether Applications in Space, Phase III," NASA Contract NAS8-36617.

-- TRANSPORTATION --**Shuttle External Tank Deorbit**

APPLICATION: Shuttle Orbiter boost using momentum scavenging of external tank.

DESCRIPTION: The external tank is brought along with the Shuttle into a stable orbit configuration. The tank is deployed downward toward the Earth along a tether. The tether is then severed, boosting the Shuttle into its desired orbit while deboosting the external tank into a nonstable orbit for disposal.

**CHARACTERISTICS:**

- Tether Length: 37 km (20 nmi)
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Shuttle Orbiter impacts
- Integration costs
- Permanent vs. removable system
- Safety/disposal implications
- Attachment point/mechanism of tether

STATUS:

- Studied by MM/Michoud
- Feasibility shown with preliminary design by JSC/EH (Contella)

DISCUSSION: A tethered deployment of the Shuttle external tank would serve several purposes. By transferring momentum from the tank to the Shuttle, less fuel would be required to obtain its desired orbit, hence, payload capacity is increased. Another benefit of a tethered external tank deorbit is the removal of launch azimuth restrictions caused by the external tank flight pattern over water. A third benefit is the increase in time available for the scavenging of cryo propellants from the external tank.

CONTACTS:

- James Walker

REFERENCES:

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

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"Preliminary Feasibility Study of the External Tank (ET) Deorbit by a Tether System," Martin Marietta Memo 83-SES-665, May 24, 1983.

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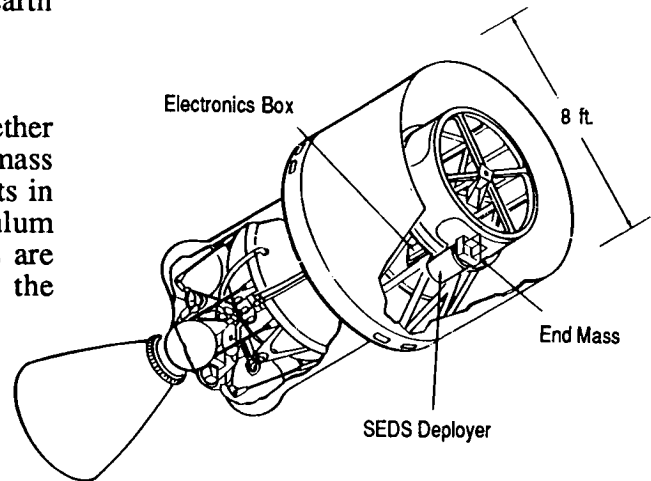
J.A. Carroll, "Tethers and External Tanks: Enhancing the Capabilities of the Space Transportation System," Research and Consulting Services, La Jolla, California, December 20, 1982.

-- TRANSPORTATION --

Small Expendable Deployer System

APPLICATION: To boost a payload from the STS into an orbit higher than the STS can reach. Also to deboost payloads from the Space Station to Earth reentry orbits.

DESCRIPTION: This system uses a simple tether deployer about the size of a basketball. The end mass is deployed under low tether tension. This results in near-horizontal deployment, followed by a pendulum swing to the vertical. The tether and end mass are released simultaneously, allowing reentry into the Earth's atmosphere.



CHARACTERISTICS:

- Tether Length: 20 km
- System Mass: 30 kg
- Tether Diameter: ≥ 0.7 mm
- Potential For Technology Demonstration: Near-Term

CRITICAL ISSUES:

- Tether and payload oscillations during deployment and pendulum swing
- Tether failure followed by recoil
- Tether deployer design and performance
- Overall system reliability

STATUS:

- SBIR Phase II Development Contract with Energy Science Laboratories completed in 1987
- Demonstration Flight hardware development in 1989 for Delta II launch vehicle flight in 1990 or 1991

DISCUSSION: The operation of this system uses spring ejection to initiate end mass deployment. This simplifies the deployer design and eliminates the need for payload thrusters. Discarding the tether eliminates the time and hardware needed to retrieve it. Problems such as tether and end mass oscillations do appear to be controllable. Possible applications for SEDS include boosting small STS payloads and deorbiting small packages from the Space Station back to Earth.

CONTACTS:

- Joe Carroll
- James K. Harrison
- Charles C. Rupp

REFERENCES:

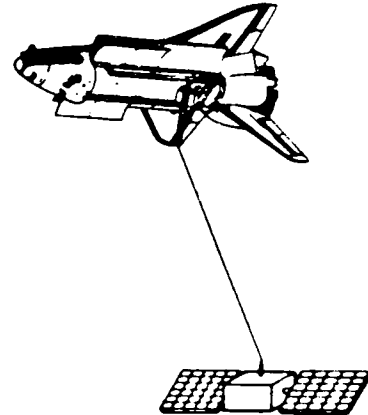
Applications of Tethers in Space, Volume 2, Workshop Proceedings, Venice, Italy, NASA CP-2422, March 1986. (pp. 5-7, 9-30)

-- 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
- Potential flight experiment application for the Tethered Satellite System (TSS)

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:

- James Walker
- Joe Carroll

REFERENCES:

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

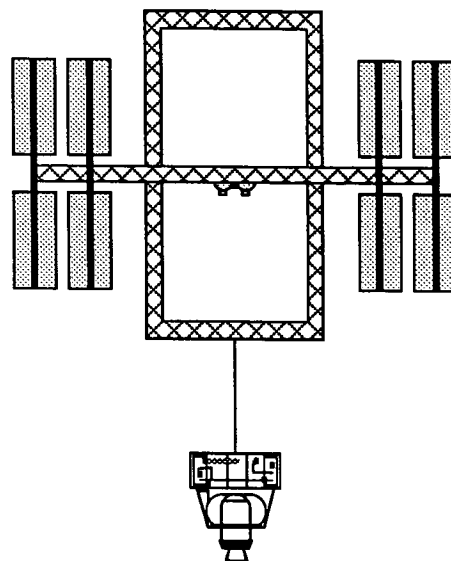
-- TRANSPORTATION --**Tether Rendezvous System**

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
- Dale Stuart
- Franco Bevilacqua

REFERENCES:

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

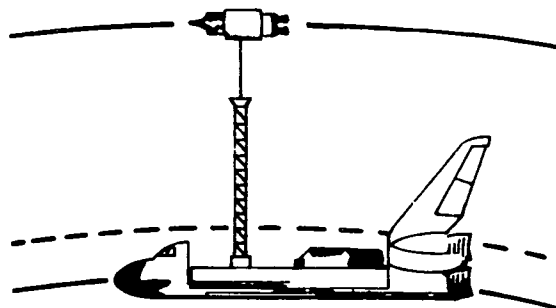
Stuart, D. G., "Guidance and Control for Cooperative Tether-Mediated Orbital Rendezvous," Draper Labs, submitted for publication in Journal of Spacecraft and Rockets, 1988.

-- 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 TSS-derived 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:

- MDAC assessment complete on this study
- Ball Brothers, Selected Tether Applications Study, Phase III

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.

CONTACTS:

- James K. Harrison
- Dan McMann
- Mauro Pecchioli

REFERENCES:

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

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

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

Pecchioli, M., and Graziani, F., "A Thrusted Sling in Space: A Tether-assist Maneuver for Orbit Transfer," Int. Conf. 1987.

SECTION 3.0 TETHER FUNDAMENTALS

**Tether
Fundamentals**

3.1 Gravity Gradient

3.1.1 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 3.1 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 3.2 (see Ref. 1, p. 3-5).

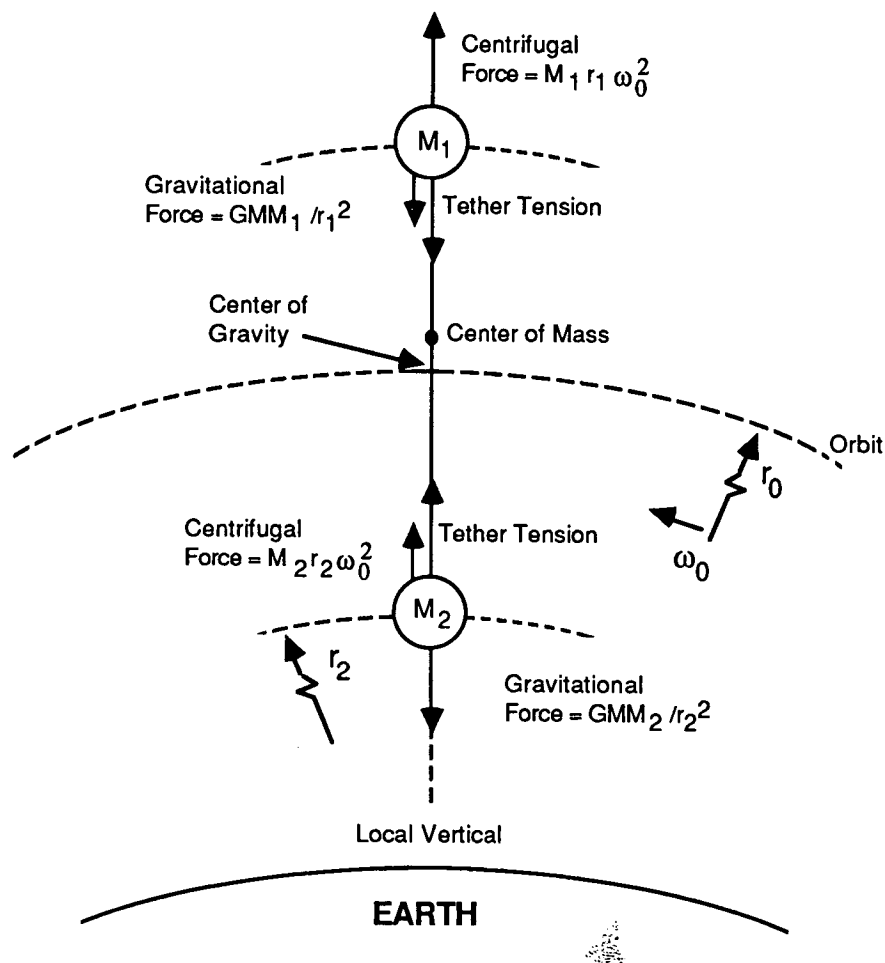


Figure 3.1 Forces on Tethered Satellites

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.

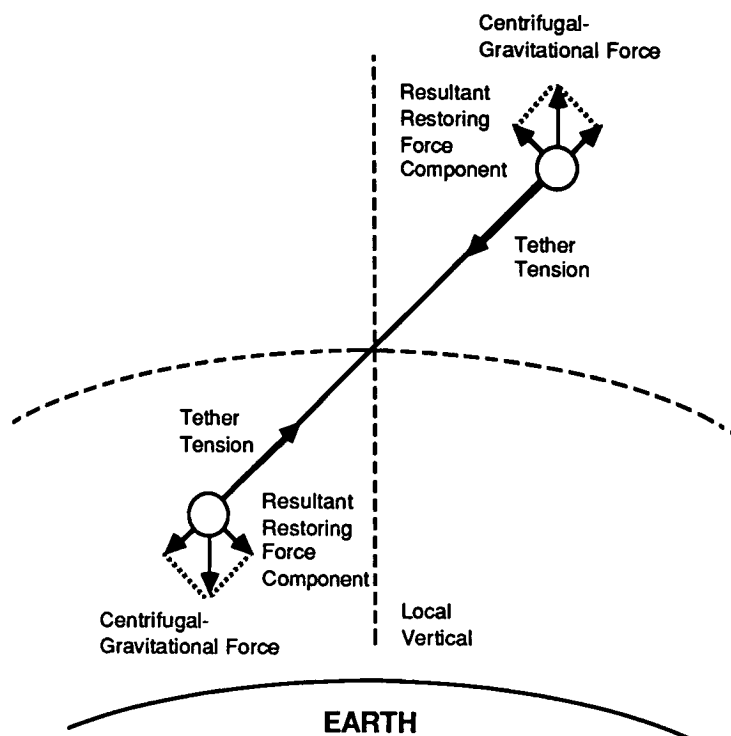


Figure 3.2 Restoring Forces on Tethered Satellites

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,

$$\frac{GM M_0}{r_0^2} = M_0 r_0 \omega_0^2 \quad \text{and}$$

$$\omega_0^2 = \frac{GM}{r_0^3} \quad ; \text{ where}$$

G = universal gravitational constant ($6.673 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$),

M = mass of the Earth ($5.979 \times 10^{24} \text{ kg}$),

M_0 = total tether system mass (kg),

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

ω_0 = 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 Appendix A of Ref. 2, and also in Ref. 3). Figures 3.3 and 3.4 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 3.5 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.

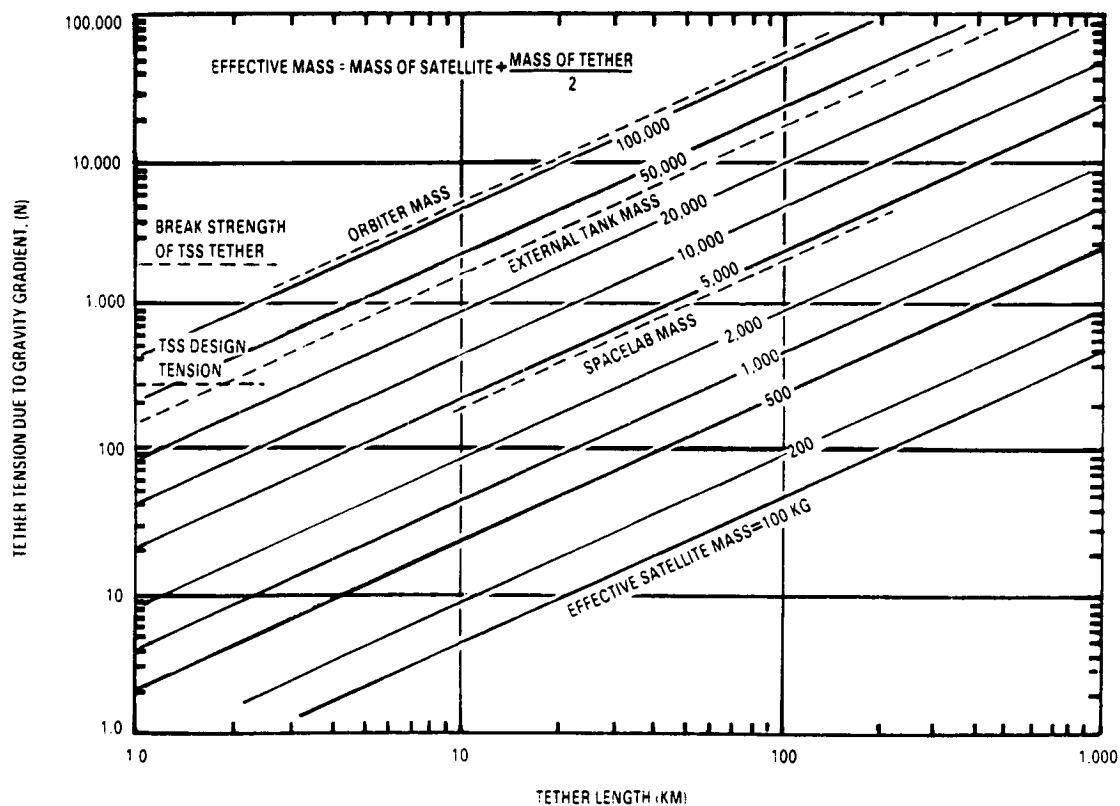


Figure 3.3 Tether Tension Due to Gravity Gradient Versus Tether Length From Center of Gravity and Effective Satellite Mass In LEO

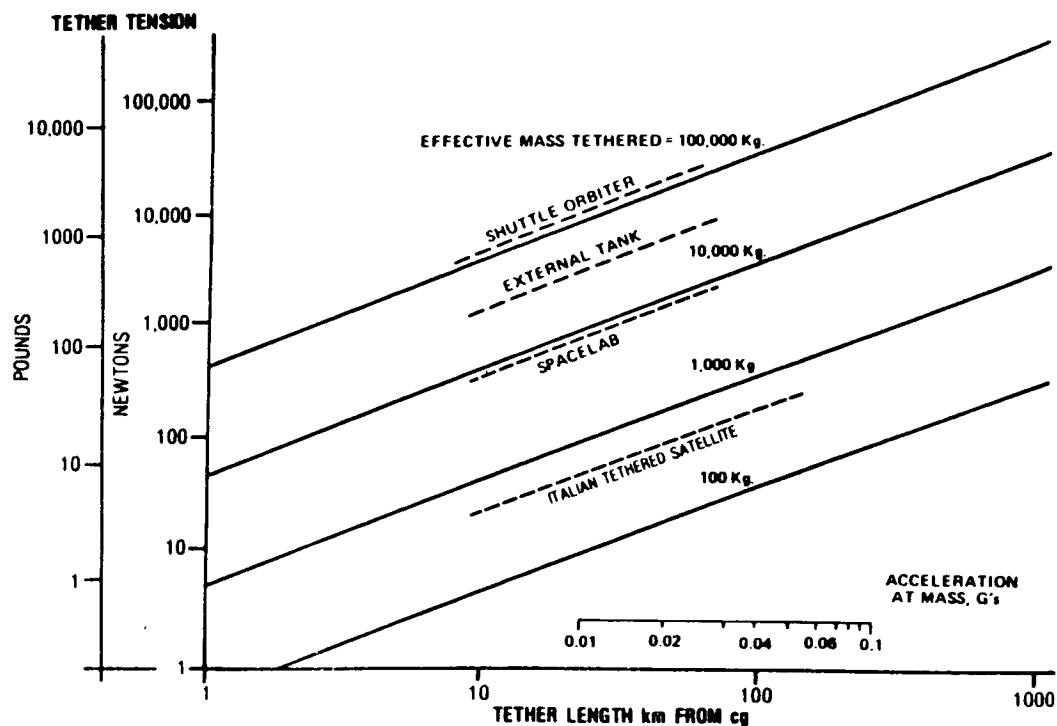


Figure 3.4 "Artificial Gravity" at Tethered Masses in LEO

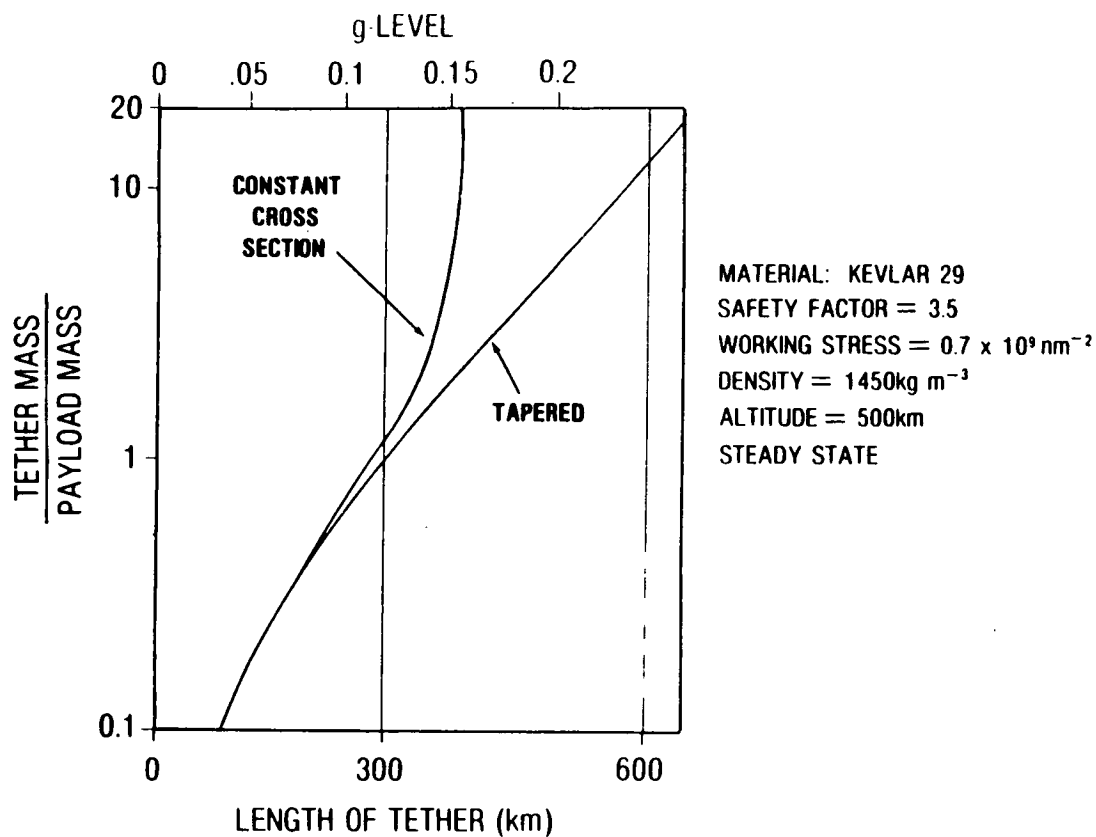


Figure 3.5 Tether Mass and g-Level Versus Tether Length for Kevlar 29 Tethers

Since the gravity-gradient force and acceleration in orbit vary with GM/r_0^3 (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 ($0.3\text{-}0.4 \times 10^{-3} \text{ g/km}$ 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 $1.6 \times 10^{-6} \text{ g/km}$ 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 $\sqrt{3} \omega_0 = 1.732 \omega_0$, and $2 \omega_0$ for out-of-plane librations (a detailed derivation is contained in Appendix A of 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 4.0.

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 3.5, 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 3.3, entitled "Momentum Exchange."

3.1.2 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, Vol. 2, p. 56, 60). 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 3.2.

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 4×10^{-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 3.6 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
- "G" GRADIENT SHOULD NOT EXCEED 0.01 G/FOOT IN RADIAL DIRECTION
- TETHER MASS MIGHT BE LIMITED TO 10,000 TO 20,000 POUNDS

ARTIFICIAL GRAVITY PARAMETERS

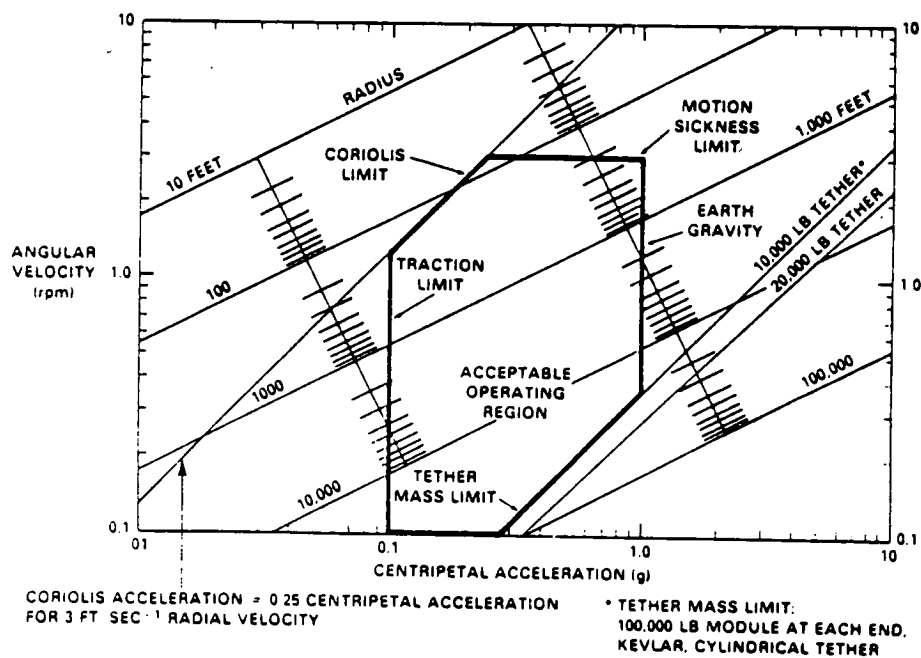


Figure 3.6 Acceptable Values of Artificial-Gravity Parameters

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 3.7 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 2.0) 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 (Bo)**

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

ρ = FLUID DENSITY
 σ = SURFACE TENSION COEFFICIENT
 D = TANK DIAMETER
- **FLUID SETTLES IF $Bo > 10$**
 - $Bo = 50$ CHOSEN TO BE CONSERVATIVE

PROPELLANT SETTling ON A STATIC TETHER ($Bo = 50$)

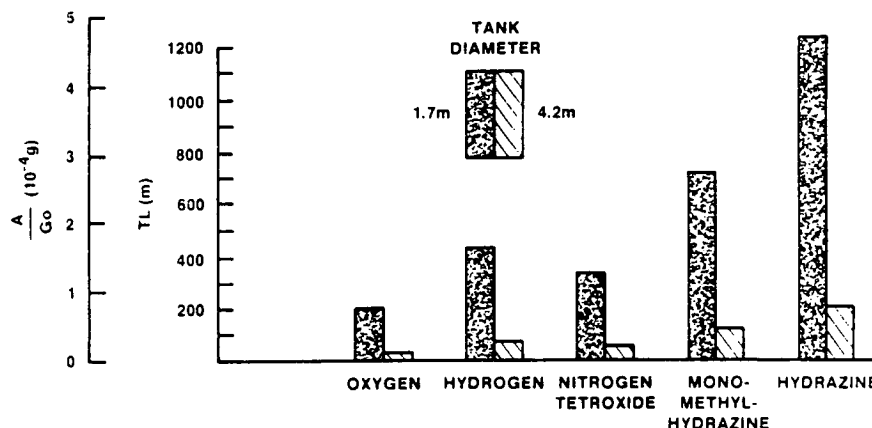


Figure 3.7 Fluid Settling Properties of Various Liquid Propellants Under Conditions of Artificial Gravity - Required Tether Length Versus Propellant

3.1.3 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.

Tethered constellations are divided into the two basic categories shown in Figure 3.8 (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-dimensional, horizontal), drag-and gravity-gradient-stabilized (two-dimensional), and electromagnetically 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.

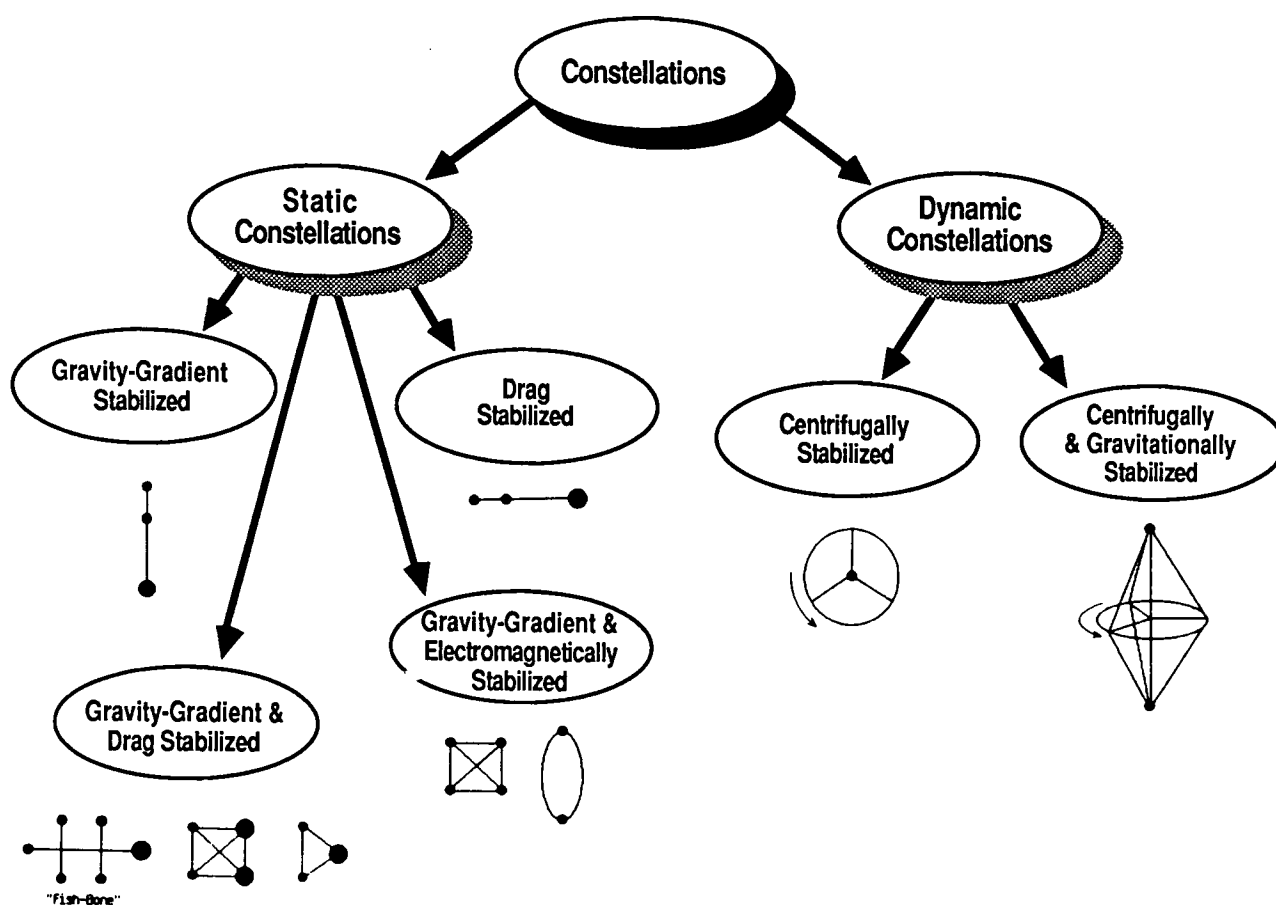


Figure 3.8 Types of Tethered Constellations

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 3.9. 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.

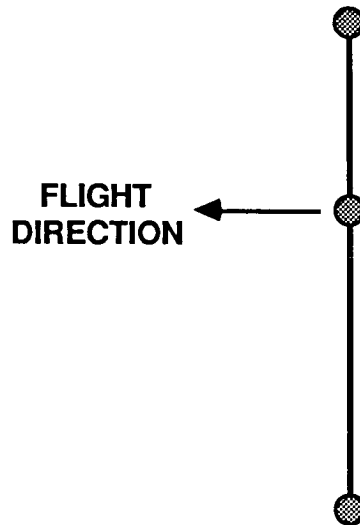


Figure 3.9 Example Configuration of 1-D, Gravity-Gradient-Stabilized, Vertical Constellation

Stability in one-dimensional, horizontal constellations is provided by tensioning the tethers. (Such a constellation is depicted in Figure 3.10.) 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 3.10 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 3.11. 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 3.11 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.

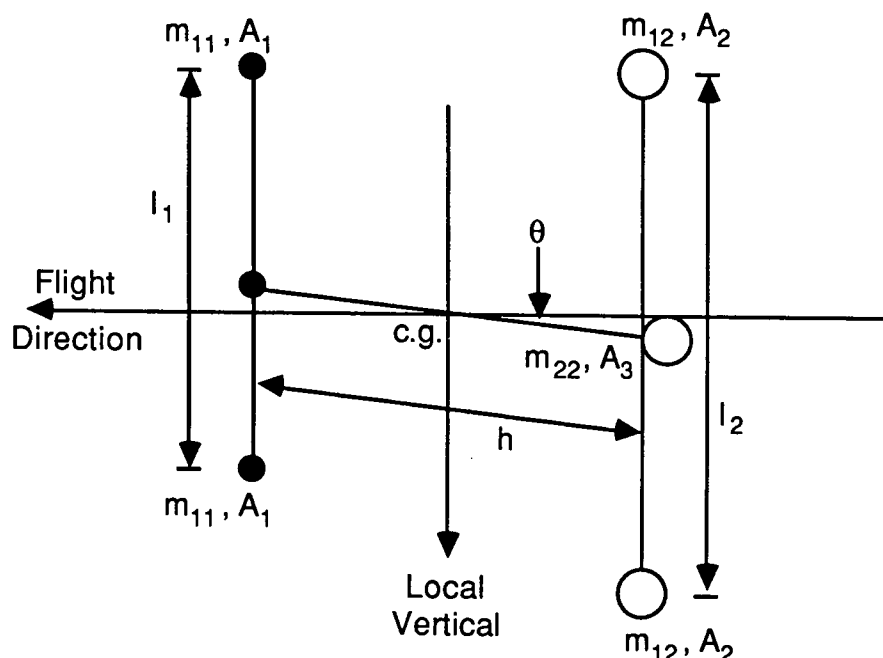


Figure 3.11 Example Configuration of 2-D, "Fish-Bone"

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 3.12. 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).

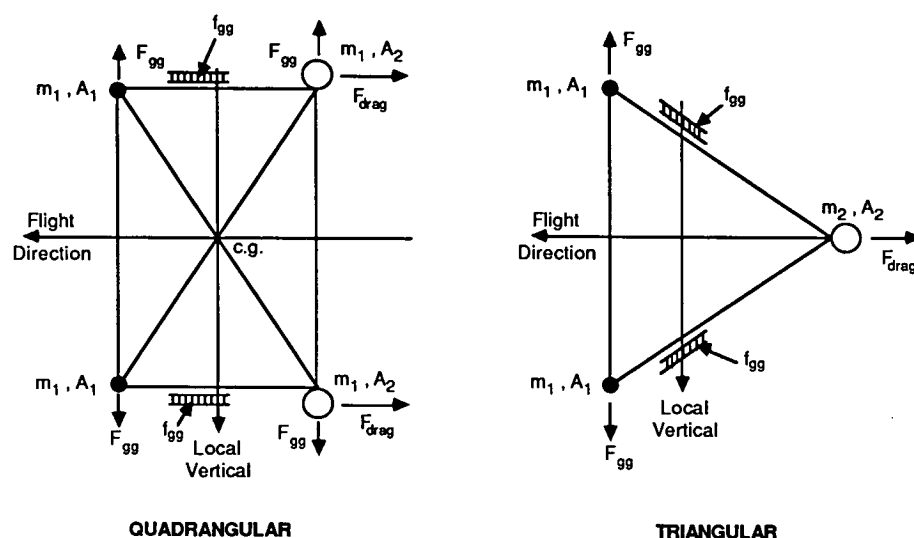


Figure 3.12 Two Designs of 2-D DSC Constellations Horizontally

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 3.13. 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 Section 2.4.) 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).

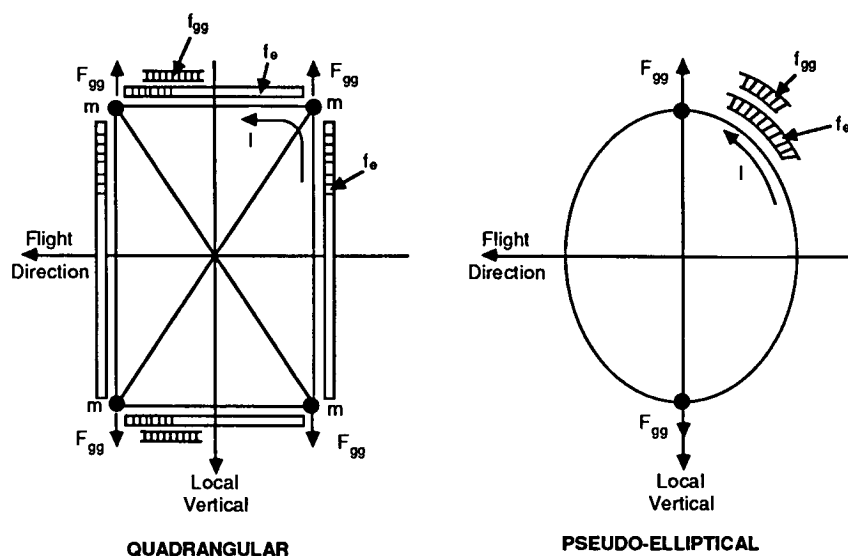


Figure 3.13 Two Designs of ESC 2-D Constellations Where Shape Stability is Provided by Electromagnetic Forces

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.

3.2 ROTATION OF TETHER SYSTEMS

3.2.1 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.

3.2.2 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 3.14, 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.

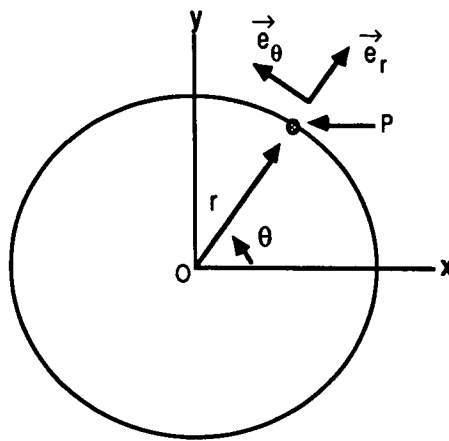


Figure 3.14 Circular Motion of a Point.

The acceleration can then be found by the expression:

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

where,

\vec{a} = acceleration at the point P (m/s²),

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

\vec{e}_θ = unit vector in tangential (velocity) direction,

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

ω = angular velocity (rad/s),

$\dot{\omega}$ = angular acceleration (rad/s²).

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

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

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):

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

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

3.3 MOMENTUM EXCHANGE

3.3.1 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 3.15) as,

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

where

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

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}).

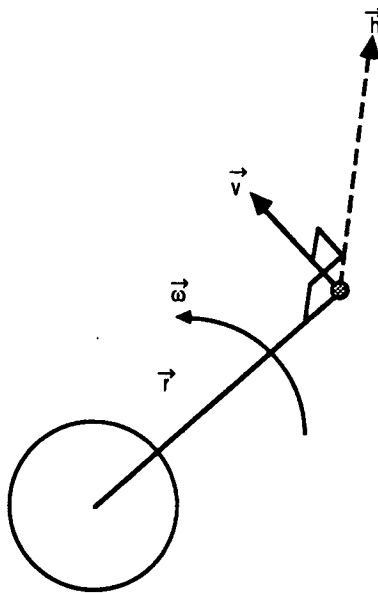


Figure 3.15 Angular Momentum in a Rotating System

In general, momentum exchange can be used for various tether applications using different momentum exchange techniques. These techniques will be described first, followed by examples of their application. A useful chart is presented in Subsection 4.4.4 of Section 4.0, "Tether Data".

3.3.2 Tether Payload Deployment

Consider a system composed of two bodies connected by a variable-length tether as in Figure 3.16 (see Ref. 9).

In order to initiate a tethered deployment, such as deploying a payload (M_2) downward from the Shuttle (M_1), it is first necessary to provide an initial impulse to the payload to start separation. After a certain length of tether has been deployed, the masses are in sufficiently different orbits so that gravity-gradient and centrifugal forces continue the separation. If the two masses were not constrained by a tether, mass M_1 would acquire a lower orbital circular velocity and M_2 would obtain a higher orbital circular velocity in their new orbits. This is because as M_1 moves further away from the Earth'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.

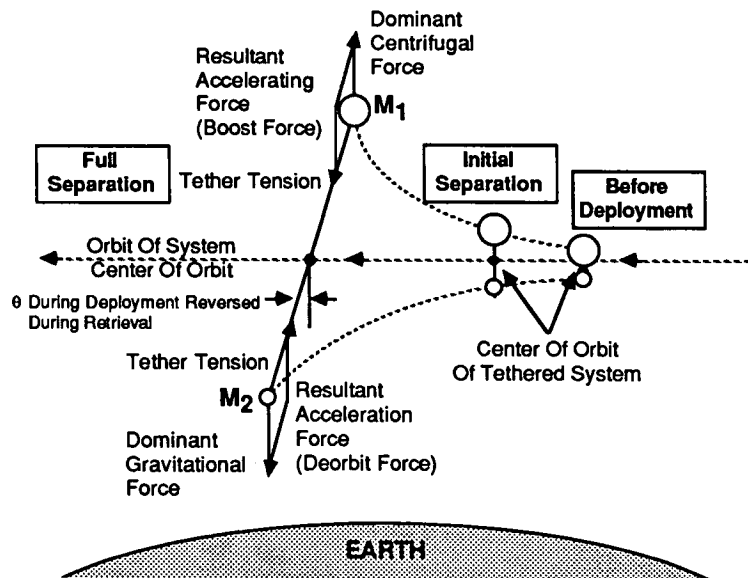


Figure 3.16. Tethered Deployment

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.

3.3.3 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 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 3.17 (Ref. 9).

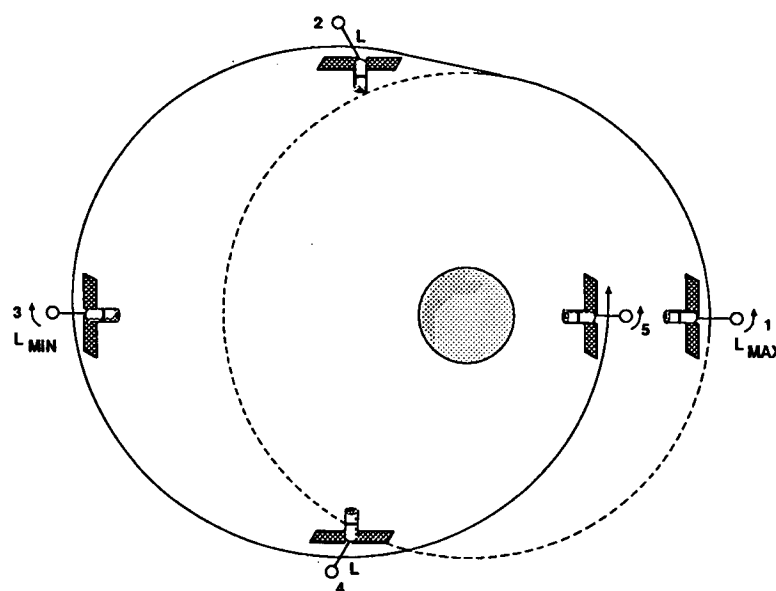


Figure 3.17 Orbit Eccentricity Change

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.

3.4 ELECTRODYNAMICS

3.4.1 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.

3.4.2 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 3.18 (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:

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

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/m²), and

$d\vec{l}$ = 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:

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

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:

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

where

$$\theta = \text{angle between } \vec{v} \text{ and } \vec{B}.$$

(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.)

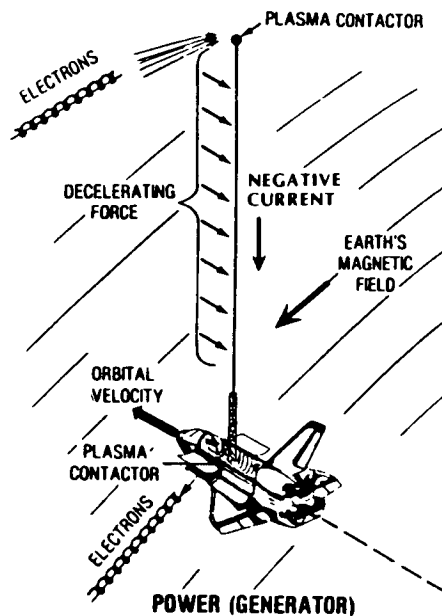


Figure 3.18 Power Generation With an Electrodynamic Tether

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 3.19. 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.

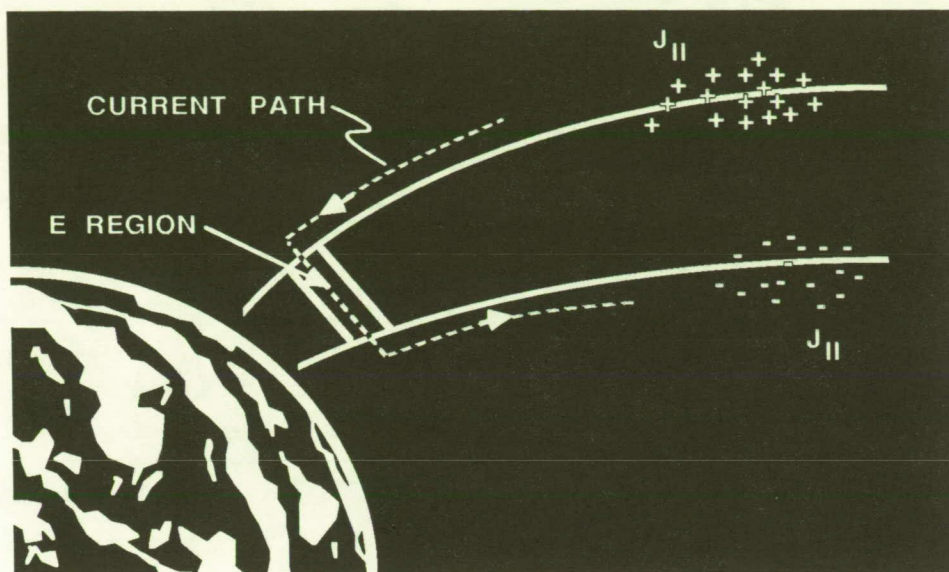


Figure 3.19 The Current Path External To An Orbiting Electrodynamic Tether System

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 3.20. Additional diagrams and information relating to the construction and operation of the PMG hollow cathode plasma contactor are given in Figures 3.21, 3.22 and 3.23. Typical characteristics of a hollow cathode and an electron gun are compared in Figures 3.24 and 3.25.

Although current research and modeling results indicate that hollow cathodes are far superior to electron guns and passive contactors for producing high current contact with the ionosphere, this has not been verified by flight tests. In addition, there may be particular applications for which passive contactors or electron guns are desirable.

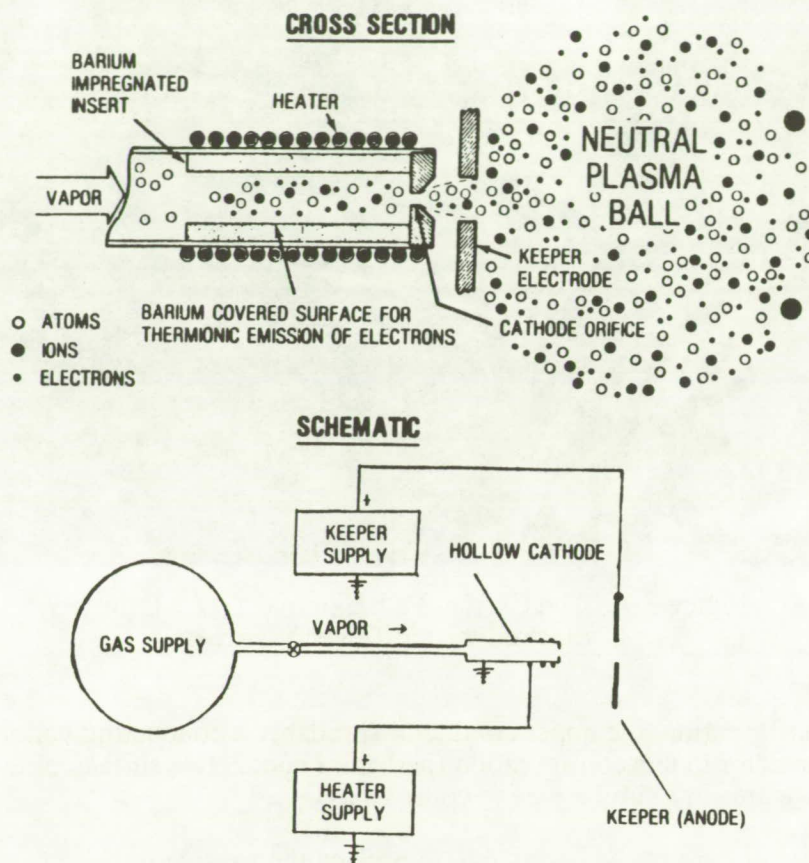


Figure 3.20 Diagrams of a Hollow Cathode Plasma Contactor

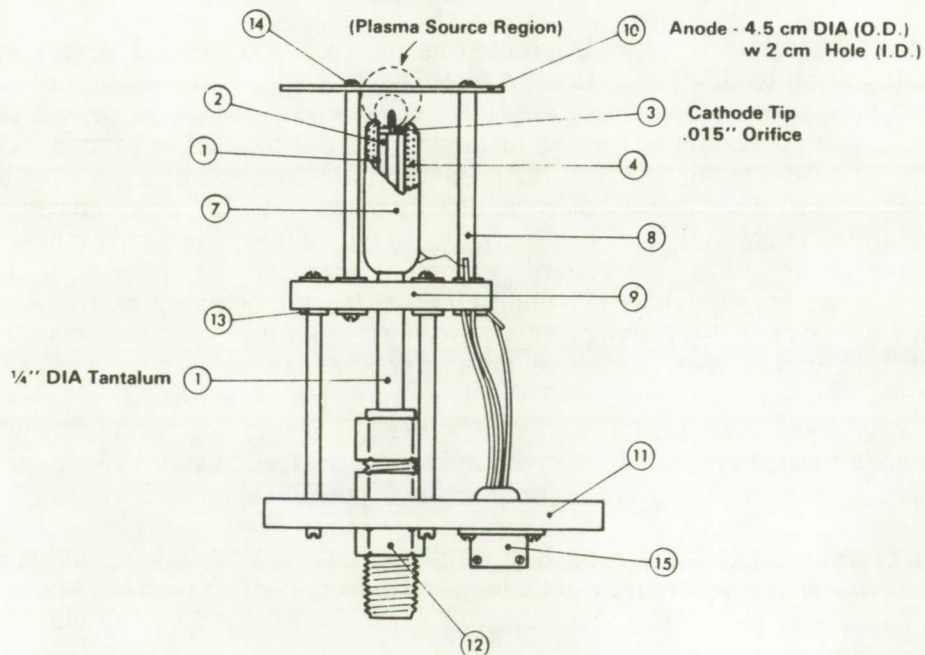


Figure 3.21 Diagram of the Plasma Motor/Generator (PMG) Hollow Cathode Assembly

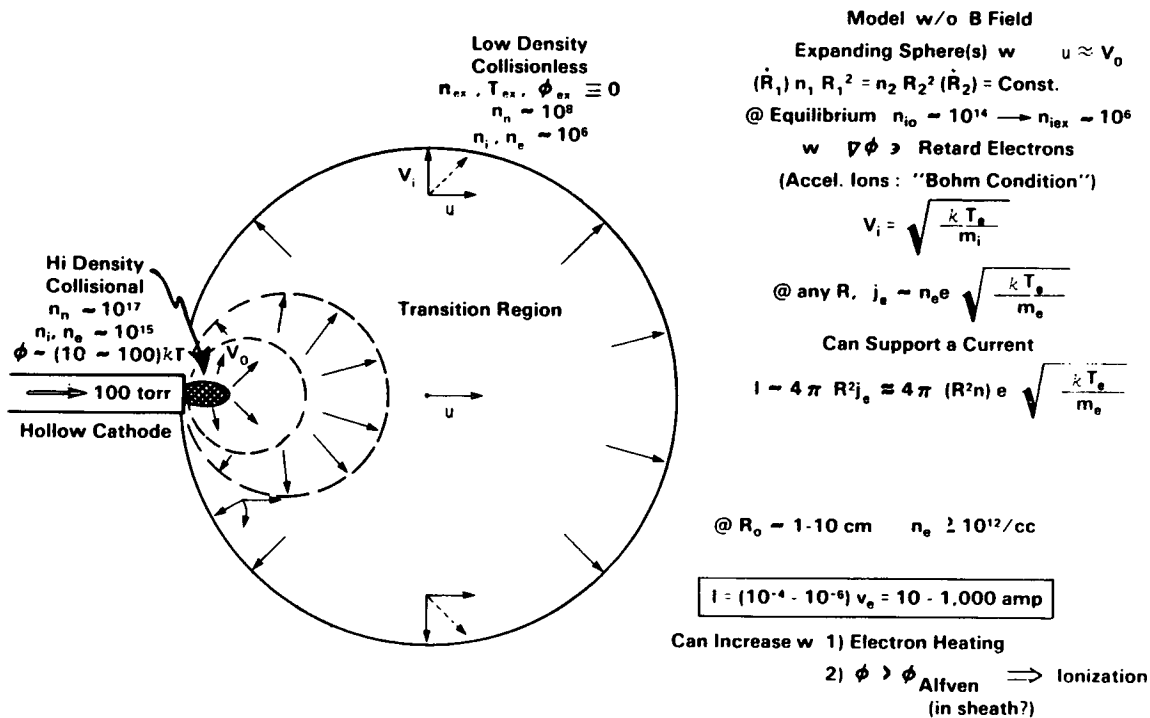


Figure 3.22 Plasma Cloud Expansion for PMG Hollow Cathode Plasma Contactor

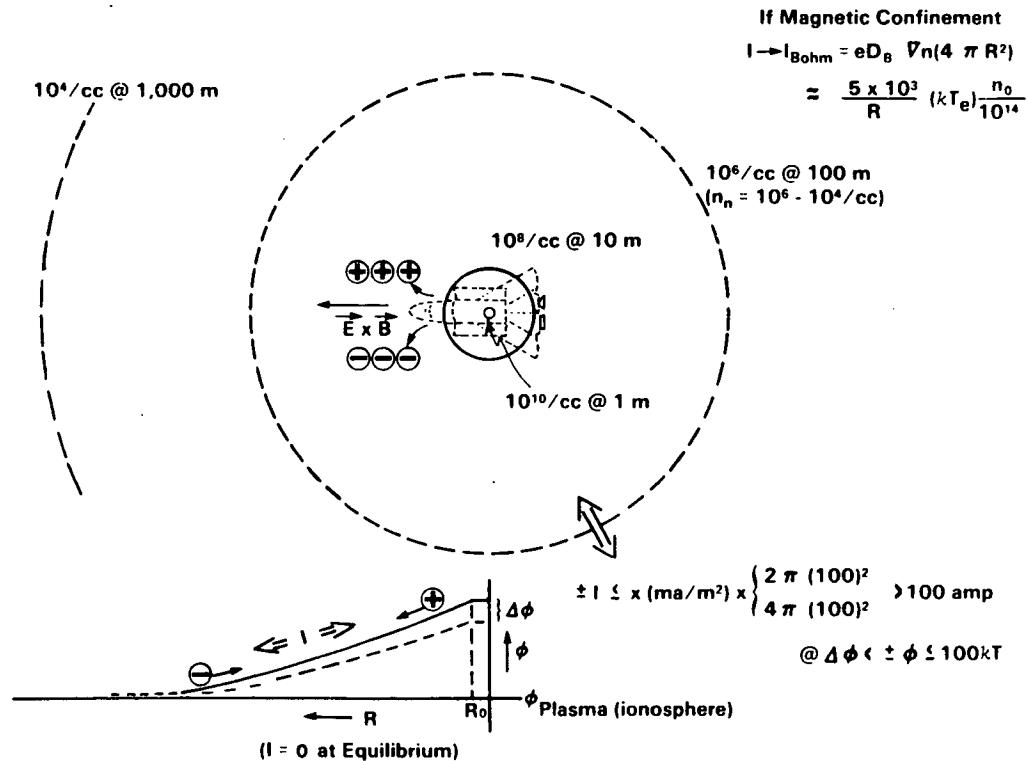


Figure 3.23 Electron Current Flow To/From the Ionosphere for PMG Hollow Cathode Plasma Contactor

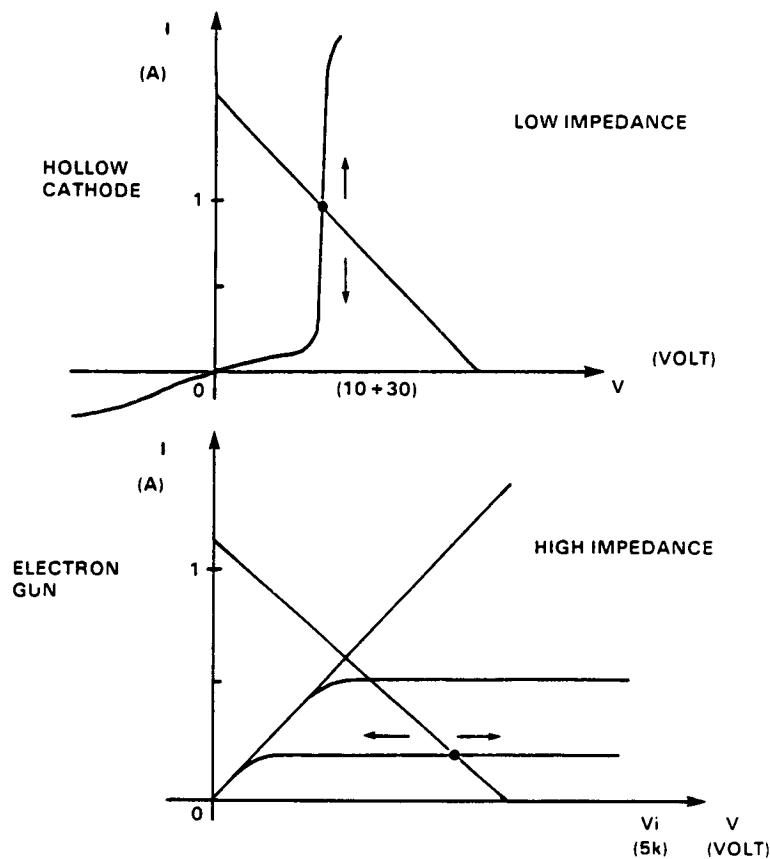


Figure 3.24 Comparison of the IV Characteristics of a Hollow Cathode and Electron Gun

	<u>Electron Gun</u>	<u>Hollow Cathode</u>
- Current Range:	$I_e \lesssim 1A$	$*I_{e,i} > 10A, 1A$
- Power Consumption	$\sim 1 \text{ kW}$	$\sim 10W$
- Life Time:	Similar	Similar
- Automatic Switching	No	Yes
- Main Applications	Basic Science Exp. and Power Dissipation	Low Impedance Coupling Power Generation Thrusting

*Nominal Values

Figure 3.25 Comparative Characteristics of an Electron Gun and a Hollow Cathode

Since hollow cathodes are projected to allow much larger tether currents than the other types of plasma contactors, PMG systems should obtain desired electrical power levels at lower voltages than the other tether systems and thereby avoid requirements for technology advances to handle very high voltages. PMG systems are expected, therefore, to use shorter and more massive tethers, greatly reducing the mass required for a stabilizing end mass, and simplifying tether deployment and dynamics. 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.

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 is a significant thermal control and heat rejection problem.

PMG systems, on the other hand, use DC impedance matching to control the tether current and power. This is accomplished by adjusting a continuously variable effective load impedance in order to match the varying tether voltage and power with the spacecraft load power requirements. This control system is a variation of a DC/DC converter, developed at NASA/Lewis Research Center as the power converter module for the "Electric Airplane" project. The conductivity of the hollow cathode assembly is not readily controllable and it acts as an upper limit on tether current. Tether current is variable over its full \pm range with little interaction with the hollow cathode assembly controller.

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

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

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:

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

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. Data exist which indicate that plasmas released from hollow cathode plasma contactors should greatly reduce the sheath impedance between the contactors and the

ambient plasma surrounding them. Data from one study of hollow cathodes predict Z_{LOW} (electron emitting end) to be on the order of 20 ohms, and Z_{UP} (electron collecting end) to be on the order of 10-1000 ohms (Ref. 4, p. 499-546). Studies of PMG systems with hollow cathode plasma contactors, have indicated that there is a nearly constant voltage. Therefore, for the PMG model, the voltage across the tether is simply reduced by 20 volts to account for the voltage drop at both tether ends. 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 for some sample systems are presented in Figures 3.26 through 3.29.

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.

PMG - 20 KW REFERENCE SYSTEM

TETHER LENGTH	10 KM	WORKING TENSION	21 N
NOMINAL VOLTAGE	2 KV	WORKING ANGLE	7 DEG
RATED POWER	20 KW	RATED THRUST	2.5 N
PEAK POWER	125 KW	PEAK THRUST	>40. N
CONDUCTOR	#2 AWG ALUMINUM WIRE DIAMETER 6.5 MM @ 20°C RESISTANCE 8.4 OHMS @ 20°C 7.7 OHMS @ 0°C 7.1 OHMS @ -20°C		908 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)		99 KG
FAR END MASS	10 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)		10 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HDWR. (POWER DISSIPATION LOSSES @1% = 200W)		83 KG
ARGON SUPPLY & CONTINGENCY RESERVE			<u>100 KG</u>
TOTAL			<u>1,200 KG</u>
TETHER DYNAMICS CONTROL	PASSIVE, 1XB PHASING		
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING		
TETHER OUTSIDE DIAMETER	7.5 MM		
TETHER BALLISTIC DRAG AREA	75 SQ. METERS		
	-11 3		
DRAG FORCE @ 10	KG/M	.045 N	.36 KW
(300 KM 1976 USSA-400 KM SOLAR MAX)			
2			
I R LOSSES @ 20 KW			.77 KW
HOLLOW CATHODE POWER			.50 KW
IONOSPHERIC LOSS @ 10 AMP			<u>.05 KW</u>
TOTAL PRIMARY LOSSES			1.68 KW
EFFICIENCY	ELECTRIC (18.68 KW NET @ 10 AMP/20 KW)	93.4%	
	OVERALL (20.36 MECH. TO 18.68 ELEC. KW)	91.7%	
INCLUDING CONTROLLER/POWER PROCESSOR LOSSES @ 1%			<u>.20 KW</u>
TOTAL (NET POWER OUT 18.48 KW)			1.88 KW
FINAL EFFICIENCY	ELECTRIC = 92.4%	OVERALL = 90.8%	

Figure 3.26 Calculated Performance of an Example Electromagnetic Tether System

<u>PMG - 200 KW REFERENCE SYSTEM</u>			
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 OHMS @ 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. HWWR. (POWER DISSIPATION LOSSES @1% = 2 KW)		94 KG
ARGON SUPPLY & CONTINGENCY RESERVE			<u>163 KG</u>
TOTAL			<u>4,200 KG</u>
TETHER DYNAMICS CONTROL	PASSIVE, 1XB PHASING		
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING		
TETHER OUTSIDE DIAMETER	10.3 MM		
TETHER BALLISTIC DRAG AREA	206 SQ METERS		
-11 3			
DRAG FORCE @ 10 ² KG/M	.12 N		.96 KW
(300 KM 1976 USSA-400 KM SOLAR MAX)			
I R LOSSES @ 200 KW			19.25 KW
HOLLOW CATHODE POWER			2.50 KW
IONOSPHERIC LOSS @ 50 AMP			<u>1.25 KW</u>
TOTAL PRIMARY LOSSES			23.96 KW
EFFICIENCY	ELECTRIC (177 KW NET @ 50 AMP/200 KW)	88.5%	
	OVERALL (201 MECH. TO 177 ELEC. KW)	88.1%	
INCLUDING CONTROLLER/POWER PROCESSOR LOSSES @ 1%			<u>2.00 KW</u>
TOTAL (NET POWER OUT 175.0 KW)			25.96 KW
FINAL EFFICIENCY	ELECTRIC = 87.5%	OVERALL = 87.1%	

Figure 3.27 Calculated Performance of an Electromagnetic Tether System

PMG - MEGAWATT REFERENCE SYSTEM

TETHER LENGTH	20 KM (10 UP+10 DN)	WORKING TENSION	190 N
NOMINAL VOLTAGE	4 KV	WORKING ANGLE	10 DEG
RATED POWER	500 KW	RATED THRUST	65 N
PEAK POWER	>2 MW	PEAK THRUST	>400 N
CONDUCTOR	2 CM ALUMINUM WIRE DIAMETER 20.0 MM @ 20°C RESISTANCE 1.68 OHMS @ 20°C 1.54 OHMS @ 0°C 1.42 OHMS @ -20°C		17,860 KG
INSULATION	0.5 MM TEFLON (100 VOLTS/MIL)		580 KG
FAR END MASS	125 AMP HOLLOW CATHODE ASS'Y (INCLUDING ELECTRONICS & CONTROL)		50 KG
TETHER CONTROLLER	ELECTRONICS & MISC. HWWR. (POWER DISSIPATION LOSSES @1% = 5 KW)		120 KG
ARGON SUPPLY & CONTINGENCY RESERVE			<u>290 KG</u>
TOTAL			<u>19,000 KG</u>
TETHER DYNAMICS CONTROL	PASSIVE, IXB PHASING		
TETHER CURRENT/POWER CONTROL	DC IMPEDANCE MATCHING		
TETHER OUTSIDE DIAMETER	21.0 MM		
TETHER BALLISTIC DRAG AREA	420 SQ METERS		
-11	3		
DRAG FORCE @ 10 KG/M	.25 N		2.0 KW
(300 KM 1976 USSA-400 KM SOLAR MAX)			
2			
I R LOSSES @ 500 KW			<u>24.1 KW</u>
HOLLOW CATHODE POWER			5.0 KW
IONOSPHERIC LOSS @ 125 AMP			<u>7.8 KW</u>
TOTAL PRIMARY LOSSES			36.9 KW
EFFICIENCY	ELECTRIC (463.1 KW NET @ 500 KW)		92.6%
	OVERALL (502 MECH. TO 463 ELEC. KW)		92.3%
INCLUDING CONTROLLER/POWER PROCESSOR LOSSES @ 1%			<u>5.0 KW</u>
TOTAL (NET POWER OUT 458.1 KW)			41.9 KW
FINAL EFFICIENCY	ELECTRIC = 91.6%	OVERALL = 91.3%	

Figure 3.28 Calculated Performance of an Example Electromagnetic Tether System

RECOMMENDED APPLICATIONS

- I. THRUST - USE WITH SOLAR ARRAYS IN LOW EARTH ORBIT TO OFFSET DRAG
 - 100 KG SYSTEM PRODUCING .1 NEWTON THRUST
 - 8 KW/N ELECTRIC POWER CONSUMPTION = .8KW
 - ELIMINATES DELTA-V FUEL REQUIRED: >1,000 KG/YR
 - KEEP 100 KW SOLAR ARRAY @ SPACE STATION ORBIT
 - INCREASE TO 200 KG SYSTEM @ 1-2 N THRUST
 - KEEP SPACE STATION + 100KW ARRAY IN <300 KM ORBIT ALTITUDE
 - NO ORBIT MAINT. FUEL REQUIRED; CONSUMABLES = < 60 KG/YR (ARGON)
 - USES 10-15 KW FROM 100 KW AVAILABLE

- II. THRUST - USE FOR ORBITAL MANUEVERING PROPULSION
 - 2,000 KG SYSTEM (PLUS 80 KW POWER SUPPLY: SOLAR, NUCLEAR, WHAT-EVER)
 - 10 NEWTON THRUST - CONTINUOUS AS LONG AS POWER AVAILABLE
 - ALTITUDE CHANGE
 - 7 KM/DAY - 200,000 KG (SPACE STATION)
 - 30 KM/DAY - 50,000 KG (PLATFORM)
 - 150 KM/DAY - 10,000 KG (FREE-FLYER)
 - TOTAL IMPULSE: 864,000 N-SEC/DAY (194,000 LB-SEC/DAY)
 - 17 M/SEC/DAY - 50,000 KG (PLATFORM)
 - 86 M/SEC/DAY - 10,000 KG (FREE-FLYER, OMV, OR "TUG")
 - ORBIT PLANE CHANGE: 30 DEGREE IN 6 MONTHS MAY BE POSSIBLE
 - "FLY" ENTIRE SPACE STATION DOWN TO 200-250 KM ALTITUDE & MAINTAIN
 - GROWTH VERSION: 200 N @ 1.6 MW, 20,000 KG + POWER SUPPLY

- III. POWER STOREAGE - 100KW SOLAR ARRAY SYSTEM
 - + 2,000 KG REVERSIBLE MOTOR/GENERATOR TETHER SYSTEM
 - 60 KW THRUST DURING DAY (POWER STOREAGE AS ORBIT ENERGY)
 - 100 KW POWER GENERATION DURING DARK
 - TOTAL SYSTEM WEIGHT 40% OF CONVENTIONAL ARRAY WITH BATTERIES
 - 10% REDUCTION IN SOLAR ARRAY SIZE
 - 60% REDUCTION IN POWER PROCESSING HEAT REJECTION REQUIRED

Figure 3.29 Recommended Applications and Calculated Performance of Example Electromagnetic Tether Systems

3.4.3 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 3.30). This force is given by:

$$\vec{F} = \int_{\text{along length of tether}} (I \, d\vec{l}) \times \vec{B} = I \int_{\text{along length of tether}} d\vec{l} \times \vec{B} ;$$

where

\vec{F} = force exerted on the tether by the magnetic field (newtons),

I = tether current (amps),

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

\vec{B} = magnetic field strength (webers/m²)

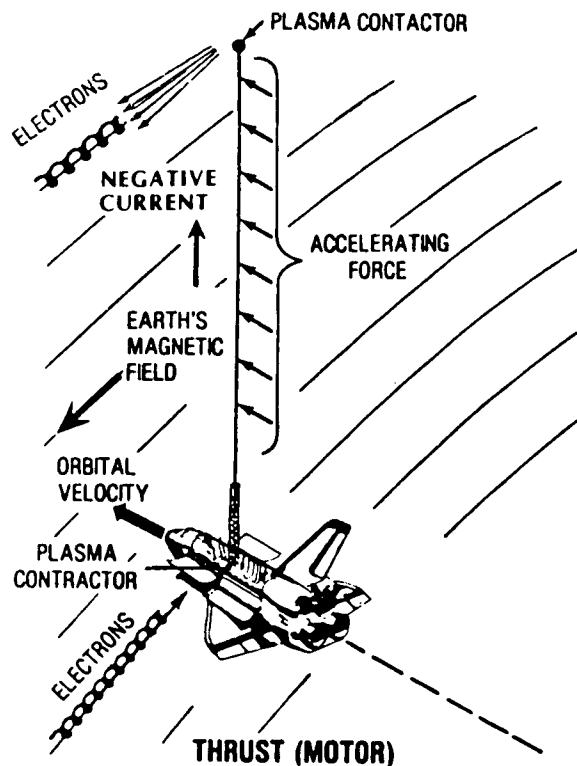


Figure 3.30 Thrust Generation With An Electrodynamic Tether System

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

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

where

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

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

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

where

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

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 number of example systems are presented in Figures 3.26 through 3.29.

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 4.0.

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 $IL \times B$ 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. The proposed PMG systems will use passive $IL \times B$ phasing to control tether dynamics and a long, light ballast tether will be attached to the end of the PMG tether for missions requiring more control. Additional information on electromagnetic libration control issues is shown also in Section 4.0.

3.4.4 ULF/ELF/VLF Antennas

As discussed in Section 3.4.2, 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 3.31.) This current loop (or so-called "phantom loop") acts as a large ULF, ELF, and VLF antenna. (The phantom loop is shown in Figure 3.32). The electromagnetic waves generated by this loop should propagate to the Earth's surface, as shown in Figure 3.33. 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 3.33. 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).

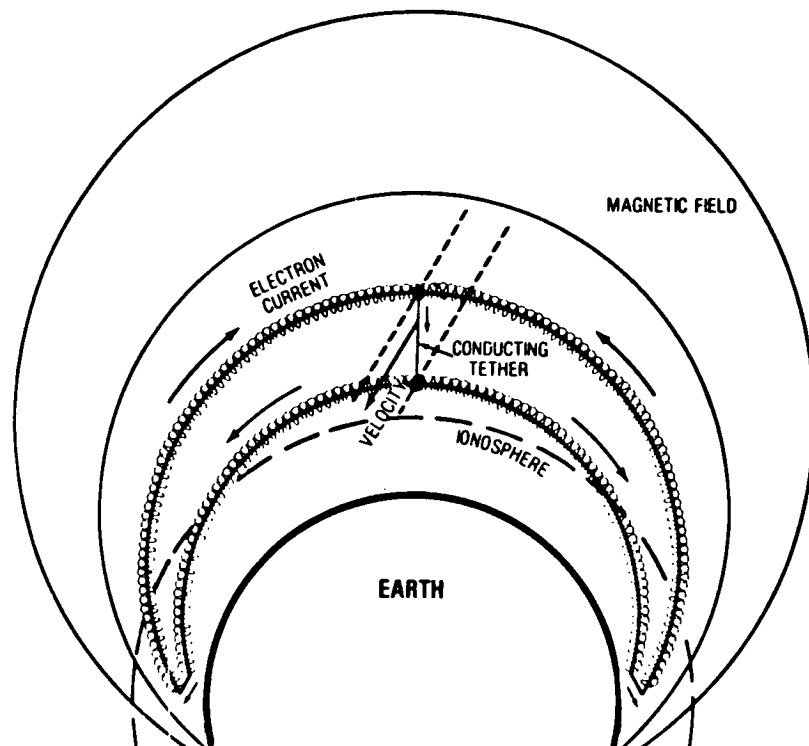


Figure 3.31 Electron Paths in the Electrodynamic Tether Generator

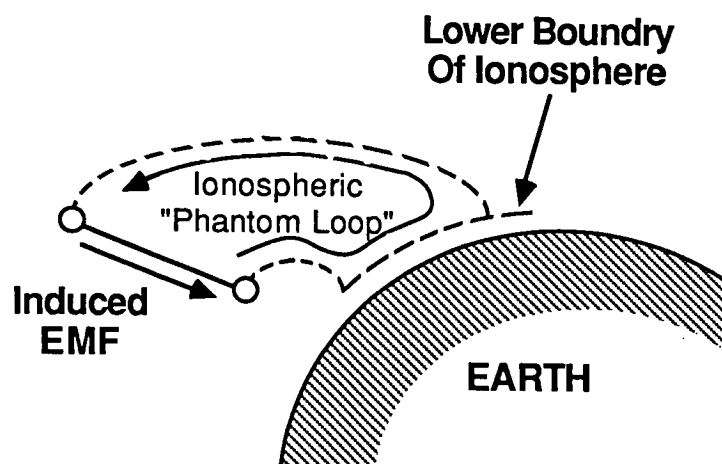


Figure 3.32 The "Phantom Loop" of the ULF/ELF Tether Antenna

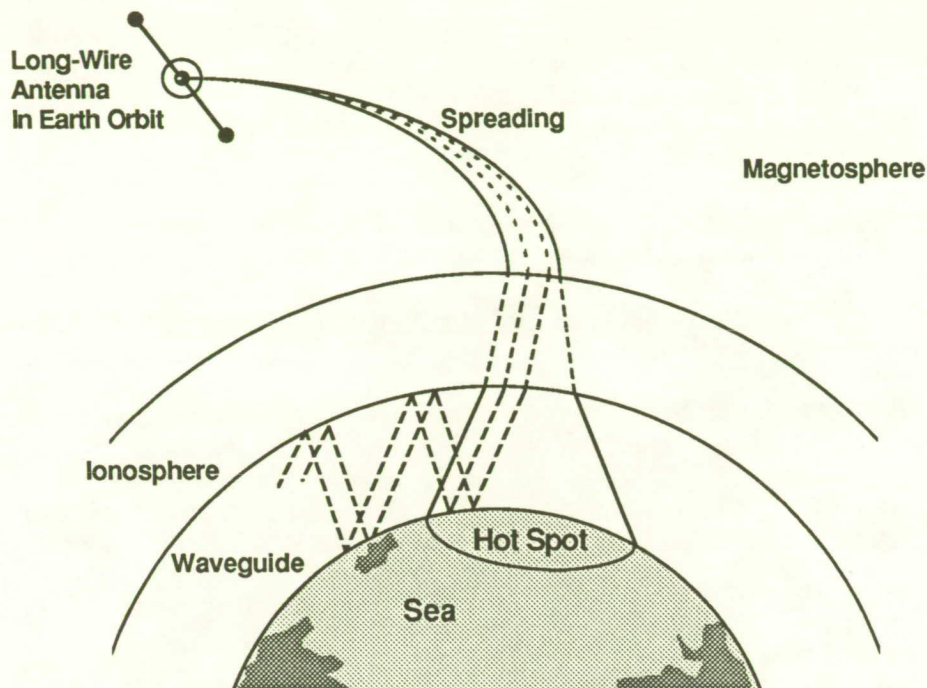


Figure 3.33 Propagation of ULF/ELF/VLF Waves To The Earth's Surface From An Orbiting Tether Antenna

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.

3.4.5 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 3.13). The force exerted on a current in a tether is exactly the force described in Section 3.4.3. 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.

3.5 References

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SECTION 4.0 TETHER DATA

Tether Data

4.1 General

This handbook would not be complete without providing the user with specific data and other information relevant to the analysis of tether applications. To the authors' knowledge, the best summarization of this data is contained in J. A. Carroll's Guidebook for Analysis of Tether Applications, published in 1985 under contract to the Martin Marietta Corporation. It provides a concise review of those technical areas which are essential to tether analyses. For the uninitiated, it is the first exposure they should have to ensure that they understand the broad implications of any application they might consider. From here, they can explore the many references given in the Bibliography.

The Guidebook is reproduced here in full, except for its bibliography which would be redundant. J. A. Carroll's introductory remarks and credits are presented below:

This Guidebook is intended as a tool to facilitate initial analyses of proposed tether applications in space. The guiding philosophy is that at the beginning of a study effort, a brief analysis of all the common problem areas is far more useful than a detailed study in any one area. Such analyses can minimize the waste of resources on elegant but fatally flawed concepts, and can identify the areas where more effort is needed on concepts which do survive the initial analyses.

In areas in which hard decisions have had to be made, the Guidebook is:

Broad, rather than deep
Simple, rather than precise
Brief, rather than comprehensive
Illustrative, rather than definitive

Hence the simplified formulas, approximations, and analytical tools included in the Guidebook should be used only for preliminary analyses. For detailed analyses, the references with each topic and in the bibliography may be useful. Note that topics which are important in general but not particularly relevant to tethered system analysis (e.g., radiation dosages) are not covered.

This Guidebook was presented by the author under subcontract RH4-394049 with the Martin Marietta Corporation, as part of their contract NAS8-35499 (Phase II Study of Selected Tether Applications in Space) with the NASA Marshall Space Flight Center. Some of the material was adapted from references listed with the various topics, and this assisted the preparation greatly. Much of the other material evolved or was clarified in discussions with one or more of the following: Dave Arnold, James Arnold, Ivan Bekey, Guiseppe Colombo, Milt Contella, Dave Criswell, Don Crouch, Andrew Cutler, Mark Henley, Don Kessler, Harris Mayer, Jim McCoy, Bill Nobles, Tom O'Neil, Paul Penzo, Jack Slowey, Georg von Tiesenhausen, and Bill Thompson. The author is of course responsible for all errors, and would appreciate being notified of any that are found.

4.2 Generic Issues

MAJOR CONSTRAINTS IN MOMENTUM-TRANSFER APPLICATIONS

CONSTRAINT: APPLICATION:	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Apside location	Forces on end masses	μ meteoroid sensitivity	Tether recoil at release
Librating		Tether can go slack		Facility attitude & "g"s variable
Spinning		High loads on payload		Retrieval can be difficult
Winching		High loads on payload		Extremely high power needed
Rendezvous	Orbit planes must match			Short launch & capture windows
Multi-stage	Dif. nodal regression			Waiting time between stages
High deltaV	Gravity losses	Control of dynamics	Tether mass & lifetime	Retrieval energy; Facility Δ alt.

MAJOR CONSTRAINTS WITH PERMANENTLY-DEPLOYED TETHERS

CONSTRAINTS: APPLICATION:	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Aero. drag	Libration	Degradation, μ meteoroids & debris impact.	Recoil & orbit changes after tether break
Electrodynamic	Misc changes in orbit	Plasma disturbances	High-voltage insulation	
Aerodynamic	Tether drag & heating			
Beanstalk (Earth)			Tether mass; debris impact	Consequences of failure
Gravity Use: Hanging Spinning		Libr-sensitive		<.1 gee only. Docking awkward

4.3 Orbit Equations and Data

4.3.1 Orbits and Orbital Perturbations

KEY POINTS Basic orbit nomenclature & equations are needed frequently in following pages. Comparison of tether & rocket operations requires orbit transfer equations.

The figures and equations at right are a summary of the aspects of orbital mechanics most relevant to tether applications analysis. For more complete and detailed treatments and many of the derivations, consult refs 1-3.

The first equation in the box is known as the Vis Viva formulation, and to the right of it is the equation for the mean orbital angular rate, n . Much of the analysis of orbit transfer ΔV s and tether behavior follows from those two simple equations. Some analyses require a close attention to specific angular momentum, h , so an expression for h (for compact objects) is also given here.

In general, six parameters are needed to completely specify an orbit. Various parameter sets can be used (e.g., 3 position coordinates & 3 velocity vectors). The six parameters listed at right are commonly used in orbital mechanics. Note that when $i=0$, Ω becomes indeterminate (and unnecessary); similarly with w when $e=0$. Also, i & Ω are here referenced to the central body's equator, as is usually done for Low Earth Orbit (LEO). For high orbits, the ecliptic or other planes are often used. This simplifies calculation of 3rd body effects.

NOTES The effects of small ΔV s on near-circular orbits are shown at right. The relative effects are shown to scale: a ΔV along the velocity vector has a maximum periodic effect 4 times larger than that of the same ΔV perpendicular to it (plus a secular effect in θ which the others don't have). Effects of oblique or consecutive ΔV s are simply the sum of the component effects. Note that out-of-plane ΔV s at a point other than a node also affect Ω .

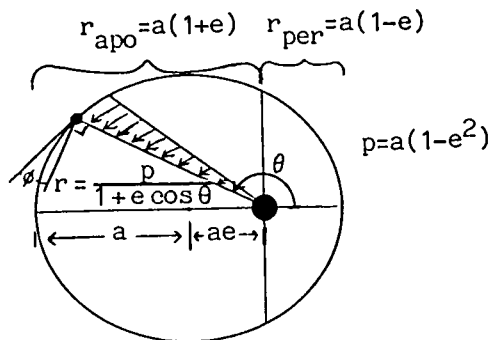
For large ΔV s, the calculations are more involved. The perigee and apogee velocities of the transfer orbit are first calculated from the Vis Viva formulation and the constancy of h . Then the optimum distribution of plane change between the two ΔV s can be computed iteratively, and the required total ΔV found. Typically about 90% of the plane change is done at GEO.

To find how much a given in-plane tether boost reduces the required rocket ΔV , the full calculation should be done for both the unassisted and the tether-assisted rocket. This is necessary because the tether affects not only the perigee velocity, but also the gravity losses and the LEO/GEO plane change split. Each m/s of tether boost typically reduces the required rocket boost by .89 m/s (for hanging release) to .93 m/s (for widely librating release).

Note that for large plane changes, and large radius-ratio changes even without plane changes, 3-impulse "bi-elliptic" maneuvers may have the lowest total ΔV . Such maneuvers involve a boost to near-escape, a small plane and/or perigee-adjusting ΔV at apogee, and an apogee adjustment (by rocket or aerobrake) at the next perigee. In particular, this may be the best way to return aerobraking OTVs from GEO to LEO, if adequate time is available.

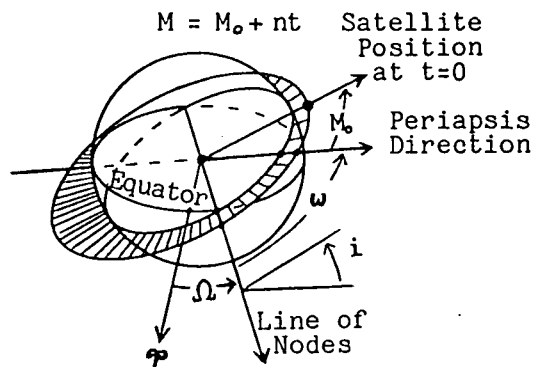
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Orbit & Orbit Transfer Equations

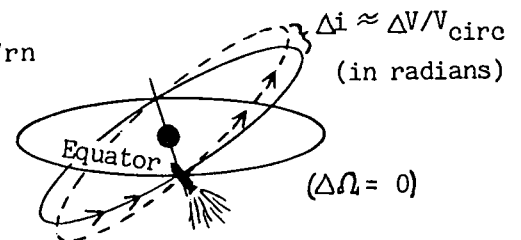
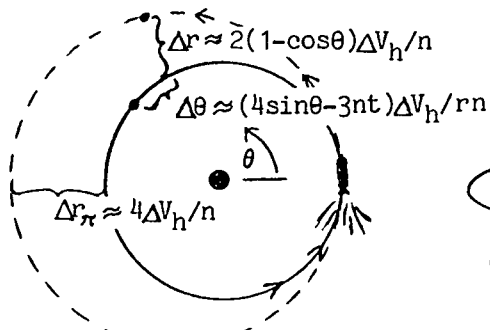
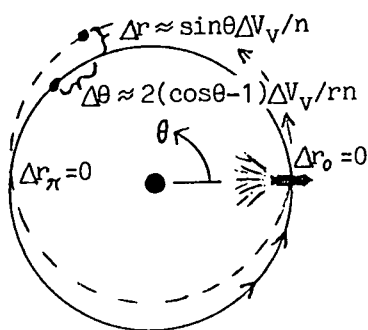


$v^2 = \mu \left(\frac{2}{r} - \frac{1}{a} \right)$	$n = \dot{\theta} = \sqrt{\mu/a^3}$
$v_{circ}^2 = \mu/r$	$h = \sqrt{\mu p} = r^2 \dot{\theta} = r v \cos \phi$
$v_{esc}^2 = 2\mu/r$	$\mu_{earth} = 398601 \text{ km}^3/\text{sec}^2$
	$\mu_x = G * \text{Mass of } x$

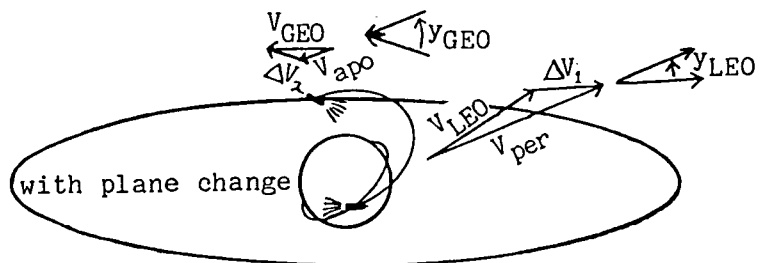
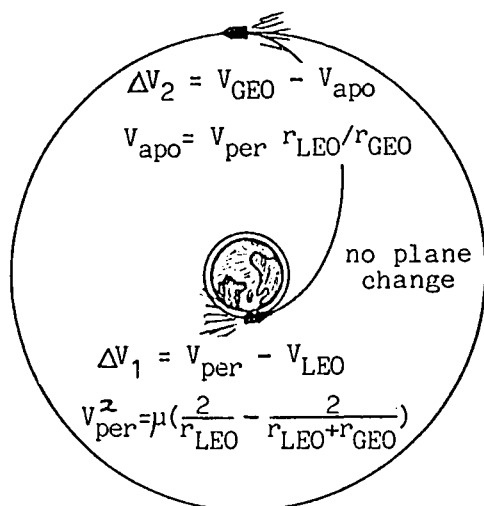
BASIC ORBIT EQUATIONS



ORBITAL ELEMENTS	
a	= semi-major axis
e	= eccentricity
i	= inclination
Ω	= long. of asc. node
ω	= argument of periaapsis
M_0	= position at epoch



Effects of Small ΔV s on Near-Circular Orbits



Total ΔV is minimized when $\frac{\sin \gamma_{LEO}}{\sin \gamma_{GEO}} = \frac{r_{LEO}}{r_{GEO}}$

Large Orbit Transfers (e.g., LEO—GEO)

4.3.2 Orbital Perturbations

KEY POINTS Differential nodal regression severely limits coplanar rendezvous windows. Apsidal recession affects STS deboost requirements from elliptical orbits. Third bodies can change the orbit plane of high-orbit facilities.

The geoid (earth's shape) is roughly that of a hydrostatic-equilibrium oblate ellipsoid, with a 296:297 polar:equatorial radius ratio. There are departures from this shape, but they are much smaller than the 1:297 oblateness effect and have noticeable effects only on geosynchronous and other resonant orbits.

The focus here is on oblateness, because it is quite large and because it has large secular effects on Ω and ω for nearly all orbits. (Oblateness also affects n , but this can usually be ignored in preliminary analyses.) As shown at right, satellites orbiting an oblate body are attracted not only to its center but also towards its equator. This force component imposes a torque on all orbits that cross the equator at an angle, and causes the direction of the orbital angular momentum vector to regress as shown.

$\dot{\Omega}$ is largest when i is small, but the plane change associated with a given $\Delta\Omega$ varies with $\sin i$. Hence the actual plane change rate varies with $\sin i \cos i$, or $\sin 2i$, and is highest near 45° . For near-coplanar rendezvous in LEO, the required out-of-plane ΔV changes by $78 \sin 2i$ m/s for each phasing "lap". This is independent of the altitude difference (to first order), since phasing & differential nodal regression rates both scale with Δa . Hence even at best a rendezvous may require an out-of-plane ΔV of 39 m/s. At other times, out-of-plane ΔV s of $2 \sin i \sin(\Delta\Omega/2) V_{\text{circ}}$ (=up to $2 V_{\text{circ}}$!) are needed.

NOTES The linkage between phasing and nodal regression rates is beneficial in some cases: if an object is boosted slightly and then allowed to decay until it passes below the boosting object, the total $\Delta\Omega$ is nearly identical for both. Hence recapture need not involve any significant plane change.

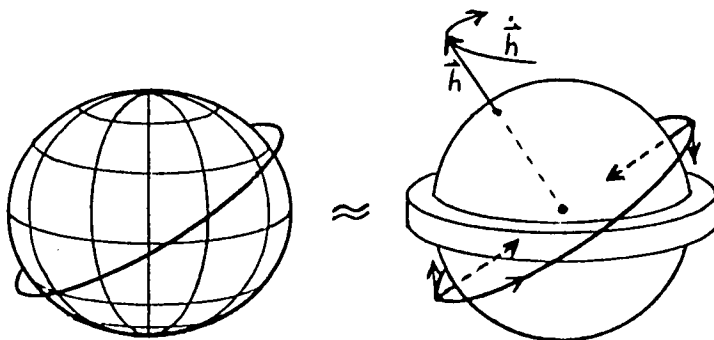
Apsidal recession generally has a much less dominant effect on operations, since apsidal adjustments (particularly of low- e orbits) involve much lower ΔV s than nodal adjustments. However, tether payload boosts may often be done from elliptical STS orbits, and perigee drift may be an issue. For example, OMS deboost requirements from an elliptical STS orbit are tonnes lower (and payload capability much higher) if perigee is near the landing site latitude at the end of the mission. Perigee motion relative to day/night variations is also important for detailed drag calculations, and for electrodynamic day-night energy storage (where it smears out and limits the eccentricity-pumping effect of a sustained day-night motor-generator cycle).

Just as torques occur when the central body is non-spherical, there are also torques when the satellite is non-spherical. These affect the satellite's spin axis and cause it to precess around the orbital plane at a rate that depends on the satellite's mass distribution and spin rate.

In high orbits, central-body perturbations become less important and 3rd-body effects more important. In GEO, the main perturbations (~ 47 m/s/yr) are caused by the moon and sun. The figure at right shows how to estimate these effects, using the 3rd body orbital plane as the reference plane.

-
- REFERENCES**
1. A.E. Roy, Orbital Motion, Adam Hilger Ltd., Bristol, 1978.
 2. Bate, Mueller, & White, Fundamentals of Astrodynamics, Dover Pub., 1971.

Orbital Perturbations



OBLATENESS CAUSES LARGE
SECULAR CHANGES IN $\dot{\Omega}$ & $\dot{\omega}$:

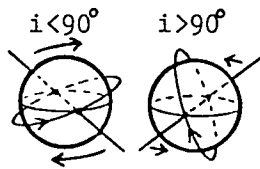
$\dot{\Omega}$: up to 1 rad/week in LEO

$\dot{\omega}$: up to 2 rad/week in LEO

Nodal Regression in LEO:

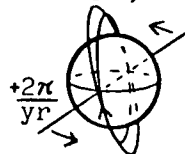
$$\dot{\Omega} \approx \frac{-63.6 \cos i \text{ rad/yr}}{(a/r_e)^{3.5} (1-e^2)^2}$$

$(r_e = 6378 \text{ km})$



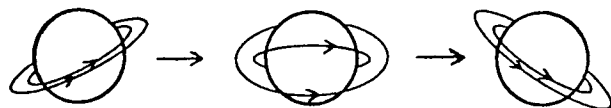
For sun-synchronous orbits: $(i=100^\circ \pm 4^\circ)$

$$\cos i \approx -.0988(a/r_e)^{3.5}(1-e^2)^2$$



For coplanar low- ΔV rendezvous
between 2 objects ($e_1=e_2 \approx 0$, $i_1=i_2$),
nodal coincidence intervals are:

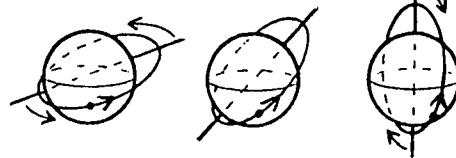
$$\Delta t_{nc} \approx \frac{180 (\bar{a}/r_e)^{4.5}}{\Delta a |\cos i|} \text{ km} \cdot \text{yrs}$$



Apsidal recession in LEO:

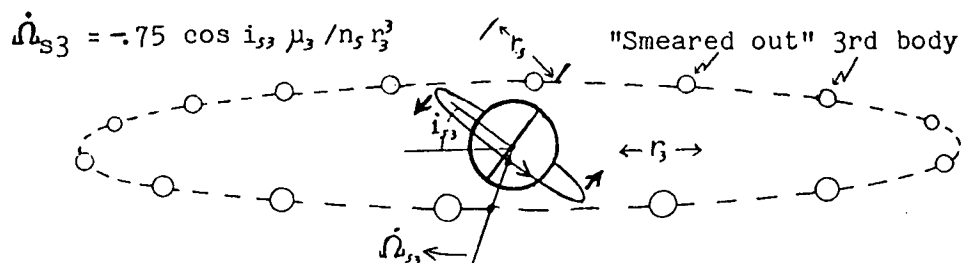
$$\dot{\omega} \approx \frac{63.6(2 - 2.5 \sin^2 i)}{(a/r_e)^{3.5} (1-e^2)^2} \text{ rad/yr}$$

$i < 63.4^\circ$ $i = 63.4^\circ$ $i > 63.4^\circ$



Motion of the longitude of
perigee with respect to the
sun's direction ("noon") is:

$$\bar{\dot{\omega}}_s = \dot{\omega} + \dot{\Omega} - 2\pi/\text{yr}$$



Third-Body Perturbations (non-resonant orbits)

4.3.3 Aerodynamic Drag

KEY POINTS

Tether drag affects tether shape & orbital life; at. oxygen degrades tethers. Out-of-plane drag component can induce out-of-plane tether libration. The main value of payload boosting by tether is the increased orbital life. Unboosted orbital life of space facilities is affected by tether operations.

The figure at right shows the orbiter trolling a satellite in the atmosphere, as is planned for the 2nd TSS mission in the late 1980s. The tether drag greatly exceeds that on the end-masses and should be estimated accurately. The drag includes a small out-of-plane component that can cause ϕ -libration.

Tether drag is experienced over a range of altitudes, over which most of the terms in the drag equation vary: the air density ρ , the airspeed V_{rel} , and the tether width & angle of attack. In free-molecular flow, C_L is small, and C_D (if based on A_{\perp}) is nearly constant at 2.2. (C_D rises near grazing incidence, but then A_{\perp} is low.)

Only ρ varies rapidly, but it varies in a way which lends itself to simple approximations. Empirical formulae have been developed by the author and are shown at right. They give values that are usually within 25% of ref. 1, which is still regarded as representative for air density as a function of altitude & exosphere temperature. These estimates hold only for $\rho > 1E-14$, beyond which helium & hydrogen dominate & the density scale height H increases rapidly.

NOTES

Note that over much of LEO, atomic oxygen is the dominant species. Hyperthermal impact of atomic oxygen on exposed surfaces can cause rapid degradation, and is a problem in low-altitude applications of organic-polymer tethers.

The space age began in 1957 at a 200-yr high in sunspot count. A new estimate of mean solar cycle temperatures (at right, from ref. 2), is much lower than earlier estimates. Mission planning requires both high & mean estimates for proper analysis. Ref. 2 & papers in the same volume discuss models now in use.

If the tether length L is $\ll H$, the total tethered system drag can be estimated from the total A_{\perp} & the midpoint V & ρ . If $L \gg H$, the top end can be neglected, the bottom calculated normally, and the tether drag estimated from $1.1 \rho_{bottom} * \text{tether diameter} * H * V_{rel}^2$, with H & V_{rel} evaluated one H above the bottom of the tether. For L between these cases, the drag is bounded by these cases.

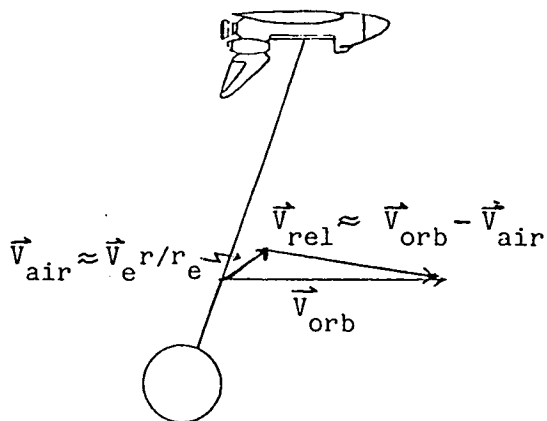
As shown at right, the orbital life of more compact objects (such as might be boosted or deboosted by tether) can be estimated analytically if T_{ex} is known. For circular orbits with the same r , V_{rel} & $\bar{\rho}$ both vary with i , but these variations tend to compensate & can both be ignored in first-cut calculations.

The conversion of elliptical to "equal-life" circular orbits is an empirical fit to an unpublished parametric study done by the author. It applies when apsidal motions relative to the equator and relative to the diurnal bulge are large over the orbital life; this usually holds in both low & high- i orbits. For a detailed study of atmospheric drag effects, ref. 3 is still useful.

REFERENCES

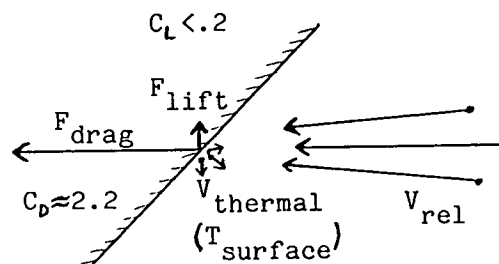
1. U.S. Standard Atmosphere Supplements, 1966. ESSA/NASA/USAF, 1966.
2. K.S.W Champion, "Properties of the Mesosphere and Thermosphere and Comparison with CIRA 72", in The Terrestrial Upper Atmosphere, Champion and Roemer, ed.; Vol 3, #1 of Advances in Space Research, Pergamon, 1983.
3. D.G. King-Hele, Theory of Satellite Orbits in an Atmosphere, Butterworths, London, 1964.

Aerodynamic Drag



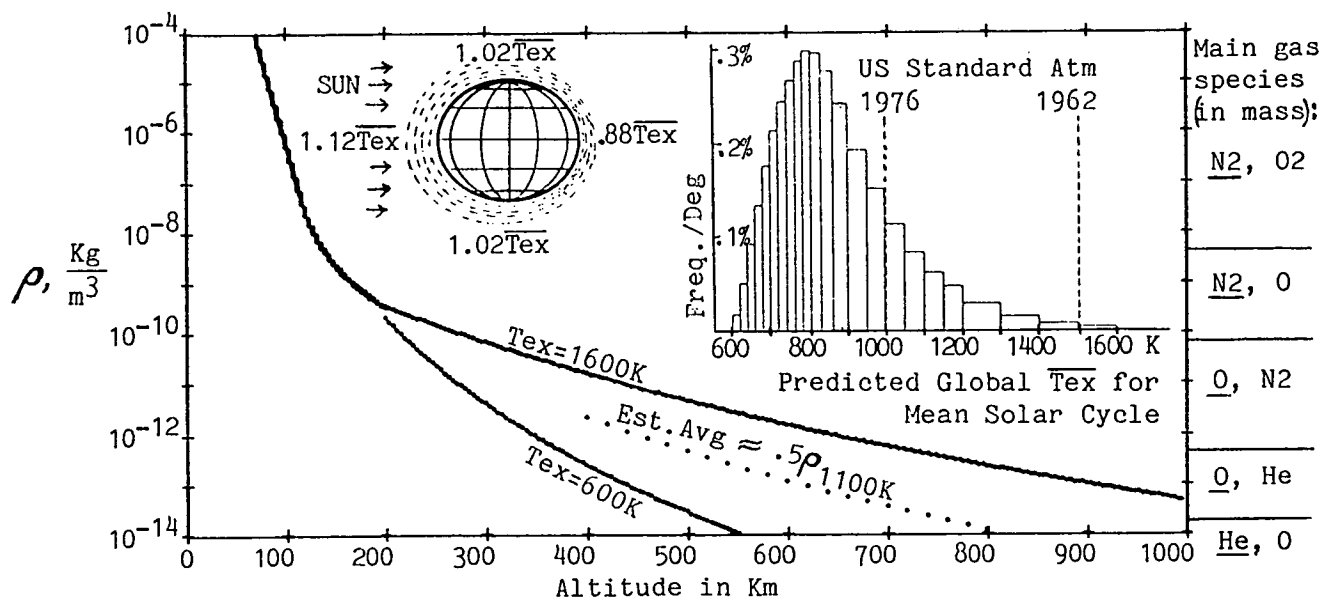
$$F_{drag} = .5 \int \rho C_D V_{rel}^2 \text{ Width } \delta r$$

$$V_e = .465 \cos(\text{Lat}) \text{ km/sec}$$



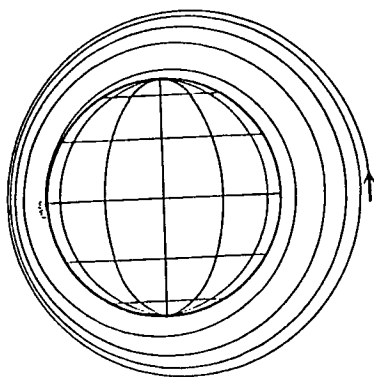
Lift & Drag in Free-Molecular Flow

$$(\bar{\lambda} \gg D_{tether}; \bar{\lambda} \approx \frac{10^{-7} \text{ kg/m}^2}{\rho})$$



Air Density as Function of Altitude & Exosphere Temperature

$70 < \text{Alt} < 118$	$\rho \approx 11 \exp(-\text{Alt}/6)$	$-\rho/\dot{\rho} = H = 6 \text{ (km)}$
$118 < \text{Alt} < 200$	$\rho \approx (\text{Alt}-95)^{-3}/2600$	$H = (\text{Alt}-95)/3$
$200 < \text{Alt}$	$\rho \approx \frac{1.47 \text{E}-16 \text{ Tex}(3000-\text{Tex})}{(1+2.9(\text{Alt}-200)/\text{Tex})^{10}}$	$H = .1(\text{Alt}-200) + \text{Tex}/29$
$\rho > 1 \text{E}-14$		



$$\text{Circular Orbit Life} \approx \frac{.15 \text{ m}^2 \text{ yr}}{\text{kg}} \frac{M}{C_D A} \frac{(1 + 2.9(r-6578)/\text{Tex})^{11}}{3000 - \text{Tex}}$$

$(-14 < \text{Log } \rho < -10)$

$$\text{Equal-Life Circ. Alt.} \approx \text{Perigee} + \frac{\text{Apo} - \text{Per}}{2 + .154(\text{Apo} - \text{Per})/H_{\text{Per}}}$$

4.3.4 Thermal Balance

KEY POINTS Aerothermal heating of tethers is severe at low altitudes (<120 km). Tether temperature affects strength, toughness, & electrical conductivity. Extreme thermal cycling may degrade pultruded composite tethers. "View factors" are also used in refined micrometeoroid risk calculations.

Preliminary heat transfer calculations in space are often far simpler than typical heat transfer calculations on the ground, since the complications introduced by convection are absent. However the absence of the "clamping" effect of large convective couplings to air or liquids allows very high or low temperatures to be reached, and makes thermal design important.

At altitudes below about 140 km in LEO, aerodynamic heating is the dominant heat input on surfaces facing the ram direction. The heating scales with ρ as long as the mean free path λ is much larger than the object's radius. It is about equal to the energy dissipated in stopping incident air molecules. In denser air, shock & boundary layers develop. They shield the surface from the incident flow and make \dot{Q} rise slower as ρ increases further. (See ref 1.)

Because tethers are narrow, they can be in free molecular flow even at 100 km, and may experience more severe heating than the (larger) lower end masses do. Under intense heating high temperature gradients may occur across non-metallic tethers. These gradients may cause either overstress or stress relief on the hot side, depending on the sign of the axial thermal expansion coefficient.

NOTES At higher altitudes the environment is much more benign, but bare metal (low-emittance) tethers can still reach high temperatures when resistively heated or in the sun, since they radiate heat poorly. Silica, alumina, or organic coatings >1 μm thick can increase emittance and hence reduce temperatures. The temperature of electrodynamic tethers is important since their resistance losses (which may be the major system losses) scale roughly with T_{abs} .

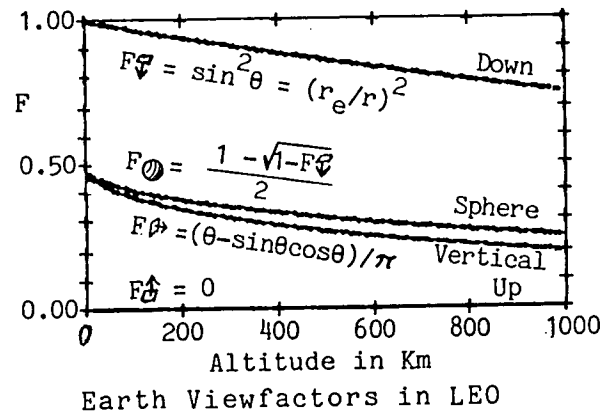
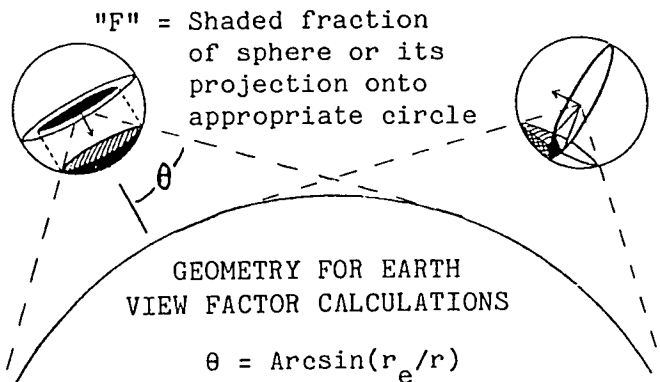
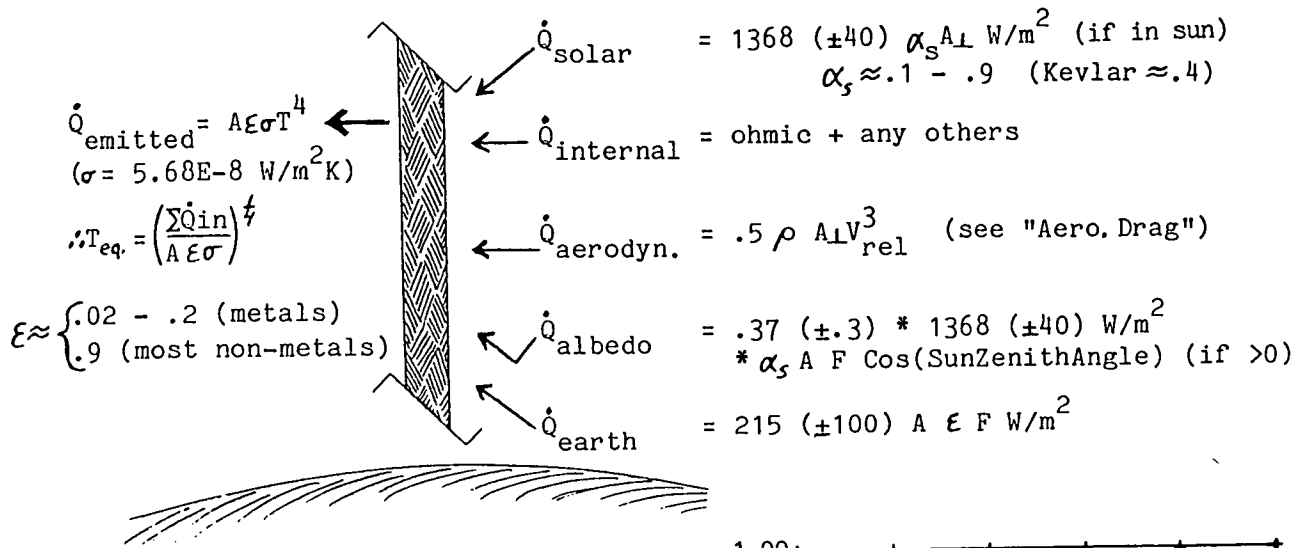
For a good discussion of solar, albedo, and longwave radiation, see ref. 2. The solid geometry which determines the gains from these sources is simple but subtle, and should be done carefully. Averaged around a tether, earth view-factors change only slowly with altitude & attitude, and are near .3 in LEO.

Surface property changes can be an issue in long-term applications, due to the effects of atomic oxygen, UV & high-energy radiation, vacuum, deposition of condensible volatiles from nearby surfaces, thermal cycling, etc. Hyper-thermal atomic oxygen has received attention only recently, and is now being studied in film, fiber, and coating degradation experiments on the STS & LDEF.

Continued thermal cycling over a wide range (such as shown at bottom right) may degrade composite tethers by introducing a maze of micro-cracks. Also, temperature can affect the strength, stiffness, shape memory, and toughness of tether materials, and hence may affect tether operations and reliability.

-
- REFERENCES**
1. R.N. Cox & L.F. Crabtree, Elements of Hypersonic Aerodynamics, The English Universities Press Ltd, London, 1965. See esp. Ch 9, "Low Density Effects"
 2. F.S. Johnson, ed., Satellite Environment Handbook, Second Edition, Stanford University Press, 1965. See chapters on solar & earth thermal radiation.
 3. H.C. Hottel, "Radiant Heat Transmission," Chapter 4 of W.H. McAdams, HEAT TRANSMISSION, 3rd edition, McGraw-Hill, New York, 1954, pp. 55-125.

Thermal Balance

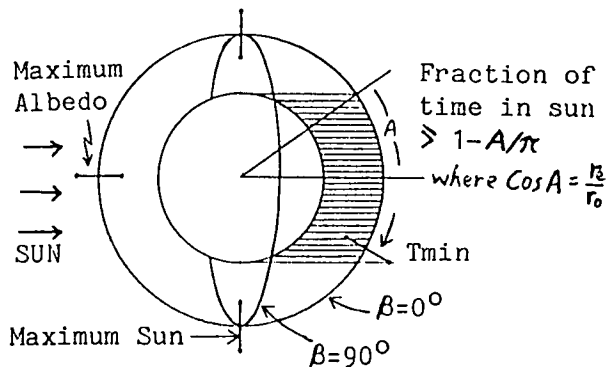


$$F_{\parallel} = F_{\rightarrow}$$

$$F_{\rightarrow} \approx (F_{\uparrow} + F_{\downarrow} + 2F_{\rightarrow})/4$$

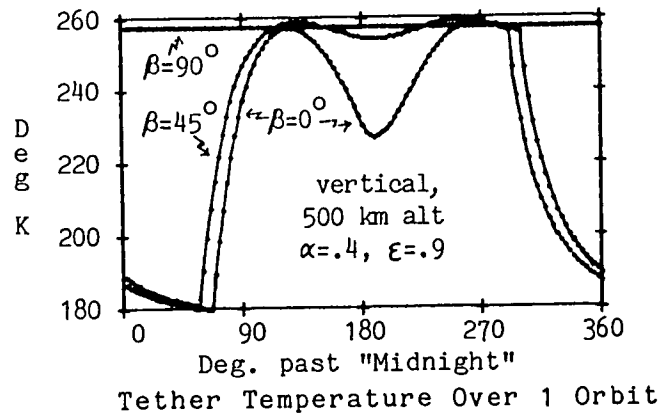
$$F_{\parallel} < F_{\rightarrow} < F_{\leftarrow}$$

Earth Viewfactors for Tethers



Inclination	β Range
0°	$0-23.5^\circ$
28.5°	$0-52^\circ$
$>66.5^\circ$	$0-90^\circ$

(β = Sun out-of-plane angle)



4.3.5 Micrometeoroids and Debris

KEY POINTS Micrometeoroids can sever thin tethers & damage tether protection/insulation. Orbiting debris can sever tethers of any diameter.

At the start of the space age, estimates of meteoroid fluxes varied widely. Earth was thought to have a dust cloud around it, due to misinterpretation of data such as microphone noise caused by thermal cycling in spacecraft. By the late 1960s most meteoroids near earth were recognized to be in heliocentric rather than geocentric orbit. The time-averaged flux is mostly sporadic, but meteor showers can be dominant during their occurrence.

There is a small difference between LEO and deep-space fluxes, due to the focusing effect of the earth's gravity (which increases the velocity & flux), and the partial shielding provided by the earth & "sensible" atmosphere. For a typical meteoroid velocity of 20 km/sec, these effects combine to make the risk vary as shown at right in LEO, GEO, and beyond. The picture of a metal plate after hypervelocity impact is adapted from ref. 3.

NOTES

The estimated frequency of sporadic meteoroids over the range of interest for most tether applications is shown by the straight line plot at right, which is adapted from ref. 4 & based on ref. 1. (Ref 1 is still recommended for design purposes.) For masses $< 1\text{E}-6$ gm ($< .15$ mm diam. at an assumed density of .5), the frequency is lower than an extension of that line, since several effects clear very small objects from heliocentric orbits in geologically short times.

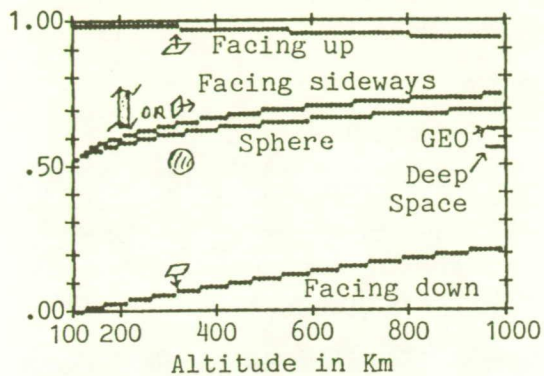
Over an increasing range of altitudes and particle sizes in LEO, the main impact hazard is due not to natural meteoroids but rather to man-made objects. The plots at right, adapted from refs 4 & 5, show the risks presented by the 5,000 or so objects tracked by NORAD radars (see ref. 6). A steep "tail" in the 1995 distribution is predicted since it is likely that several debris-generating impacts will have occurred in LEO before 1995. Such impacts are expected to involve a 4-40 cm object striking one of the few hundred largest objects and generating millions of small debris fragments.

Recent optical detection studies which have a size threshold of about 1 cm indicate a population of about 40,000 objects in LEO. This makes it likely that debris-generating collisions have already occurred. Studies of residue in small surface pits on the shuttle and other objects recovered from LEO indicate that they appear to be due to titanium, aluminum, and paint fragments (perhaps flaked off satellites by micrometeoroid hits). Recovery of the Long Duration Exposure Facility (LDEF) later this year should improve this database greatly, and will provide data for LEO exposure area-time products comparable to those in potential long-duration tether applications.

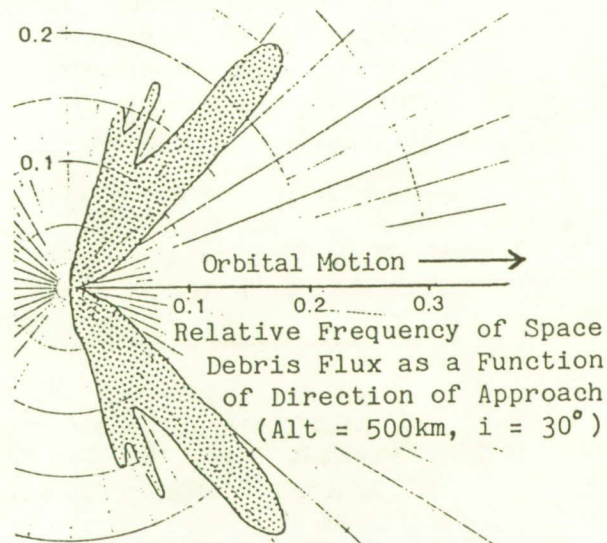
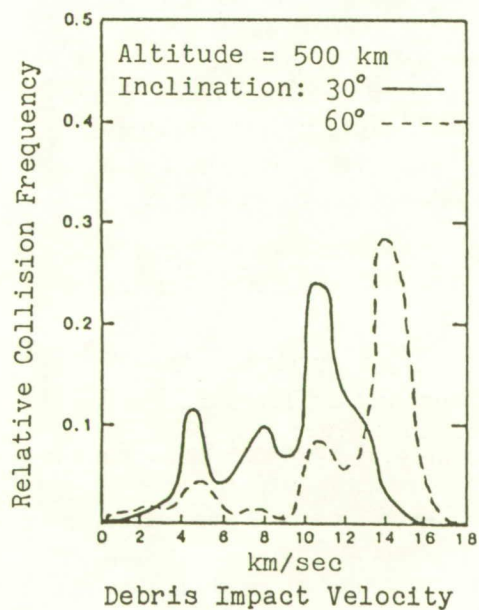
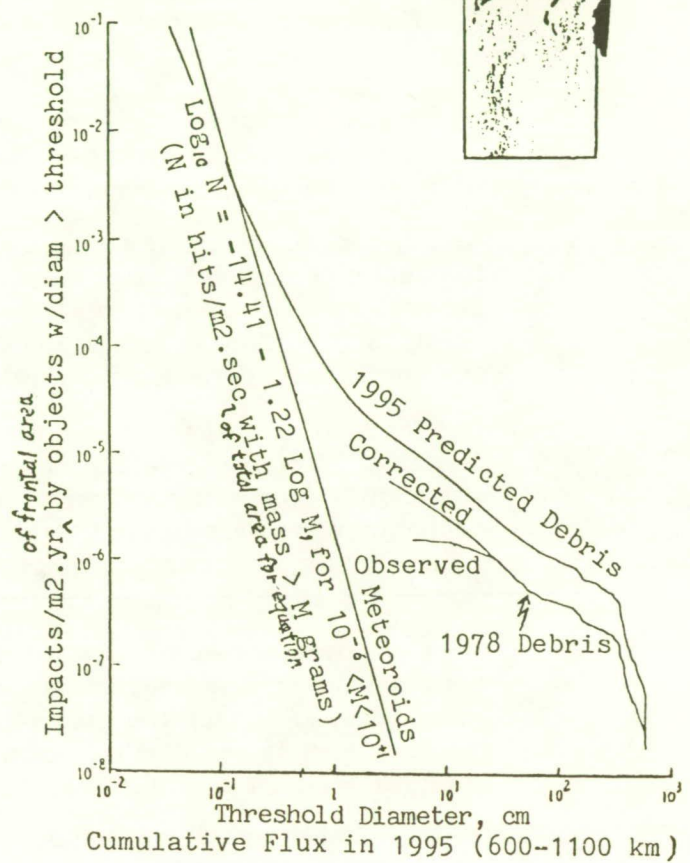
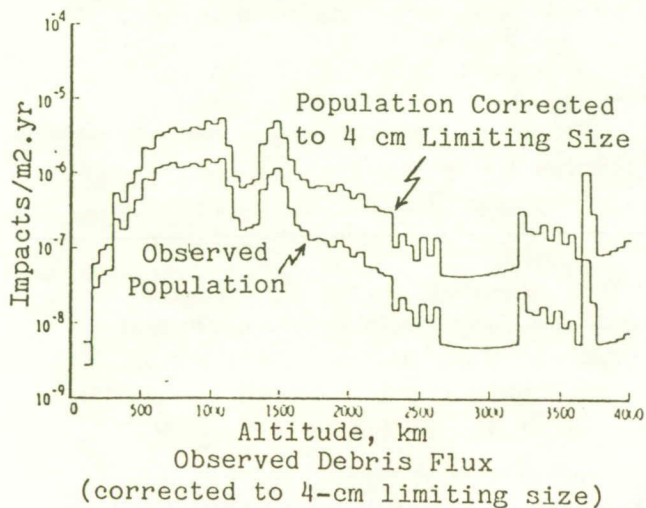
REFERENCES

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1. Meteoroid Environment Model—1969 [Near Earth to Lunar Surface], NASA SP-8013, March 1969.
 2. Meteoroid Environment Model—1970 [Interplanetary and Planetary], NASA SP-8038, October 1970.
 3. Meteoroid Damage Assessment, NASA SP-8042, May 1970. Shows impact effects.
 4. D.J. Kessler, "Sources of Orbital Debris and the Projected Environment for Future Spacecraft", in J. of Spacecraft & Rockets, Vol 18 #4, Jul-Aug 1981.
 5. D.J. Kessler, Orbital Debris Environment for Space Station, JSC-20001, 1984.
 6. CLASSY Satellite Catalog Compilations. Issued monthly by NORAD/J5YS, Peterson Air Force Base, CO 80914.

Micrometeoroids & Debris



$$[\text{RelRisk} \approx (1 - F_{\text{earth}})(.57 + .43r_e/r)]$$



4.4 Tether Dynamics and Control

4.4.1 Gravity Gradient Effects

KEY POINTS "Microgee" environments are possible only in small regions (~5 m) of a LEO facility. Milligee-level gravity is easy to get & adequate for propellant settling, etc.

The figure at right shows the reason for gravity-gradient effects. The long tank-like object is kept aligned with the local vertical, so that the same end always faces the earth as it orbits around it. If one climbs from the bottom to the top, the force of gravity gradually decreases and the centrifugal force due to orbital motion increases. Those forces cancel out only at one altitude, which is (nearly but not exactly) the altitude of the vehicle's center of mass.

At other locations an object will experience a net force vertically away from the center of mass (or a net acceleration, if the object is allowed to fall). This net force is referred to as the "gravity-gradient force." (But note that 1/3 of the net force is actually due to a centrifugal force gradient!) Exact and approximate formulas for finding the force on an object are given at right.

NOTES

The force occurs whether or not a tether is present, and whether or not it is desirable. Very-low-acceleration environments, which are needed for some types of materials processing and perhaps for assembling massive structures, are only available over a very limited vertical extent, as shown at right. Putting a vehicle into a slow retrograde spin can increase the "height" of this low-gee region, but that then limits the low-gee region's other in-plane dimension.

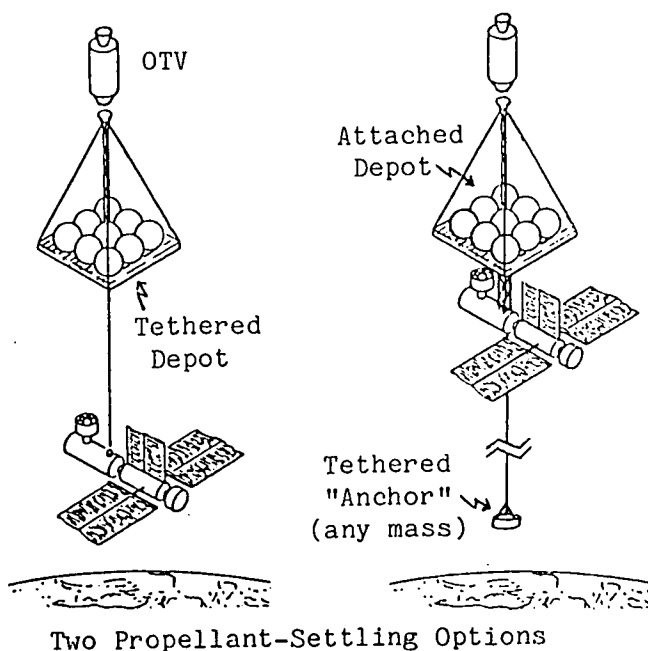
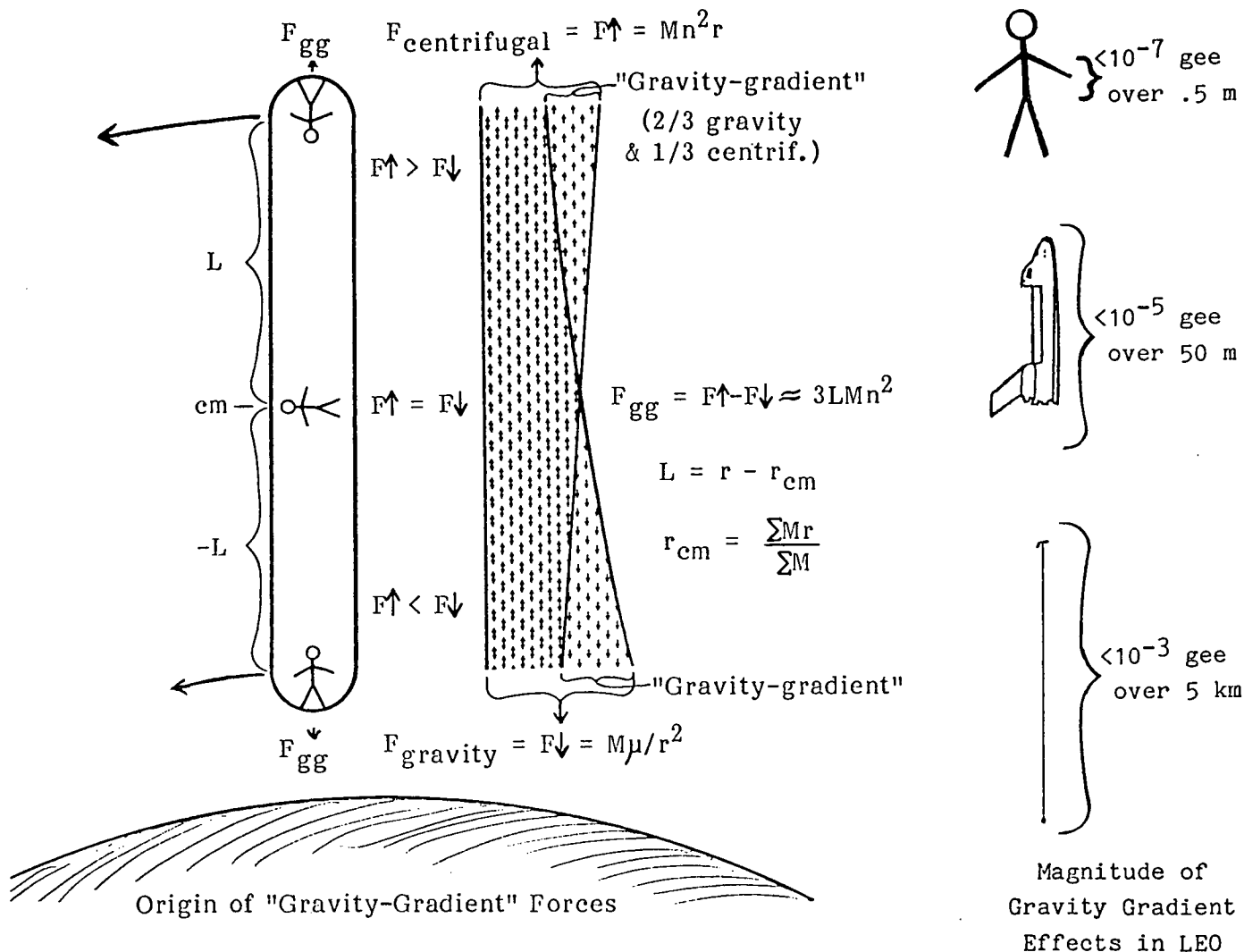
Since gravity gradients in low orbits around various bodies vary with μ/r^3 , the gradients are independent of the size of the body, and linearly dependent on its density. Hence the gradients are highest (.3-.4 milligee/km) around the inner planets and Earth's moon, and 60-80% lower around the outer planets. In higher orbits, the effect decreases rapidly (to 1.6 microgee/km in GEO).

The relative importance of surface tension and gravity determines how liquids behave in a tank, and is quantified with the Bond number, $Bo = \rho a r^2 / \sigma$. If $Bo > 10$, liquids will settle, but higher values ($Bo = 50$) are proposed as a conservative design criterion.² On the other hand, combining a small gravity gradient effect ($Bo < 10$) with minimal surface-tension fluid-management hardware may be more practical than either option by itself. Locating a propellant depot at the end of a power-tower structure might provide an adequate gravity-gradient contribution. If higher gravity is desired, but without deploying the depot, another option is to deploy an "anchor" mass on a tether, as shown at right.

Many nominally "zero-gee" operations such as electrophoresis may actually be compatible with useful levels of gravity (i.e., useful for propellant settling, simplifying hygiene activities, keeping objects in place at work stations, etc). This needs to be studied in detail to see what activities are truly compatible.

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- REFERENCES**
1. D. Arnold, "General Equations of Motion," Appendix A of Investigation of Electrodynamical Stabilization and Control of Long Orbiting Tethers, Interim Report for Sept 1979 — Feb 1981, Smithsonian Astrophys. Observ., March 1981.
 2. K.R. Kroll, "Tethered Propellant Resupply Technique for Space Stations," IAF-84-442, presented at the 35th IAF Congress, Lausanne Switzerland, 1984.

Gravity Gradient Effects



Crystal Growth	→ ?	? ← Calcium Retention
Latex Reactors	→ ?	? ← Walking
Electrophoresis	→ ?	? ← "Desktop" work
LSS Assembly	→ ?	? ← Eating, Hygiene
	→ ?	? ← Fluid Settling
Microgravity		Full Gravity
		10^{-3} G

Potential Overlap of Regions for Low-Gee & Gee-Dependent Operations

4.4.2 Dumbbell Libration in Circular Orbit

KEY POINTS Libration periods are independent of length, but increase at large amplitude. Out-of-plane libration can be driven by weak forces that have a $2n$ component. Tethers can go slack if $\theta_{\max} > 65^\circ$ or $\phi_{\max} > 60^\circ$.

The two figures at right show the forces on a dumbbell in circular orbit which has been displaced from the vertical, and show the net torque on the dumbbell, returning it towards the vertical. The main difference between the two cases is that the centrifugal force vectors are radial in the in-plane case, and parallel in the out-of-plane case. This causes the net force in the out-of-plane case to have a smaller axial component and a larger restoring component, and is why ϕ -libration has a higher frequency than θ -libration.

Four aspects of this libration behavior deserve notice. First, the restoring forces grow with the tether length, so libration frequencies are independent of the tether length. Thus tether systems tend to librate "solidly", like a dumbbell, rather than with the tether trying to swing faster than the end-masses as can be seen in the chain of a child's swing. (This does not hold for very long tethers, since the gravity gradient itself varies.) For low orbits around any of the inner planets or the moon, libration periods are roughly an hour.

NOTES Second, tethered masses would be in free-fall except for the tether, so the sensed acceleration is always along the tether (as shown by the stick-figures). Third, the axial force can become negative, for $\phi > 60^\circ$ or near the ends of retrograde in-plane librations $> 65.9^\circ$. This may cause problems unless the tether is released, or retrieved at an adequate rate to prevent slackness.

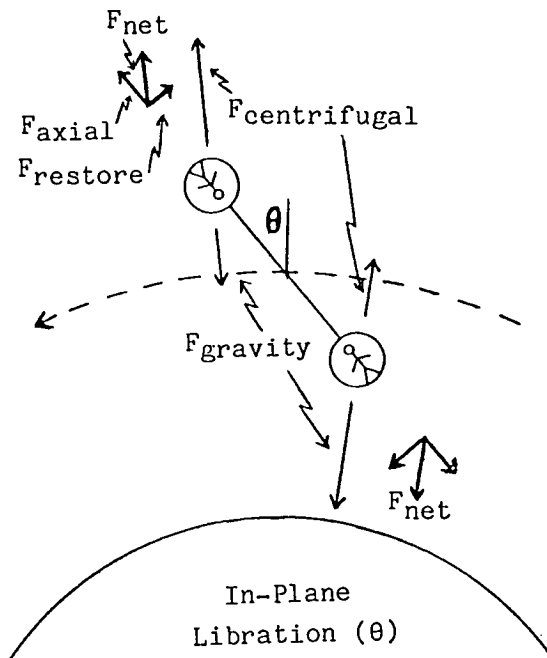
And fourth, although θ -libration is not close to resonance with any significant driving force, ϕ -libration is in resonance with several, such as out-of-plane components of aerodynamic forces (in non-equatorial orbits that see different air density in northward and southward passes) or electrodynamic forces (if tether currents varying at the orbital frequency are used). The frequency droop at large amplitudes (shown at right) sets a finite limit to the effects of weak but persistent forces, but this limit is quite high in most cases.

The equations given at right are for an essentially one-dimensional structure, with one principal moment of inertia far smaller than the other two: $A \ll B < C$. If A is comparable to B & C , then the θ -restoring force shrinks with $(B-A)/C$, and the θ -libration frequency by $\sqrt{(B-A)/C}$. Another limitation is that a coupling between ϕ & θ behavior (see ref. 1) has been left out. This coupling is caused by the variation of end-mass altitudes twice in each ϕ -libration. This induces Coriolis accelerations that affect θ . This coupling is often unimportant, since $4n$ is far from resonance with $1.73n$.

Libration is referenced to the local vertical, and when a dumbbell is in an eccentric orbit, variations in the orbital rate cause librations which in turn exert periodic torques on an initially uniformly-rotating object. In highly eccentric orbits this can soon induce tumbling.²

- REFERENCES**
1. D. Arnold, "General Equations of Motion," Appendix A of Investigation of Electrodynamic Stabilization and Control of Long Orbiting Tethers, Interim Report for Sept 1979—Feb 1981, Smithsonian Astrophys. Observ., March 1981.
 2. P.A. Swan, "Dynamics & Control of Tethers in Elliptical Orbits," IAF-84-361, presented at the 35th IAF Congress, Lausanne, Switzerland, October 1984.

Dumbbell Libration in Circular Orbit

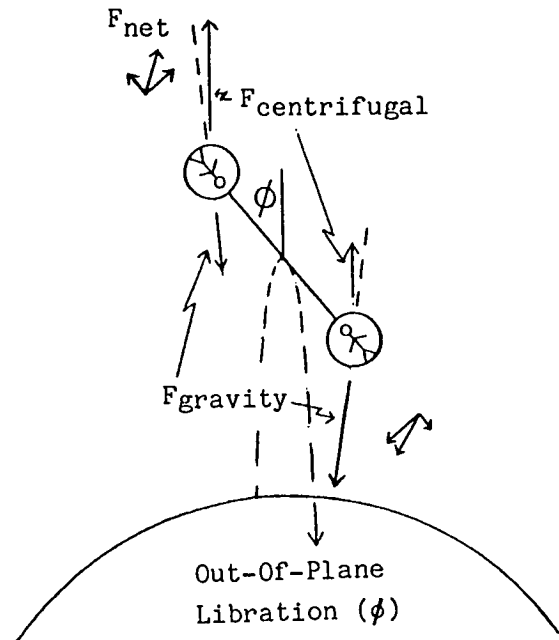


$$\ddot{\theta} \approx -3n^2 \sin\theta \cos\theta = -1.5n^2 \sin(2\theta)$$

$$\dot{\theta} \approx \pm \sqrt{3} n \sqrt{\sin^2 \theta_{\max} - \sin^2 \theta}$$

$$(\dot{\theta} \approx \pm \sqrt{3} n \sin \theta_{\max} \text{ when } \theta=0)$$

$$n_{\theta} \approx n \sqrt{3 \cos \theta_{\max}}$$

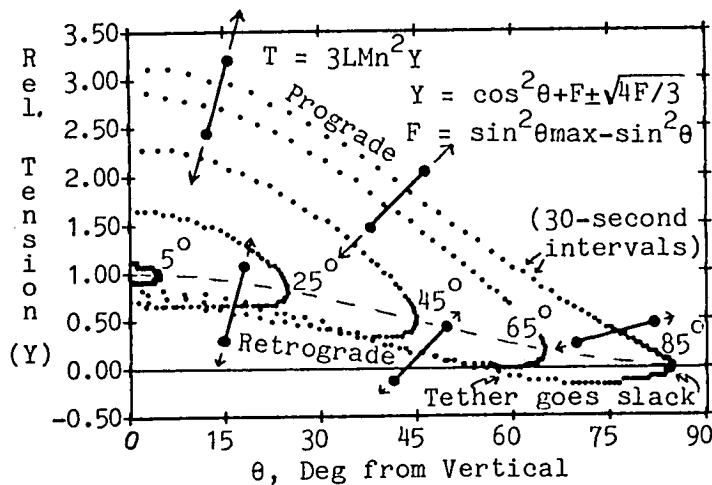


$$\ddot{\phi} \approx -4n^2 \sin\phi \cos\phi = -2n^2 \sin(2\phi)$$

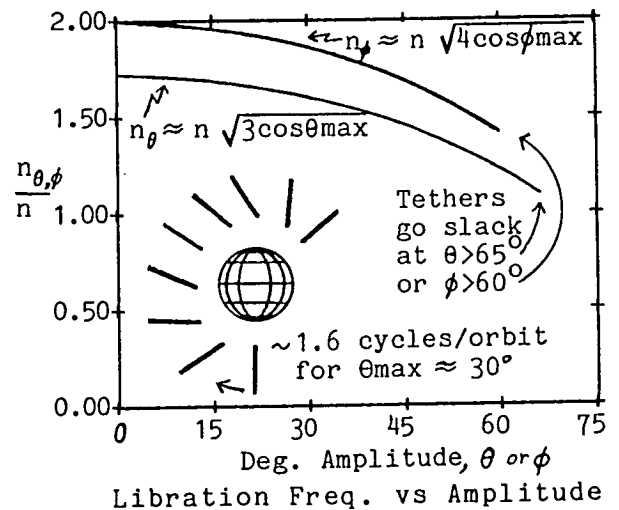
$$\dot{\phi} \approx \pm 2n \sqrt{\sin^2 \phi_{\max} - \sin^2 \phi}$$

$$(\dot{\phi} \approx \pm 2n \sin \phi_{\max} \text{ when } \phi=0)$$

$$n_{\phi} \approx 2n \sqrt{\cos \phi_{\max}}$$



Tension Variations in Librating Dumbbells
(compared to tension in hanging dumbbells)



Libration Freq. vs Amplitude

4.4.3 Tether Control Strategies

KEY POINTS Open-loop control is adequate for deployment; full retrieval requires feedback. Tension laws can control θ & ϕ -libration plus tether oscillations. Many other options exist for libration, oscillation, & final retrieval control.

The table at right shows half a dozen distinct ways in which one or more aspects of tethered system behavior can be controlled. In general, anything which can affect system behavior (and possibly cause control problems) can be part of the solution, if it itself can be controlled without introducing other problems.

Thus, for example, stiff tethers have sometimes been considered undesirable, because the stiffness competes with the weak gravity-gradient forces near the end of retrieval. However, if the final section of tether is stiff AND nearly straight when stress-free (rather than pig-tail shaped), then "springy beam" control laws using a steerable boom tip might supplement or replace other laws near the end of retrieval. A movable boom has much the same effect as a stiff tether & steerable boom tip, since it allows the force vector to be adjusted.

NOTES The basic concepts behind tension-control laws are shown at right. Libration damping is done by paying out tether when the tension is greater than usual and retrieving it at other times. This absorbs energy from the libration. As shown on the previous page, in-plane libration causes large variations in tension (due to the Coriolis effect), so "yoyo" maneuvers can damp in-plane librations quickly. Such yoyo maneuvers can be superimposed on deployment and retrieval, to allow large length changes ($>4:1$) plus large in-plane libration damping (or initiation) in less than one orbit, as proposed by Swet.¹

Retrieval laws developed for the TSS require more time than Ref. 1, because they also include damping of out-of-plane libration built up during stationkeeping. Rupp developed the first TSS control law in 1975;² much of the work since then is reviewed in (3). Recent TSS control concepts combine tension and thrust control laws, with pure tension control serving as a backup in case of thruster failure.⁴ Axial thrusters raise tether tension when the tether is short, while others control yaw & damp out-of-plane libration to allow faster retrieval.

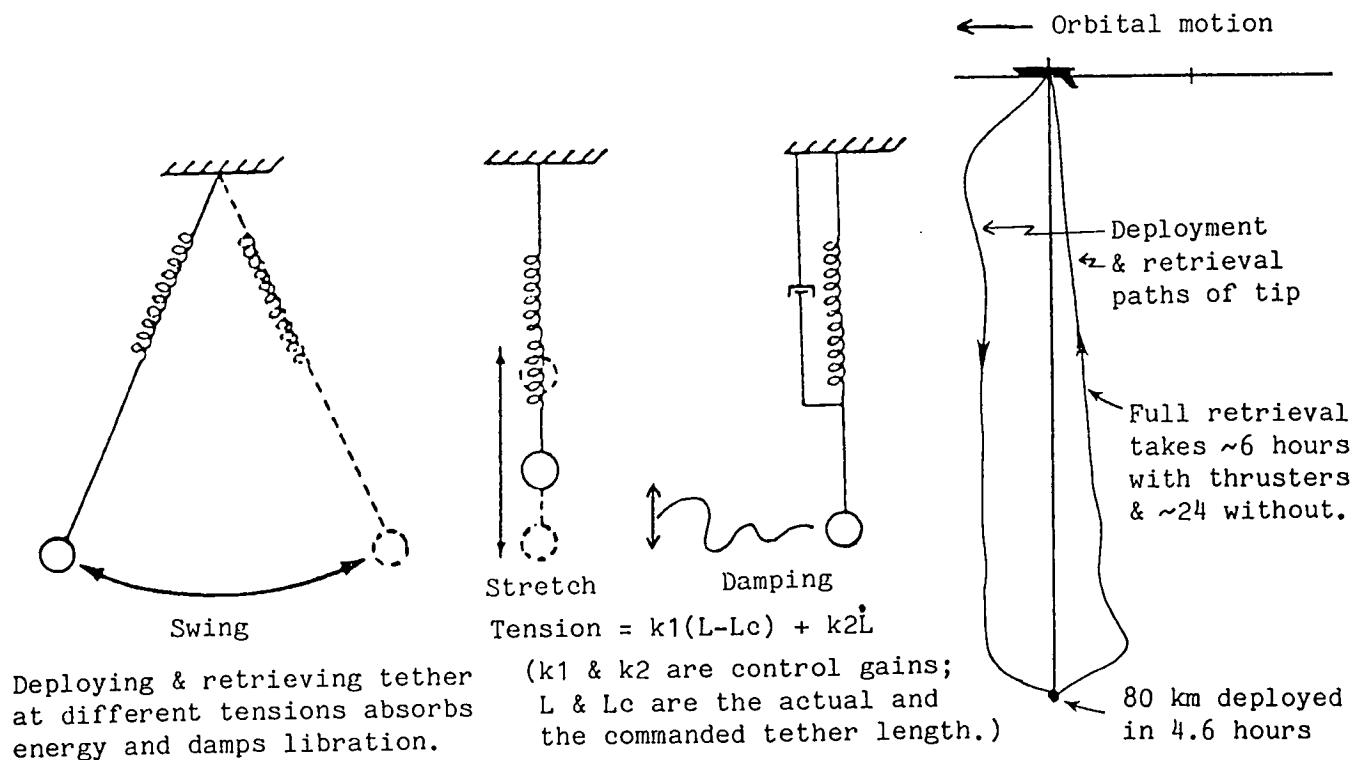
A novel concept which in essence eliminates the final low-tension phase of retrieval is to have the end mass climb up the tether.⁵ Since the tether itself remains deployed, its contribution to gravity-gradient forces and stabilization remains. The practicality of this will vary with the application.

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- REFERENCES**
1. C.J. Swet, "Method for Deploying and Stabilizing Orbiting Structures", U.S. Patent #3,532,298, October 6, 1970.
 2. C.C. Rupp, A Tether Tension Control Law for Tether Subsattellites Deployed Along Local Vertical, NASA TM X-64963, MSFC, September 1, 1975.
 3. V.J. Modi, Geng Chang-Fu, A.K. Misra, and Da Ming Xu, "On the Control of the Space Shuttle Based Tethered Systems," *Acta Astronautica*, Vol. 9, No. 6-7, pp. 437-443, 1982.
 4. A. K. Banerjee and T.R. Kane, "Tethered Satellite Retrieval with Thruster Augmented Control," AIAA 82-1-21, presented at the AIAA/AAS Astrodynamics Conference, San Diego, Calif., 1982.
 5. T.R. Kane, "A New Method for the Retrieval of the Shuttle-Based Tethered Satellite," *J. of the Astronaut. Sci.*, Vol 32, No. 3, July-Sept. 1984.

Tether Control Strategies

EFFECTIVENESS OF VARIOUS CONTROL CONCEPTS

APPLICATION CONTROL OUTPUT	Libration		Tether Oscillations		Endmass Attitude Osc.	
	In-plane	Out-of-plane	Longitudinal	Transverse	Pitch & Roll	Yaw
Tension	Strong	Weak (Note: tension control is weak when tether is short)	Strong	Strong	Strong	None
El. Thrust	Only if $M1 \neq M2$		None	Only odd harmonics	None	None
Thruster	Strong, but costly if prolonged			None	Strong, but costly if prolonged	
Movable mass	Good w/short tether		Possible but awkward		None	None
Stiff tether, Movable boom	Strong if tether is very short; weak otherwise					
Aerodynamic	High drag—use only if low altitude needed for other reasons.					



TENSION CONTROL FOR LIBRATION DAMPING... AND DEPLOYMENT/RETRIEVAL

4.4.4 Momentum Transfer Without Release

KEY POINTS Tethers merely redistribute angular momentum; they do not create it. Changes in tether length, libration, and spin all redistribute momentum. Momentum transfer out-of-plane or in deep space is possible but awkward.

The two figures at right show two different tether deployment (and retrieval) techniques. In both cases, the initial deployment (which is not shown) is done with RCS burns or a long boom. In the case at left, the tether is paid out under tension slightly less than the equilibrium tension level for that tether length. The tether is slightly tilted away from the vertical during deployment, and librates slightly after deployment is complete.

In the other case, after the initial near-vertical separation (to about 2% of the full tether length), the two end masses are allowed to drift apart in near-free-fall, with very low but controlled tension on the tether. Just under one orbit later, the tether is almost all deployed and the range rate decreases to a minimum (due to orbital mechanics). RCS burns or tether braking are used to cushion the end of deployment and prevent end mass recoil. Then the tether system begins a large-amplitude prograde swing towards the vertical.

NOTES In both cases, the angular momentum transferred from one mass to the other is simply, as stated in the box, the integral over time of the radius times the horizontal component of tether tension. In one case, transfer occurs mainly during deployment; in the other, mainly during the libration after deployment. In each case, momentum transfer is greatest when the tether is vertical, since the horizontal component of tether tension changes sign then.

An intermediate strategy—deployment under moderate tension—has also been investigated.¹ However, this technique results in very high deployment velocities and large rotating masses. It also requires powerful brakes and a more massive tether than required with the other two techniques.

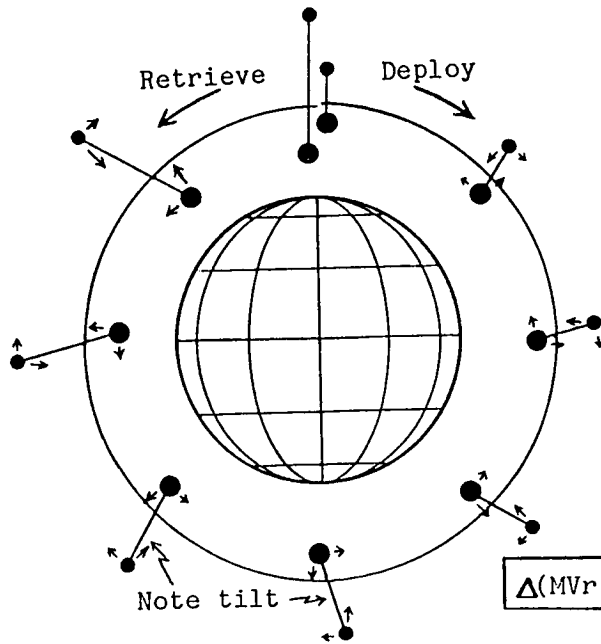
As discussed under Tether Control Strategies, changing a tether's length in resonance with variations in tether tension allows pumping or damping of libration or even spin. Due to Coriolis forces, in-plane libration and spin cause far larger tension variations than out-of-plane libration or spin, so in-plane behavior is far easier to adjust than out-of-plane behavior. Neglecting any parasitic losses in tether hysteresis & the reel motor, the net energy needed to induce a given libration or spin is simply the system's spin kinetic energy relative to the local vertical, when the system passes through the vertical.

Two momentum transfer techniques which appear applicable for in-plane, out-of-plane, or deep-space use are shown at right. The winching operation can use lighter tethers than other tethered-momentum-transfer techniques, but requires a very powerful deployer motor. The tangential ΔV simply prevents a collision.

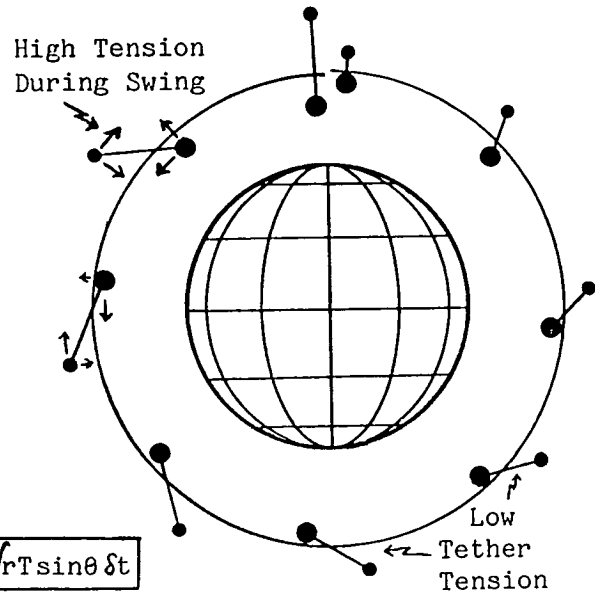
The spin-up operation (proposed by Harris Mayer) is similar to the winching operation. It uses a larger tangential ΔV , a tether with straight and tapered sections, and a small motor. Retrieval speeds up the spin by a factor of L^{-2} . Surprisingly, the long tapered section of tether can be less than half as massive as the short straight section that remains deployed after spin-up.

REFERENCE 1. J. Tschirgi, "Tether-Deployed SSUS-A, report on NASA Contract NAS8-32842, McDonnell Douglas, April 1984.

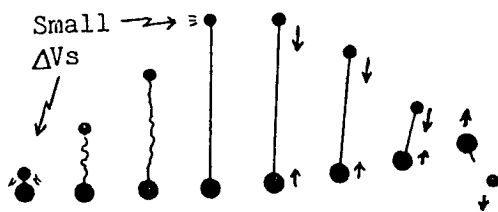
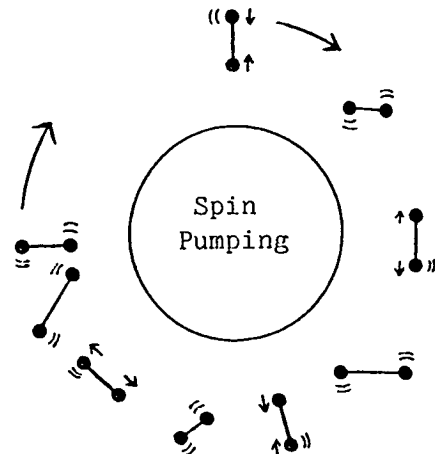
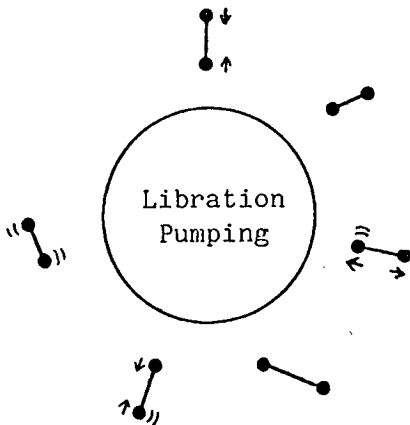
Momentum Transfer



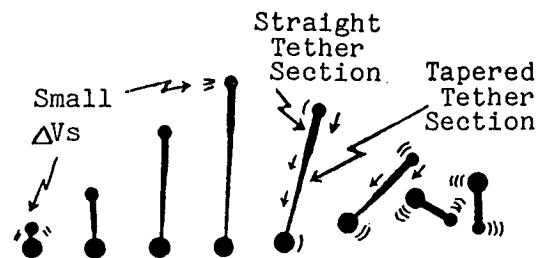
Momentum Transfer During
Deployment & Retrieval



Momentum Transfer During Libration
(after low-tension deployment)



Deployment Followed by Winching
(in orbit or in deep space)



One Spin-Up Technique
For Use in Deep Space

4.4.5 Orbit Transfer by Release or Capture

KEY POINTS The achievable orbit change scales with the tether length (as long as $\Delta r \ll r$). Retrograde-libration releases are inefficient, but allow concentric orbits. Apogee & perigee boosts have different values in different applications. Tethered capture can be seen as a time-reversal of a tether release operation.

The figures to the right show the size of the orbit changes caused by various tether operations. When released from a vertical tether, the end masses are obviously one tether length apart in altitude. The altitude difference 1/2 orbit later, Δr , varies with the operation but is usually far larger. The linear relationship shown becomes inaccurate when Δr approaches r . Tethered plane changes are generally limited to a few degrees and are not covered here.

Tether release leaves the center-of-mass radius at each phase angle roughly unchanged: if the upper mass is heavier, then it will rise less than the lower mass falls, and vice-versa. Note that the libration amplitude, θ_{\max} , is taken as positive during prograde libration & negative during retrograde libration. Hence retrograde libration results in $\Delta r < 7L$. In particular, the pre-release & post-release orbits will all be concentric if $\theta_{\max} = -60^\circ$. But since methods of causing -60° librations usually involve $+60^\circ$ librations (which allow much larger boosts by the same tether), prograde releases may usually be preferable unless concentric orbits are needed or other constraints enter in.

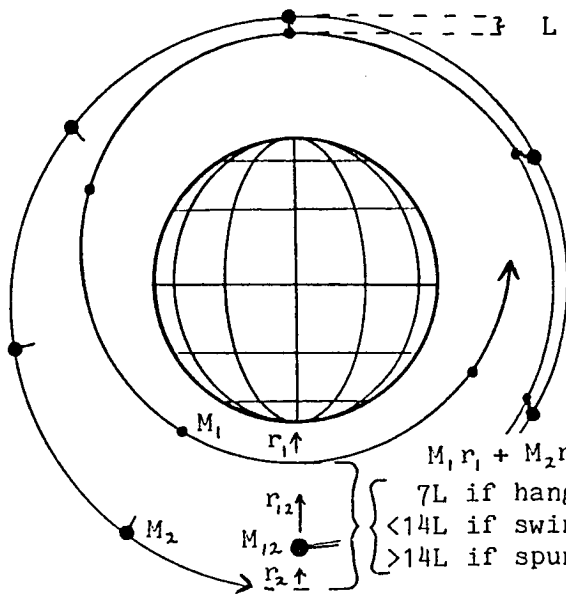
NOTES The relative tether length, mass, peak tension, and energy absorbed by the deployer brake during deployment as a function of (prograde) libration angle are all shown in the plot at right. Libration has a large effect on brake energy. This may be important when retrieval of a long tether is required, after release of a payload or after tethered-capture of a free-flying payload.

The double boost-to-escape operation at right was proposed by A. Cutler. It is shown simply as an example that even though momentum transfer is strictly a "zero sum game", a tethered release operation can be a "WIN-win game" (a large win & a small one). The small win on the deboost-end of the tether is due to the reduced gravity losses 1/2 orbit after release, which more than compensate for the deboost itself. Another example is that deboosting the shuttle from a space station can reduce both STS-deboost & station-reboost requirements.

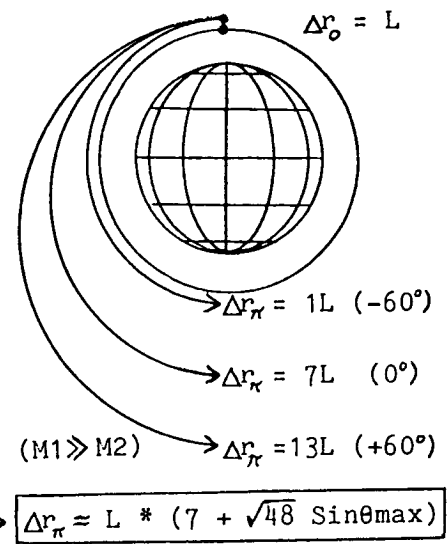
Rendezvous of a spacecraft with the end of a tether may appear ambitious, but with precise relative-navigation data from GPS (the Global Positioning System) it may not be difficult. The relative trajectories required are simply a time-reversal of relative trajectories that occur after tether release. Approach to a hanging-tether rendezvous is shown at right. Prompt capture is needed with this technique: if capture is not achieved within a few minutes, one should shift to normal free-fall techniques. Tethered capture has large benefits in safety (remoteness) and operations (no plume impingement; large fuel savings). The main hazard is collision, due to undetected navigation or tether failure.

- REFERENCES**
1. G. Colombo, "Orbital Transfer & Release of Tethered Payloads," SAO report on NASA Contract NAS8-33691, March 1983.
 2. W.D. Kelly, "Delivery and Disposal of a Space Shuttle External Tank to Low Earth Orbit," J. of the Astronaut. Sci., Vol. 32, No. 3, July-Sept 1984.
 3. J.A. Carroll, "Tether-Mediated Rendezvous," report to Martin Marietta on Task 3 of contract RH3-393855, March 1984.
 4. J.A. Carroll, "Tether Applications in Space Transportation", IAF 84-438, at the 35th IAF Congress, Oct 1984. To be published in ACTA ASTRONAUTICA.

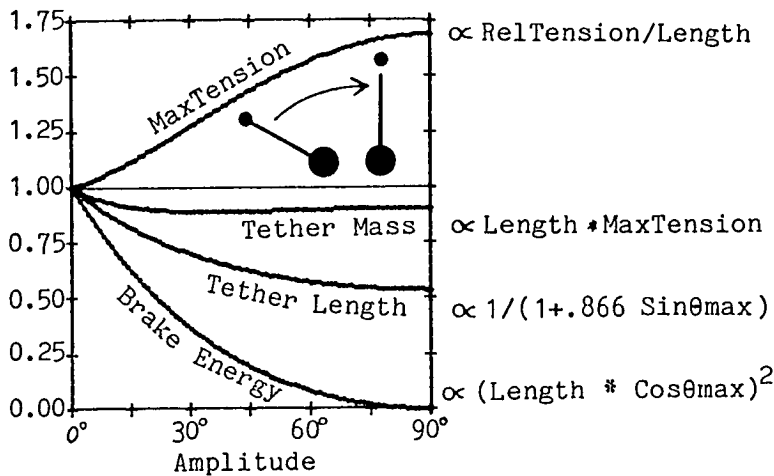
Orbit Transfer by Tethered Release or Capture



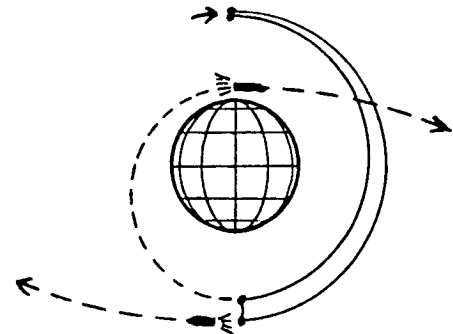
Effects of Tether Deployment and Release



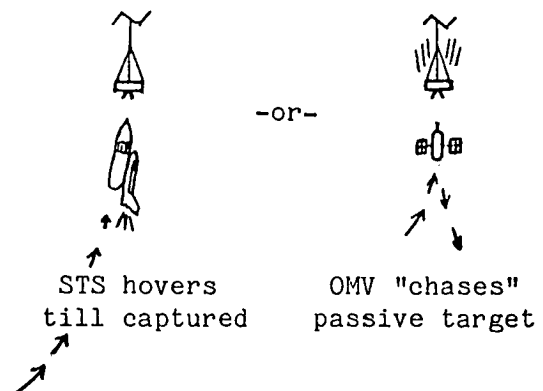
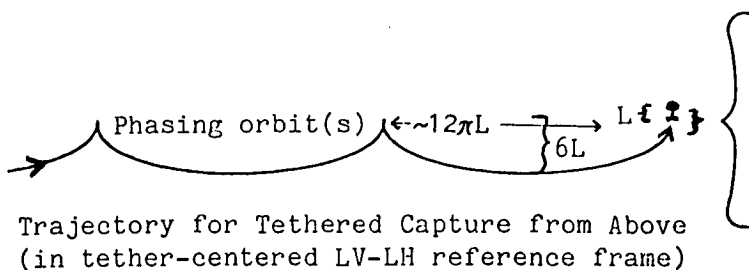
Effect of Libration on Boost
(release at middle of swing)



Effects of Libration
(for equal- Δa boosts)



If done right, a tether
boost/deboost operation
can reduce ΔV -to-escape
for both end masses!



4.4.6 Energy and Angular Momentum Balance

KEY POINTS Tether operations cause higher-order repartitions of energy & angular momentum. First-order approximations that neglect these effects may cause large errors. Extremely long systems have strange properties such as positive orbital energy.

The question and answer at right are deceptively simple. The extent to which this is so, and the bizarre effects which occur in extreme cases, can be seen in the 3 graphs at right. At top, deploying & retrieving two masses on a very long massless tether changes not only the top & bottom orbital radii but also that of the CM. In addition, the free-fall location drops below the CM. Other key parameter changes under the same conditions are plotted underneath.

Note that when the tether length exceeds about 30% of the original orbital radius, the entire system lies below the original altitude. Also, at a radius ratio near 1.95:1, the maximum tether length compatible with a circular orbit is reached. At greater lengths (and the initial amount of angular momentum), no circular orbit is possible at any altitude.

Tether retrieval at the maximum-length point can cause the system to either rise or drop, depending on the system state at that time. If it continues to drop, there is a rapid rise in tether tension, and the total work done by the deployer quickly becomes positive. This energy input eventually becomes large enough (at 2.89:1) to even make the total system energy positive. The system is unstable beyond this point: any small disturbance will grow and can cause the tether system to escape from the body it was orbiting. (See ref. 2.)

NOTES

The case shown is rather extreme: except for orbits around small bodies such as asteroids, tethers either will be far shorter than the orbital radius, or will greatly outweigh the end masses. Either change greatly reduces the size of the effects shown. The effects on arbitrary structures can be calculated using the equations listed at right, which are based on a generalization of the concept of "moments" of the vertical mass distribution. Changes in tether length or mass distribution leave h unchanged, so other parameters (including r_{cm} , n , and E) must change. (For short tethers, the changes scale roughly with the square of the system's radius of gyration.) In many cases different conditions are most easily compared by first finding the orbital radius that the system would have if its length were reduced to 0, $r_{Lt}=0$.

The mechanism that repartitions energy and angular momentum is that length changes cause temporary system displacements from the vertical. This causes both torques and net tangential forces on the system, which can be seen by calculating the exact net forces and couples for a non-vertical dumbbell. The same effect occurs on a periodic basis with librating dumbbells, causing the orbital trajectory to depart slightly from an elliptical shape.

Other topics which are beyond the scope of this guidebook but whose existence should be noted are: eccentricity changes due to deployment, orbit changes due to resonant spin/orbit coupling, and effects of 2- & 3-dimensional structures.

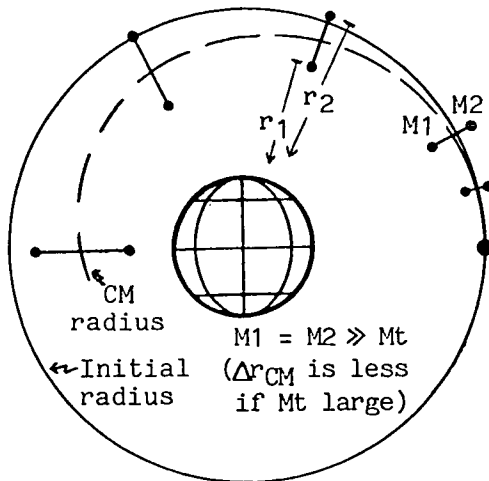
REFERENCES

1. G. Colombo, M. Grossi, D. Arnold, & M. Martinez-Sanchez, "Orbital Transfer and Release of Tethered Payloads," continuation of NAS8-33691, final report for the period Sept 1979—Feb 1983, Smithsonian Astrophysical Observatory, March 1983. (in particular, see the table on page 21)
2. D. Arnold, "Study of an Orbiting Tethered Dumbbell System Having Positive Orbital Energy," addendum to final report on NAS8-35497, SAO, Feb 1985.

Energy & Momentum Balance

Question: What are the sources of the dumbbell spin angular momentum and deployer brake energy?

Answer: Orbit changes which repartition h & E .



For arbitrary nearly-one-dimensional vertical structures in circular orbit, analysis can be based on 5 "moments":

$$I_N = \sum M_i r_i^N \quad (\text{for } N: -2..2)$$

Each of these has physical meaning:

$$F_{\text{grav}} = \mu I_{-2}$$

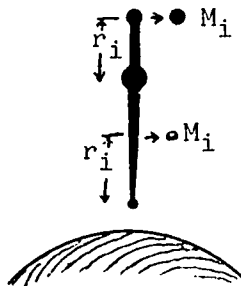
$$E_{\text{pot}} = -\mu I_{-1}$$

$$\text{Mass} = I_0$$

$$F_{\text{cen}} = n^2 I_1$$

$$h_{\text{tot}} = n I_2$$

$$E_{\text{kin}} = .5n^2 I_2$$



Some other useful equations include:

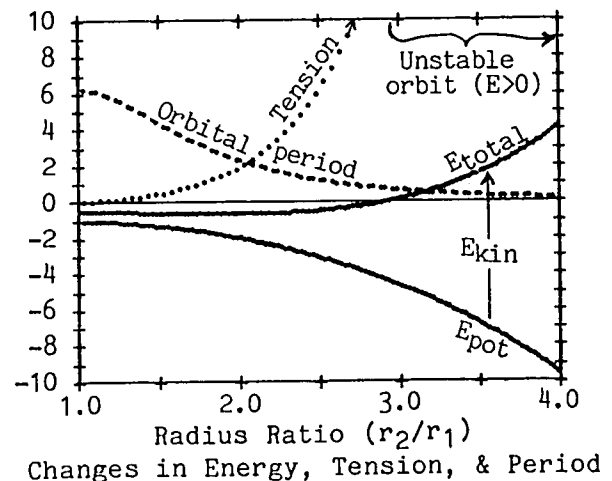
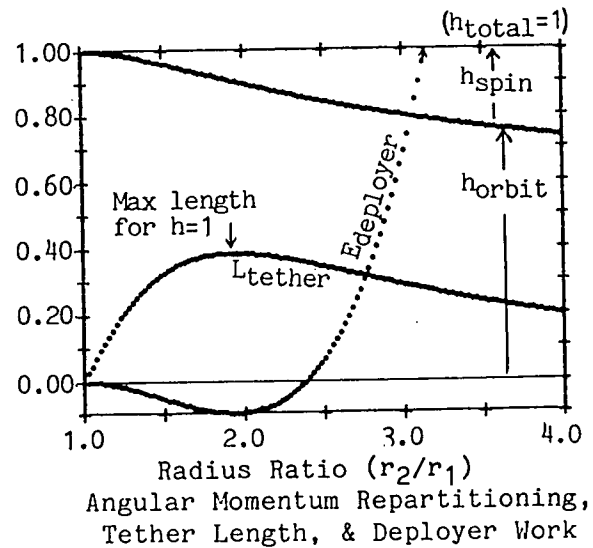
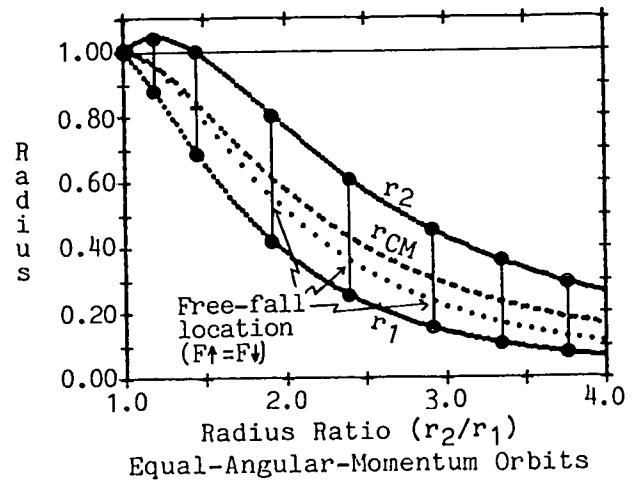
$$r_{\text{cm}} = I_1/I_0$$

$$n^2 = \mu I_{-2}/I_1$$

$$E = \mu ((.5I_{-2} * I_2/I_1) - I_{-1})$$

$$r_{(L_t=0)} = I_{-2}(I_2)^2/(I_1 * (I_0)^2)$$

VERY-LONG-TETHER EFFECTS:



4.5 Tether Material Consideration

4.5.1 Tether Strength and Mass

KEY POINTS Tether strength/weight ratio constrains performance in ambitious operations. Required tether mass is easily derivable from ΔV and payload mass.

Usable specific strength can be expressed in various ways. Three ways are shown at right. V_c , L_c , and L_{lg} are here defined in terms of a typical design stress (new/m²) rather than the (higher) ultimate stress. Including the safety factor here streamlines the subsequent performance calculations. Higher safety factors are needed with non-metals than with metals since non-metals are often more variable in their properties, brittle, abrasion-sensitive, and/or creep-sensitive. A safety factor of 4 (based on short-term fiber strength) is typical for Kevlar, but the most appropriate safety factor will vary with the application.

The "characteristic velocity," V_c , is the most useful parameter in tether-boost calculations, because the tether mass can be calculated directly from $\Delta V/V_c$, independently of the orbit, and nearly independently of the operation. The table at the bottom, which lists tether/rocket combinations that have the lowest life-cycle mass requirements, holds whenever $kV_c = 1$ km/sec & $I_{sp} = 350$ sec.

NOTES The characteristic length L_c is useful in hanging-tether calculations. It varies with the orbital rate n . (The simple calculation given assumes $L \ll r$; if this is not true, $1/r$ effects enter in, and calculations such as those used in refs 3-5 must be used.) The safe 1-gee length L_{lg} is mainly useful in terrestrial applications, but is included since specific strength is often quoted this way. (Note that V_c and L_c vary with $\sqrt{\text{strength}}$, and L_{lg} directly with strength.)

The specific modulus is of interest because it determines the speed of sound in the tether (C = the speed of longitudinal waves), the strain under design load ($\Delta L/L = \{V_c/C\}^2$), & the recoil speed after failure under design load ($= V_c^2/C$).

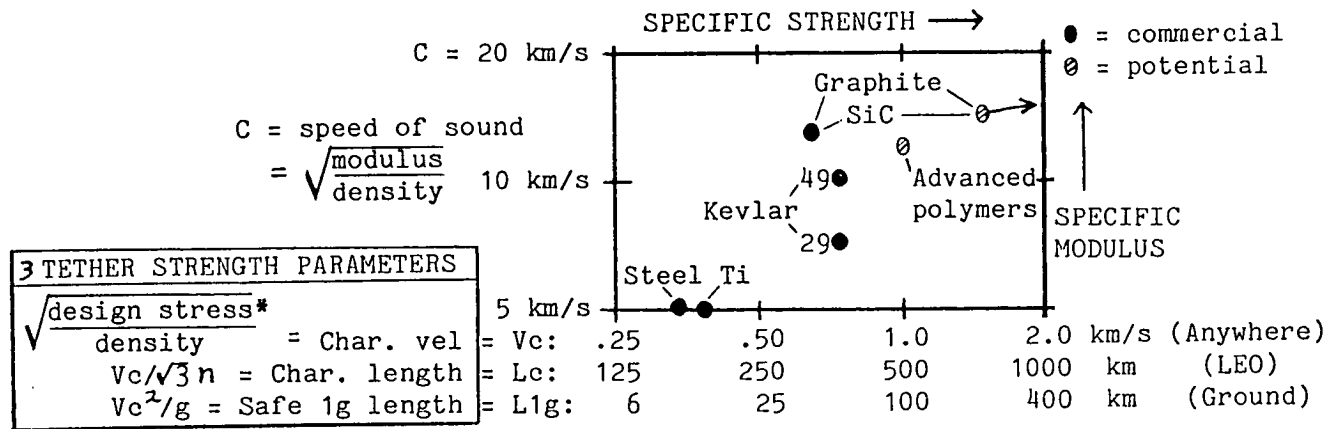
Tether mass calculations are best done by considering each end of the tether separately. If $M_{p1} \gg M_{p2}$, then M_{t1} can be neglected in preliminary calculations.

Du Pont's Kevlar is the highest-specific-strength fiber commercially available. Current R&D efforts on high-performance polymers indicate that polyester can exhibit nearly twice the strength of Kevlar.² Two fiber producers have already announced plans to produce polymers with twice the specific strength of Kevlar.

In the long run, the potential may be greater with inorganic fibers like SiC & graphite. Refs. 3-5 focus on the requirements of "space elevators." They discuss laboratory tests of single-crystal fibers and suggest that 10-fold improvements in specific strength (or 3-fold in V_c & L_c) are conceivable.

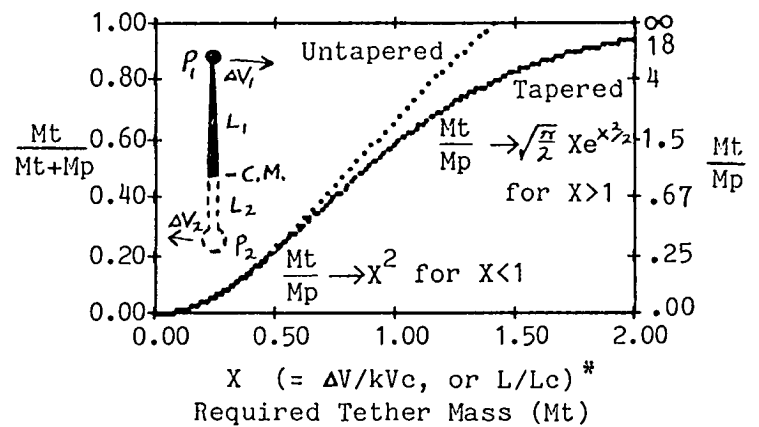
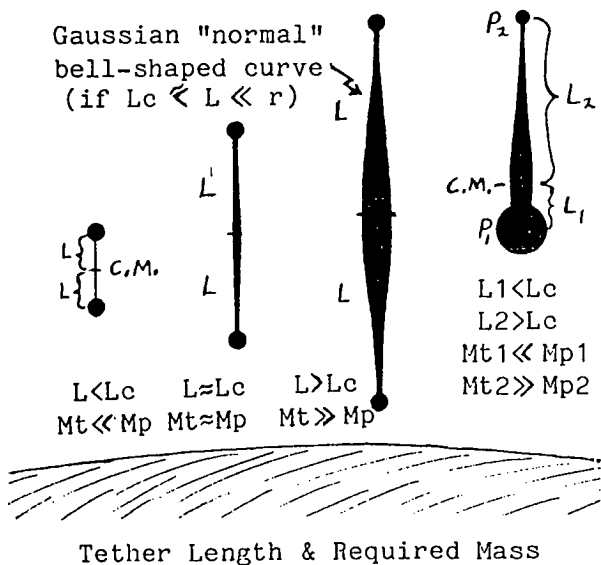
- REFERENCES**
1. Characteristics and Uses of Kevlar 49 Aramid High Modulus Organic Fiber. available from Du Pont's Textile Fibers Department, 1978.
 2. G. Graff, "Superstrong Plastics Challenge Metals," High Technology magazine, February 1985, pp. 62-63.
 3. J. Isaacs, H. Bradner, G. Backus, and A. Vine, "Satellite Elongation into a True "Skyhook"; a letter to Science, Vol. 151, pp. 682-683, Feb 11, 1966.
 4. J. Pearson, "The Orbital Tower: a Spacecraft Launcher Using the Earth's Rotational Energy," Acta Astronautica, Vol. 2, pp. 785-799, Pergamon, 1975.
 5. H. Moravec, "A Non-Synchronous Orbital Skyhook," J. of the Astronautical Sciences, Vol. XXV, No. 4, pp. 307-322, Oct-Dec 1977.

Specific Strength and Required Tether Mass



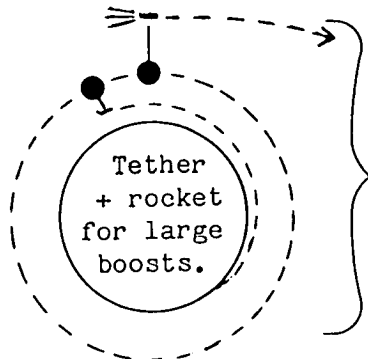
* Design stress is assumed to be 1/2 the ultimate strength for metals and 1/4 the short-term individual fiber strength for other materials.

SPECIFIC STRENGTH & MODULUS OF SEVERAL TETHER MATERIALS



* $k = \begin{cases} 1.00 & \text{for spinning operations} \\ 1.15 & \text{for hanging} \\ 1.21 \pm .01 & \text{for swinging} \\ 1.41 & \text{for winching} \end{cases}$

$\Delta V = \text{Sum of perigee + apogee boosts}$



Expected # of uses	1	10	100	1000
Best tether ΔV , km/s	.14	.9	1.8	2.6
Required M_t/M_p	.02	1	11	95

(For $kV_c = 1 \text{ km/s}$ and rocket $I_{sp} = 350$ seconds; marginal deployer & dry rocket masses neglected.)

Best Tether ΔV for Combined Tether/Rocket Boosts

4.5.2 Tether Impact Hazards

KEY POINTS Micrometeoroids can sever thin tethers & damage tether protection/insulation. Orbiting debris (or other tethers) can sever tethers of any diameter. Debris could impact an Earth-based "Space Elevator" over once per year.

Sporadic micrometeoroids are usually assumed to have an typical density of about .5 and a typical impact velocity in LEO of approximately 20 km/sec.¹ At impact speeds above the speed of sound, solids become compressible and the impact shock wave has effects like those of an explosion. For this reason, the risk curve assumes that if the EDGE of an adequately large meteoroid comes close enough to the center of the tether (within 45° or .35 Dt), failure will result.

Experiments done by Martin Marietta on TSS candidate materials have used glass projectiles fired at 6.5 km/sec, below the (axial) speed of sound in Kevlar. Two damaged tethers from those tests are shown at right. The scaling law used ($\rho \cdot v^{.67}$) indicates that this is representative of orbital conditions, but that law (used for impacts on sheet metal) may not apply to braided fibers.

NOTES For tethers much thicker than 10 mm or so (depending on altitude), the risk does not go down much as Dt increases, because even though the micrometeoroid risk still decreases, the debris risk (which INCREASES slightly with Dt) begins to dominate. As with micrometeoroids, the tether is assumed to fail if any part of the debris passes within .35 Dt of the center of the tether.

The debris risk at a given altitude varies with the total debris width at that altitude. This was estimated from 1983 CLASSY radar-cross-section (RCS) data, by simply assuming that $W = \text{Sqrt}(\text{RCS})$ and summing $\text{Sqrt}(\text{RCS})$ over all tracked objects in LEO.⁶ This underestimates W for objects with appendages, and overestimates it for non-librating elongated objects without appendages.

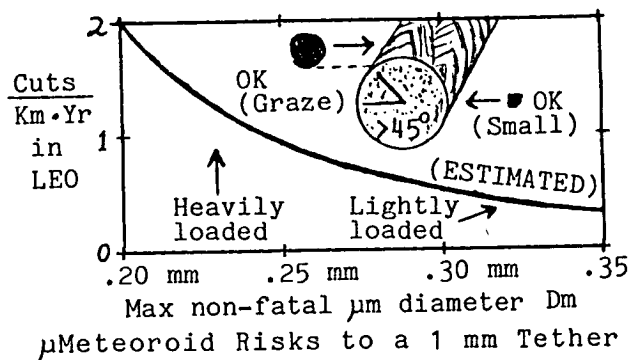
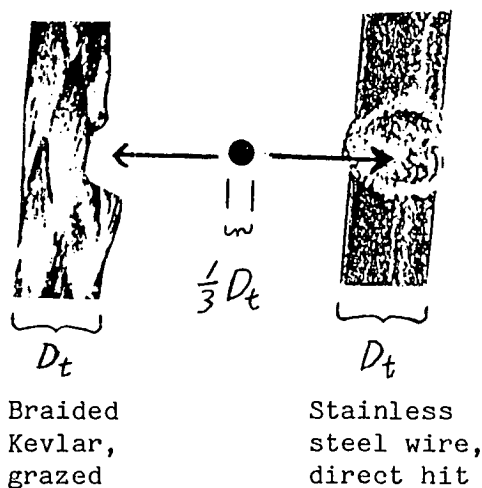
CLASSY RCS data are expected to be accurate for $\text{RCS} > 7 \text{ m}^2$. The 700 objects with $\text{RCS} > 7 \text{ m}^2$ account for 3 km of the total 5 km width, so errors with smaller objects are not critical. Small untracked objects may not add greatly to the total risk: 40,000 objects averaging 2 cm wide would increase the risk to a 1-cm tether by only 20%. \bar{W} was assumed independent of altitude, so the distribution of risk with altitude could be estimated by simply scaling Figure 1 from Ref. 4.

As shown at right, debris impact with a space elevator could be expected more than once per year at current debris populations. The relative density at 0° latitude was estimated from data on pp. 162-163 of ref. 6.

Similar calculations can be made for two tethers in different orbits at the same altitude. If at least one is spinning or widely librating, the mutual risks can exceed .1 cut/km.yr. This makes "tether traffic control" essential.

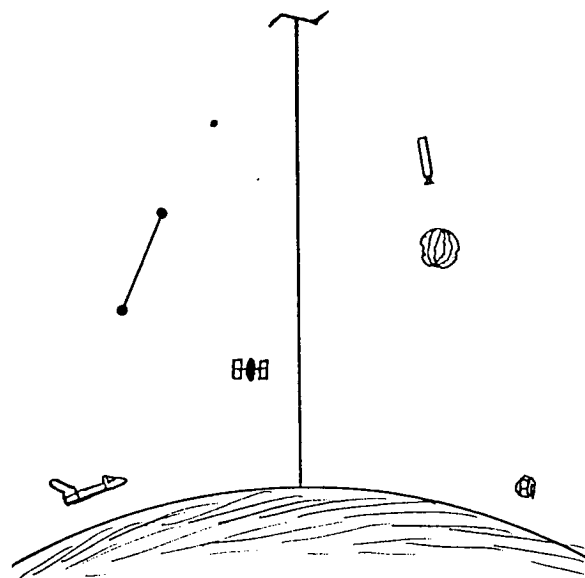
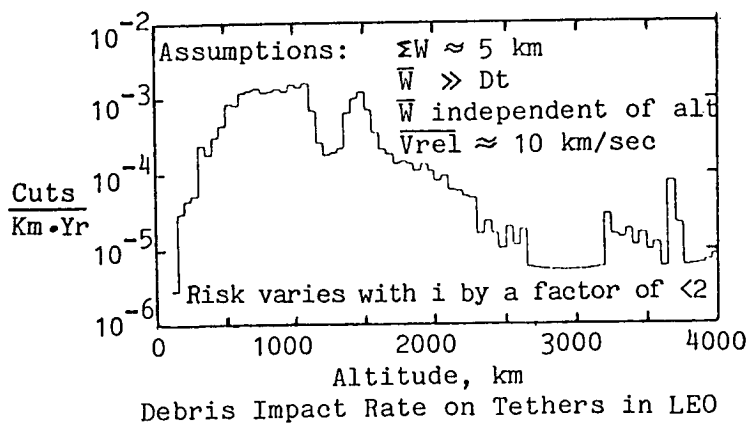
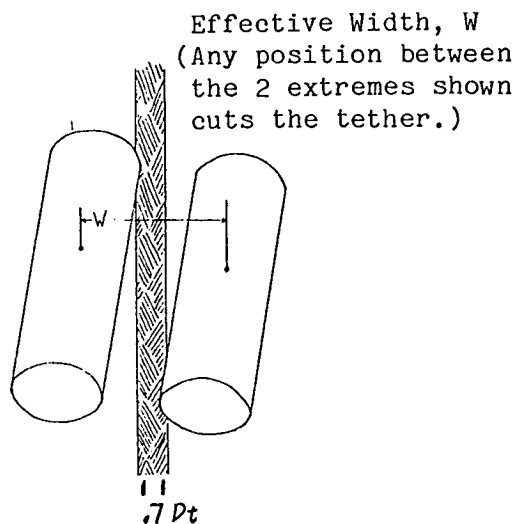
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- REFERENCES**
1. Meteoroid Environment Model—1969 [Near Earth to Lunar Surface], NASA SP-8013, March 1969.
 2. Meteoroid Environment Model—1970 [Interplanetary and Planetary], NASA SP-8038, October 1970.
 3. Meteoroid Damage Assessment, NASA SP-8042, May 1970. (Shows impact effects)
 4. D.J. Kessler, "Sources of Orbital Debris and the Projected Environment for Future Spacecraft", in J. of Spacecraft & Rockets, Vol 18 #4, Jul-Aug 1981.
 5. D.J. Kessler, Orbital Debris Environment for Space Station, JSC-20001, 1984.
 6. CLASSY Satellite Catalog Compilations as of 1 Jan 1983, NORAD/J5YS, 1983.

Impact Hazards for Tethers



For tethers with $D_t > 1 \text{ (mm)}$,
& Max non-fatal $D_m = .25 \text{ Dt}$,

$$\frac{\mu\text{m cuts}}{\text{Km.Yr}} \approx D_t^{-2.6}$$



Debris Risk to the Lowest 4000 km
of an Earth-based Space Elevator:

$$\begin{aligned} \text{Risk} &= \frac{\Sigma \text{Width} * \bar{V} * \text{RelDensity at } \lambda=0}{\text{Earth "Surface Area" at Alt}} \\ &= \frac{\sim 5 \text{ km} * \sim 7.3 \text{ km/sec} * \sim .72}{4 * \pi * \text{Sqr}(\sim 7378 \text{ km})} \\ &\approx 3.9\text{E-}8/\text{sec} \approx \boxed{1.2 \text{ cuts/year}} \end{aligned}$$

4.6 Electrodynamic Tethers

4.6.1 Interactions with Earth's Magnetic Field and Plasma

KEY POINTS Tether (& other) resistance can limit the output of electrodynamic tethers. Electron collection methods & effectiveness are important—and uncertain.

Since the publication of ref. 1, 20 years ago, electrodynamic tether proposals and concepts have been a frequent source of controversy, mainly in these areas:

1. What plasma instabilities can be excited by the current?
2. What is the current capacity of the plasma return loop?
3. What is the best way to collect electrons from the plasma?

The first Tethered Satellite mission may do much to answer these questions. The discussion below and graphics at right merely seek to introduce them.

The current flowing through an electrodynamic tether is returned in the surrounding plasma. This involves electron emission, conduction along the geomagnetic field lines down to the lower ionosphere, cross-field conduction by collision with neutral atoms, and return along other field lines.

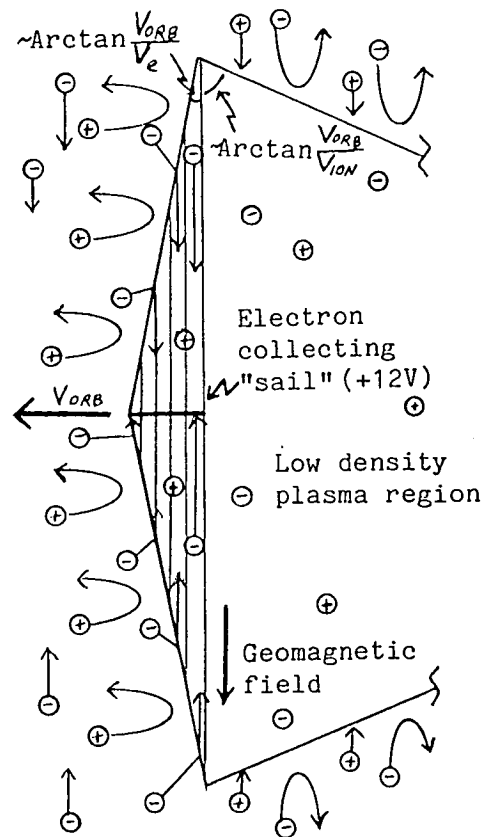
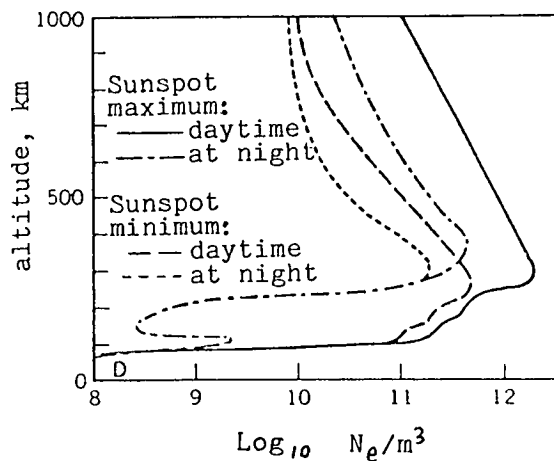
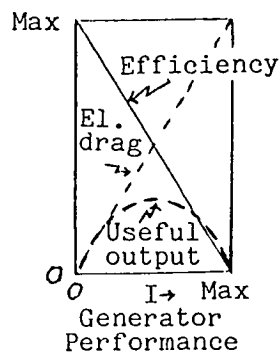
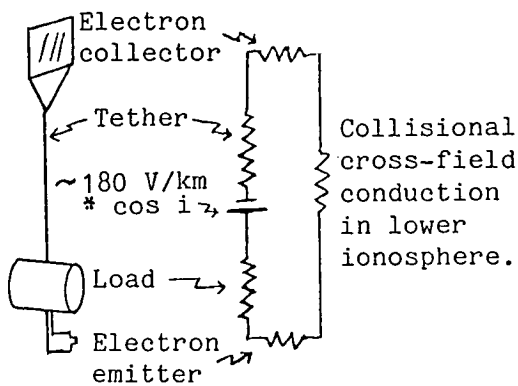
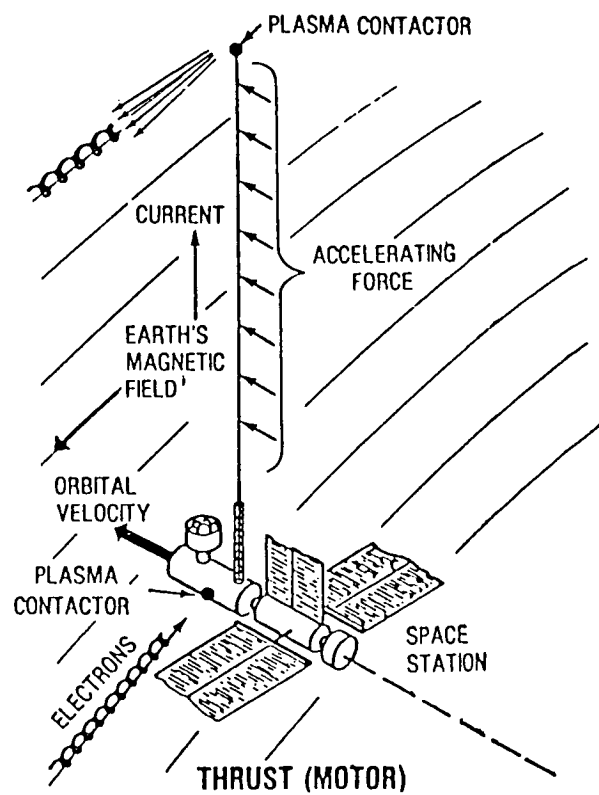
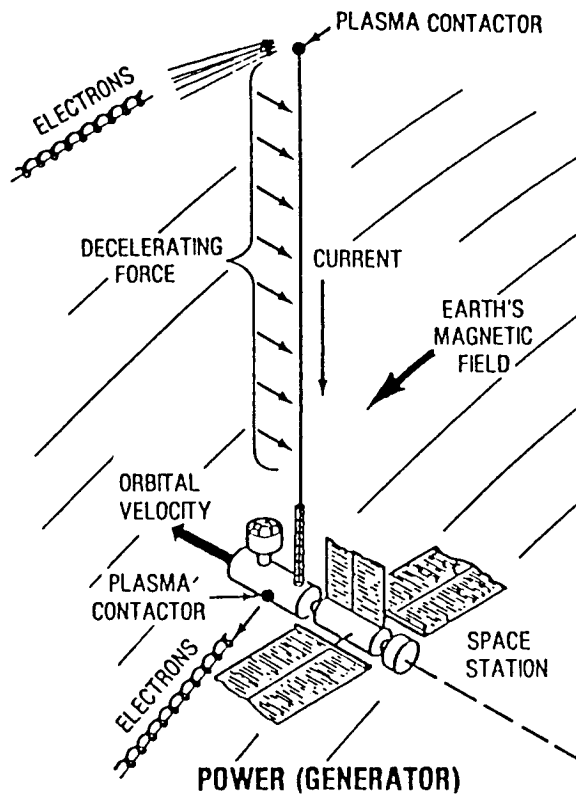
NOTES The tether current causes a force on the tether (and on the field) perpendicular to both the field and the tether (horizontal, if the tether is vertical). Motion of the tether through the geomagnetic field causes an EMF in the tether. This allows the tether to act as a generator, motor, or self-powered ultra-low-frequency broadcast antenna.² The motion also causes each region of plasma to experience only a short pulse of current, much as in a commutated motor.

Based on experience with charge neutralization of spacecraft in high orbit, it has been proposed that electrons be collected by emitting a neutral plasma from the end of the tether, to allow local cross-field conduction.³ In GEO, the geomagnetic field traps a plasma in the vicinity of the spacecraft, and "escape" along field lines may not affect its utility. This may also hold in high-inclination orbits in LEO. But in low inclinations in LEO, any emitted plasma might be promptly wiped away by the rapid motion across field lines.

A passive collector such as a balloon has high aerodynamic drag, but a end-on sail can have an order of magnitude less drag. The electron-collection sketch at bottom right is based on a preliminary analysis by W. Thompson.⁵ This analysis suggests that a current moderately higher than the electron thermal current ($=Ne \cdot \sim 200$ km/sec) might be collected on a surface normal to the field. This is because collecting electrons requires that most ions be reflected away from the collection region as it moves forward. This pre-heats and densifies the plasma ahead of the collector. The voltage required for collection is just the voltage needed to repel most of the ions, about 12 V.

- REFERENCES**
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 2. M. Grossi, "A ULF Dipole Antenna on a Spaceborne Platform of the PPEPL Class," Report on NASA Contract NAS8-28203, May 1973.
 3. R.D. Moore, "The Geomagnetic Thruster—A High Performance "Alfvén Wave" Propulsion System Utilizing Plasma Contacts," AIAA Paper No. 66-257.
 4. S.T. Wu, ed., University of Alabama at Huntsville/NASA Workshop on The Uses of a Tethered Satellite System, Summary Papers, Huntsville AL, May 1978. See papers by M. Grossi et al, R. Williamson et al., and N. Stone.
 5. W. Thompson, "Electrodynamic Properties of a Conducting Tether," Final Report to Martin Marietta Corp. on Task 4 of Contract RH3-393855, Dec. 1983.

Electrodynamic Tether Principles



Top View of Electron Collection

4.6.2 Electrodynamic Orbit Changes

KEY POINTS Electrodynamic tether use will affect the orbit—whether desired or not. Stationkeeping and/or large orbit changes without propellant use are possible.

The offset dipole approximation shown at right is only a first approximation to the geomagnetic field: harmonic analyses of the field give higher-order coefficients up to 20% as large as the fundamental term. Ref. 1 contains computerized models suitable for use in detailed electrodynamic studies.

The geomagnetic field weakens rapidly as one moves into higher orbits, and becomes seriously distorted by solar wind pressure beyond GEO. However, ohmic losses in a tether are already significant in LEO, so electrodynamic tethers are mainly useful in low orbits where such distortions are not significant.

As the earth rotates, the geomagnetic field generated within it rotates also, and the geomagnetic radius and latitude of a point in inertial space vary over the day. If a maneuvering strategy which repeats itself each orbit is used (necessary unless the spacecraft has large diurnal power storage capacity), then the average effect, as shown at right, will be a due east thrust vector.

NOTES Variations in geomagnetic latitude (and thus in B_h) cancel out variations in the component of flight motion perpendicular to the field, so these variations do not cause large voltage variations in high-inclination orbits. (Note that the relevant motion is motion relative to a rotating earth.) Out-of-plane libration, variations in geomagnetic radius, and diurnal variation of the "geomagnetic inclination" of an orbit can all cause voltage variations. Peak EMFs (which drive hardware design) may approach 400 V/km.

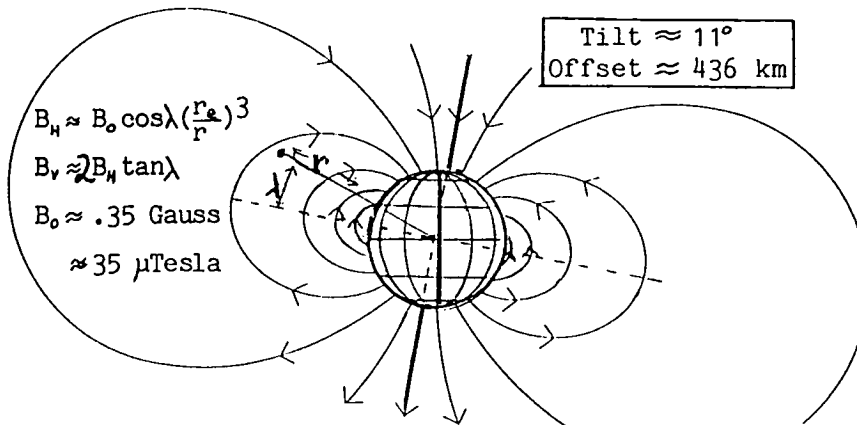
However these variations need not affect the thrust much if a spacecraft has a variable-voltage power supply: neglecting variations in parasitic power, constant power investment in a circular orbit has to give constant in-plane thrust. The out-of-plane thrust is provided "free" (whether desired or not). Average voltage & thrust equations for vertical tethers are shown at right.

The table shows how to change all six orbital elements separately or together. Other strategies are also possible. Their effects can be calculated from the integrals listed. For orbits within 11° of polar or equatorial, diurnally-varying strategies become more desirable. Computing their effects requires using the varying geomagnetic inclination instead of i (& moving it inside the integral). Note that the "DC" orbit-boosting strategy also affects i . This can be cancelled out by superimposing a $-2 \cos(2\phi)$ current on the DC current.

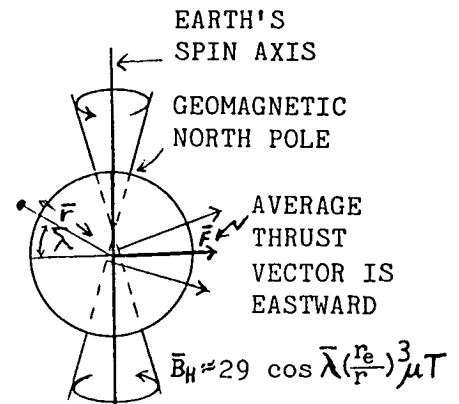
As discussed under Electrodynamic Libration Control Issues, eccentricity and apside changes can strongly stimulate ϕ -libration unless the spacecraft center of mass is near the center of the tether. Other maneuvers should not do this, but this should be checked using high-fidelity geomagnetic field models.

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- REFERENCES**
1. E.G. Stassinopoulos & G.D. Mead, ALLMAG, GDALMG, LINTRA: Computer Programs for Geomagnetic Field & Field-Line Calculations, Feb. 1972, NASA Goddard.
 2. R.D. Moore, "The Geomagnetic Thruster—A High Performance "Alfven Wave" Propulsion System Utilizing Plasma Contacts," AIAA Paper No. 66-257.
 3. H. Alfven, "Spacecraft Propulsion; New Methods," Science, Vol. 176, 14 April 1972, pp. 167-168.

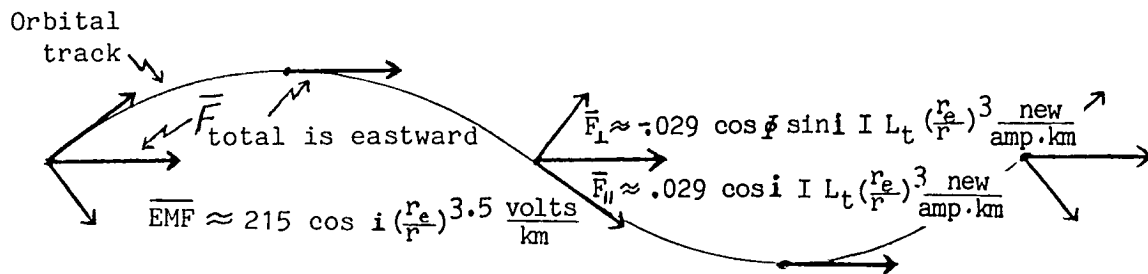
Electrodynamic Orbit Changes



OFFSET DIPOLE APPROXIMATION TO GEOMAGNETIC FIELD



EFFECT OF EARTH'S SPIN ON TIME-AVERAGED FIELD



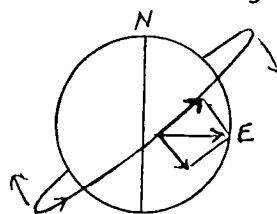
HOW TO CHANGE ORBITS USING AN ELECTRODYNAMIC TETHER

Element	Strategy	Thrust Vector	Effect
Semimajor axis	DC		$\Delta a \approx \cos(i) \frac{kl}{m} \int I dt$
Phase	Sawtooth		$\Delta M \approx \cos(i) \frac{1.5 kln}{ma} \int I t dt$
Eccentricity	$\cos(\theta)$		$\Delta e \approx \cos(i) \frac{kl}{ma} \int I \cos(\theta) dt$
Line of apsides	$\sin(\theta)$		$\Delta w \approx \cos(i) \frac{kl}{mae} \int I \sin(\theta) dt$
Inclination	$-\cos(2\bar{\phi})$		$\Delta i \approx \frac{-kl}{2ma} \int I \sin(i) \cos^2(\bar{\phi}) dt$
Ascending node	$-\sin(2\bar{\phi})$		$\Delta \Omega \approx \frac{-kl}{2ma} \int I \sin(\bar{\phi}) \cos(\bar{\phi}) dt$

θ = POSITION OF VEHICLE WITH REFERENCE TO ITS PERIGEE

$\bar{\phi}$ = POSITION WITH REFERENCE TO ASCENDING NODE

k = $\sim 4 \text{ TONNES PER AMPERE DAY} * (r_e/r)^{4.5}$



l = TETHER LENGTH

m = TOTAL VEHICLE MASS

n = ORBITAL ANGULAR RATE

4.6.3 Tether Shape and Libration Control

KEY POINTS Properly controlled AC components can be used to control θ and ϕ -libration. Solar-energy storage and e or ω changes strongly stimulate ϕ -libration. AC currents other than 1 & 3/orbit should not affect ϕ -libration much.

The maneuvering strategies on the previous page have assumed that electrodynamic tethers will stay vertical. However, as shown at right, the distributed force on the tether causes bowing, and that bowing is what allows net momentum transfer to the attached masses. Note that net momentum can be transferred to the system even if the wire is bowed the wrong way (as when the current is suddenly reversed); momentum transferred to the wire gets to the masses later.

This figure also illustrates two other issues:

1. Bowing of the tether causes it to cross fewer field lines.
2. Unequal end masses and uniform forces cause overall torques & tilting.

The bowing causes the tether to provide less thrust while dissipating the same parasitic power. The net force on the system is the same as if the tether were straight but in a slightly weaker magnetic field.

NOTES The torque on the system causes it to tilt away from the vertical, until the torque is balanced by gravity-gradient restoring torques. For a given system mass and power input, disturbing torques vary with L and restoring torques with L^2 , so longer systems can tolerate higher power. The mass distribution also affects power-handling capability, as seen in the sequence at top right.

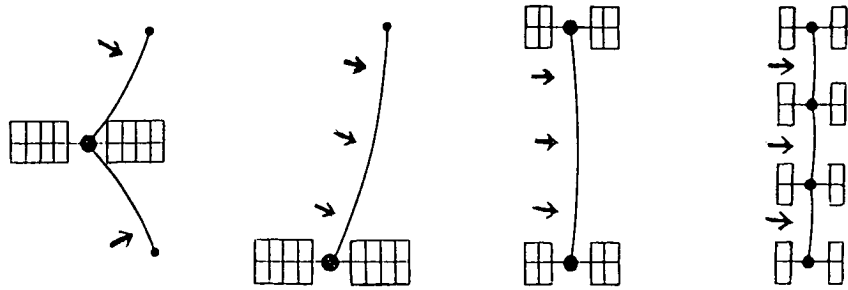
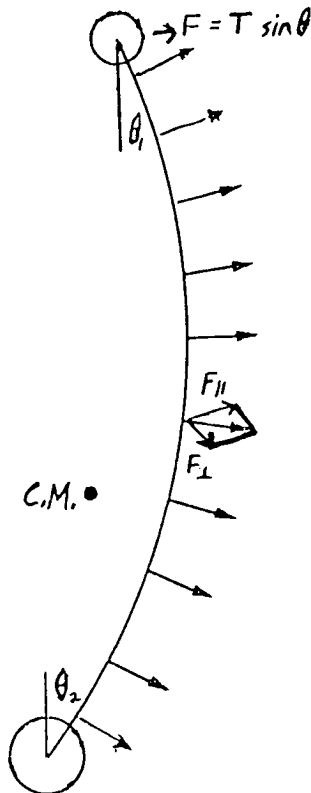
Modulating the tether current modulates any electrodynamic torques. Current modulation at 1.73 n can be used to control in-plane libration. Out-of-plane torques can also be modulated, but another control logic is required. This is because the once-per-orbit variation in out-of-plane thrust direction makes a current with frequency F (in cycles per orbit) cause out-of-plane forces and torques with frequencies of $F-1$ and $F+1$, as shown in the Fourier analysis at bottom right. Hence ϕ libration control ($F=2$) requires properly phased $F=1$ or $F=3$ currents. Higher frequencies can damp odd harmonics of any tether bowing oscillations. Control of both in- & out-of-plane oscillations may be possible since they have the same frequencies and thus require different currents.

Applications that require significant $F=1$ components for other reasons can cause problems. Four such strategies are shown at right. Sin & Cos controls allow adjustment of e or ω . The two "Sign of ..." laws allow constant power storage over 2/3 of each orbit and recovery the rest of the orbit. These laws would be useful for storing photovoltaic output for use during dark periods.

These strategies drive out-of-plane libration (unless the center of mass is at the center of the tether). The libration frequency decreases at large amplitudes, so if the system is not driven too strongly, it should settle into a finite-but-large-amplitude phase-locked loop. This may be unacceptable in some applications, due to resulting variations in gravity or tether EMF. In some cases, such as eccentricity changes, adding a $F=3$ component might cancel the undesired effect of an $F=1$ current while keeping the desired effect.

REFERENCE 1. G. Colombo, M. Grossi, M. Dobrowolny, and D. Arnold, Investigation of Electrodynamic Stabilization & Control of Long Orbiting Tethers, Interim Report on Contract NAS8-33691, March 1981, Smithsonian Astrophysical Observatory.

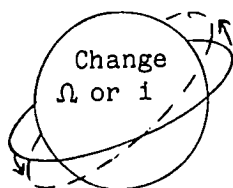
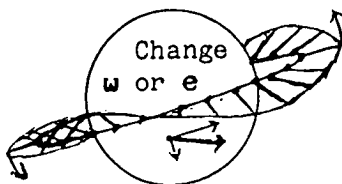
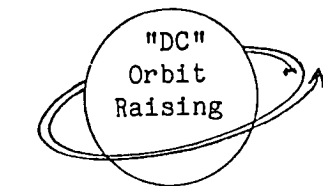
Electrodynamic Libration Control Issues



INCREASING STABILITY \longrightarrow
(for fixed total length & mass & I)

FOR CONTROL OF:	MODULATE I AT:
Out-of-plane libration*	1 n or 3 n
In-plane libration*	1.73 n
Tether oscillations	>5 n

* I or mass distribution must be lopsided



Tether Current:

$$I = 1.0$$

$$I = \sin \phi$$

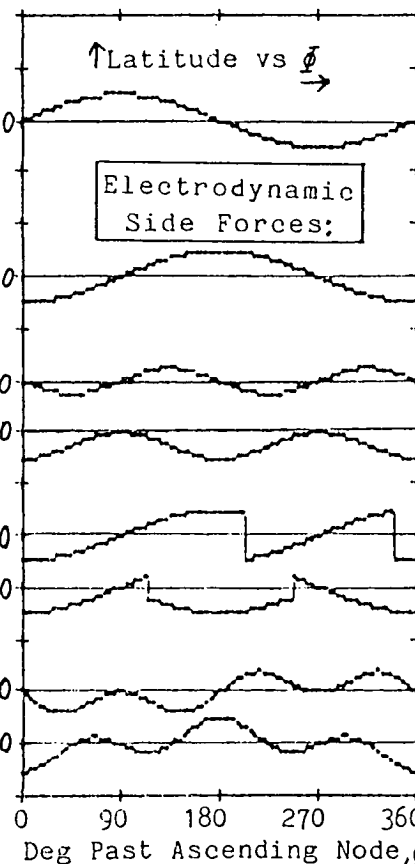
$$I = \cos \phi$$

$$I = \text{Sign of } (.5 + \sin \phi)$$

$$I = \text{Sign of } (.5 + \cos \phi)$$

$$I = \sin 2\phi$$

$$I = \cos 2\phi$$



Fourier Analysis of Out-Of-Plane Forces:

	1n	2n	3n
$I = 1.0$.50	0	0
$I = \sin \phi$	0	.50*	0
$I = \cos \phi$	0	.50	0
$I = \text{Sign of } (.5 + \sin \phi)$.50	.65	.39
$I = \text{Sign of } (.5 + \cos \phi)$.03	.51	.07

* drives ϕ libration

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SECTION 5.0

CONFERENCE SUMMARIES

**Conference
Summaries**

5.1 General

The following sections (5.2 First International Conference On Tethers In Space, 5.3 Second International Conference On Tethers In Space, and 5.4 Third International Conference On Tethers In Space) contain the programs of each conference. These programs list the papers presented, authors, Session Chairmen/Co-Chairmen, and workshops conducted during the course of the conference. Note that the program for the Third International Conference On Tethers In Space is a preliminary agenda, since at the time of this printing, this conference had not been held. Phone numbers and addresses of the participating individuals may be found in Section 7.0 "Contacts."

5.2 First International Conference On Tethers In Space (1986)

OBJECTIVE

The objective of the Conference is to provide a broad overview of how tethers in space may be used to study Earth's atmosphere and plasma environment, produce power in the kilo or megawatt range, generate variable gravity, and boost satellites. The era of tethers will begin in 1988 with the Shuttle flight of the Tethered Satellite System (TSS), a joint U.S. and Italian project. Many studies by both countries have generated applications to the Space Station, such as tethered platforms, propellant depots, and variable gravity modules for commercial and life science experiments. The number of applications is expanding to include lunar and planetary exploration. Jupiter's strong magnetic field, for example, may someday be used with electrodynamic tethers to produce power and thrust for a more versatile vehicle.

The Conference will cover tether fundamentals, the spectrum of tether applications, current national and international activities, status and plans for the TSS, hardware development, demonstration missions, Space Station applications, planetary applications, and tether technology developments being conducted or planned by the U.S. or Italy.

The Conference is sponsored by the National Aeronautics and Space Administration (NASA) and the Piano Spaziale Nazionale (PSN) of Consiglio Nazionale delle Ricerche (CNR), Italy. It is cosponsored by the American Institute of Aeronautics and Astronautics (AIAA), the American Astronautical Society (AAS) and the Associazione Italiana di Aeronautica e Astronautica (AIDAA), Italy. It is operated by the American Institute of Aeronautics and Astronautics.

SYMPOSIUM ORGANIZATION

General Chairman

IVAN BEKEY

Director, Advanced Programs, Office of Space Flight, NASA Headquarters

International Chairman

LUCIANO GUERRIERO

Director, Piano Spaziale Nazionale, Italy

Program Chairman

PAUL A. PENZO

Jet Propulsion Laboratory

Administrative Committee

MIREILLE GERARD

American Institute of Aeronautics and Astronautics

PAMELA EDWARDS

American Institute of Aeronautics and Astronautics

WILLIAM A. BARACAT

General Research Corporation

Program Committee

PETER M. BAINUM

American Astronautical Society/Howard University

EDWARD J. BRAZILL

NASA Headquarters

DALE A. FESTER

Martin Marietta Denver Aerospace

MIREILLE GERARD

American Institute of Aeronautics and Astronautics

VITTORIO GIAVOTTO

Associazione Italiana di Aeronautica e Astronautica, Italy

VINCENZO LETICO

Piano Spaziale Nazionale, Italy

DAVE MORUZZI

Italian Advanced Industries, Inc./Aeritalia

TERRENCE REESE

General Research Corporation

S. CAL RYBAK

Ball Aerospace Systems Division

EXPECTED ATTENDANCE

The Conference is designed to assemble current and potential participants in all aspects of using tethers in space, including planners, thinkers, builders, entrepreneurs, policy makers, engineers, scientists and researchers.

HOTEL ACCOMMODATIONS

The Conference will be held at the Hyatt Regency Crystal City, 2799 Jefferson Davis Highway, Arlington, Virginia 22202. Telephone (703) 486-1234. Special hotel rates have been secured for the nights of Tuesday, September 16, 1986 through Thursday, September 18, 1986 at \$95 for a single or double room. There are also a limited number of rooms at \$66 per night for **U.S. government employees only** (presentation of a valid government identification card required upon registration at hotel). All reservations should be made directly with the hotel mentioning the International Conference on Tethers in Space **before August 16, 1986**. After this date, the rooms will be released to the general public and reservation requests will be accepted on a space-available basis.

REGISTRATION

All attendees must register in advance by mail as follows:

Government, Congressional and University attendees	/ \$250
Industry attendees	/ \$350
Student attendees	/ \$50

Since space is limited, registrations will be taken on a first-come, first-served basis. All registrations must include the fee. Please return the enclosed registration card and fee by **August 15, 1986** to:

Ms. Pamela Edwards
Conference Administrator
AIAA
1633 Broadway
New York, NY 10019

The registration fees cover the cost of the three luncheons on September 17, 18, and 19, coffee breaks during the symposium hours, and a reception on the evening of Wednesday, September 17. It also includes copies of all available papers.

No refunds for cancellations received after September 1, 1986.

For further information, please contact Pamela Edwards, AIAA Headquarters (212) 408-9778.

MESSAGES AND INFORMATION

Messages will be recorded and posted for the person on a bulletin board in the registration area. It is not possible to page conferees. Please call (703) 486-1234 and ask for the AIAA Message Center.

ADDITIONAL AND OPTIONAL WORKSHOP**Tether Dynamics Simulation
(TDS) Workshop**

A one day workshop will be held 8:15 a.m. to 5:00 p.m. on Tuesday, September 16, 1986 prior to the Conference. There is a nominal charge for attending this Workshop, and it will be open to all regardless of their participation in the Conference. A summary presentation of the Workshop will be given in Session VI of the International Conference, Friday, September 19, 1986 at 10:00 a.m.

OBJECTIVE

The objective of the TDS Workshop is to provide a forum to discuss the structure and status of existing computer programs which are used to simulate the dynamics of a variety of tether applications. A major topic will be concerned with the purpose of having different simulation models, and how our confidence in them can be improved. Validation of specific models will be limited by budget constraints and lack of experimental data. Guidance on future work in this area will be sought from a panel of preselected workshop participants representing resource and technical managers and dynamics analysts. TDS Workshop attendees will be invited to participate in arriving at a consensus through open discussion and written comments.

The TDS Workshop is sponsored by NASA and will hear simulation descriptions from several NASA centers, industry, and university representatives who have a significant capability in tether dynamics simulations. Computer simulation demonstrations will be available for review. Following the presentations, a panel discussion will be held, inviting comments from all attendees.

WORKSHOP ORGANIZERS

CHRIS C. RUPP
NASA Marshall Space
Flight Center

WILLIAM A. BARACAT
General Research
Corporation

HOTEL ACCOMMODATIONS

Hotel rates for the Conference apply to Monday, September 15, 1986. Please refer to main section on hotel accommodations for more information.

REGISTRATION

All attendees must register in advance by mail as follows:
Students / Free (no lunch included)
All others / \$50

August 15, 1986 is the registration deadline. All registrations must include the fee. The registration fee includes coffee breaks, continental breakfast and lunch on September 16. Please refer to the main section on registration for more information.

For further information on the Workshop, please contact William A. Baracat, General Research Corporation (703) 893-5900 ext. 544.

Wednesday / 17 September 1986**AM**

8:00 Registration

9:00 Opening Remarks

IVAN BEKEY

Director, Advanced Programs,
Office of Space Flight,
NASA Headquarters

THOMAS O. PAINE

Thomas Paine Associates
Chairman, National Commission on Space

9:45 Break

**SESSION I / WHAT CAN TETHERS
DO IN SPACE? A Tutorial**

Co-Chairmen

GEORGE V. BUTLER

McDonnell Douglas Astronautics Company

ERNESTO VALLERANI

Aeritalia Space Systems Group, Italy

Organizer

GEORG VON TIESENHAUSEN

NASA Marshall Space Flight Center

10:00 Introduction

10:10 *Historical Evolution of Tethers in Space*

IVAN BEKEY

NASA Headquarters

10:40 *The Behavior of Long Tethers in Space*

DAVID A. ARNOLD

Smithsonian Astrophysical Observatory

11:00 *Scientific Purposes of Earth Orbital Tether Operations*

WILLIAM J. WEBSTER, JR.

NASA Goddard Space Flight Center

11:20 *Scientific Applications of Tethered Satellites*

ERNESTO VALLERANI

and **FRANCO BEVILACQUA**

Aeritalia Space Systems Group, Italy

11:40 *A Survey of Tether Applications to Planetary Exploration*

PAUL A. PENZO

Jet Propulsion Laboratory

12:00

noon Lunch

Wednesday / 17 September 1986

(continued)

SESSION II/SHUTTLE FLIGHTS: OPENING THE ERA OF TETHERS

Co-Chairmen

GIANFRANCO MANARINI

Piano Spaziale Nazionale, Italy

THOMAS STUART

NASA Headquarters

Organizer

GEORGE LEVIN

NASA Headquarters

PM

1:30 Introduction

1:40 *Deployment of a Tethered Satellite Pair into Low Earth Orbit for Plasma Diagnostics*

A. H. VON FLOTOW

and **P. R. WILLIAMSON**

Stanford University

2:00 *A Small Expendable Deployment System (SEDS)*

JOE CARROLL

Energy Science Laboratories

2:20 *Electrodynamic Plasma Motor/Generator Experiment*

JAMES E. MCCOY

NASA Johnson Space Center

2:40 *Attitude Control of Tethered Spacecraft*

LARRY LEMKE

NASA Ames Research Center

DAVID POWELL

and **XIAOHUA HE**

Stanford University

3:00 Break

3:20 *Feasibility Assessment of the Get-Away Tether Experiment*

MICHAEL GREENE

University of Alabama at Huntsville

CHRIS C. RUPP

NASA Marshall Space Flight Center

ANDREA LORENZONI

Piano Spaziale Nazionale, Italy

3:40 *The Tethered Elevator and Pointing Platform Demonstrations: A Shuttle Flight Test of Scaled Engineering Models*

PIETRO MERLINA, WALTER BOGO

and **SALVATORE CIARDO**

Aeritalia Space Systems Group, Italy

4:00 *Tethered Satellite System (TSS) Core Science Equipment*

CARLO BONIFAZI

Piano Spaziale Nazionale/CNR, Italy

4:20 *Tethered Satellite System Capabilities*

THOMAS D. MEGNA

Martin Marietta Denver Aerospace

4:40 *The RETE and TEMAG Experiments for the TSS Missions*

MAURIZIO CANDIDI

and **MARINO DOBROWOLNY**

Istituto Fisica Spazio Interplanetario

(IFSI)/CNR, Italy

FRANCO MARIANI

University of Rome, Italy

5:00 Adjournment

5:15 Reception

Thursday / 18 September 1986

Sessions III and IV are Parallel Sessions

SESSION III/TETHER DYNAMICS: UNDERSTANDING BEHAVIOR AND CONTROL

Co-Chairmen

VINOD J. MODI

University of British Columbia, Canada

VITTORIO GIAVOTTO

Politecnico di Milano, Italy

Organizer

PETER M. BAINUM

Howard University

AM

8:30 Introduction

8:40 *Pumping a Tethered Configuration to Boost its Orbit Around an Oblate Planet*

JOHN V. BREAKWELL

and **JAMES W. GEARHART**

Stanford University

9:05 *Dynamical Effects of Tether Structural Damping: A Preliminary Model*

SILVIO BERGAMASCHI

University of Padova, Italy

ANNA SINOPOLI

University of Venice, Italy

9:30 *Nonlinear Control Laws for Tethered Satellites*

ALEXANDER BOSCHITSCH

and **ODDVAR O. BENDIKSEN**

Princeton University

9:55 Break

10:20 *The Dynamics and Control of a Space Platform Connected to a Tethered Subsatellite*

FAN RUYING and **PETER M. BAINUM**

Howard University

10:45 *Tether Satellite Program Control Strategy*

CARL BODLEY and **HOWARD FLANDERS**

Martin Marietta Denver Aerospace

11:10 *Disturbance Propagation in Orbiting Tethers*

FILIPPO GRAZIANI

and **SILVANO SGUBINI**

University of Rome, Italy

11:35 *Gravity Gradient Enhancement during Tethered Payload Retrieval*

RON E. GLICKMAN

and **S. CAL RYBAK**

Ball Aerospace Systems Division

SESSION IV/ELECTRODYNAMICS: NEW APPROACHES TO SPACE POWER

Co-Chairmen

LESTER J. LIPPY

Martin Marietta Denver Aerospace

FRANCO BEVILACQUA

Aeritalia Space Systems Group, Italy

Organizer

JOSEPH C. KOLECKI

NASA Lewis Research Center

AM

8:30 Introduction

8:40 *A System Study of a One Hundred Kilowatt Electrodynamic Tether*

MANUEL MARTINEZ-SANCHEZ

and **D. E. HASTINGS**

Massachusetts Institute of Technology

9:00 *Three Dimensional Simulation of the Operation of a Hollow Cathode Electron Emitter on the Shuttle Orbiter*

IRA KATZ, MYRON J. MANDELL

and **VICTORIA A. DAVIS**

S-Cubed

9:20 *Plasma Contactors for Electrodynamic Tether*

MICHAEL J. PATTERSON

NASA Lewis Research Center

PAUL J. WILBUR

Colorado State University

9:40 *Tether Power Supplies Exploiting the Characteristics of Space*

CHRISTOPHER R. PURVIS

Jet Propulsion Laboratory

10:00 Break

Thursday / 18 September 1986*(continued)*

- 10:20** *Plasma Motor / Generator Reference Systems Designs for Power and Propulsion*
JAMES E. McCOY
 NASA Johnson Space Center
- 10:40** *Electrodynamic Tethers for Energy Conversion*
WILLIAM O. NOBLES
 Martin Marietta Denver Aerospace
- 11:00** *Power Generation and Storage with Tethers*
MARCELLO VIGNOLI, MARCO MATTEONI and FRANCO BEVILACQUA
 Aeritalia Space Systems Group, Italy
- 11:20** *Self Powered, Drag Compensated, Tethered Satellite System as an Orbiting Transmitter at ULF/ELF*
ROBERT D. ESTES and MARIO D. GROSSI
 Smithsonian Astrophysical Observatory
- 11:40** *Results from a Series of U.S. / Japan Tethered Rocket Experiments*
S. SASAKI, K-I. OYAMA, N. KAWASHIMA and T. OBAYASHI
 Institute of Space and Astronautical Science, Japan
- K. HIRAO**
 Tokai University, Japan
- W. J. RAITT**
 Utah State University
- P. R. WILLIAMSON and P. M. BANKS**
 Stanford University
- W. F. SHARP**
 University of Michigan
- 12:00**
noon Lunch
Speaker to be announced

SESSION V / THE SPACE STATION ERA: TETHERS FOR SCIENCE, TECHNOLOGY AND OPERATIONS*Co-Chairmen***DALE A. FESTER**

Martin Marietta Denver Aerospace

LUIGI G. NAPOLITANO

Istituto U. Nobile, Italy

*Organizer***DALE A. FESTER**

Martin Marietta Denver Aerospace

PM**2:00** Introduction**2:05** *Benefits of Tether Momentum Transfer to Space Station Operations***WILLIAM R. WOODIS****and JOHN M. VAN PELT**

Martin Marietta Denver Aerospace

2:25 *Tether Implications on Space Station Gravity Level***KENNETH R. KROLL**

NASA Johnson Space Center

2:45 *Comparison of a Tethered Refueling Facility to a Zero-Gravity Refueling Depot***ERLINDA R. KIEFEL, L. KEVIN RUDOLPH****and DALE A. FESTER**

Martin Marietta Denver Aerospace

3:05 Break**3:20** *Tethered Platforms: New Facilities for Scientific and Applied Research in Space***FRANCO BEVILACQUA, PIETRO MERLINA****and ALBERTO ANSELMi**

Aeritalia Space Systems Group, Italy

3:40 *J₂ Perturbations on the Motion of Tethered Platforms***SILVIO BERGAMASCHI**

University of Padova, Italy

CLARE SAVAGLIO

University of Michigan

4:00 *Tether Systems and Controlled Gravity***LUIGI G. NAPOLITANO****and RODOLFO MONTI**

Istituto U. Nobile, Italy

4:20 Preliminary Analysis of a SAR Interferometer Using a Tethered Antenna
SERGIO VETRELLA and ANTONIO MOCCIA
 University of Naples, Italy

4:40 Japanese Tether Concepts
S. SASAKI and M. NAGATOMO
 Institute of Space and Astronautical Science,
 Japan

5:00 Space Transportation without Rockets
CHARLES SHEFFIELD
 Vice President
 Earth Satellite Corporation

6:00 Adjournment

Friday/19 September 1986

SESSION VI/TECHNOLOGY DEVELOPMENT: THE KEY TO SUCCESS

Co-Chairmen

LEONARD A. HARRIS
 NASA Headquarters

CARLO BUONGIORNO
 Ministry of Scientific and Technological
 Research, Italy

Organizer

GEORG VON TIESENHAUSEN
 NASA Marshall Space Flight Center

AM

8:30 Introduction

**8:40 Development, Testing, and Evaluation of New
Tether Materials**
RALPH F. ORBAN
 Material Concepts, Inc.

**9:00 Technology and Applications—Convergence to
a Tether Capability**
JOHN L. ANDERSON
 NASA Headquarters

**9:20 Critical Space Technology Needs for Tether
Applications**

WILLIAM A. BARACAT
and CHARLES F. GARTRELL
 General Research Corporation

**9:40 A Survey on the Dynamics and Control of
Tethered Satellite Systems**

ARUN K. MISRA
 McGill University, Canada
VINOD J. MODI
 University of British Columbia, Canada

**10:00 Summary of the September 16 Tether
Dynamics Simulation Workshop**

CHRIS C. RUPP
 NASA Marshall Space Flight Center

10:30 Break

10:45 Panel:

The Future Impact of Tethers in Space

Moderators

IVAN BEKEY
 Director, Advanced Programs
 Office of Space Flight
 NASA Headquarters

LUCIANO GUERRIERO
 Director
 Piano Spaziale Nazionale, Italy

**Representatives from industry, military,
academia and government will be
members of this panel.**

12:00

noon Lunch

PM

2:00 Adjournment

Tether Dynamics Simulation (TDS) Workshop

Tuesday / 16 September 1986

AM

7:45 Registration/Continental Breakfast

8:15 Introduction

CHRIS C. RUPP

NASA Marshall Space Flight Center

WILLIAM A. BARACAT

General Research Corporation

Simulation Descriptions

8:30 **VINOD J. MODI**

University of British Columbia, Canada

ARUN K. MISRA

McGill University, Canada

9:00 **CARL BODLEY**

Martin Marietta Denver Aerospace

9:30 **Speaker to be announced**

NASA Johnson Space Center Systems Engineering Simulator

10:00 **DAVID D. LANG**

David D. Lang Associates

10:30 **JOHN R. GLAESE**

Control Dynamics Company

11:00 *Skyhook Program*

DAVID A. ARNOLD

Smithsonian Astrophysical Observatory

11:20 *Slack Program*

DAVID A. ARNOLD

Smithsonian Astrophysical Observatory

11:40 *Artificial Gravity Laboratory*

ENRICO LORENZINI

Smithsonian Astrophysical Observatory

12:00

noon Lunch

Demonstration of Computer Simulations

Simulation Descriptions—Continued

PM

1:30 **SILVIO BERGAMASCHI**

University of Padova, Italy

2:00 **Speaker to be announced**

Aeritalia Space Systems Group, Italy

2:30 *Validation of TSS Simulations*

KEITH MOWERY

NASA Marshall Space Flight Center

3:00 *TSS-1 Dynamics Flight Experiments*

GORDON E. GULLAHORN

Smithsonian Astrophysical Observatory

3:30 **Panel Discussion on Future Validation Activities**

5:00 **Adjournment**

5.3 Second International Conference On Tethers In Space (1987)

OBJECTIVE

The objective of the Second International Conference on Tethers in Space is to provide a focus on how tethers may be used for science in the era of the Space Station. The era of tethers will begin in 1991 with the Shuttle flight of the Tethered Satellite System (TSS), a joint U.S. and Italian project. Many studies by both countries have resulted in applications to the Space Station such as tethered platforms, propellant depots, and variable gravity modules for commercial and life science experiments. The number of applications is expanding to include lunar and planetary exploration. Jupiter's strong magnetic field, for example, may someday be used with electrodynamic tethers to produce power and thrust for a more versatile vehicle.

The Conference will cover tether fundamentals, the spectrum of tether applications, current national and international activities, status and plans for the TSS, hardware development, demonstration missions, early experimental validation, Space Station applications, planetary applications, and tether technology developments being conducted or planned by the U.S. and Italy. Additionally, a special Tether Dynamics Simulation Workshop will be held.

The Conference is sponsored by the Piano Spaziale Nazionale (PSN) of Consiglio Nazionale delle Ricerche (CNR), Italy, the National Aeronautics and Space Administration (NASA), and the European Space Agency (ESA). It is co-sponsored by the Associazione Italiana di Aeronautica e Astronautica (AIDAA), the American Institute of Aeronautics and Astronautics (AIAA), and the American Astronautical Society (AAS).

CONFERENCE ORGANIZATION

General Chairman
LUCIANO GUERRIERO
Director, PSN/CNR

Co-Chairmen
JEAN-JACQUES DORDAIN
Head, Space Station and
Platforms, Promotion and
Utilization Dept.,
European Space Agency

IVAN BEKEY
Director for Policy Planning
NASA Headquarters

Program Committee Chairman
WILLIAM DJINIS
Advanced Programs,
Office of Space Flight,
NASA Headquarters

Logistical Co-Chairmen
MARISA ADDUCI
Centro Internazionali Congressi

MARINELLA ERCOLI
PSN/CNR

TERRENCE G. REESE
Director, Aerospace Systems Group
General Research Corporation

Program Committee

JOHN L. ANDERSON
NASA Headquarters

PETER M. BAINUM
American Astronautical
Society/Howard University

WILLIAM A. BARACAT
General Research Corporation

EDWARD J. BRAZILL
NASA Headquarters

DALE A. FESTER
Martin Marietta
Denver Aerospace

MIREILLE GERARD
American Institute of
Aeronautics and Astronautics

VITTORIO GIAVOTTO
Associazione Italiana di
Aeronautica e Astronautica

RONALD I. GILJE
TRW

LEONARD HARRIS
NASA Headquarters

JAMES K. HARRISON
NASA MSFC

JOSEPH C. KOLECKI
NASA Headquarters

JAMES R. LEASE
NASA Headquarters

VINCENZO LETICO
PSN/CNR

ALBERTO LORIA
PSN/CNR

GIANFRANCO MANARINI
PSN/CNR

FRANCO MARIANI
University of Rome

DAVE MORUZZI
Italian Advanced Industries,
Inc./Aeritalia

PAUL PENZO
JPL

REMO RUFFINI
Societa' Italiana di Fisica/
University of Rome

CHARLES C. RUPP
NASA MSFC

ATTILIO SALVETTI
University of Pisa

ERNESTO VALLERANI
Aeritalia

GEORGE M. WOOD
NASA LaRC

GENERAL INFORMATION

CONFERENCE LOCATION

The Second International Conference on Tethers in Space will be held at the Scuola Grande San Giovanni Evangelista in Venice, Italy.

REGISTRATION

All Conference attendees are required to register. Please complete and return the enclosed registration form, along with your hotel deposit, by July 22, 1987.

Badging will be conducted at the Conference in the lobby of the Scuola Grande San Giovanni Evangelista on Sunday, October 4 from 5:00 to 8:00 p.m., and from 8:00 a.m. to 6:00 p.m. on Monday, October 5.

FEE

The fee for the Conference is 380,000 Lire (approx. \$300 U.S.) per person and covers the cost of working lunches each day of the Conference, refreshments, administrative charges, a concert on Tuesday, a gala dinner on Wednesday, and the conference proceedings. The fee is payable in Lire before July 22.

TRANSPORTATION

Conference participants should coordinate their transportation needs individually.

HOTEL ACCOMMODATIONS

The Conference has reserved blocks of rooms at various hotels in Venice. To make your reservation, send the information required on the Hotel Reservation Form to Marisa Adduci. We must have your reservation and deposit, equivalent to one night's stay at your hotel (in Lire) no later than July 22.

Hotel rooms are usually at a premium in Venice -- and with a competing conference (Workshop on Science and the Space Station) during the same time period, the situation is critical.

SPECIAL EVENTS

An evening cruise around the lagoon including dinner, drinks and dancing will take place on Monday, October 5 starting at approximately 7:00 p.m. The cost per person will be 60,000 Lire (approx. \$50 U.S.).

On Tuesday, October 6, a concert featuring a local Venetian string quintet will be held. The cost for a registrant and one guest is included in the registration fee. This concert will be held at the Chiesa dei Frari in Venice.

A gala dinner will be held at the Palazzo Pisani-Moretta on Wednesday, October 7. This is a very ancient and famous palace on the Canal Grande, still intact with the original art and furnishings. The cost for a registrant and one guest is included in the conference registration fee.

Special excursions and tours will be available for spouses. Information on these events will be available at registration on Sunday and Monday.

MESSAGE AND TRAVEL DESK

Messages for conference attendees may be left at telephone number 39-41-718234.

CONFERENCE PROCEEDINGS

Conference proceedings will be sent to all conference attendees. This document will contain a copy of all presented papers. The cost for one copy has been included in the registration fee.

Note: All fees shown in US dollars are approximate.

SUNDAY, 4 OCT 1987

5:00 p.m. - 8:00 p.m. Registration

MONDAY, 5 OCT 1987

8:00 a.m. - 6:00 p.m. Registration

SESSION I / MONDAY, 5 OCT 1987 SPACE PROGRAM: CONTEXT FOR TETHERS

Session Chairmen:

Carlo Buongiorno - MRST

Frederick Engstrom - ESA Headquarters

Session Organizer:

Amalia Ercoli Finzi - Politecnico di Milano

AM

9:00 Welcome/Opening Remarks
Luciano Guerriero, PSN/CNR

9:30 Keynote Speaker
Ivan Bekey, NASA Headquarters

10:00 "Tether History and Historiography"
Mario D. Grossi, Smithsonian Astrophysical
Observatory (SAO)

10:20 "Tether Programs - PSN"
Gianfranco Manarini, PSN/CNR

10:40 "Status and Plans for the Space Station
Program"
Alfonso V. Diaz, Code S, NASA
Headquarters

11:00 "Columbus Program"
Jean-Jacques Dordain, ESA Headquarters

11:20 "Status of Tethered Satellite System (TSS)
Development"
Jay H. Laue, Deputy Manager, Tethered
Satellite System Project, NASA Marshall
Space Flight Center

11:40 "Tether Tutorial"
David A. Arnold, Smithsonian Astrophysical
Observatory (SAO)

SESSION II / MONDAY, 5 OCT 1987 EARLY EXPERIMENTAL VALIDATION

Session Chairmen:

Len Harris - NASA Headquarters
Ernesto Vallerani - Aeritalia

Session Organizer:

Ron Gilje - TRW

PM

- 2:00 "Early Tether Dynamics Flight Experiment"
Lawrence G. Lemke, NASA ARC;
Charles C. Rupp, NASA MSFC; William
J. Webster, NASA GSFC; George M.
Wood, NASA LaRC

- 2:20 "Small Expendable Deployer System
(SEDS)"
Joseph A. Carroll, Energy Science
Laboratories

- 2:40 "The Get Away Tether Experiment (GATE):
Experimental Plans"
Michael Greene, Justin Walls, Theron Car-
ter, Auburn University, Department of
Electrical Engineering; Charles C. Rupp,
Marshall Space Flight Center; and Douglas
Wheelock, University of Alabama in
Huntsville, Department of Electrical Engi-
neering

- 3:00 "MAIMIK, A Tethered "Mother" -
"Daughter" Electron Accelerator Rocket"
B.N. Maehlum, Norwegian Defense
Research Establishment

- 3:20 "Recent Laboratory Results of the KITE
Control System and Attitude Dynamics
Simulator"
Lawrence G. Lemke, NASA ARC;
J. David Powell and R. Schoder, Stanford
University

- 3:40 "Absorptive Tether, A First Test in Space"
Wubbo J. Ockels, ESA

- 4:00 "Hollow Cathode Rocket Experiment
(HOCAT)"
Richard C. Olsen, Physics Department,
Naval Postgraduate School

- 4:20 "Validation of Tethered Package Deploy-
ment for the Space Station"
Richard S. Post, J. D. Sullivan, J. H. Irby,
Massachusetts Institute of Technology;
Enrico C. Lorenzini, SAO

- 4:40 "Scientific Achievement of a Series of Tether
Rocket Experiments"
N. Kawashima, Institute of Space and
Astronautical Science, Tokyo

SESSION III / TUESDAY, 6 OCT 1987 TETHER DYNAMICS SIMULATION WORKSHOP

Session Chairmen:

Charles C. Rupp - NASA MSFC
Silvio Bergamaschi - University of
Padova

Session Organizer:

Peter Bainum - AAS / Howard University

SIMULATION TECHNIQUES

AM

- 9:00 "Optimal State Estimation for a Tethered
Satellite System"
Daniel S. Swanson and Robert F. Stengel,
Princeton University, Department of
Mechanical and Aerospace Engineering

- 9:25 "Effect of Tether Flexibility on the
Tethered Shuttle Subsatellite Stability
and Control"
Liu Liangdong and Peter M. Bainum,
Department of Mechanical Engineering,
Howard University

- 9:50 "Dynamics and Control of Two Space
Platforms Connected by a Short Tether"
Antonio Moccia, Sergio Vetrella,
Cattedra di Ingegneria dei Sistemi
Aerospaziali, University of Naples

- 10:15 "Interaction of the Space Shuttle On-Orbit
Autopilot with Tether Dynamics"
Edward V. Bergmann, C. S. Draper
Laboratory

- 10:40 "The Tethered Satellite System on the
Systems Engineering Simulator"
Ronald W. Humble, Lockheed Engineer-
ing and Management Services Company

- 11:05 "Dynamics Simulation of the TSS
Actively Controlled Satellite"
Bruna Cibrario, Bruno Musetti, Mario
Rossello, Floriano Venditti, Aeritalia
Space Systems Group

11:30 "Out-of-Plane Perturbations of a Resonant Tether"
John V. Breakwell, Stanford University;
James W. Gearhart, Lockheed

11:55 "Tethsim: A Dynamics Simulation Software Package for Tethered Systems"
Bruna Cibrario; Floriano Venditti,
Aeritalia Space Systems Group, Torino;
Gianni Origgi, Politecnico di Milano

PM
2:00 **Test Case Results:** In-depth review of dynamics simulation of some test cases. Digest of current tether dynamics simulations, focus on capabilities, inadequacies and verification. Recommendations for additions and extensions of performance to enable greater precision and validity. Ground and flight test verification experiments.

VISCOELASTIC TETHER DYNAMICS

4:00 "Effects of Damping on TSS Vibrations Stability"
Anna Sinopoli, Institute of Architecture,
University of Venice

4:22 "Tether Damping in Space"
Xiaohua He and J. David Powell, Stanford University

4:44 "Tether as a Dynamic Transmission Line"
Gordon E. Gullahorn, SAO; Robert G. Hohlfield, Boston University

5:06 "Tether Dynamics and Vibration Analysis"
R. L. Engelstad and E. Lovell, University of Wisconsin

SESSION IV / TUESDAY, 6 OCT 1987 ELECTRODYNAMICS

Session Chairmen:

Peter Banks - Stanford University
Franco Mariani - University of Rome

Session Organizer:

Joseph C. Kolecki - NASA Headquarters

SYSTEMS

AM

9:00 "Shuttle Electrodynamic Tether System"
P. Roger Williamson and Peter M. Banks,
STARLAB, Stanford University

9:30 "Passive Current Collection to a Conducting Tether"
William B. Thompson, University of California, San Diego

10:00 "Laboratory Investigation of the Electrodynamic Interaction of a Tethered Satellite in an Ionospheric Plasma: Preliminary Results"
Carlo Bonifazi, Michele Smargiassi, and Jean Pierre Lebreton, CNR Frascati

10:30 "Current Distribution and Fields Generated by a Body Moving Through a Magnetoplasma"
Kenneth J. Harker, Peter M. Banks, D.J. Donahue, STARLAB, Stanford Univ.

11:00 "Model of the Interaction of a Hollow Cathode with the Ionosphere"
Marino Dobrowolny and Luciano Iess, Istituto di Fisica dello Spazio Interplanetario, CNR Frascati

11:30 "Plasma Motor Generator Tether System for Orbit Reboost"
Neal D. Hulkower and Roger J. Rusch, TRW Space and Technology Group

12:00 "Alfven Propulsion at Jupiter"
Steven B. Gabriel, R. M. Jones, JPL

12:30 "Hollow Cathode Discharge Characteristics in Space: Flight Demonstrations"
James E. McCoy, NASA JSC

TECHNOLOGY

PM

2:00 "TSS Core Equipment: A High Perveance Electron Generator for the Electrodynamic Missions"
Carlo Bonifazi, PSN; Paolo Musi, Aeritalia; Gianfranco Cirri, Proel Elettr.

2:30	"On the Need for Space Tests of Plasma Contactors as Electron Collector" Ira Katz, Victoria A. Davis, and Donald E. Parks, S-CUBED	AM 9:00	Opening Remarks TBD
3:00	"Experimental Validation of a Phenomenological Model of the Plasma Contacting Process" Paul J. Wilbur and John D. Williams, Department of Mechanical Engineering, Colorado State University	9:20	"Cosmic Rays and Particle Physics" TBD
3:30	"Hollow Cathode Laboratory Activities at Frascati" Giuliano Varnaroni, Cristiano Cosmovici, IFSI; Carlo Bonifazi, PSN/IFSI; James McCoy, NASA JSC	9:40	"Small Payloads in Astrophysics" TBD
4:00	"Ground-Based Plasma Contactor Characterization for Spaceflight Experiment Definition" Michael J. Patterson, NASA LeRC	10:00	"Physics and Chemistry in Zero-G" TBD
4:30	"A Two-Dimensional Theory of Plasma Contactor Clouds Used in the Ionosphere with an Electrodynamic Tether" Daniel E. Hastings, N. Gatsonis, and D. Rivas, Department of Aeronautics and Astronautics, MIT	10:20	"Solar System and Planetology" TBD
5:00	"A Rocket-Borne Experiment to Demonstrate, Test, and Characterize the Fundamental Science and Engineering Principles of Hollow Cathode Discharge Operations in Space" Edward P. Szuszczewicz, Science Applications International Corporation; James E. McCoy, NASA JSC; Marino Dobrowolny, IFSI/CNR; Carlo Bonifazi, PSN/IFSI	10:40	"Innovative Uses of Tethers in Space" Paul A. Penzo, JPL
		11:00	"Outer Atmospheric Research - One Tether Capability" John L. Anderson, NASA HQ, OAST
		11:20	"Role of Tethers in a LEO-Lunar Ferry" David B. Weaver, McDonnell Douglas Astronautics Co.
		11:40	"Artificial Gravity for a Mars Spaceship Design" TBD

SESSION VI / WEDNESDAY, 7 OCT 1987 TETHERS IN SPACE: A BROAD PERSPECTIVE

Session Chairmen:

James K. Harrison - NASA MSFC
Franco Bevilacqua - Aeritalia

Session Organizer:

John R. Glaese - Control Dynamics Co.

SESSION V / WEDNESDAY, 7 OCT 1987 TETHERS FOR SCIENCE AND INNOVATIVE USES

Session Chairmen:

Roger Bonnet - ESA Headquarters
Thomas Donahue - National Academy of Sciences

Session Organizer:

Remo Ruffini - Societa' Italiana di Fisica/
University of Rome

PM

2:00 "From Space Elevators to Space Tethers: An Historical Perspective"
Jerome Pearson, Air Force Wright Aeronautical Laboratories

2:30 "Tether Applications in the European Scenario"
Chris A. Markland, ESA;

- 3:30 "The Tethered Space Elevator System"
Franco Bevilacqua, Pietro Merlina,
Aeritalia
- 4:00 "Environmental Factors Affecting
Atmospheric Research with Tethered
Satellites"
Jack W. Slowey, SAO
- 4:30 "The Use of Tethers for an Artificial
Gravity Facility"
Lawrence G. Lemke, Fred Mascy, Byron
L. Swenson, NASA ARC
- 5:00 "Dynamics of Tethers in Artificial
Gravity Applications"
John R. Glaese, Control Dynamics
Company
- 5:30 "Lower Thermosphere Studies from
Tether"
J. H. Hoffman and R. R. Hodges,
University of Texas at Dallas

SESSION VII / WEDNESDAY, 7 OCT 1987 TETHER DYNAMICS

Session Chairmen:

John V. Breakwell - Stanford University
Enrico Lorenzini - SAO

Session Organizer:

Alberto Loria - PSN/CNR

PM

- 2:00 "Dynamical Stability of a Flexible
Tether"
William B. Thompson, University of
California, San Diego
- 2:22 "Tethered Diagnostic Package for Use
from Space Station"
James D. Sullivan, Richard D. Post, J. H.
Irby, MIT; Enrico C. Lorenzini, SAO
- 2:44 "Effects of Atmospheric Density Gradi-
ent on the Stability and Control of Teth-
ered Subsatellite"
Naoyuki Watanabe and Junjiro Onoda,
The Institute of Space and Astronautical
Science, Tokyo

- 3:06 "Study of an Orbiting Tethered Dumbbell
System Having Positive Orbital Energy"
Enrico Lorenzini, David A. Arnold,
Mario D. Grossi, Gordon E. Gullahorn,
SAO
- 3:28 "Dynamics and Control of the Space
Station Based Tethered Payload"
P. K. Lakshmanan, Vinod J. Modi,
Department of Mechanical Engineering,
University of British Columbia;
Arun K. Misra, McGill University
- 3:50 "Free Dynamics of Tethered Satellite
System"
Angelo Luongo, Marcello Pignatari,
Universita di Roma "La Sapienza" ;
Fabrizio Vestroni, Universita dell' Aquila
- 4:12 "Order of Magnitude Evaluation of the
Lifetime of a Free Tether in Orbit "
Silvio Bergamaschi, Marco Morana,
Institute of Applied Mechanics,
Padua University

- 4:34 "Thermal Effects on Tether Dynamics"
Filippo Graziani, Universita di Roma

- 4:56 "Effect of the Attitude Dynamics on
Tether Propulsion"
Arun K. Misra and Z. E. Amier,
Department of Mechanical Engineering,
McGill University; Vinod J. Modi,
Department of Mechanical Engineering,
University of British Columbia

SESSION VIII / THURSDAY, 8 OCT 1987 TETHERS ON STATIONS AND PLAT- FORMS

Session Chairmen:

Jean-Jacques Dordain - ESA Headquar-
ters
Dale A. Fester - Martin Marietta Denver
Aerospace

Session Organizer:

George M. Wood - NASA LaRC

AM		PM	
9:00	Chairmen Remarks	2:00	"Early Roles for Expendable Tether Systems on Space Stations and Platforms" Joseph A. Carroll, Energy Science Laboratories
9:10	"Tethered System/Space Platform Integration: TSS Lessons Learned" L. Kevin Rudolph, Martin Marietta Denver Aerospace	2:20	"Space Station Tethered Waste Disposal" Charles C. Rupp, NASA MSFC
9:30	"Tether Applications Scenarios for Space Station/Platform Systems" James D. Walker, Martin Marietta Denver Aerospace	2:40	"Tethered Capability to Return Space Station Material" Mario Burigo and Cosimo Chiarelli, Aeritalia
9:50	"Consideration of Requirements for Space Station with Attached Tethers" Melvin R. Carruth, Jr., NASA MSFC	3:00	"Tethered Space Recovery Vehicle Deployment / Re-entry Demonstration" Dwight Florence, General Electric Re-entry Systems
10:10	"Space Station Gravity Gradient Stabilization by Tethers" Franco Bevilacqua, Salvatore Ciardo, Aeritalia; Alberto Loria, PSN	3:20	"Thrusting Sling in Space - A Tether Assist Maneuver for Orbit Transfer" Mario Pecchioli and Filippo Graziani, Università di Roma
10:30	"Acceleration Levels on Board the Space Station and a Tethered Elevator for Micro- and Variable-Gravity Applications" Enrico C. Lorenzini, Mario Cosmo, SAO; Sergio Vetrella, Antonio Moccia, University of Naples	SESSION IX / THURSDAY, 8 OCT 1987 TETHER TECHNOLOGY Session Chairmen: John Anderson - NASA Headquarters Vittorio Giavotto - Politecnico di Milano Session Organizer: James Lease - NASA Headquarters	
10:50	"Double Tether System Improving Automatic Docking Maneuvers" Amalia Ercoli Finzi, Biagio Mignemi, Politecnico di Milano	AM	
11:10	"Tethered Astrometric Telescope Facility" Lawrence G. Lemke, Martha Smith, NASA ARC	9:00	"Tether Dynamics Simulation Workshop Summary" Charles C. Rupp, NASA MSFC
11:30	"The Use of Tethers to Construct and Deploy Solar Sails from the Space Station" John M. Garvey, McDonnell Douglas Astronautics	9:20	"Electrodynamics Session Summary" Joseph C. Kolecki, NASA Headquarters
11:50	"Electrodynamic Tethers for Energy Conversion" William Nobles, Martin Marietta Denver Aerospace	9:40	"An Overview of a Tether Deployment Monitoring System" Paul Ibanez and Alejandro Levi, ANCO Engineers, Inc.
12:10	"Opportunities for Tether Experiments and Applications in the Columbus Program" Karl Knott, ESA		

- 10:00 "Simulation and Measurement of Disturbance Propagation in a Single Tether System"
Michael Greene, Theron Carter, Department of Electrical Engineering, Auburn University;
Charles C. Rupp, NASA MSFC
- 10:20 "Feasibility Assessment of TSS Terminal Phase Retrieval Procedures"
James E. Oberg, RSOC, JSC
- 10:40 "Optimization of Motion Control Laws for Tether Crawler or Elevator Systems"
Frank R. Swenson, Georg von Tiesenhausen, Tri-State University
- 11:00 "Space Tethers: Comments on Their Scope and on the Accessibility of Their Use with Aerodynamic Forces"
J. W. Flower, University of Bristol
- 11:20 "STARFAC: Advanced Concept Definition and Mission Analysis"
R. Kenneth Squires, Henry Wolf, Martin W. Henry, Analytical Mechanics Associates, Inc.; Paul M. Siemers III and George M. Wood, Jr., NASA LaRC; Giovanni M. Carlomagno, University of Naples
- PM
2:00 "Technologies Applicable to Space Tethers"
William A. Baracat, General Research Corporation, Aerospace Systems Group
- 2:20 "Acceptance and Qualification Test Results of the 20 KM Electromechanical Tether for TSS-1"
Leland S. Marshall, Martin Marietta Denver Aerospace
- 2:40 "TSS-2 Technology"
Andrea Lorenzoni, PSN; E. Allais, Aeritalia; T. Megna, MMA
- 3:00 "Hypervelocity Impact Testing of Tethers"
Francis I. Tallentire and William R. Woodis, Martin Marietta Denver Aerospace

- 3:20 "Tether Inspection and Repair Experiment (TIRE)"
George M. Wood, NASA LARC; Alberio Loria, PSN/CNR; James K. Harrison, NASA MSFC
- 3:40 "Some Open Questions on Tether Technology"
Joseph A. Carroll, Energy Science Laboratories

SESSION X / THURSDAY, 8 OCT 1987 CONFERENCE SUMMARY

PM

- 4:00 Luciano Guerriero, PSN/CNR
Jean-Jacques Dordain, ESA Headquarters
Ivan Bekey, NASA Headquarters

SESSION XI / THURSDAY, 8 OCT 1987 PANEL DISCUSSION: THE NEXT STEP?

PM

- 4:30 Moderators:
Gianfranco Manarini, PSN Headquarters
Darrell R. Branscome, NASA Headquarters
Roger Bonnet, ESA Headquarters

Organizer:

George Butler, McDonnell Douglas

Panel Members:

Luigi Napolitano, University of Naples
Remo Ruffini, Societa' Italiana di Fisica/
University of Rome
Ernesto Vallerani, Aeritalia
Col. George Hess, USAF
Paul Penzo, JPL
Frank Van Rensselaer, Martin Marietta

- 6:30 Adjournment

5.4 Third International Conference On Tethers In Space (1989)

Objective and Approach

For more than a decade the excitement of a potential new space capability has accompanied the concept, development, analysis and research related to tethers in space. Based on this work the capability of tethering research and operational craft together to obtain unique properties and performance seems promising for several applications. The next steps toward operational reality are already being taken. Flight demonstrations for the purpose of validating the dynamics and operating principles of tethered systems are under development. Also, activities to define specific user operational and systems requirements and to define flight validation experiments for promising applications are underway.

The theme of the Third International Conference on Tethers in Space is "TOWARD FLIGHT". The conference will focus on tether applications with strong user interest and where appropriate, on planned flight systems and experiments. Its objective is to identify tethered system users for specific applications and begin to focus the attention of the tether community on helping to define and meet the requirements of potential user communities.

The conference will be preceded by two specialist workshops, held in parallel on 16 May, one addressing the dynamics of tether behavior and control and the other addressing the electrodynamics of conducting tethers moving through the earth's magnetic field within the ionosphere.

This conference is being organized and operated by the American Institute of Aeronautics and Astronautics (AIAA) and co-sponsored by the National Aeronautics and Space Administration (NASA), the Agenzia Spaziale Italiana (ASI) and the European Space Agency (ESA) in cooperation with the American Astronautical Society (AAS) and the Associazione Italiana di Aeronautica e Astronautica (AIDAA).

Conference Organization

Conference Cochairmen
Darrell R. Branscome
Director, Advanced Program
Development Division
NASA Headquarters

Cort Durocher
Executive Director
American Institute of
Aeronautics and Astronautics

Luciano Guerriero
President
Italian Space Agency

Heinz Stoewer
Head, Systems Engineering
and Programmatic
Department
ESA European Space
Technology Center

Joseph C. Kolecki
NASA
Lewis Research Center

Vincenzo Letico
Italian Space Agency

Alberto Loria
European
Italian Space Agency

Ian Pryke
European
Space Agency

Charles C. Rupp
NASA Marshall
Space Flight Center

George M. Wood
NASA Langley
Research Center

Technical Advisor
Ivan Bekey
NASA Headquarters

Program Committee

Program Cochairmen
John L. Anderson
NASA Headquarters

Daie A. Fester
Martin Marietta
Space Systems and
American Institute of
Aeronautics and Astronautics

Philip J. Baker
Aeritalia

Silvio Bergamaschi
University of Padua, Italy

Carlo Bonifazi
Italian Space Agency

Edward J. Brazill
NASA Headquarters

William Djinis
NASA Headquarters

Mireille M. Gerard
American Institute of
Aeronautics and Astronautics

Administrative Committee

Kaye E. Anderson
SRS Technologies

William A. Barakat
General Research
Corporation

Joanne M. Hauser
American Institute
of Aeronautics
and Astronautics

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OF POOR QUALITY

**PRELIMINARY PROGRAM
WEDNESDAY/17 MAY 1989**

AM		AM		PM	
9:00	Introductory Remarks <i>Program Cochairman</i> J. Anderson NASA Headquarters	11:20	Overview of ESA Tether Activities K. Reinhartz ESA European Space Technology Center	3:10	Small Expendable-Tether Deployer System (SEDS) Development Status J. Harrison, C. Rupp NASA Marshall Space Flight Center J. Carroll, C. Alexander, E. Pulliam Energy Science Laboratories, Inc.
9:05	Welcome and Opening Addresses <i>Conference Cochairmen</i> C. Durocher American Institute of Aeronautics and Astronautics D. Branscome NASA Headquarters L. Guerriero Italian Space Agency H. Stoewer ESA European Space Technology Center	11:40	Overview of DFVLR Tether Activities W. Seboldt German Aerospace Research Establishment	3:30	<i>Break</i>
9:25	Tethers - Evolution from Ideas to International Conferences I. Bekey NASA Headquarters	PM		3:50	Tether-Initiated Space Recovery System (TISRS): Italian Activities Toward Flight Demonstration P. Merlina, M. Burigo Aeritalia
9:45	Overview of the 1987 Venice Conference J. Kolecki NASA Lewis Research Center	12:00	Overview of Soviet Tether Activities V. Sarychev USSR Academy of Sciences (Invited)	4:10	Delta II Secondary Payload Opportunities for Tether Demonstration Experiments J. Garvey McDonnell Douglas Astronautics Company
10:00	<i>Break</i>	12:20	<i>Adjournment</i>	4:30	Get-Away Tether Experiments (GATE) for the Tether Dynamics Explorer Series (TDE) M. Greene, J. Walls, D. Freeman, G. Stoverl Auburn University
			Session II Flight Demonstration (Parallel Session) <i>Cochairmen</i> George M. Levin NASA Headquarters Alberto Loria Italian Space Agency <i>Organizer</i> Edward J. Brazill NASA Headquarters	4:50	High Current Plasma Contactor Neutralizer System C. Collett, J. Beattie, W. Williamson, J. Matossian Hughes Research Laboratories
	Session I Tether Programs <i>Cochairmen</i> John L. Anderson NASA Headquarters Dale A. Fester Martin Marietta Space Systems <i>Organizer</i> John L. Anderson	2:00	<i>Introduction</i>	5:10	<i>Adjournment</i>
10:15	<i>Introduction</i>	2:10	Tethered Satellite System TSS-I Flight Status J. Price NASA Marshall Space Flight Center	6:00	<i>Reception</i> (See page 10 under Special Events for detailed information)
10:20	Overview of the National Aeronautics and Space Administration Tether Activities P. Penzo Jet Propulsion Laboratory	2:30	Joint ASI/NASA Efforts in Tether Flight Demonstrations A. Loria Italian Space Agency J. Harrison NASA Marshall Space Flight Center		
10:50	Overview of ASI Tether Activities G. Manarini Italian Space Agency	2:50	Plasma Motor/Generator Experiments J. McCoy NASA Johnson Space Center		

WEDNESDAY/17 MAY 1989**Session III
Electrodynamics
(Parallel Session)**

Cochairpersons
Carlo Bonifazi
Italian Space Agency

Carolyn K. Purvis
NASA Lewis Research Center

Organizer
Michael J. Patterson
NASA Lewis Research Center

PM

2:00 *Introduction*

2:10 **Calculating the
Electromagnetic Field on
the Earth Due to an
Electrodynamics Tethered
System in the Ionosphere**

R. Estes
Harvard-Smithsonian Center
for Astrophysics

2:25 **Current Distribution
Generated by Conducting
Bodies Moving
Through a Magnetoplasma**
D. Donohue, K. Harker, P. Banks
Stanford University

2:40 **Space-Based Tethered
Array Antenna**
M. Kaplan, C. King
Naval Research Laboratory

2:55 **Waves and Wings from
Tethers and Electrodes in a
Laboratory Plasma**
J. Urrutia, R. Stenzel
University of California
at Los Angeles

3:10 **Plasma Contactor Clouds:
A Comparison of Theory
and Experiment**
M. Oberhardt
U.S. Air Force Geophysics Lab
D. Hastings
Massachusetts Institute of
Technology

3:25 *Break*

3:45 **A Fluid Model of Plasma
Contactors in the
Ionosphere**
L. Iess, M. Dobrowolny
Institute of Physics of the Inter-
planetary Space/
National Research Council, Italy

PM

4:00

**An Experimental
Investigation of the Plasma
Contacting Process**

J. Williams, P. Wilbur
Colorado State University

4:15 **Hollow Cathode Plasma
Contactor Technology**

M. Patterson
NASA Lewis Research Center
T. Verhey
Sverdrup Technology, Inc.

4:45 *Adjournment*6:00 *Reception*

(See page 10 under *Special Events*
for detailed information.)

THURSDAY / 18 MAY 1989**Session IV
Downward Deployed Tethers
(Parallel Session)**

Cochairmen
Giovanni Carlomagno
University of Naples

Stanley D. Shawhan
NASA Headquarters

Organizer
George M. Wood
NASA Langley Research Center

AM

8:30 *Introduction*

8:40 **Tethered Satellite System-2:
A Proposed Program**

J. Anderson
NASA Headquarters

9:00 **Aerodynamic Aspects of
Tethered Satellite Design and
Utilization**

R. Boettcher
German Aerospace Research
Establishment

9:20 **Satellite-Tethered
Upper-Atmospheric Research
Facility**

C. Butner, C. Gartrell
General Research Corporation

9:40 **Tethered Dynamics
Explorer Series**

K. Crumbly, G. Wood, R. DeLoach
NASA Langley Research Center
C. Rupp, J. Harrison
NASA Marshall Space Flight Center

AM

10:00

**Tether De-Orbit System:
A Promising Alternative**

F. Bevilacqua, M. Burigo
Aeritalia

10:20 **High Altitude
Aerothermodynamic
Research Opportunities
with Large Tethered
Satellites**

L. DeLuca, G. Caricmagno
University of Naples
G. Wood, P. Siemers
NASA Langley Research Center

10:40 *Break*

11:00 **The Impact of Tethers on
Atmospheric Science**

J. Slowey
Harvard-Smithsonian Center for
Astrophysics

11:20 **Applications of a Downward-
Deployed Tether in Polar
Orbits**

S. Gabriel, H. Garrett
Jet Propulsion Laboratory
J. Forbes
Boston University

11:40 **Atmospheric Density
Variations via Tethered
Satellite Drag**

G. Gullahorn
Harvard-Smithsonian Center for
Astrophysics

PM

12:00 *Adjournment***Session V
Dynamics
(Parallel Session)**

Cochairmen
Vittorio Giavotto
Polytechnic of Milan

Thomas R. Kane
Stanford University

Organizers
Silvio Bergamaschi
University of Padua, Italy

Charles C. Rupp
NASA Marshall
Space Flight Center

AM

8:30 *Introduction*

THURSDAY/18 MAY 1989								
AM	8:40	Tethered Satellite System Control Systems Design C. Bodley Martin Marietta Astronautics D. Mowery, D. Tomlin NASA Marshall Space Flight Center	PM	12:00	16 May 1989 Dynamics Workshop Summary C. Rupp NASA Marshall Space Flight Center	PM	4:35	Tethered Gravity Laboratories F. Bevilacqua, P. Merlina Aeritalia E. Lorenzini, M. Cosmo Smithsonian Astrophysical Observatory S. Bergamaschi University of Padua
			12:20	<i>Adjournment</i>				
9:00		Three-Dimensional Vibrations of Tethered Satellite System P. Monica, P. Marcello, L. Angelo University of Rome			Session VI Stations, Nodes and Platforms (Parallel Session) <i>Cochairmen</i> Earle K. Huckins NASA Headquarters Remo Ruffini University of Rome <i>Organizers</i> Phillip J. Baker Aeritalia William Djinis NASA Headquarters	5:00	Two-Phase Flow-Induced Vibrations of Space Tethers R. Engelstad, E. Lovell University of Wisconsin	
9:20		Passive Tethered Satellite Retrieval R. Humble Lockheed Engineering and Sciences Company				5:25	<i>Adjournment</i>	
9:40		A Length Rate Control Law Applicable to Space Station Tether Deployment/Retrieval J. Glaese Control Dynamics Company						Session VII Electrodynamics (Parallel Session) <i>Cochairpersons</i> Carlo Bonifazi Italian Space Agency Carolyn K. Purvis NASA Lewis Research Center <i>Organizer</i> Michael J. Patterson NASA Lewis Research Center
10:00		Space Station Based Tethered Payload: Control Strategies and Their Relative Merit P. Lakshmanan, V. Modi The University of British Columbia A. Misra McGill University, Canada	2:00	<i>Introduction</i>		PM	2:00	<i>Introduction</i>
10:20		<i>Break</i>						
10:40		Orbit Evolution and Decay of Tether-Launched Space Systems S. Bergamaschi University of Padua	2:35	Analysis of the Performances of a Tethered Stabilized Schmidt Telescope Assembled to the Space Station F. Bertola, P. Rafanelli, F. Angrilli, G. Bianchini, M. DaLio, G. Fanti University of Padua		2:10	Shuttle Electrodynamic Tether System P. Williamson, P. Banks Stanford University W. Raitt Utah State University	
11:00		Robust Attitude Control of a Tethered Nuclear Power Plant-Space Station System R. Yedavalli Ohio State University M. Ernst, C. Lawrence NASA Lewis Research Center	3:00	The Outpost Platform, A Place for Tether Research and Transportation Node Operations in Orbit T. Taylor, C. Cook, W. Good Global Outpost, Inc.		2:30	Determination of the Tethered Satellite Location for the Shuttle Electrodynamic Tether System First Mission S. Williams, P. Williamson Stanford University	
11:20		Dynamics and Control of Tethered Antennas / Reflectors in Orbit L. Liangdong, P. Bainum Howard University	3:25	<i>Break</i>		2:50	Electrical Characteristics of the Tethered Satellite System One D. Lauben, P. Williamson Stanford University	
11:40		General 3-D Animation Techniques for Tether Dynamics D. Lang Lang Associates C. Soderland NASA Johnson Space Center	4:10	A Design for a Space Station Tethered Elevator M. Haddock, L. Anderson University of Central Florida				

THURSDAY/18 MAY 1989**Session VII
Electrodynamics
(continued)**

- PM
3:10 **A Systematic Approach to Sensors Evaluation of Ground-Track Measurement Systems for TSSI**
G. Carelli
Institute of Physics of the Interplanetary Space/National Research Council, Italy
G. Tacconi, A. Tiano
University of Genoa
- 3:30 *Break*
- 3:50 **Tethered Satellite System - Electromagnetic Field and FEM Effect Numerical Simulation in Near Proximity of TSS Satellite**
A. Lorenzini
Italian Space Agency
E. Pierazostini
Telespazio Roma
- 4:10 **The Active Control of the Electrodynamic Interaction of a Tethered Satellite by the Core Electron Generator**
C. Bonifazi
Institute of Physics of the Interplanetary Space/ National Research Council, Italy
- 4:30 **Shuttle Potential and Return Electron Experiment**
M. Oberhardt, D. Hardy
U.S. Air Force
Geophysics Laboratory
- 4:50 **VLF Space Transmitter**
R. Olsen
Naval Postgraduate School
- 5:10 **18 May 1989
Electrodynamics Workshop
Summary**
J. Kolečki
NASA Lewis Research Center
- 5:30 *Adjournment*

FRIDAY / 19 MAY 1989**Session VIII
Transportation
(Parallel Session)**

Cochairmen
Maxwell W. Hunter
Consultant

Carlo Buongiorno
Italian Space Agency

Organizer
Paul A. Penzo
Jet Propulsion Laboratory

- AM
8:30 *Introduction*
- 8:40 **Tether as Upper Stage for Launch to Orbit**
B. Tilotson
Space Research Associates, Inc.
- 9:00 **On the Tilting Tethered Crane Concept**
A. Finzi, G. Origgi
Polytechnic of Milan
- 9:20 **Transportation Using Spinning Tethers with Emphasis on Phasing and Plane Change**
D. Henderson
Jet Propulsion Laboratory
- 9:40 **A Comparative Analysis of an Electrodynamic Tether as a Propulsive Device**
T. Verhey
Sverdrup Technology, Inc.
- 10:00 **Materials Transport between LEO and the Moon Using Tethers**
M. Stern, J. Arnold
University of California at San Diego
- 10:20 *Break*

**Session IX
Gravity and Rotating
Tether Systems
(Parallel Session)**

Cochairmen
Jean Pierre Lebreton
ESA European Space Technology Center

Luigi Napolitano
University of Naples

Organizer
Franco Bevilacqua
Aeritalia

- 10:40 *Introduction*

AM

- 10:50 **How Tethered Systems Can Benefit Microgravity Research in the Space Station Era**
M. Lavitola, F. Giani, M. Briccarello
Aeritalia

- 11:10 **An Artificial Gravity Demonstration Experiment**
C. Rupp
NASA Marshall Space Flight Center
L. Lemke
NASA Headquarters
P. Penzo
Jet Propulsion Laboratory

- 11:30 **Attitude Dynamics of the Tether Elevator/Crawler System for Microgravity Applications**
S. Vetrella, A. Moccia
University of Naples
E. Lorenzini, M. Cosmo
Harvard-Smithsonian Center for Astrophysics

- 11:50 **Optimization of the G-Level in Microgravity Experimentation: A Motivation for the Variable Gravity Tethered Platform**
R. Monti, C. Golis, L. G. Napolitano
University of Naples

PM

- 12:10 *Adjournment*

**Session X
Tether Technology
(Parallel Session)**

Cochairmen
James K. Harrison
NASA Marshall Space Flight Center

Ernesto Vallerani
Aeritalia

Organizer
William A. Baracat
General Research Corporation

AM

- 8:30 *Introduction*

- 8:40 **Pan-Spheric Diagnostics Using an Umbilical Tether**
J. Sullivan
MIT Plasma Fusion Center
E. Lorenzini
Smithsonian
Astrophysical Observatory

FRIDAY/19 MAY 1989

AM

- 9:00 **Advances in Space Tether Materials**
R. Orban
Materials Concepts, Inc.
- 9:20 **A Method for Damage Inspection and Verification of Tethers**
G. Howard, A. Levi, F. Gray
ANCO Engineers, Inc.
- 9:40 **Gravity Gradient Disturbances on Rotating Tethered Systems in Circular Orbits**
A. DeCou
Northern Arizona University
- 10:00 **Development of a Tether Deployment Monitoring System**
P. Ibanez, F. Gray, A. Levi
ANCO Engineers, Inc.
- 10:20 **Development Testing of TSS-I Deployer Control System Mechanisms**
D. Tisdale, D. Bentley
Martin Marietta Space Systems
- 10:40 **Mechanical Behavior of TSS-I and TSS-2 Tethers: Experimental Results and Physical Modelling**
F. Angrilli, G. Bianchini, M. DaLio, G. Fanti
University of Padua
- 11:00 **Attitude Sensing Device of the Subsatellite Relative to the Tether**
A. Caporali, G. Coloroe
University of Padua
- 11:20 **The Use of Tethered Satellites for the Collection of Cosmic Dust and the Sampling of Man Made Orbital Debris**
G. Corso
Loyola University of Chicago
- 11:40 **Tethers in Space, and Meteorites**
E. Scala
Cortland Cable Company, Inc.

**Session XI
Operations and Safety**

Cochairmen
Joseph P. Loftus, Jr.
NASA Johnson Space Center

Klaus Reinhartz
ESA European Space
Technology Center

Organizers
Terrence G. Reese
The Bionetics Corporation

Giovanni Rum
Italian Space Agency

PM
1:30 *Introduction*

1:40 **Tethers in the Real World of Manned Space Flight**
J. Hoffman
Astronaut Office
NASA Johnson Space Center

1:55 **Operational Techniques for the TSS-I Mission**
M. Laible
Rockwell International
Shuttle Operations

2:10 **To be announced**

2:25 **Tether Inspection and Repair: The Key for the Development of Permanent Tethered Facilities**
F. Bevilacqua, S. Ciardo
Aeritalia

2:40 **Operation of Small Tethered Payloads from the Space Station**
G. He, B. Lee,
E. Stoneking, S. Williams
Stanford University

2:55 *Break*

**Session XII
Critical Issues Panel**

Chairman
Robert Rosen
NASA Headquarters

Organizers
Gianfranco Manarini
Italian Space Agency

Thomas D. Stuart
NASA Headquarters

3:15 **Panel**
Participants
W. Bollendonk
Martin Marietta Space Systems

D. Branscome
NASA Headquarters

C. Buongiorno
Italian Space Agency

J.J. Dordain
ESA European Space
Technology Center

E. Harkleroad
NASA Headquarters

J. Hoffman
Astronaut Office
NASA Johnson Space Center

L. Napolitano
University of Naples

H. Stoewer
ESA European Space
Technology Center

E. Vallerani
Aeritalia

PM
5:00

Closing Remarks
Program Cochairman
J. Anderson
NASA Headquarters

5:10 *Adjournment*

Objective and Approach**Dynamics Workshop**

In keeping with the theme of the conference, "Toward Flight", the objective of the workshop is to provide a forum for describing flight experiments, data reduction methods, and parameter identification techniques. Instrumentation requirements for future flight experiments will be solicited.

Electrodynamics Workshop

The theme of the Electrodynamics Workshop is, "Beyond TSS-I: The Next Logical Steps". The objective of the workshop is to discuss questions and issues dealing with the future development of the electrodynamic tether as a multipurpose tool for space in the upcoming decade and beyond. Specifically, three broad questions will be addressed:

- 1) What type of missions would most logically follow TSS-I, and who would be the most likely users?
- 2) In which areas of application are electrodynamic tethers most competitive with other technologies?
- 3) What work needs to be done to bring electrodynamic tethers to a state of user readiness in the power ranges and areas of application deemed most desirable?

In order to facilitate these discussions panels of speakers have been assembled to deliver papers. Time will be allowed between papers for workshop participants to respond to each of the topics. Open discussion and/or written comments are welcome.

**PRELIMINARY PROGRAM
TUESDAY/16 MAY 1989****Dynamics Workshop***Organizers*

Silvio Bergamaschi
Italian Space Agency

Charles C. Rupp
NASA
Marshall Space Flight Center

AM

7:30 *Registration*8:30 *Introduction*8:40 **Dynamics of N-Body
Tethered Satellite Systems**

A. Misra, P. Lopez, T. Kainth
McGill University, Canada
V. Modi
University of British Columbia,
Canada

9:00 **Simulation of
Tether Motions**

G. Woodward, T. Kane
Stanford University

9:20 **Dynamical Effects of Radar
Reflectors Attached to the
Small Expendable-Tether
Deployer System (SEDS)**

M. Cosmo, E. Lorenzini
Harvard-Smithsonian
Center for Astrophysics

9:40 **Wave Propagation
Along the Tether
Elevator/Crawler System**

E. Lorenzini, M. Cosmo
Harvard-Smithsonian
Center for Astrophysics

AM

10:00 **Deployment and Retrieval of
Kane's Tethered Crawler
from Orbiting Spacecraft**

A. Banerjee, D. Levinson
Lockheed Missiles
and Space Company

10:20 **Two-Phase Flow-Induced
Vibrations of Space Tethers**

R. Englestad, E. Lovell
University of Wisconsin

10:40 **Active and Passive Control
of Tether Damping**

T. Vaneck, X. He,
J. Powell, P. Banks
Stanford University

11:00 **Retrieval Dynamics**

D. Arnold
Harvard-Smithsonian
Center for Astrophysics

11:20 **Automatic Docking
Maneuver by a Double
Tether System**

A. Finzi
Polytechnic of Milan

11:40 **A Non-Linear Analysis of
Thermal Effects on Tether
Dynamics**

S. Sgubini, F. Graziani
University of Rome

PM

12:00 *Lunch*12:20 **The Over-Extended Tether**

J. Breakwell
Stanford University

12:40 **An Earth Pointing (YAW)
Spinning Satellite with No
Counter Rotating Wheel**

W. Davis, D. Levinson
Lockheed Missiles and Space
Company

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SECTION 6.0 BIBLIOGRAPHY

Bibliography

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6.1 Abbreviations

The following abbreviations are used in the bibliography listings to avoid repetition of commonly used phrases.

Int. Conf. 1986	NASA/AIAA/PSN International Conference on Tethers in Space, Arlington, Virginia, 17-19 September 1986. Proceedings, Vol. 62, Advances in the Astronautical Sciences, <u>Tethers in Space</u> , Eds. P. M. Bainum, I. Bekey, L. Guerriero, P. A. Penzo, 1987.
Int. Conf. 1987	PSN/NASA/ESA Second International Conference on Tethers in Space, Venice, Italy, 6-9 October 1987. Conference Proceedings, Vol. 14, Societa Italiana di Fisica, <u>Space Tethers for Science in the Space Station Era</u> , Eds. L. Guerriero, I. Bekey, 1988.
Int. Conf. 1989	AIAA/NASA/ASI/ESA Third International Conference on Tethers in Space, San Francisco, California, 17-19 May 1989.
Work Shop 1978	<u>Uses of a Tethered Satellite System</u> , UAH/NASA Workshop, Huntsville, Alabama, NASA report available, Ed. S. T. Wu, May 1978.
Work Shop 1983	<u>Applications of Tethers in Space</u> , Workshop, Williamsburg, Virginia, 15-17 June 1983. Workshop Proceedings, NASA CP-2364 (Vol. 1), NASA CP-2365 (Vol. 2), March 1985.
Work Shop 1985	<u>Applications of Tethers in Space</u> , Workshop, Venice, Italy, 15-17 October 1985. Workshop Proceedings, NASA CP-2422 (Executive Summary, Vol. 1, Vol. 2), 1986.
AAS	American Astronautical Society
AIAA	American Institute of Aeronautics and Astronautics
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
IAF	International Astronautical Federation
JPL	Jet Propulsion Laboratory, Pasadena, California
MIT	Massachusetts Institute of Technology, Cambridge, Massachusetts
NASA/ARC	Ames Research Center, Moffett Field, California
NASA/GSFC	Goddard Space Flight Center, Greenbelt, Maryland
NASA/HQ	NASA Headquarters, Washington, D. C.
NASA/JSC	Lyndon B. Johnson Space Center, Houston, Texas
NASA/LaRC	Langley Research Center, Hampton, Virginia
NASA/LeRC	Lewis Research Center, Cleveland, Ohio
NASA/MSFC	Marshall Space Flight Center, Marshall Space Flight Center, Alabama
PSN	Piano Spaziale Nazionale (Italian National Space Plan)
SAO	Smithsonian Astrophysical Observatory, Cambridge, Massachusetts
UAH	University of Alabama, Huntsville, Alabama

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Aerodynamics
Concepts
Controlled Gravity
Demonstrations
Dynamics & Control

Electrodynamics
Fiction
General & Historical
Planetary
Science

Space Station
TSS-1 Mission
Technology
Transportation
Tutorial

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