Tethers and Their Role in the Space Exploration Initiative

Cheryl D. Bankston, John A. Gilbert, Dennis R. Wingo[1]

Abstract

This paper addresses some potential applications for tethers in space, and describes a mission designed to deploy a satellite from a Delta II launch vehicle, by NASA's Small Expendable Deployer System, via a 46 km long tether. The mission, targeted for 1993, will contribute to the U.S. Space Exploration Initiative, and along with the shuttle flight of the tethered satellite system, TSS1, will be one of the first attempts to experimentally characterize the dynamics of a tethered system. Data taken from two experimental packages onboard the satellite will be analyzed to verify mathematical simulations related to tether dynamics.

Introduction

On July 20, 1989, the twentieth anniversary of the first lunar landing, President Bush began the U.S. Space Exploration Initiative (SEI) with a challenge to the nation: "The time has come to look beyond brief encounters. We must commit ourselves anew to a sustained program of manned exploration of the solar system -- and yes -- the permanent settlement of space." The President set three goals: in this decade complete Space Station Freedom, "our critical step in all our space endeavors;" for the next century, go back to the Moon...this time to stay; and ultimately, make "a journey into tomorrow," a manned mission to Mars.[1]

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[1]The authors are affiliated with the University of Alabama in Huntsville, Huntsville, Alabama, 35899. Cheryl is a student member of ASCE and works as a research assistant in the College of Engineering; John is a member of ASCE and a professor of engineering mechanics; Dennis is a student member of ASCE and works as a research engineer in the UAH Research Institute.

Tethers are an exciting technological development that some have described as being as important for the exploration of space as the rocket. This paper describes two experiments, a three-axis accelerometer system and an imaging system, designed for a microsatellite to be deployed by NASA's Small Expendable Deployer System (SEDS), via a 46 km long tether. The mission will demonstrate and study the dynamics of a tether. The manuscript includes a discussion of tether technology and demonstrates how tethers can be used in space for civil engineering applications.

Tethers

The concept of tethers (cords or cables used to connect objects in space) can be traced back to 1895 when Tsiolkovsky suggested the revolutionary idea that access could be gained to the weightless environment of space using an equatorial tower.[2] For nearly a century, concepts involving tethers have been documented all over the world and, in the last twenty to thirty years, simulations of tether dynamics and control laws have been forwarded to aid in understanding tether dynamics in space. There is now substantial literature arguing that operations involving the transfer of orbital energy and payloads via tethers will become standard space techniques of the future. However, only a handful of tether experiments have been conducted, and while more ground-based work can be performed, additional flight tests are required to demonstrate and verify the dynamical models and control schemes related to tether technology.

The first flight test of a tethered system in space occurred in November, 1966, when a 200 m long tether was used to join Gemini 10 and 11. Subsequent experiments were conducted between Gemini capsules and the Atlas/Agena booster. Additional tether experiments were conducted by the Japanese in the 1970's using sounding rockets.

The joint Italian/US Tethered Satellite System, TSS1, scheduled for a shuttle flight in June, 1992, will initiate advanced operational studies of tethers. The NASA SEDS flights will follow in 1993 as the beginning of a series of low cost missions to further tether dynamics studies. The following sections describe a mission proposed for the second SEDS flight.

SEDSAT1 (Students for the Exploration and Development of Space Satellite #1)

The SEDSAT1 satellite project is being led by the UAH chapter of the Students for the Exploration and Development of Space, and has the support of universities, companies, professional groups, and governmental organizations both national and international. SEDSAT1 will be deployed via NASA's Small Expendable Deployer System (SEDS); SEDS is a lightweight spinning-reel system designed to deploy the payload attached to the 46 km long tether. The tether is made from a new high-strength, low-density polyethylene fiber called SPECTRA.[3] The deployer is currently scheduled to fly on the second stage of a McDonnell Douglas Delta II launch vehicle, as a secondary payload to an Air Force Global Positioning System (GPS) satellite launch in 1993.

SEDSAT1 will begin its deployment sequence shortly after GPS separation. SEDSAT1 will be deployed upward from the Delta II second stage at an initial altitude of 185 X 742 km with a 39° inclination. Once the tether is fully deployed, it will be severed. The severance will result in a momentum transfer which will raise the SEDSAT1 orbit to an altitude of 680 X 792 km.

SEDSAT1 contains two experiments, SEASIS and TAS, which together provide a valuable tool in the furtherance of tether studies. The synthesis of SEASIS and TAS will provide a means of decoupling the perturbations and oscillations of the satellite, from the dynamics specifically associated with tether deployment. This approach will enable researchers to better understand tether/satellite interaction; something which has not yet been modeled in detail.

<u>SEASIS</u> (SEDS Earth, Atmosphere, and Space Imaging System)

SEASIS is an imaging experiment that will visually record the attitude of SEDSAT1. Figure 1 shows the major components of SEASIS. The two lenses collect light for imaging. The Charged Coupled Device (CCD) color cameras are used to electronically resolve images and gather and amplify light in a 492 X 640 array. Each camera is able to collect an image every 1/30 second and produce an analog signal in standard video format. The frame grabber is used to convert the output from each camera to a 492 X 640 digital pixel array, where each element is one byte in length. A dedicated microprocessor is used to transfer the image data from the frame grabber to memory. The data is compressed to allow the storage of at least 430 images onboard the satellite for later downlink to Earth via an amateur radio network.

One of the camera systems is equipped with a telephoto lens for observation of Earth's atmosphere. The other camera system is equipped with a panoramic annular lens (PAL)[4] and is designed to measure, at discreet time intervals, the position of the satellite in relation to the Earth and the Delta II second stage. It is the PAL that

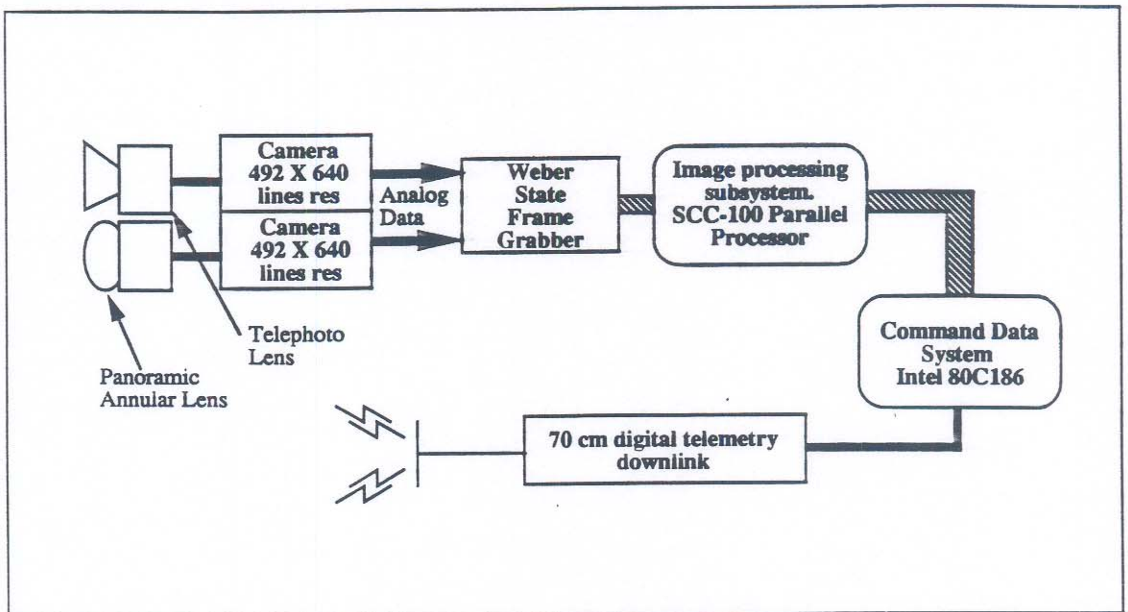

Figure 1. SEASIS (SEDS Earth, Atmosphere, and Space Imaging System).

gives SEASIS its unique ability to interface with TAS and collect comprehensive tether dynamics data.

PAL (Panoramic Annular Lens)

As shown in Figure 2, the PAL is a single element lens with spherical surfaces which collects light for imaging and then forms an internal virtual image of its surroundings. The image is collected by a transfer lens and focused onto a CCD color camera. The depth of focus of the PAL extends from the surface of the lens out to infinity; therefore, the lens requires no focusing.

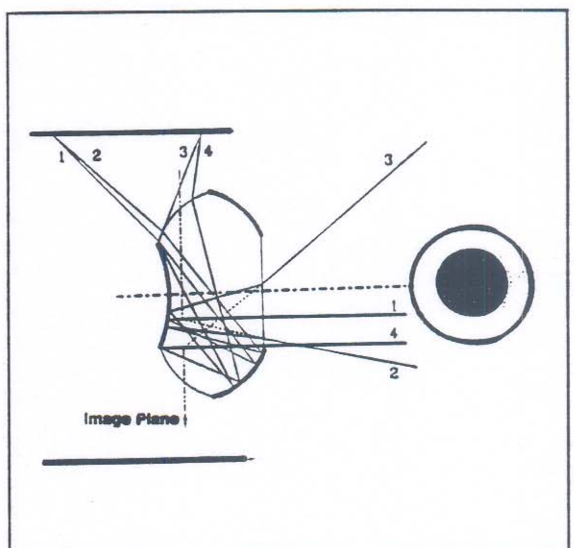

Figure 2. A ray diagram of the PAL.

Figure 3 shows that the field of view of the PAL extends from 20° below the horizon to 25° above the horizon, 360° around. Due to the unique characteristics of the PAL at least some portion of the earth will be visible in every picture taken. This feature of the PAL will be used to establish SEASIS as a sophisticated horizon detector. Both the angle

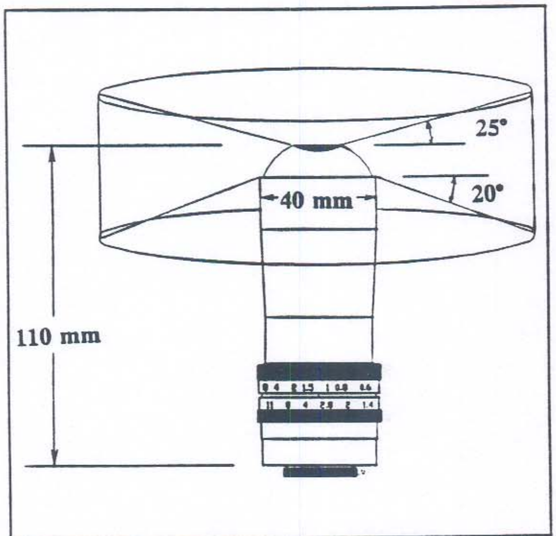

Figure 3. The field of view of the PAL. Figure provided courtesy of Optechnology, Inc., Gurley, AL.

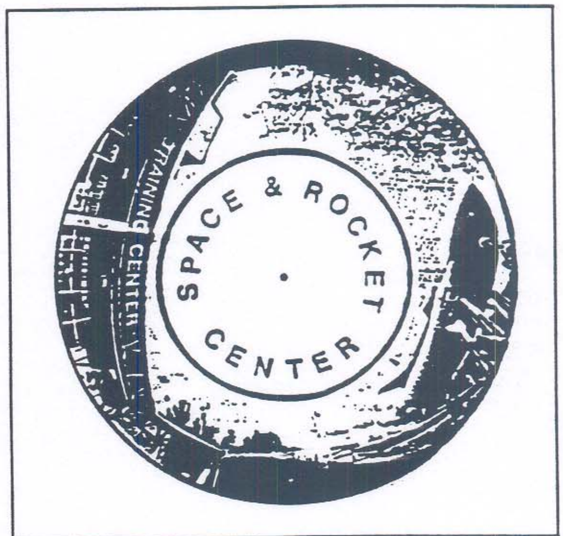

Figure 4. An image of the Alabama Space and Rocket Center with a PAL pointed toward the sky.

of the horizon and the inclination of the curve of the horizon will be measured. Figure 4 shows an image taken with the PAL to demonstrate its unique characteristics.

<u>TAS</u> (Three-axis Accelerometer System)

The second experiment on SEDSAT1 is designed to measure acceleration levels to an accuracy of one microgee. This is accomplished using a Three-axis Accelerometer System (TAS). TAS consists of three very accurate, thermally stable accelerometers, arranged in an orthogonal triad to microradian tolerances. The system must be located as close to the center of mass of the satellite as practicable. The accuracy of mounting, coupled with careful balancing of the mass distribution, is of paramount importance in reducing systematic errors in acceleration measurement. Thermal excursions must also be minimized to reduce electronic signal drift in the accelerometers.

Axis misalignment of one arc second or temperature drift of one degree can cause a bias shift of several microgees. These residual errors will be characterized by making accurate, systematic measurements and performing precision calibration, thereby allowing TAS to accurately measure all accelerations during deployment.

Calibration of the accelerometers will be carried out at the NASA Marshall Space Flight Center. Each accelerometer will be aligned perpendicular to the direction of Earth's gravity to reduce the output to a zero volt level. The accelerometer is then flipped 180° on a 0.5

arc second accuracy rotational table. The difference in the voltage of the accelerometer in this position is then noted. Then the rotational table is stepped in small increments of arc to one-half the voltage difference measured after the flip. The table is flipped again and the difference between the previous and current voltage is measured. This procedure is repeated until after each 180° flip there is no change in the measured voltage. This establishes the true "zero g" point of the accelerometer; the voltage offset from zero is noted as a systematic error and entered as an offset into the calculations during the data reduction phase of the mission.

Tether Dynamics

Figure 5 illustrates the two basic modes expected to occur during tether deployment. The spring loaded, pyrotechnic release of the satellite from the Delta II by the SEDS, causes the tether to oscillate in a transverse mode. The frequency of oscillation is expected to rise during deployment from a minimum of 0.01 Hz to a maximum of

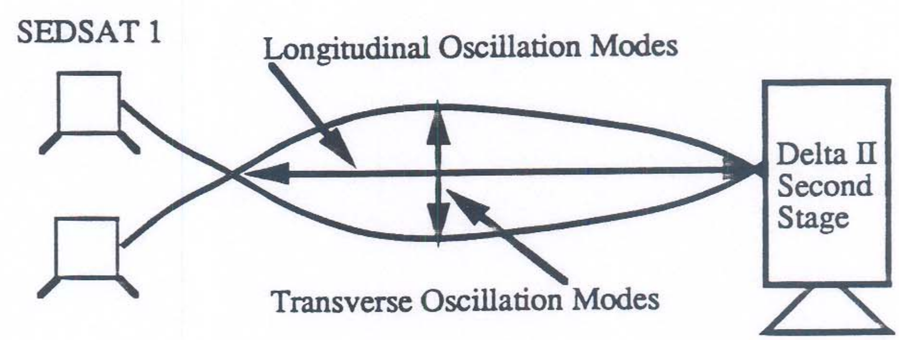

Figure 5. Tether modes of excitation due to deployment forces.

0.167 Hz. This occurs due to the progressively larger tensile force produced in the tether as a result of the increase in gravity gradient and the pendulum swing to vertical before severance. The "spinning-reel" unraveling of the tether from its spool also contributes to the transverse mode. The amplitude of this motion is relatively small as compared to that caused by the pyrotechnic release, and the frequency varies with deployment velocity and tether tension. A longitudinal mode occurs as the tether unravels from the base of the spool to the top, and back. The corresponding frequency depends on the deployment velocity and the spool diameter. Pendular librations arise from gravitational and centrifugal forces.

Thus, the dynamics of a tether deployment is anything but trivial. In addition to the dynamic forces already mentioned, there are loads associated with low earth orbital dynamics. Air drag and debris impact on the tethered system are measurable forces and will have to be taken into account during tether data analysis.

Analysis of SEASIS and TAS Data

The importance of SEASIS in measuring tether dynamics is that it specifies the position of the satellite relative to the earth. TAS, on the other hand, provides an inertial reference sensor suite relative to the reference provided by SEASIS. The gestalt of SEASIS and TAS will make it possible to decouple SEDSAT1 accelerations due to non-tether forces (spring ejection, magnetic and solar torques), from those attributed to the tether oscillation.

Tether Applications

Tethers are one of the enabling technologies for SEI. The following sections describe a number of potential applications relevant to civil engineering.

Structures/Construction and Urban Planning

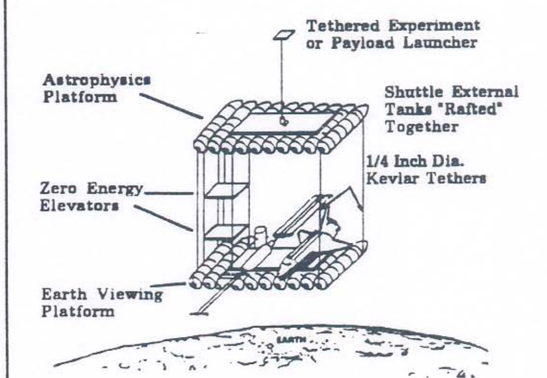

Figure 6. Shuttle tanks could be connected by tethers in a raft format to form a structure in space.

As the human race moves into space, the construction and use of relatively large tethered platforms will be of critical importance. Figure 6 shows a configuration which utilizes Shuttle external tanks in a raft format to form a structure in space. In this example, tethers are used as structural elements in an evolving space station and for links (power, data transfer, etc.) between different platforms designed for various science and materials processing applications. Some of the platforms would share resources, while being individually isolated from contamination and mechanical disturbances. Others could be used to facilitate storage of liquid propellants and other dangerous fluids, or to provide

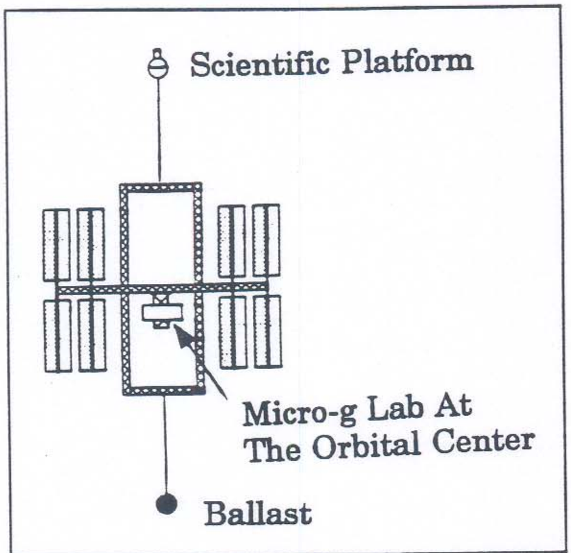

Figure 7. Tethers could be used to control the center of gravity of microgravity modules on the Space Station.

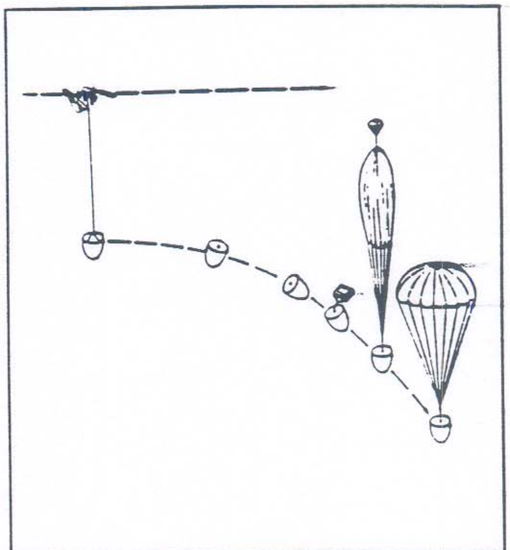

Figure 8. A tether provides a means of transferring a payload from the Space Station to Earth without the use of the Shuttle Orbiter.

variable/controlled environments to study the long-term effects of lowered gravity levels on humans.[5,6]

In addition to linking structures, tethers can be used control the center of gravity of structures. Figure 7 shows two tethers with end masses deployed vertically (one above and one below) from the Space Station. The tethers are attached to a laboratory facility, located at the vertical center of gravity of the Space Station, which would be used to conduct microgravity experiments (10^{-4} g and less) for extended periods of time. The microgravity environment would be maintained by varying the lengths of the tethers to control the Space Station's center of gravity.[7-10]

Transportation Systems

Tethered systems for transportation have been widely publicized. Most applications capitalize on their ability to transfer momentum between two bodies. Figure 8, for example, illustrates the use of a tether initiated space recovery system that provides a means of transferring a small payload (such as processed chemicals, archived engineering and experiment data, etc.) from the Space Station to the Earth without the use of the Shuttle Orbiter. The tethered payload would be released into a reentry trajectory such that it would enter the upper atmosphere within one-half orbit. During reentry, a parachute would open, slowing it to permit a soft landing.[11]

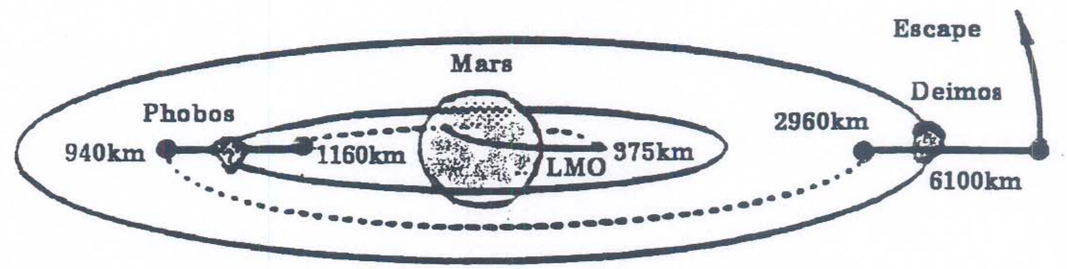

Figure 9. Tethers could transport manned vehicles from low Mars orbit out to escape or from escape to low Mars orbit.

Another scenario, shown in Figure 9, uses tethers to transport manned vehicles from low Mars orbit out to escape, or from escape to low Mars orbit without the use of propulsion. Long tethers are attached above and below the two Martian moons. A vehicle is tethered upward from a station in low Mars orbit, and is caught by a downward hanging tether from Phobos. The vehicle is then transferred to the other tether, propulsed upward, and then caught by the downward Deimos tether. The process is repeated at Deimos, resulting in Mars escape. The process is reversed for Mars capture.[12]

Geotechnical

Tethers offer a unique opportunity for planetary remote sensing. Figure 10 shows a satellite in a stable lunar orbit with analysis instruments tethered downward. Since the tether can be lowered as close to the lunar surface as desired, sensitive measurements can be made at altitudes unsuitable for lunar satellites. The proposed scenario shows the satellite in a 300 km stable orbit with the tethered payload 50 km above the lunar surface. Sensitive measurements of the lunar environment and surface can be taken as part of site selection and preparation for lunar outposts.[13]

Environmental

Tethers may have a large impact on Space Station waste disposal. Currently, the only source for removal of waste would be the shuttle orbiter, once every 90 days. This poses a potential health hazard for Space Station occupants. Figure 11, however, shows a tethered trash disposal scenario in which tethers are employed to deorbit waste into the Earth's upper atmosphere where it would completely disintegrate. Trash disposal could be achieved easily, at the leisure of the Space Station occupants.

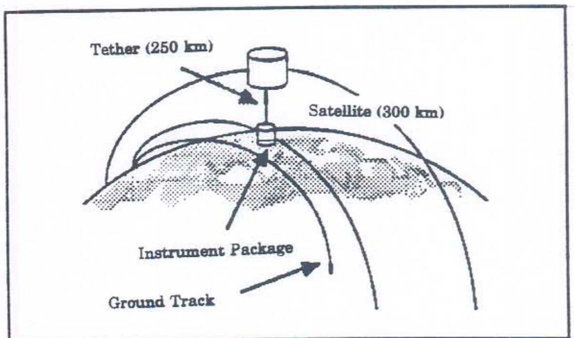

Figure 10. A tether provides measuring instrument access to low, unstable, lunar orbital altitudes.

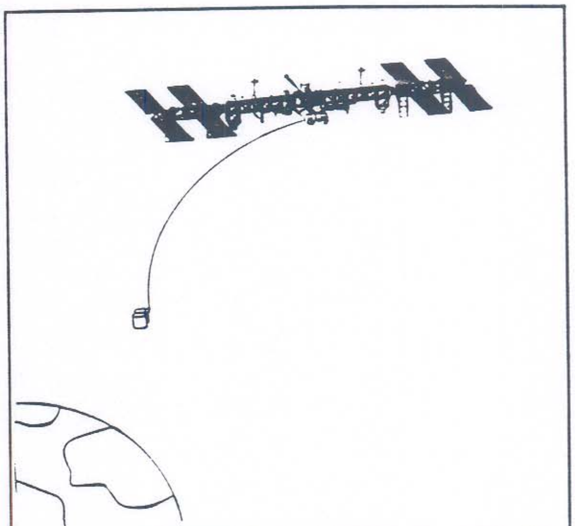

Figure 11. A tether is used to deorbit Space Station waste into the upper atmosphere where it disintegrates.

As long duration missions, both in Earth orbit and for interplanetary travel and habitation, become part of the Space Exploration Initiative, the gravity environment for man will become a crucial issue. Osteoporosis has been shown to affect humans who are exposed to long periods of microgravity, and tethers could be used to produce centrifugal forces which generate artificial gravity in space. In this application, tethers would be used to connect systems of bodies continuously rotating about a common center.[14]

Hydraulics

Most earth based hydraulic systems take advantage of gravity; consequently, in space, special artificial gravity techniques using tethers may have to be employed. Figure 12, for example, shows a tethered orbital refueling facility. The gravity gradient between the Space Station and the platform produces tension in the tether which results in equal and opposite artificial gravity throughout the platform. The artificial gravity assists the fuel transfer by allowing the fluid to settle in the tanks.[7,9,15]

Conclusion

A unique combination of experiments has been designed to experimentally characterize the dynamics of tethered systems in space. Successful completion of the proposed mission will help to verify many of the exiting analytical studies on tether dynamics. Moreover, the new knowledge which will be gained from monitoring tether/satellite interaction is crucial to the successful development of accurate models of tethered systems.

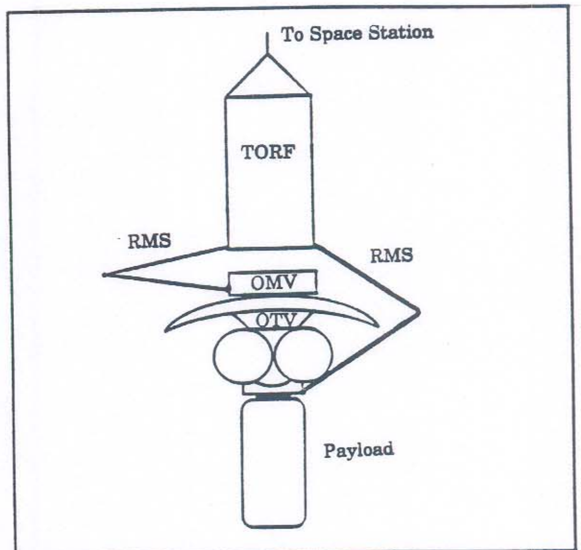

Figure 12. Tethers can be used to produce artificial gravity to assist in the transfer of liquid propellants to and from a tethered storage and refueling platform.

The SEDSAT1 mission scenario was recently included in the National Aeronautics and Space Administration's Outreach Program Report, completed on December 31, 1990. The submittal was used by a Synthesis Group, chartered by Vice President Danforth Quayle and NASA Administrator Richard Truly, to recommend specific approaches and technologies for the Space Exploration Initiative.

Acknowledgements

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