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THE ROLES OF TETHERS ON SPACE STATION

By

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16. ABSTRACT

This report describes the results of research and development that addressed the usefulness of tether applications in space, particularly for space station. A well organized and structured effort of considerable magnitude involving NASA, industry and academia have defined the engineering and technological requirements of space tethers and their broad range of economic and operational benefits. This report consolidates the work directed by seven NASA Field Centers and is structured to cover the general and specific roles of tethers in space as they apply to NASA's planned space station. This is followed by a description of tether systems and operation. The report closes with a summary of NASA's plans for tether applications in space for years to come.

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FOREWORD

By Ivan Bekey
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The concept of using tethers in space emerged from science fiction to reality with the 1973 proposal by Giuseppe Colombo to fly a tethered subsatellite from the Shuttle Orbiter. We are now well into the development of such a project, which is a cooperative effort between NASA and Italy. The first flight of this Tethered Satellite System is scheduled for 1988 and will investigate electromagnetic interactions with the plasma around Earth using a 20 km conducting tether.

In the dozen years since this proposal, the creative thinking of many scientists and engineers have discovered a broad range of tether applications ranging from generating electric power using the Earth's magnetic field, through provision of nano-gravity or variable gravity laboratories, to deploying satellites into higher orbits without using propellants. The moon and planets, also have not escaped their attention, these applications including magnetic breaking at Jupiter, and utilizing the momentum of Phobos and Deimos to supplement a transportation system between Mars surface and interplanetary trajectories.

Back on Earth, the development of tether technology is progressing. Each NASA center with the help of industry and academia are studying specific tether applications. They have identified the technology requirements and in some cases have embarked on demonstration projects which will be flown on the Shuttle. These missions are in addition to the TSS program, and are necessary to prove tether physics, dynamics, systems, and operations. This will lay the groundwork for acceptance of tether applications in the future.

NASA's leading new program today is the Space Station. This facility will offer unique opportunities for science, engineering, and commercial applications. It is only natural that tethers be considered as a means of enhancing or extending these applications. The NASA centers have been concentrating on identifying and defining tether applications which might be of most interest ot the Space Station.

This document presents a summary of such studies, as well as outlines several applications which will require further study.

My thanks go to Georg von Tiesenhausen and his Tether Applications Team which, over the past years, have provided NASA with a coherent development program for this unique technology. Their efforts will certainly be rewarded because the eventual adoption and use of tethers in space is too broad and too powerful to be long ignored.

Ivan Bekey

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Director, Advanced Programs
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ABOUT THE AUTHORS

James K. Harrison is project engineer in the Orbital Support Systems Group of the Advanced Systems Office, Program Development, George C. Marshall Space Flight Center. He is responsible for the development of the space disposable tether system, for the engineering design and costing of several tether applications to space station and for the definition of an early tethered flight experiment.

Kenneth R. Kroll is project engineer in the Systems Branch, Avionics Systems Division of the Engineering Directorate, Lyndon B. Johnson Space Center. He is responsible for planning tether applications using microgravity systems and has been defining a tethered refueling facility for a space station.

Paul M. Siemers III is project engineer in the Aerothermodynamics Branch, Space Systems Division, Langley Research Center. He is responsible for all tether applications systems technology planning. He is also developing a shuttle tethered aerothermodynamic research facility which would use the upper atmosphere as a hypersonic wind tunnel.

Georg von Tiesenhausen is Assistant to the Director, Advanced Systems Office, Program Development, George C. Marshall Space Flight Center. He is responsible for overall planning, coordination and scheduling of tether application studies within NASA under the direction of NASA Headquarters-OSF, Ivan Bekey. He is also conducting studies on several tether application concepts including tethered platforms and early tethered payload demonstration mission definitions.

Dr. William J. Webster, Jr. is a scientist in the Geophysics Branch, Laboratory for Terrestrial Physics of the Space and Earth Sciences Directorate, Goddard Space Flight Center. He is responsible for the planning of science and applications missions for NASA using tether systems. In addition he is involved in the development of the comet rendezvous and asteroid flyby mission development and in the Mars observer mission.

William Nobles has been a member of the Martin Marietta team for "Space Station Architecture Definition Studies." He served as a representative to the joint NASA/Industry working group on Space Station configuration definition. During the past 18-months he has been Program Manager for the Marshall Space Flight Center study contract for "Selected Tether Applications in Space." He is currently Manager for Science Integration for the Tethered Satellite System.

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1.0 INTRODUCTION

It has not happened very often in space flight that a long dormant but radical new element of space flight is about to appear at the scene of space operations. The last several years have seen the advent and growth of a new avenue to space utilization: the tether [1]. Well-organized and structured efforts of considerable magnitude involving NASA, industry, and academia have explored and defined the engineering and technological requirements of the use of tethers in space and have discovered their broad range of operational and economic benefits. The results of these efforts have produced a family of extremely promising candidate applications. The extensive efforts now in progress are gaining momentum and a series of flight demonstrations are being planned and can be expected to take place in a few years. This report consolidates work of seven NASA Centers and is structured to cover the general and specific roles of tethers in space, particularly as they apply to NASA's planned space station. This is followed by a description of tether systems and operations. The report closes with a summary of NASA's plans for tether applications in space for the years to come. The authors hope that the information presented here will be helpful to management and project personnel to understand the characteristic behavior of tethers in a gravity field and to appreciate their considerable beneficial applications to various space station operations.

2.0 THE BASIC ROLES OF TETHERS IN SPACE (By G. von Tiesenhausen)

2.1 General

Tethers in space are long, relatively thin, flexible cables which connect two or more masses moving together along parallel orbital trajectories. The distance between the masses can be fixed or variable. The tether connection may be permanent or temporal. In the latter case one or all masses can be disconnected from the tether.

Tethers may be electrically conductive to carry electric current or non-conductive for the exclusive transmission of loads. Tethers have to be maintained under tension at all times in order to control position and motion of the tether itself and of the attached masses. The forces that keep tethers under constant tension are dominant gravity forces, dominant "centrifugal" forces, electrodynamic forces, and combinations of forces, depending on the concept of application.

The fact that tethers have little stiffness and, therefore, are almost perfectly flexible causes them to react to any induced perturbation in a great variety of ways. This, and the fact that the two or more interconnected masses interact with the tether and with each other dynamically, has created a whole new branch of orbital system dynamics combined with orbital mechanics in order to be able to analyze, simulate, and control the behavior of tethered systems.

The results of these studies and analyses carried out over several years have been recognized as quite promising with regard to a multitude of practical and beneficial applications of tethers to space missions. The Tethered Satellite System (TSS) Project [2] is presently under development by NASA at the Marshall Space Flight Center with a conducting, electrodynamic tether for power generation to fly late in this decade, and a subsequent atmospheric research mission planned to fly thereafter. Figure 1 shows the TSS system. Several new tethered concepts have reached the stage of being candidates for demonstration missions. These missions are presently being defined and will use the shuttle orbiter as a base. The purpose of these demonstrations will be to verify analyses and design of specific applications to the shuttle, to the space station, and to independent tethered mission concepts.

2.2 Tethered Payload Deployment

2.2.1 General

By using a tether system, a spacecraft is able to deploy payloads into higher or lower orbits without expending propellants to move itself into these orbits.

2.2.2 Preservation of Angular Momentum

The process of separating two initially joined orbiting masses (e.g., spacecraft plus payload) along the gravity gradient, while they are connected by a tether, is based on the natural law of preservation of the orbiting system's total angular momentum (Fig. 2). After an initial forced separation, each tethered mass follows now dominant external forces while the systems orbital center is maintained. These two forces keep the tether in tension as long as the tether deployment system controls the deployment rate. After deployment the total system's angular momentum has

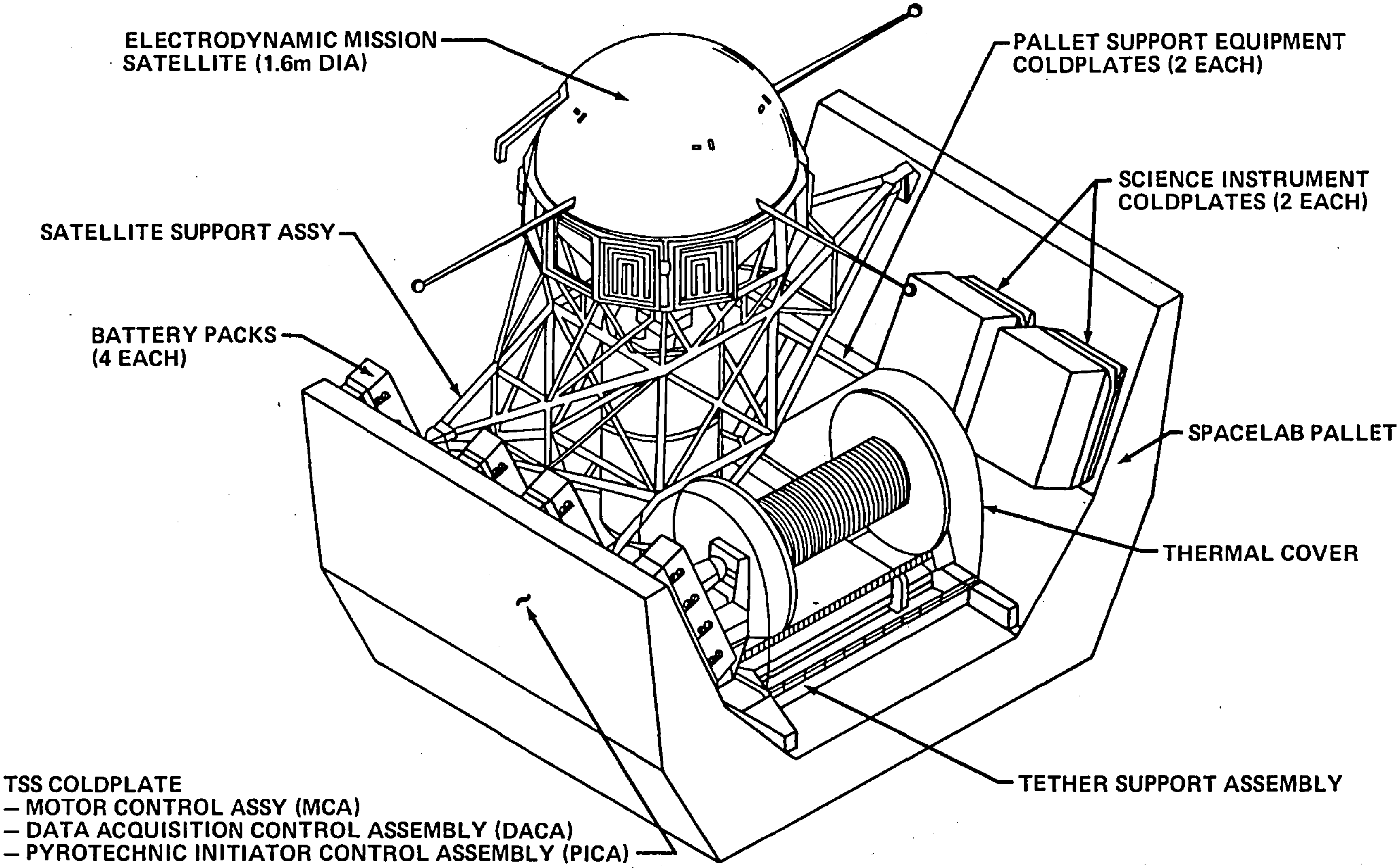


Figure 1. Typical tethered satellite system (TSS) equipment.

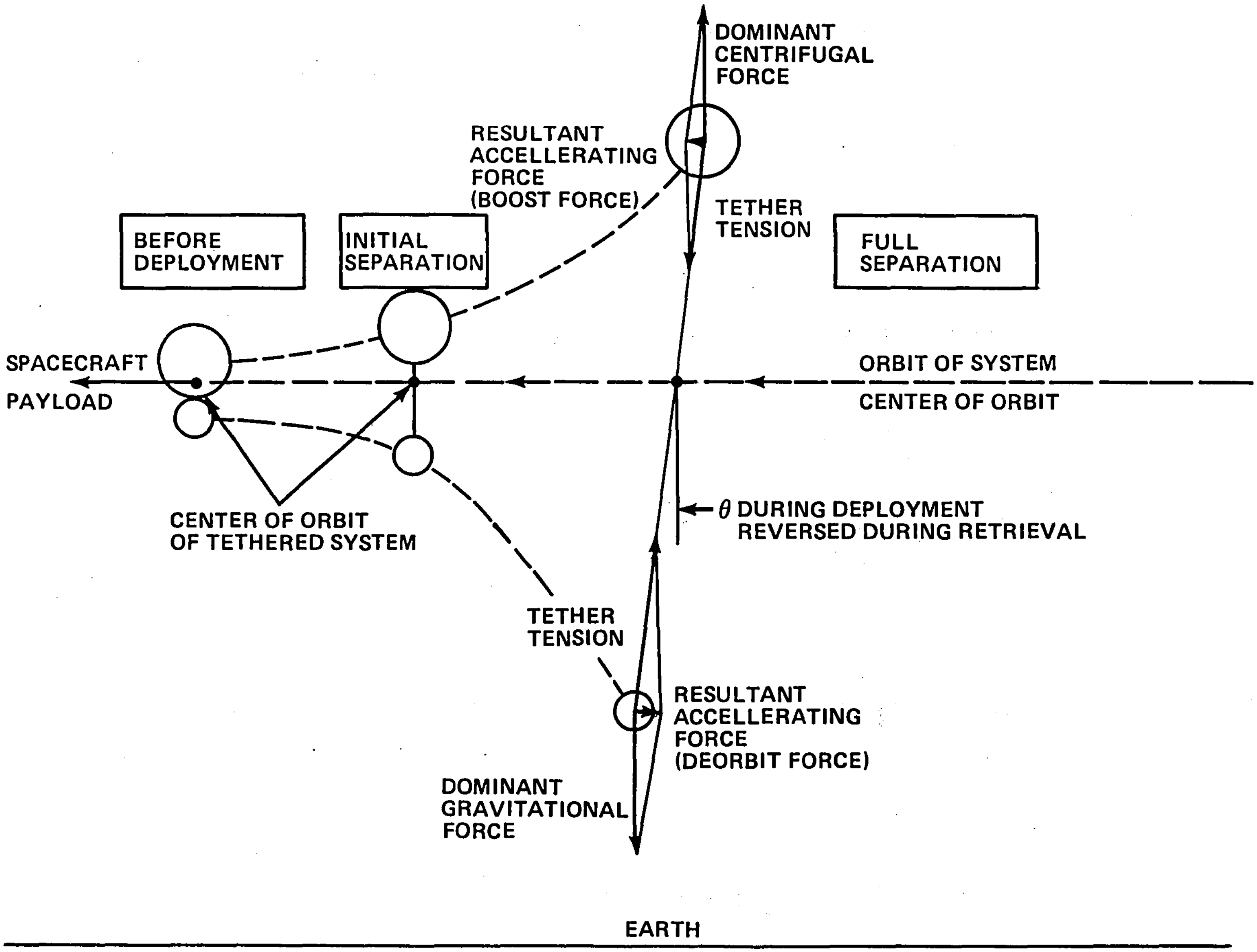


Figure 2. Forces in tethered orbital systems.

remained the same as the initial one, however, it has now split into three parts: the momentum of the upper mass, of the lower mass, and of the momentum of spin motion of the deployed system (one rotation per orbit).

2.2.3 Energy and Angular Momentum

With the anticipated tether deployment distances of 100 to 200 km, the energy efficiency of deployment and retrieval of tethered payloads is about 97 percent. During deployment the total system loses energy which is dissipated in the deployer brake system while during retrieval the reel motor puts energy back into the system. One consequence of this is that the systems orbital center is dropped somewhat during deployment and raised again during retrieval.

The mass moving downward during deployment loses potential but gains kinetic energy; therefore, the lower mass will initially lead the deploying spacecraft until gravity forces provide for an approximately vertical position of the tether [Fig. 3(a)]. During retrieval the lower mass gains potential but loses kinetic energy; therefore, the lower mass will initially trail the retrieving spacecraft [Fig. 3(b)]. If payload deployment is upward and the retrieval downward then the situation is reversed. The momentum transferring agent is the resulting horizontal component of the tether tension created by the coriolis effects, as was shown in Figure 2.

The tether tension will now cause the payload to oscillate about the spacecraft local vertical until the maximum allowable tension is reached, at which time the payload is deployed along a straight line (Fig. 4). This figure provides a specific numerical example of the relative positions of two tethered masses during deployment. The payload in this case is a small upper stage Orbital Transfer Vehicle (OTV), the spacecraft is the shuttle orbiter.

Figure 5 shows the same masses and gives an idea of deployment times versus deployment distance.

The energy required for tethered mass retrieval in low Earth orbit depends primarily on the masses and the deployed tether length. As an example, for a given power level of 1 kW, the required energies and retrieval times are given in Figure 6 for various tether lengths.

2.2.4 Tether Tension

The tension imposed on a tether which connects two masses in low Earth orbit in a gravity gradient stabilized position is primarily a function of the size of the end masses and of tether length. Several examples are shown in Figure 7. With very long tethers, the tether mass itself is a considerable contributor to its own tension. Computational background for tether tensions is given in section 4.1 of this report.

2.2.5 Tethered Payload Deployment

In order to deploy a tethered payload, an initial impulse has to be provided for initial separation of the two masses in order to provide for a sufficient build-up of excess "centrifugal" and gravity forces which then will continue the separation. Since tethered deployment of two masses in Earth orbit is based on the transfer of

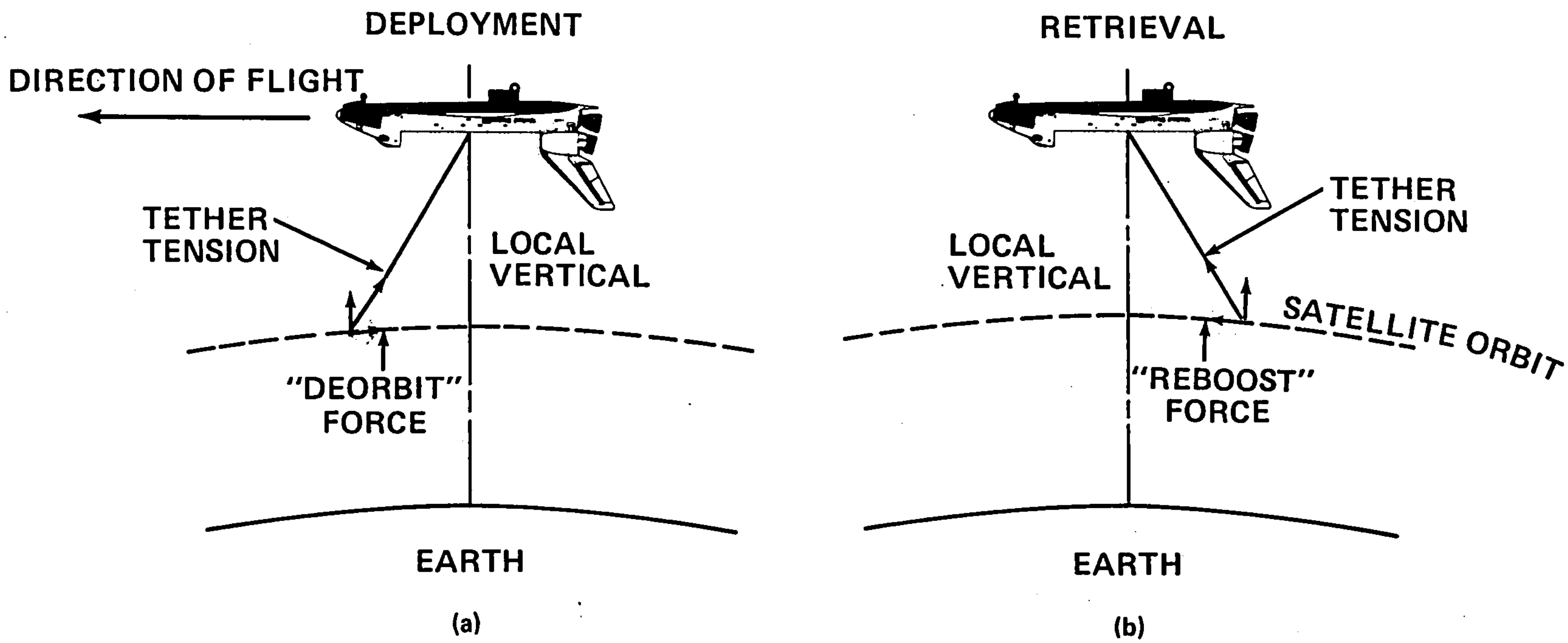


Figure 3. Tethered payload deployment and retrieval.

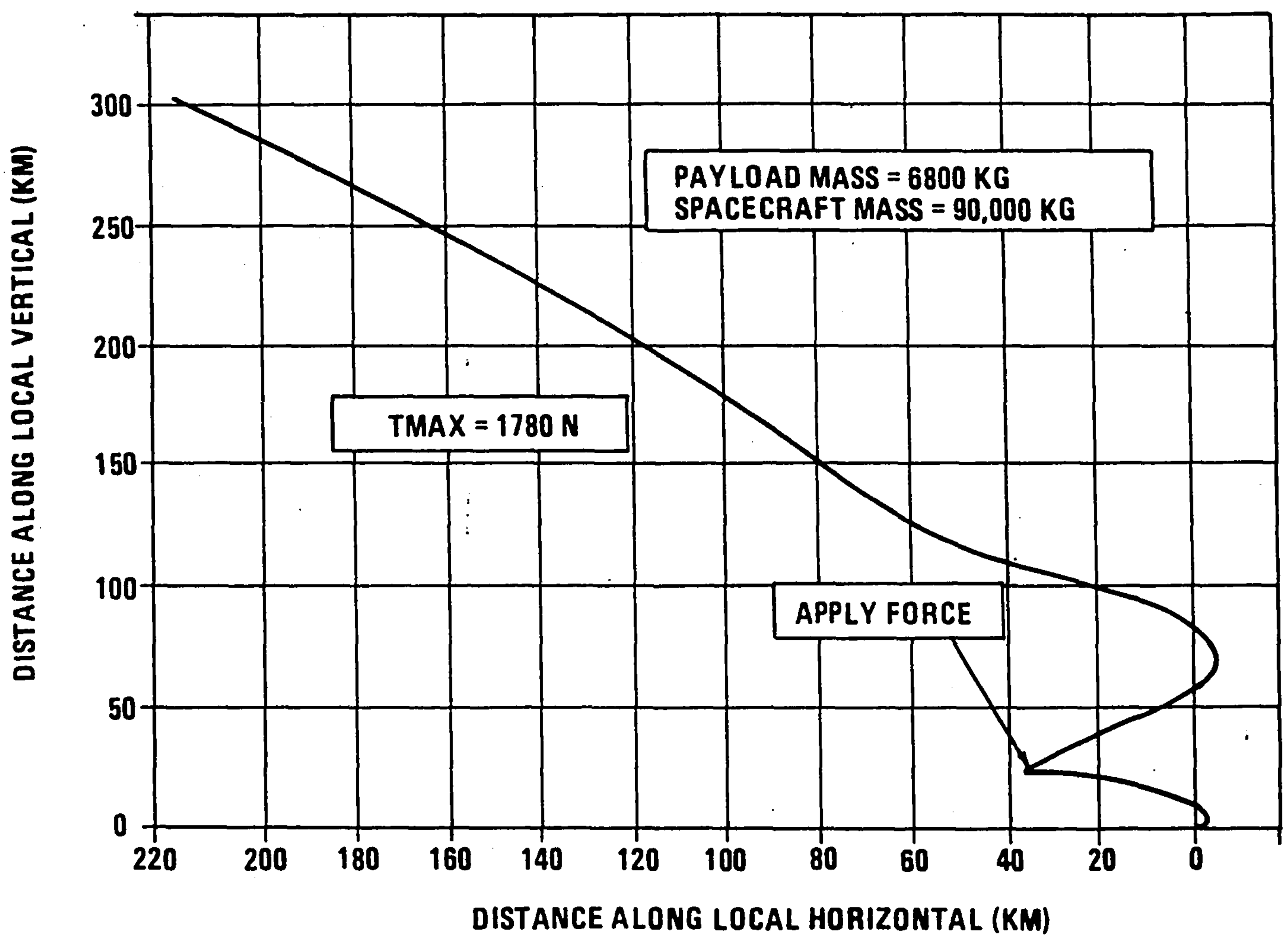


Figure 4. Payload deployment performance [6], Payload location relative to spacecraft (wait time for force buildup = 1750 sec).

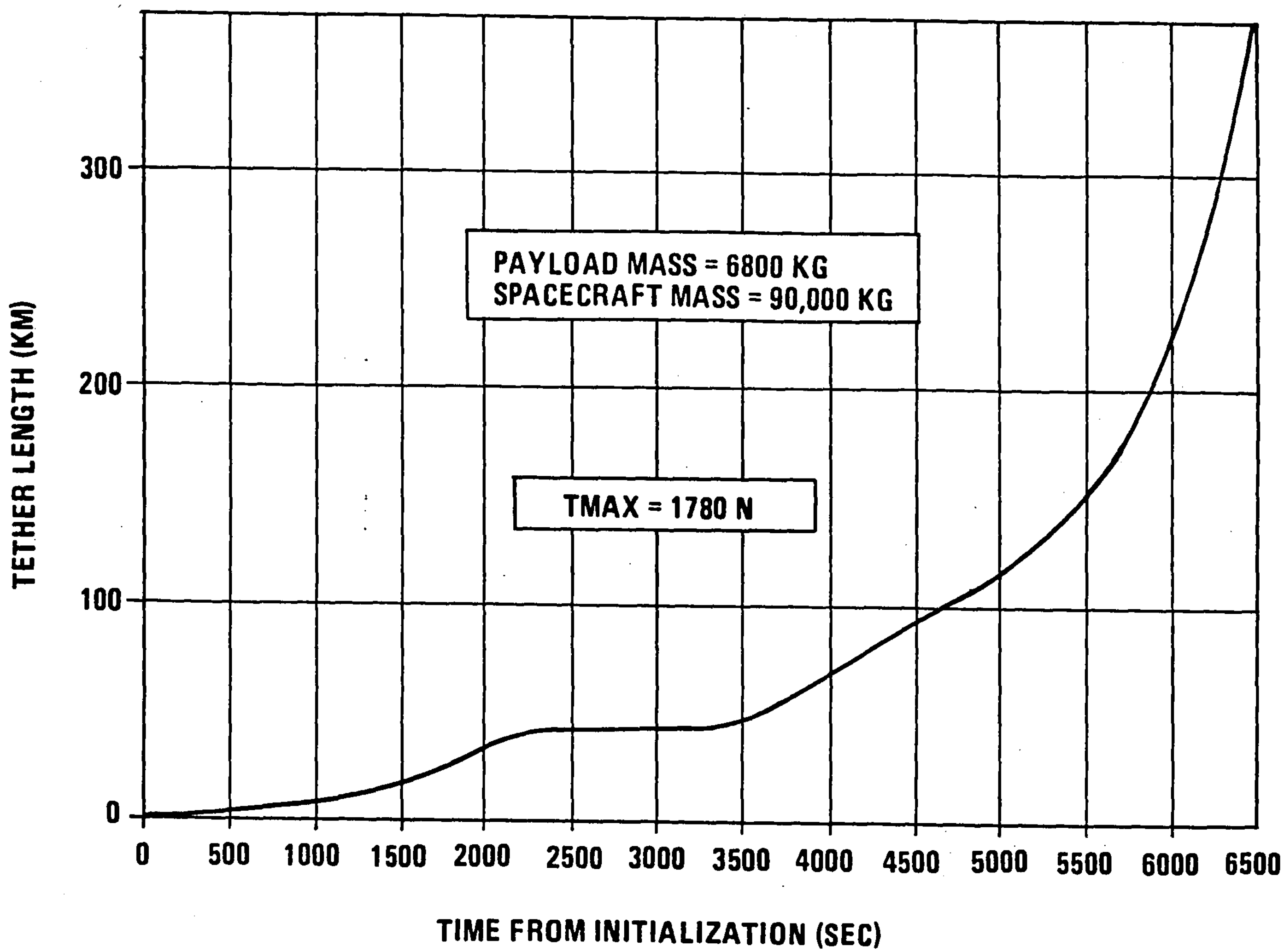


Figure 5. Payload deployment performance [6], tether length (wait time for force buildup = 1750 sec).

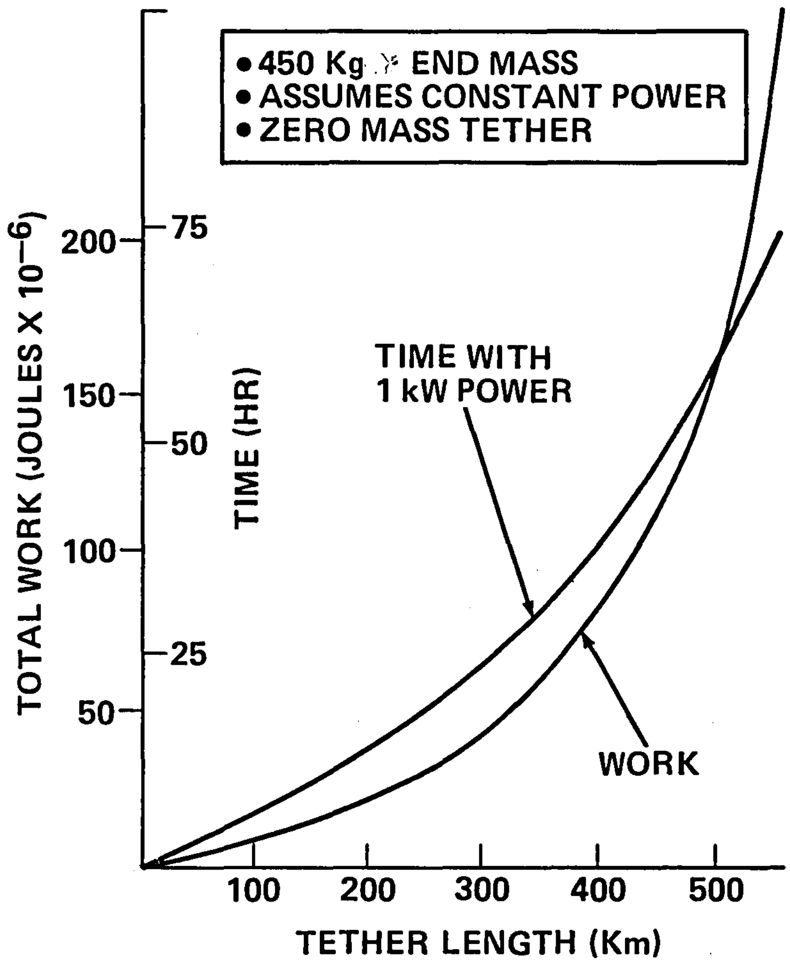


Figure 6. Tether retrieval theoretical minimum work.

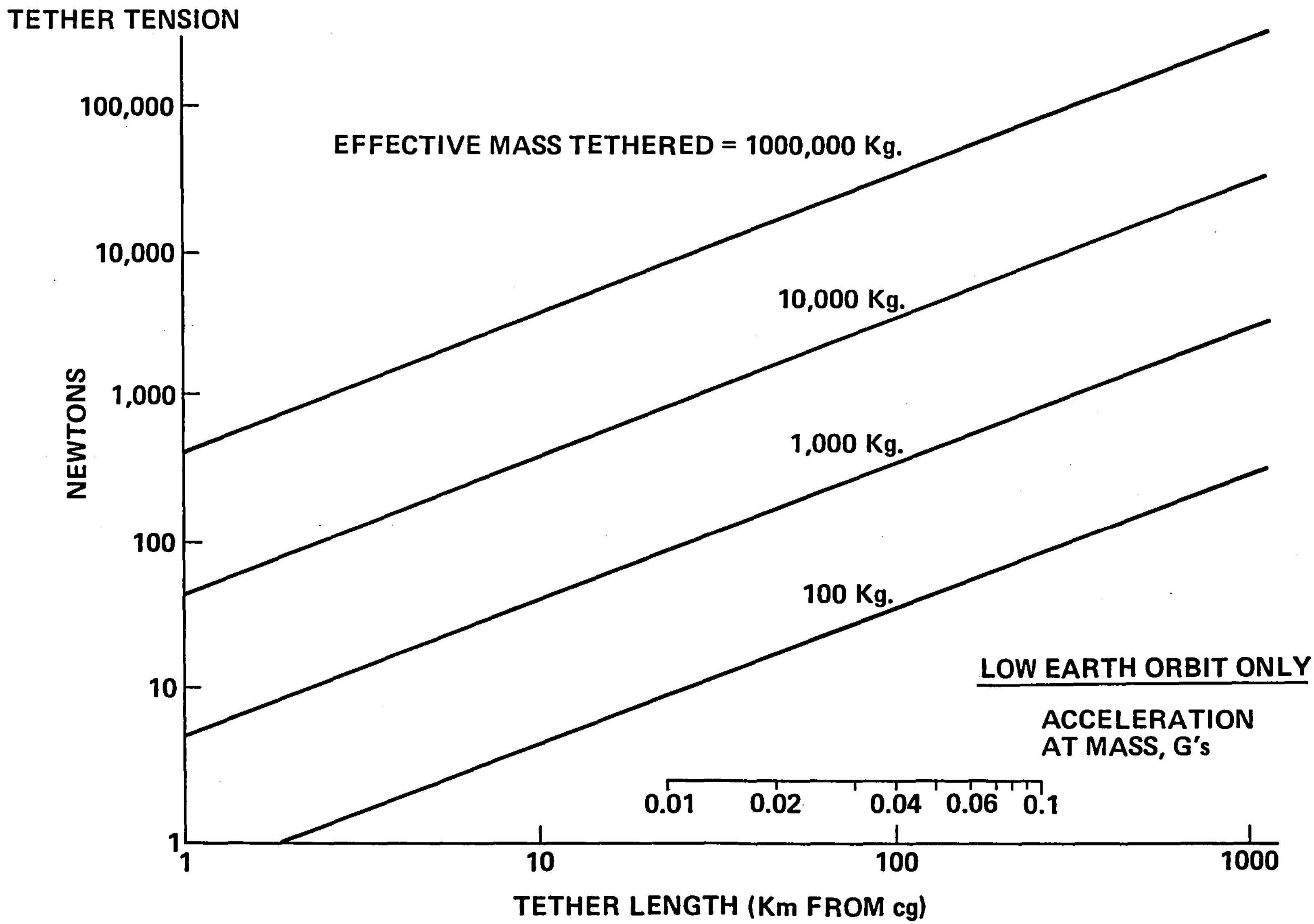


Figure 7. Tension forces in tethered systems.

angular momentum from one mass to the other (see section 2.2.2), while the total angular momentum is preserved, it will be helpful to show the various ways in which this can be accomplished.

Figure 8 shows a two-stage rocket which has been boosted into low Earth orbit. The upper stage is destined for a much higher orbit. Conventionally, this stage's propulsion system would ignite after separation and the stage would depart for its final orbit. The lower stage would be allowed to reenter the Earth's atmosphere. However, if a tether system interconnects the two stages and is deployed, then a large part of the lower stage's angular momentum can be transferred to the upper stage. While the original orbital center is preserved, both masses enter elliptical orbits after separation from the tether. At the point of separation the lower stage orbit has its apogee while the upper stage is at its perigee. The upper stage departs with increased altitude and velocity while the lower stage reenters from a lower altitude and with reduced velocity.

Figure 9 shows the principles of a static and a dynamic upward payload deployment. During static deployment [Fig. 9(a)], the tether remains under a small angle to the local vertical (see section 2.2.3). At the end of the deployment there is a slight libration due to coriolis and gravity forces. The angular momentum transfer occurs here mainly during the deployment phase.

During dynamic deployment [Fig. 9(b)], the tether tension is kept low initially, thus allowing the two masses to drift apart until the desired tether length has been deployed. Tether brakes are applied to terminate the deployment. Subsequently, the upper mass (the payload) begins a large-amplitude prograde swing toward the vertical. The angular momentum transfer occurs here mainly during this libration after deployment.

In each case, angular momentum transfer is greatest when the tether is vertical. A comparison of static versus dynamic release is given in Table 1 [3].

Four other more sophisticated tether payload deployment procedures were proposed by Carroll and Mayer [3,4] (Fig. 10). In the first method [Fig. 10(a)], the tether is alternately extended and retrieved after initial deployment in resonance with tether tension variations during librations. This is called libration pumping and is an ideal way to generate considerable amounts of electrical energy for a limited time by letting the retrieval electric motor function as an electric generator during redeployment. In the second method [Fig. 10(b)], the previous approach is carried further, such that spinning of the tethered system can be achieved. This is called spin-pumping. In both cases the added energy increases the departure velocity of a released payload.

The third method [Fig. 10(c)] can be used not only within a gravity field like all other methods but also in free space. Here, mass separation is accomplished by a small propulsion system in the deployed payload until the full tether length is deployed. A powerful retrieval motor then pulls the masses back together inducing an in-plane libration. When the maximum desirable amplitude is achieved, separation occurs.

The fourth method [Fig. 10(d)] proposed by Mayer [4] extends the previous approach into a rotational system. Due to high rotational rates and therefore large forces, the tether in this case is tapered, forming a body of constant stress.

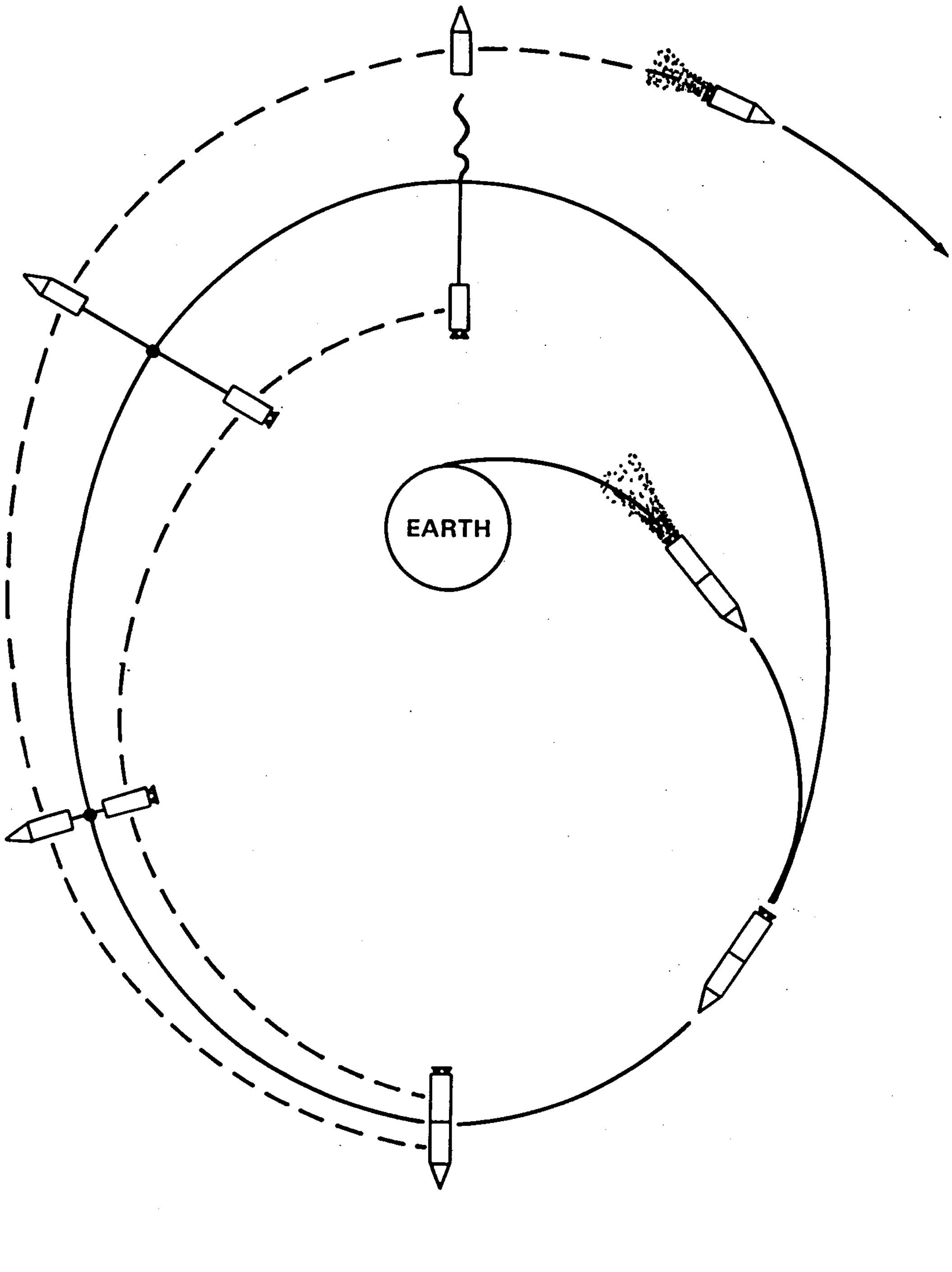


Figure 8. Tethers for upper stage boost
and lower stage deboost.

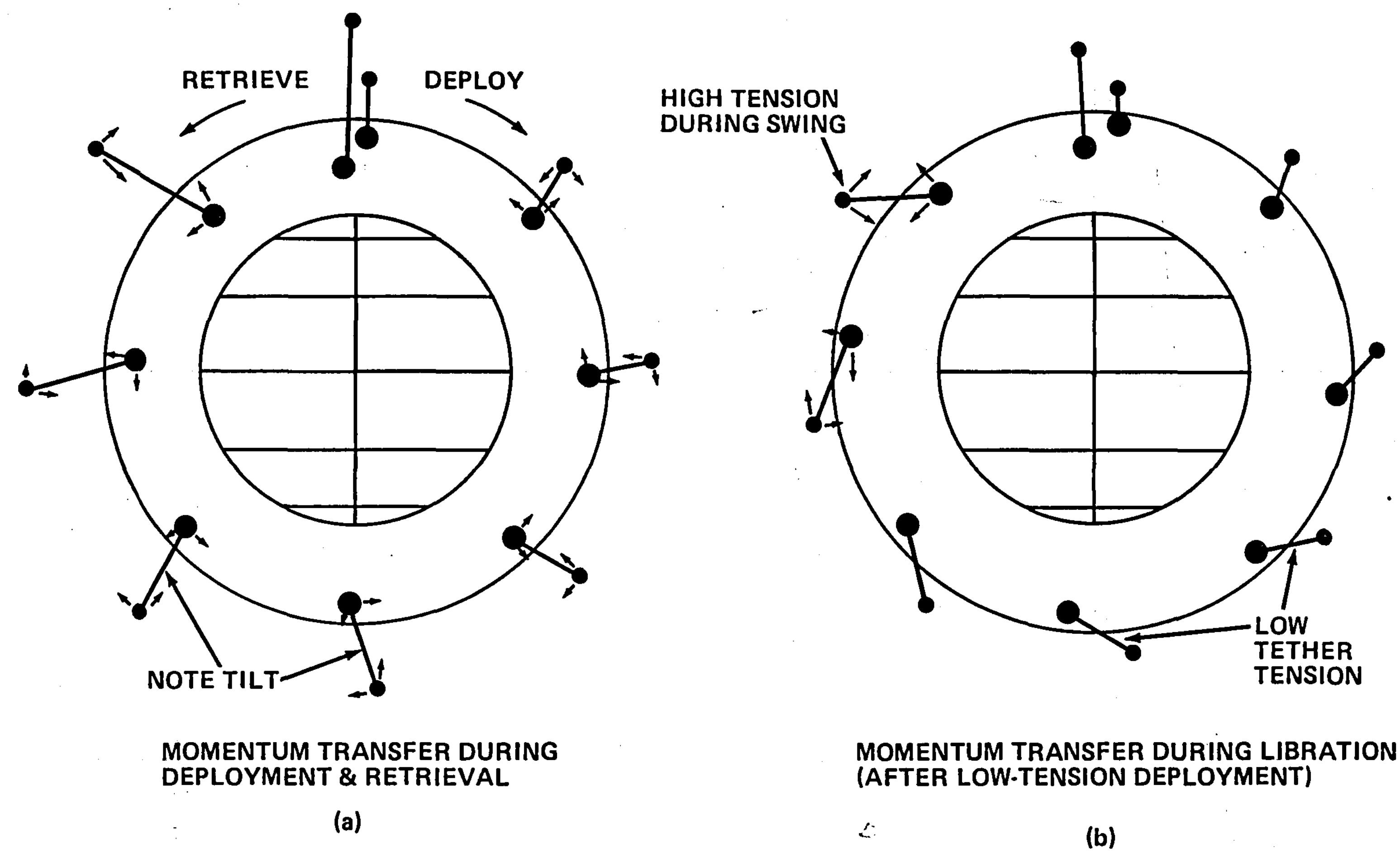


Figure 9. Momentum transfer I [3].

TABLE 1. COMPARISON OF STATIC AND DYNAMIC RELEASES FOR EQUAL ENERGY AND MOMENTUM TRANSFER [3]

SWING AMPLITUDE	0^{o}	35^{o}	85^{o}
TETHER LENGTH	1	.67	.54
MAXIMUM LOADS	1	1.33	1.69
TETHER MASS	1	.89	.91
μMETEOROID HAZARD	1	.27	.12
ENERGY DISSIPATION	1	.30	.002

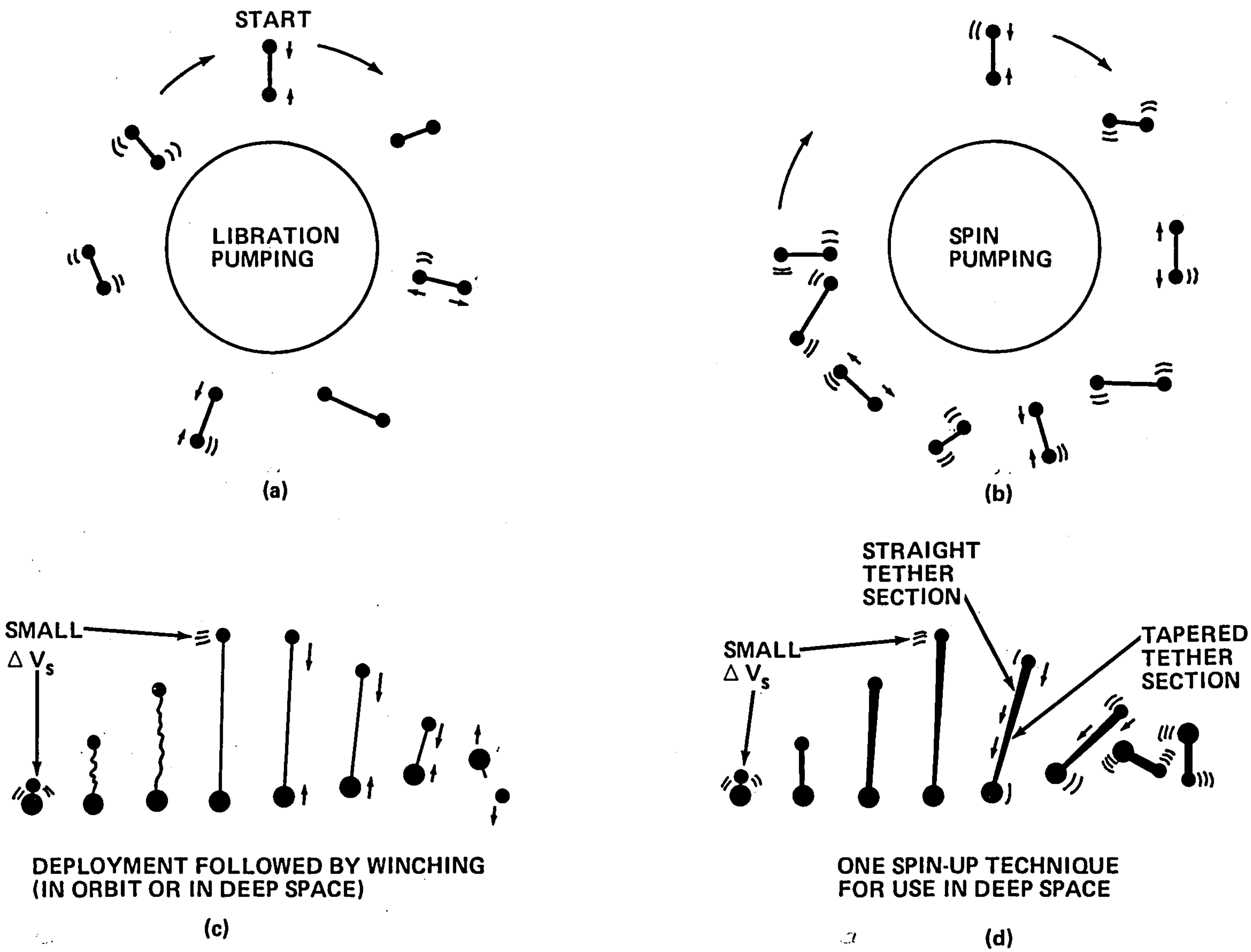


Figure 10. Momentum transfer II [3].

Finally, orbital pumping of a mass can be employed to increase or decrease the orbital eccentricity of a spacecraft. Figure 11(a) shows the following sequence of events: At (1) there is a fully deployed mass at the end of a tether extending from the parent spacecraft. Both masses are in a circular orbit. At (2) the retrieval of the tethered mass is in progress. Energy from the retrieval motor enters the system and converts in part into additional orbital energy. (The rest goes into mass acceleration.) This additional energy stretches the orbit until the mass is fully retrieved (3).

This point forms the apogee of the new orbit. At (4) the redeployment of the mass is in progress. This takes orbital energy out of the system via the deployer brakes which dissipate part of this energy in the form of heat. (The rest goes into mass deceleration.)

At full deployment (5) the system has reached its new perigee. This sequence can be repeated until a desired orbital excentricity has been achieved. Figure 11(b) shows the reverse procedure where orbital excentricity is reduced to any desired level by mass deployment beginning at perigee and retrieval initiated at apogee.

2.2.6 Example of a Payload Deployment

A simple example of tethered deployment of a payload from the space shuttle orbiter demonstrates various selected parameters involved in the process (Table 2). The purpose of the tethered payload release is to gain additional velocity for injection into a geostationary orbit.

TABLE 2. PARAMETERS OF SAMPLE CASE

Spacecraft Initial Apogee	300 km
Spacecraft Initial Perigee	300 km
Spacecraft Initial Mass	90,900 kg
Payload Initial Mass	6,800 kg
Maximum Allowed Force in Tether	1,780 N
Maximum Tether Length	370 km
Wait Time for Force Buildup	1,750 sec
Separation ΔV of Tether	7.6 m/sec

Figure 12 shows a schematic mission profile of this case:

(1) Orbit ascent

(2) Circularization of orbiter trajectory into a nominal circular orbit

(3) Preparations for payload deployment

(4) Ready for payload deployment

(5) Payload deployment in progress

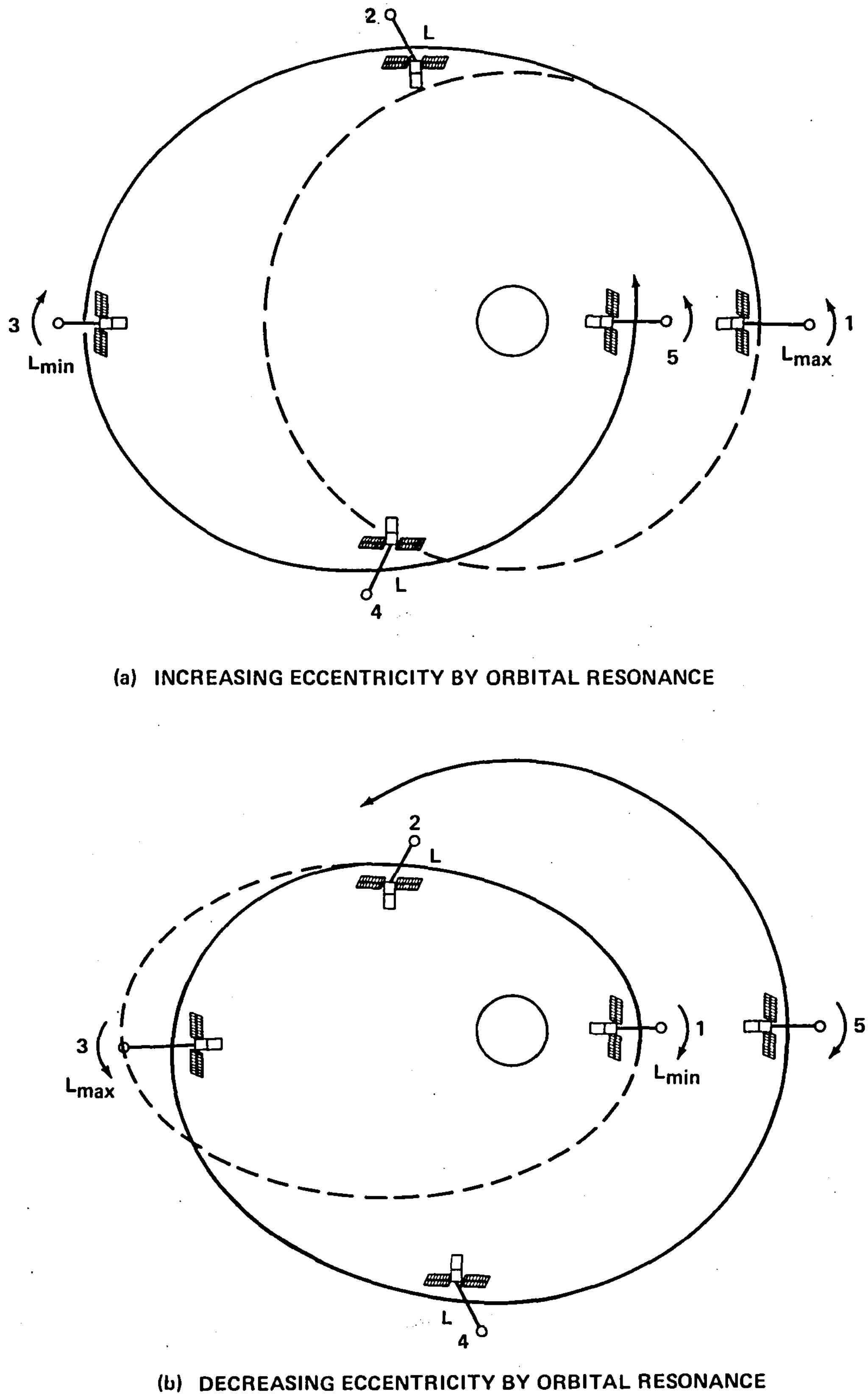


Figure 11. Changing eccentricity by orbital resonance [5].

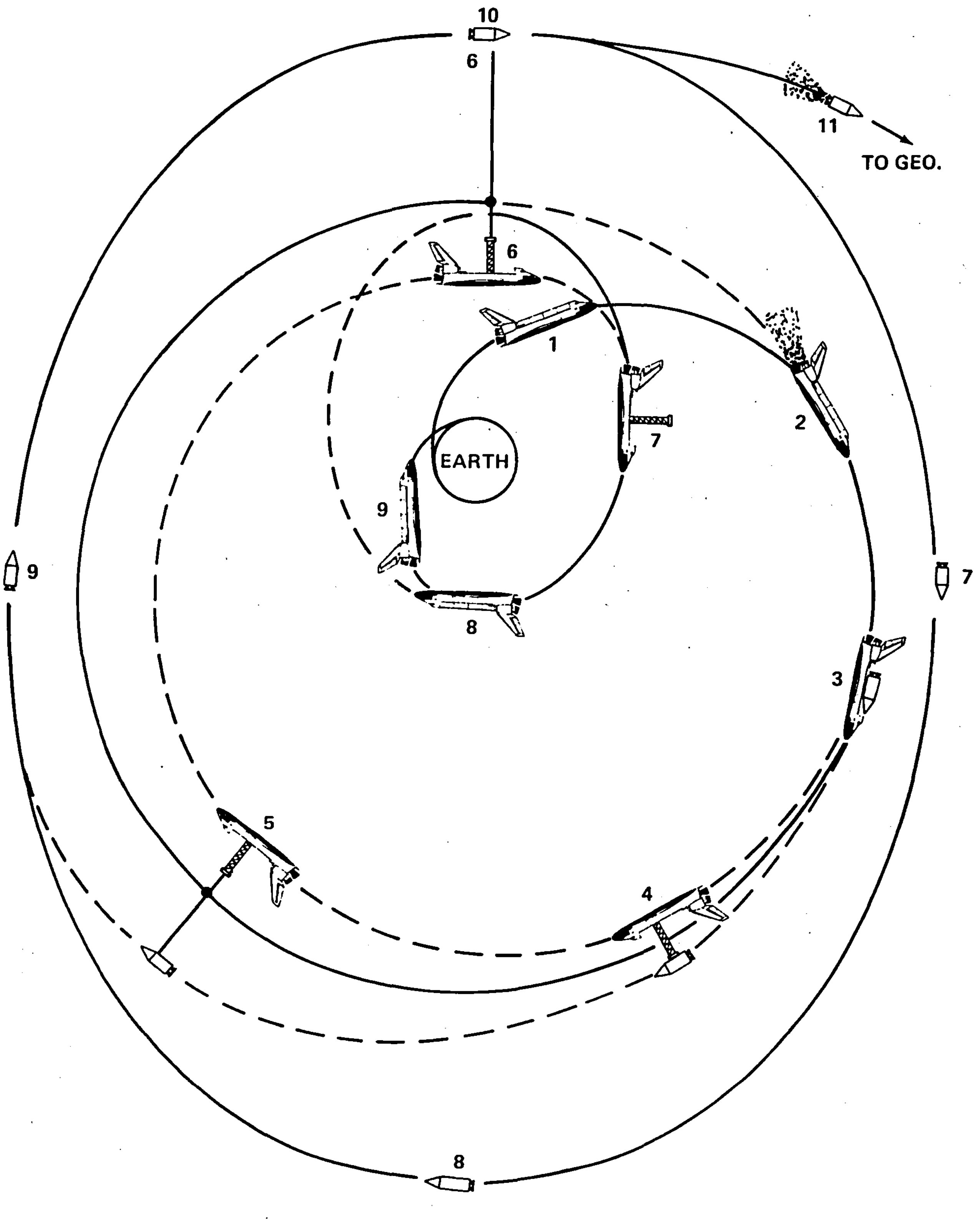


Figure 12. Tether-shuttle assist of payloads to GEO, mission scenario [5].

(6) Maximum deployment distance, payload release

(7-9) Orbiter on reentry trajectory; payload in high. elliptic orbit

(10) Payload launch at apogee

(11) Payload under power to geostationary orbit.

This schematic mission profile is now followed with a numerical example.

Figure 13 presents the tether payout rate versus time. Note that between t = 2400s and t = 3200s the tension is switched on and off to ensure that the tether is not actually reeled in but only that slack in the line is taken up. Toward the end of the deployment there is a sharp escalation of tether payout rate due to the geometric growth of the force required for steady deployment.

Figure 14 shows the spacecraft and payload apogee versus time of release. It is important to note that while the payload apogee increases steadily, spacecraft apogee suffers very little degradation. This is because at a given moment the payload is at its perigee, while the spacecraft is at its apogee. Thus, for the payload the apogee is projected, while for the spacecraft, the apogee is the current altitude.

The slight dip in payload apogee is due to the payload being ahead of the spacecraft local vertical during that time frame. [An examination of the spacecraft perigee (Fig. 15) will show a slight temporary gain.]

Figure 15 shows the spacecraft and payload perigee history. As was explained above, payload perigee is the payload's current position, while the spacecraft perigee is projected. This situation is due to the fact that throughout deployment the payload and spacecraft flight path angles are nearly zero.

Figure 16 shows the brake power required to control the payout rate of the tether. Brake power is a function of force applied and of tether payout rate.

Figure 17 presents the velocity and payload gain versus time of payload release. The payload gain is an exponential function of velocity gain, where velocity gain is the increase of the velocity required to inject the payload into geostationary equatorial orbit from a 300 km equatorial orbit. The slight dip in performance from 3700s to 4500s comes when the payload is ahead of the spacecraft local vertical.

2.2.7 Summary

The preceding section intended to provide an overview of some of the basic modes of tethered payload deployment and its basis in orbital mechanics. It omits the whole area of tether dynamics which does not lend itself very well for a brief presentation due to its great complexity and dependency on specific mission characteristics. The bibliography in section 7.0 of this report contains material on that subject for those interested in more detail.

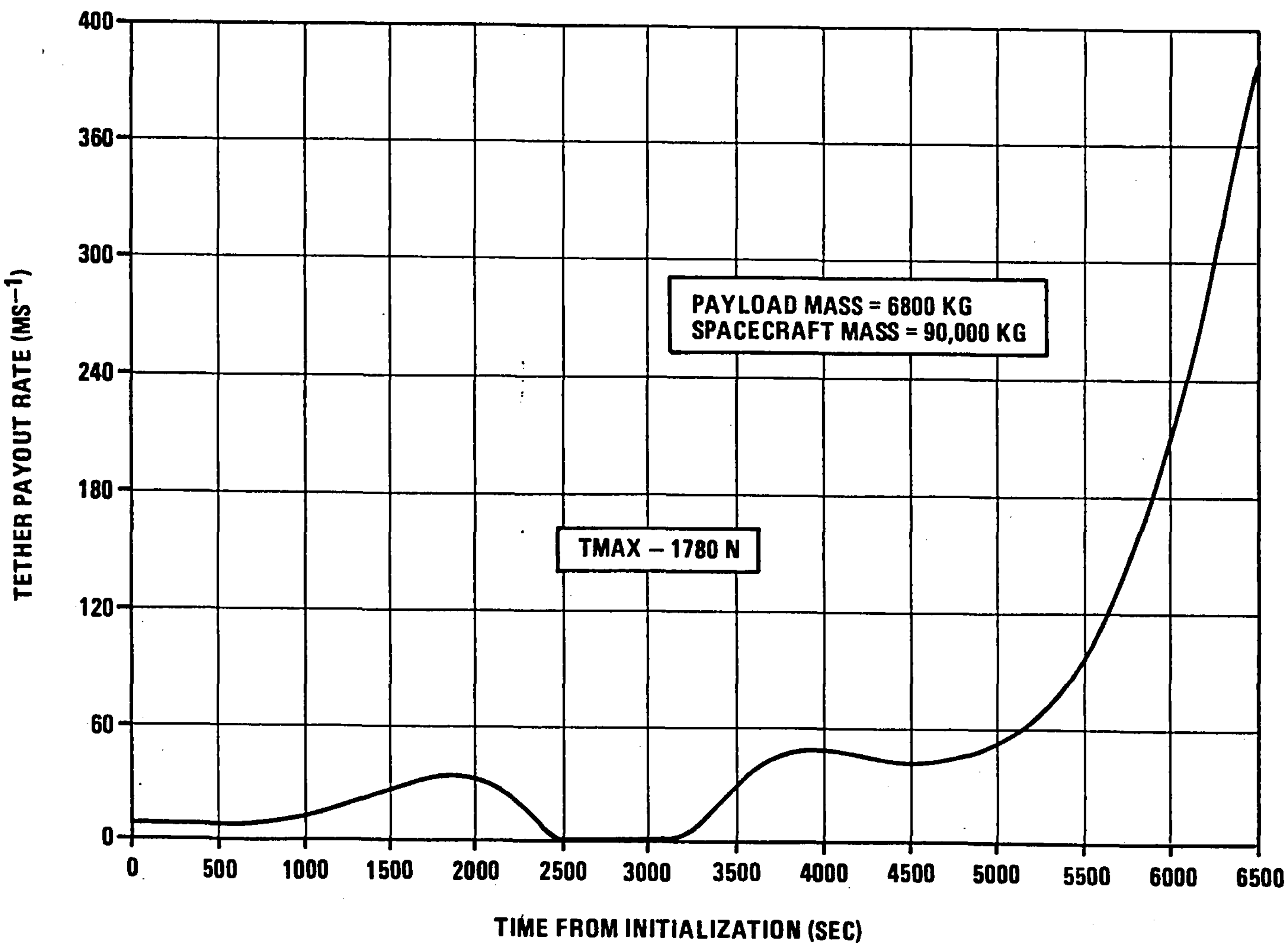


Figure 13. Tether payout rate [6] (wait time for force buildup = 1750 sec).

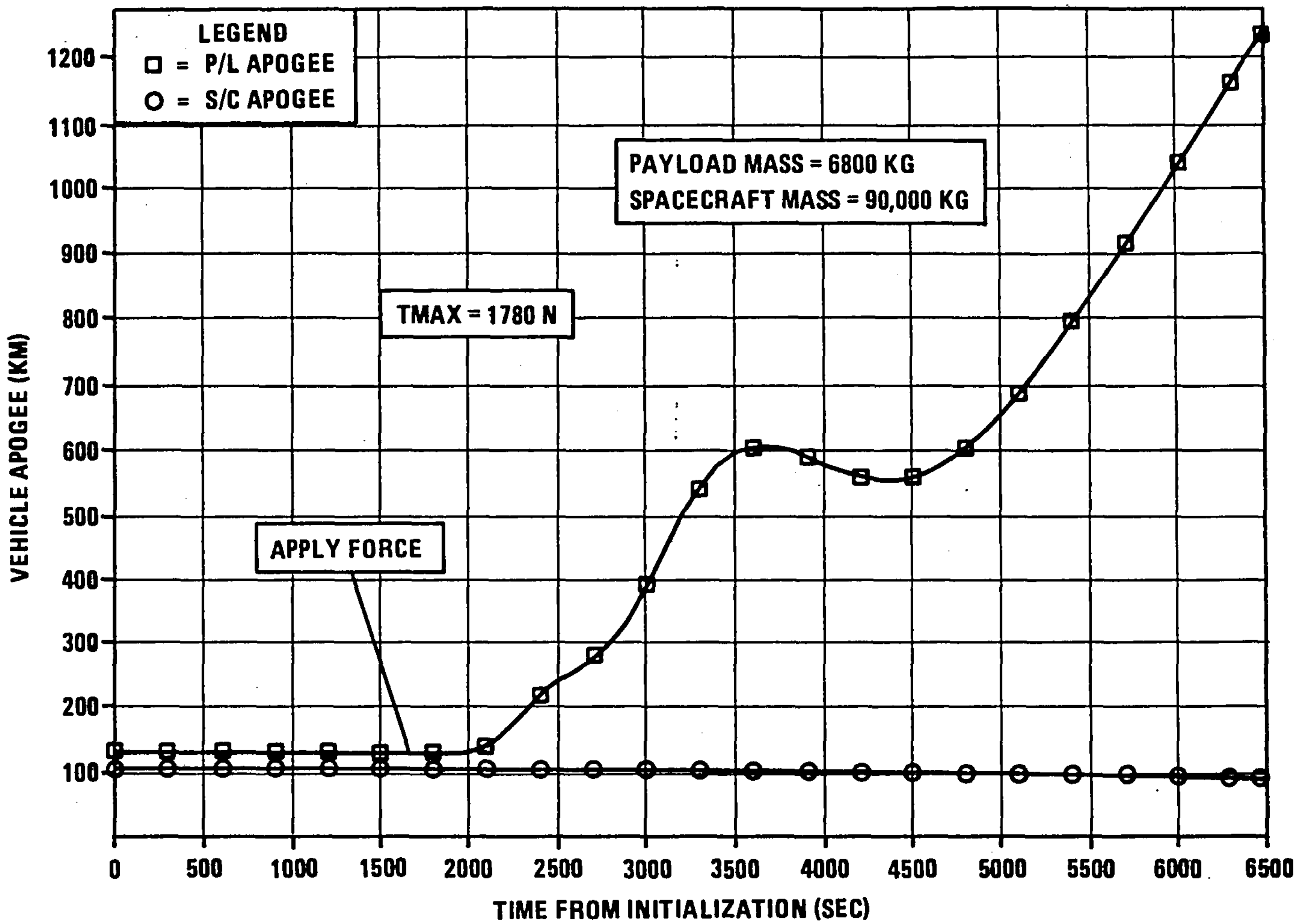


Figure 14. Payload and spacecraft apogee history [6]
(wait time for force buildup = 1750 sec).

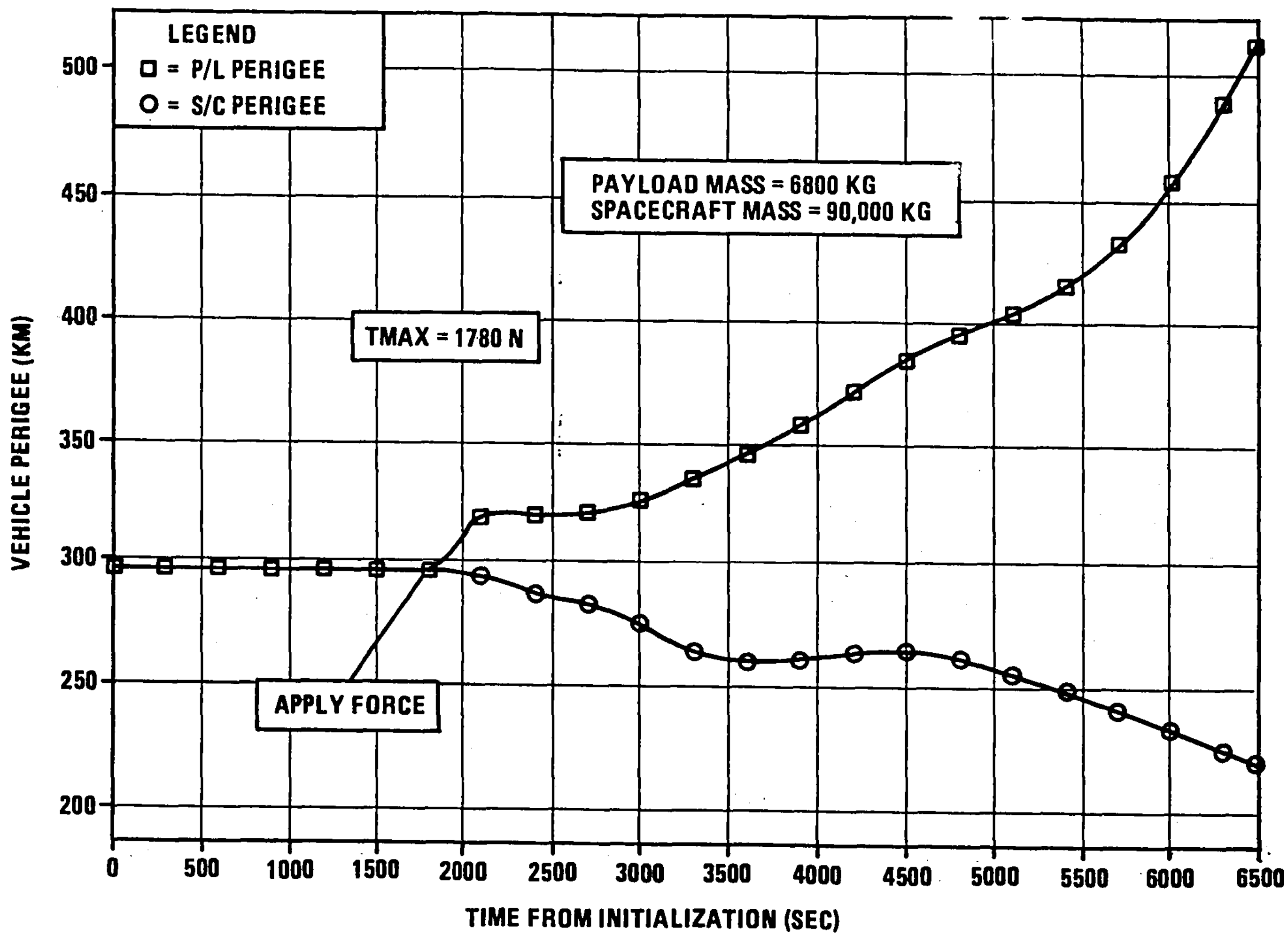


Figure 15. Payload and spacecraft perigee history [6]
(wait time for force buildup = 1750 sec).

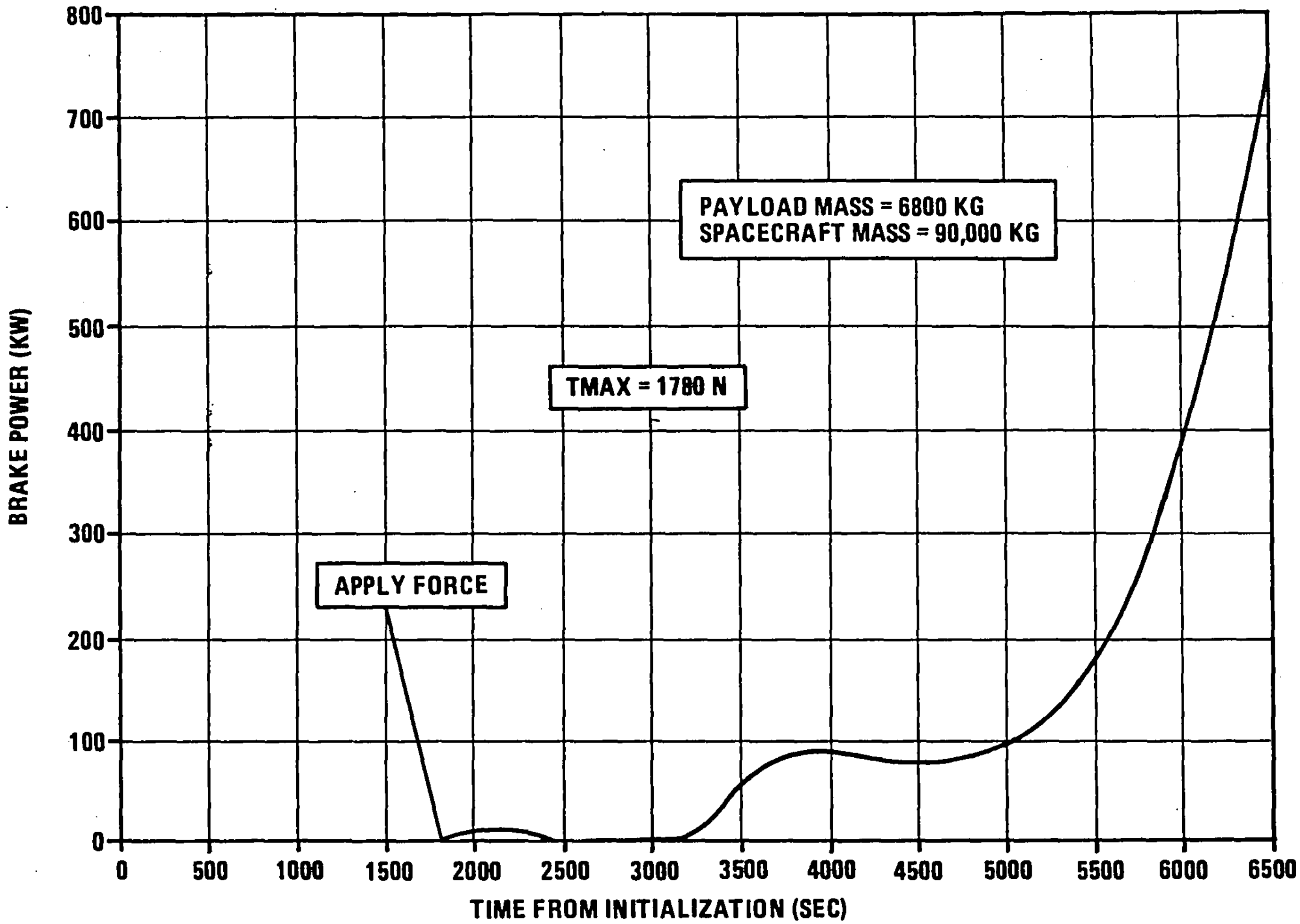


Figure 16. Brake power required [6] (wait time for force buildup = 1750 sec).

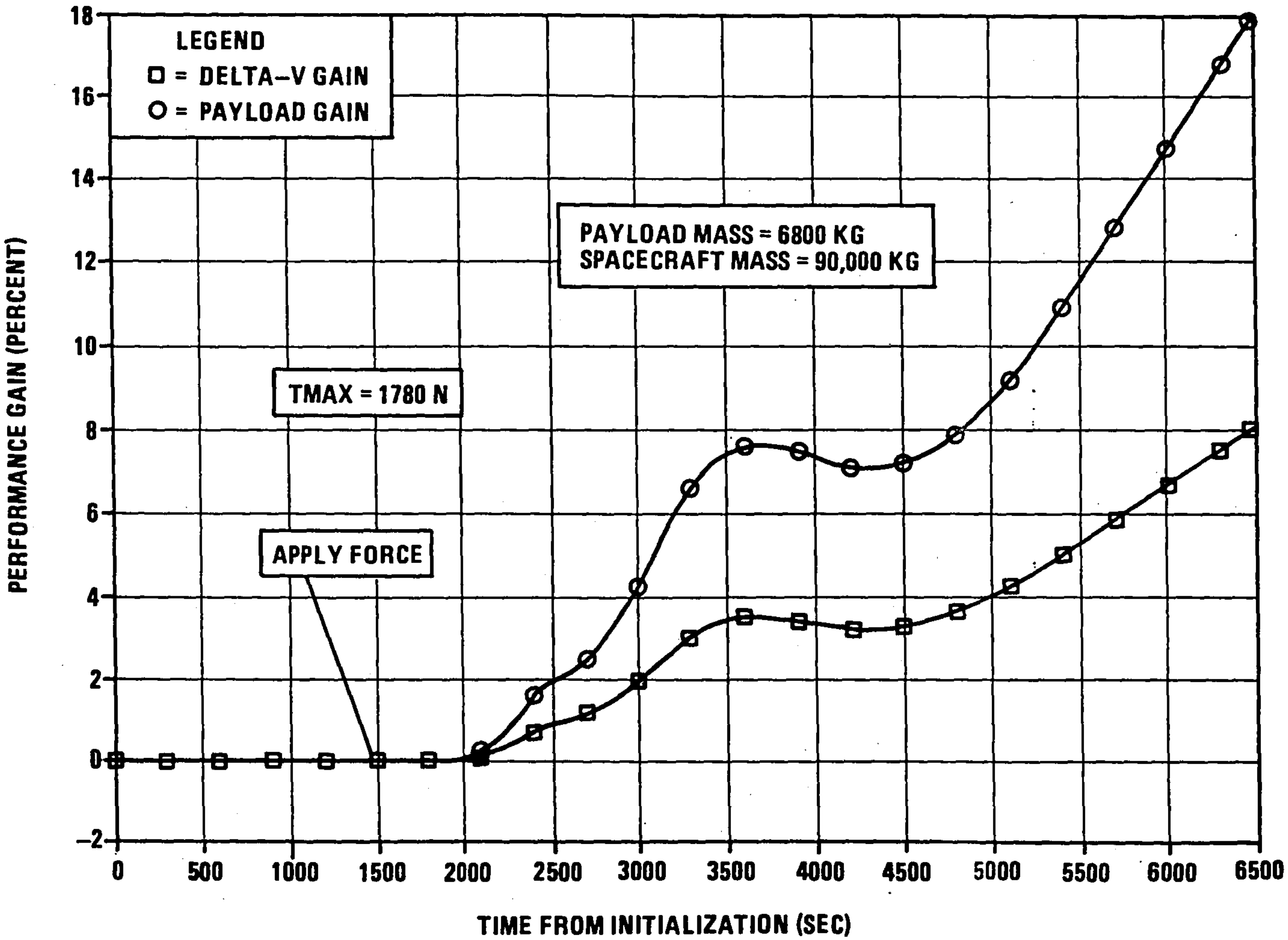


Figure 17. Delta-V and payload gain [6] (wait time for force buildup = 1750 sec).

2.3 Electrodynamic Power and Force Generation

Since Alfven it is realized that a conducting gravity gradient stabilized tether will experience an electromotoric force between the ends since, in low Earth orbit, it moves across a reasonably strong magnetic field. The tether can draw a current from the surrounding plasma, which could be used for power on a spacecraft [Fig. 18(a)]. For example, in a 200-km orbital altitude the orbital velocity is $\sim$9000 m/sec and the electric field along the tether is 0.24 V/m. The level of voltage drop along the tether depends on its position, orientation, the field, and the velocity.

A 15 gauge wire, for example, with a resistance of 10 Ω/km would allow a useable current of 10 A to be drawn. At this level 2.4 kW/km of energy would be dissipated. This generated energy causes a drag on the spacecraft carrying the tether. This electrodynamic drag force acting on a current-conducting tether can be expressed as $\bar{F} = \bar{I} \times \bar{B}$ where I denotes the current (amps), $\bar{B}$ denotes the geomagnetic flux density (Webers/m^2) and $\bar{F}$ is the force/unit length (Newtons/m). To compensate for this drag, propulsive fuel has to be expended. The energetic advantage of using fuel this way versus generating on board power with it is that the considerable kinetic energy of the fuel, which is comparable to its chemical energy, is utilized with a tether.

Instead of drawing current from the tether, electrical energy can be fed into the tether. While the spacecraft is in sunlight, surplus photovoltaic power can be used to generate a propulsive force in the tether.

An example of an electrodynamic power/force generating system is shown on Table 3 [7].

TABLE 3. ELECTRODYNAMIC POWER/FORCE SYSTEM (10 kW)

— Tether, electrodynamic, to be used as a) DC power generator b) Alfven engine (electrodynamic thruster)
— Solar cell array (to be used to boost the orbital height by day time, also to feed energy to storage system)
— DC/DC converter and regulator (suitable to accept power output of tether, solar cells, etc.)
— Storage system (batteries, or equivalent)

The overall mass of the tether system has been computed as follows:

1)	Wire, 20 km, 110 ohm total resistance, insulated with 0.38 mm polyethylene, teflon braid jacket, AWG 13, copper diameter 2 mm	675 kg
2)	Insulator at tether base, to prevent corona discharge	50 kg
3)	Winch and ancillary equipment	1500 kg
4)	Plasma contactor (one or more on the spacecraft, one on the satellite), complete with auxiliary units, two sets on spacecraft (addition of more units of negligible effect on weight)	10 kg
	Total	2235 kg

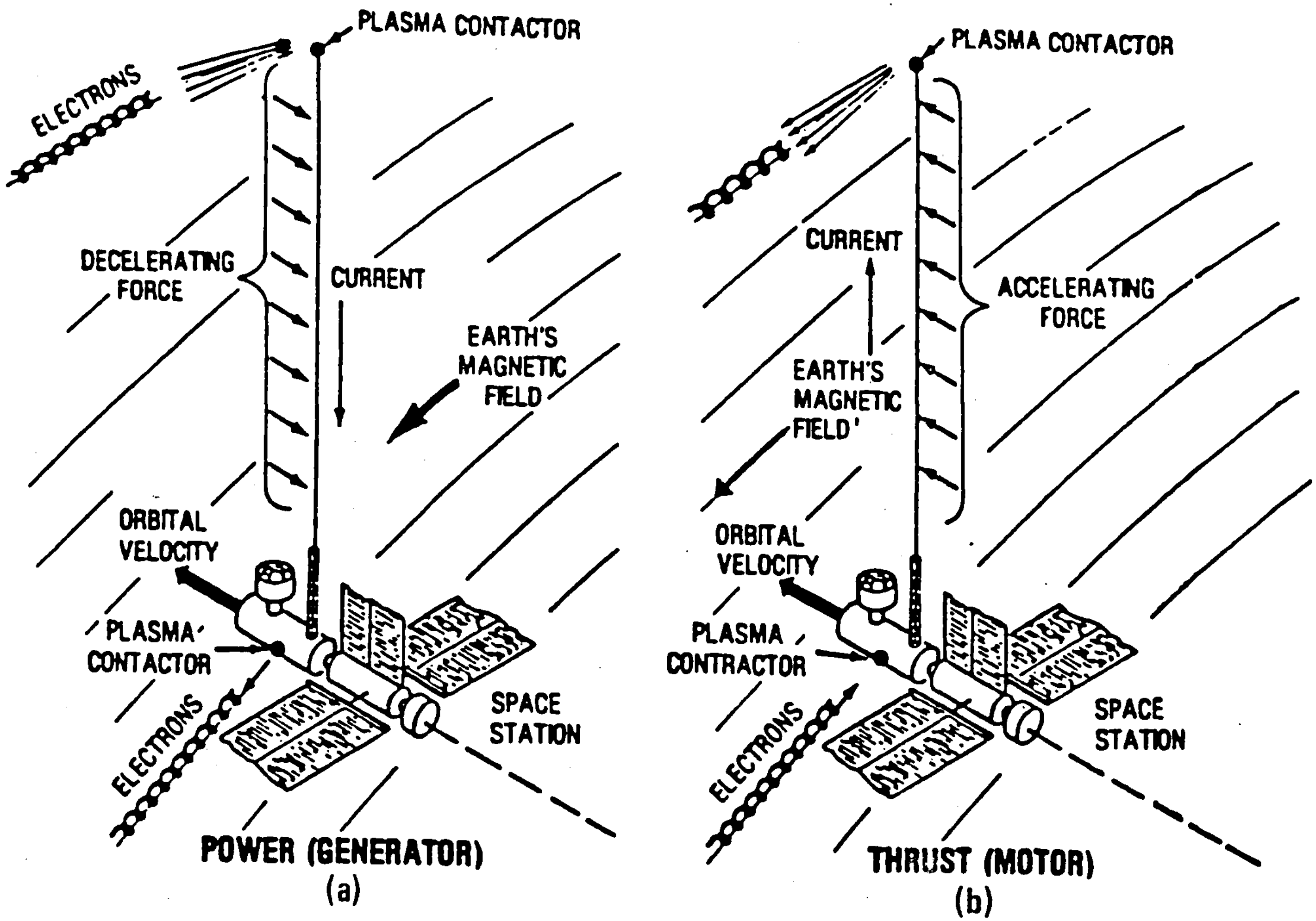


Figure 18. Electrodynamic tether principles.

The dc/dc converter and regulator and the battery bank are common to other on-board intermittent generators, such as the solar cells. Their masses are:

1)	dc/dc converter/regulator, 30 kHz, 30 kW input power	75 kg
2)	Battery storage, Ni-Cd, 200 cells, 15 kWh capacity	460 kg

These parts are not added to the systems mass because the tether is planned to work as a part of the overall integrated spacecraft system. Figure 19 shows a block diagram of an integrated system. Both the solar cell system and the electrodynamic tether system are connected to a current converter/regulator and power conditioning/distribution system. The tether system is capable of both delivering and accepting electrical energy.

2.4 Tethered Platforms and Constellations

A tethered platform is a satellite which is connected to a parent spacecraft by a tether and flys in fixed formation with it for the duration of the mission. A laboratory or service module can translate along the connecting tether from the spacecraft to the platform. The tether can also transfer power to the platform and communication signals between the two bodies.

A constellation, in general, is a fixed arrangement of three or more masses that are connected by tethers. The distance between masses and their relative position to each other is generally constant. The simplest constellations are one-dimensional, gravity gradient stabilized concepts that may include a number of masses along the tether. Two-dimensional constellations need special arrangements in order to remain stable under operational conditions. The feasibility and practicality of three-dimensional constellations has not been established at this time.

The purpose of a tethered platform is to isolate scientific instrumentation and equipment from space station high frequency vibrations, from contaminations emitted by the space station, and from limited fields of view from the space station. A tethered platform co-orbiting with the parent spacecraft is accessible at all times and for any length of time for service and reconfiguration by the spacecraft crew. This is the primary advantage over a free flying satellite. Typical missions which will benefit from a tethered space station platform are a variety of observational sciences such as astronomy, astrophysics, solar physics, space sciences, Earth science, and magnetospheric studies. Materials processing investigations and some forms of life science studies can also be accommodated.

One purpose of tethered constellations is to have a number of instrumented platforms make simultaneous measurements. Also the different stations can be specialized for different functions, so that unwanted interferences or dangerous processes can be avoided successfully.

An example of a tethered scientific platform to the space station is given in Figure 20. The platform carries an infrared telescope and associated equipment. It is deployed 10 km upward from the station. Further development could eliminate the solar arrays by providing space station power via a conducting tether to the platform. Also eliminated could be platform attitude control systems, communication and data handling electronics, and a reboost module that would be required for a free-flying platform.

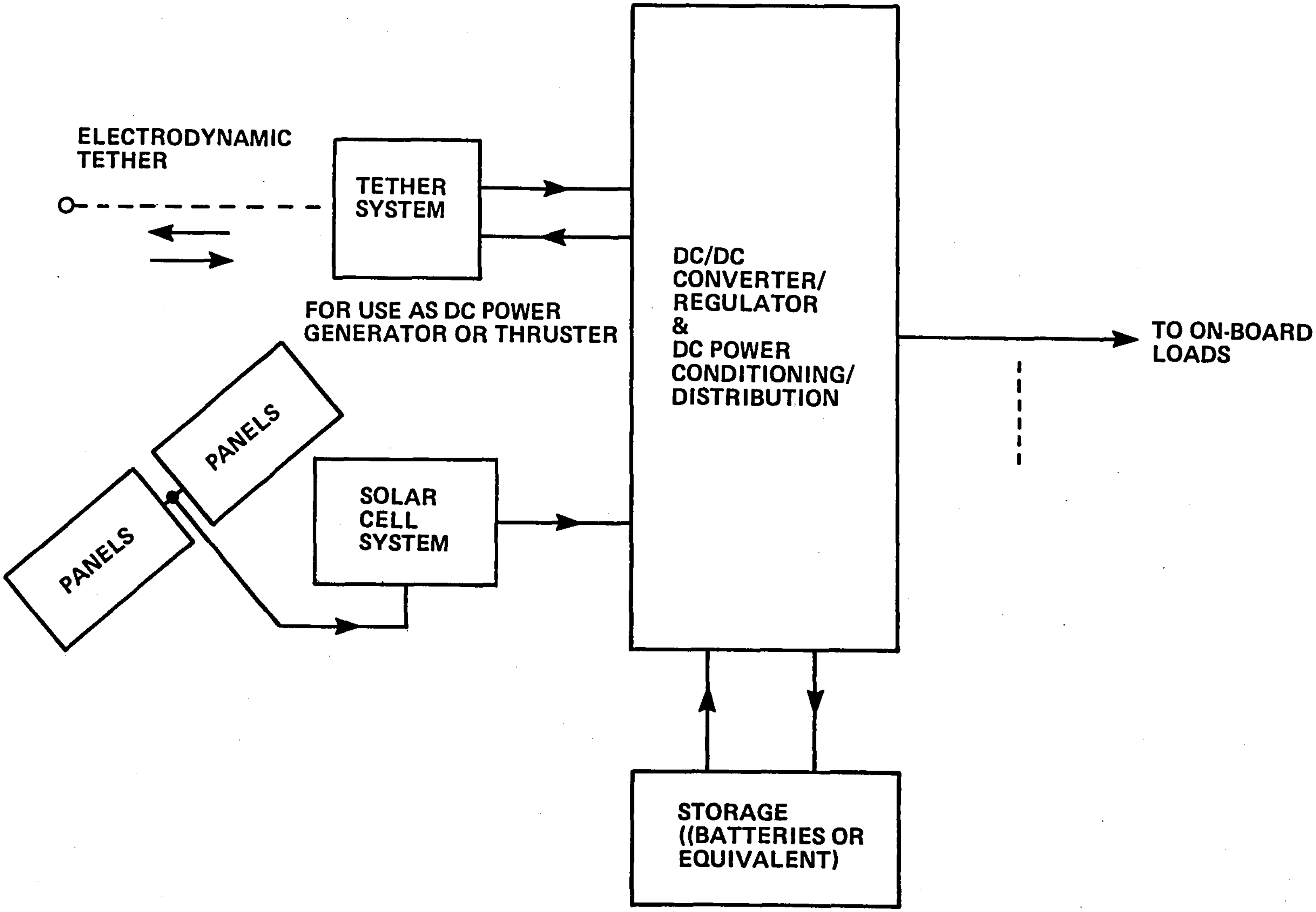


Figure 19. Block diagram of integrated system [7] for power generation and trusting.

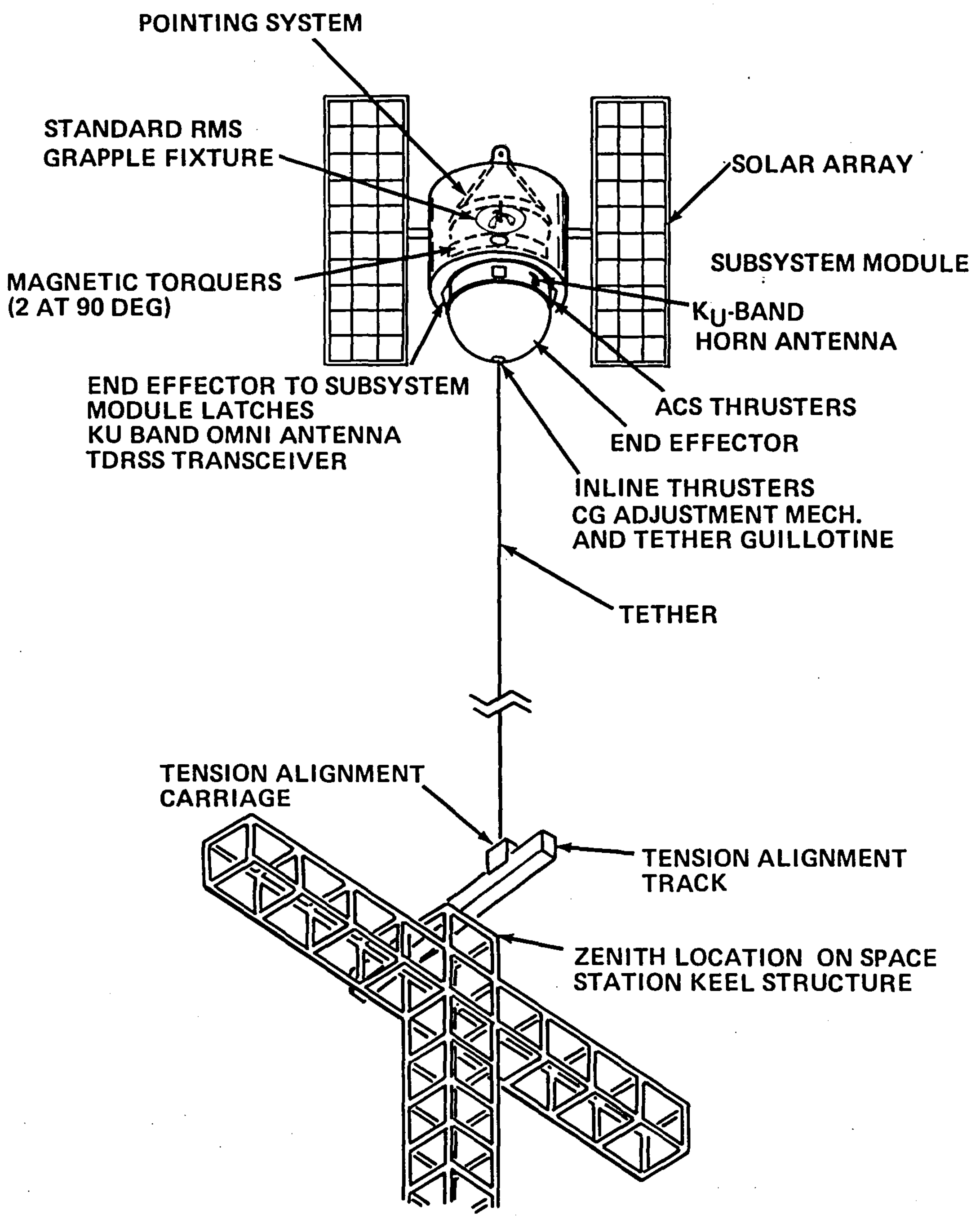


Figure 20. Gravity gradient tethered platform from space station [8].

The considerable mass and cost saving of such a tethered platform are indicated in the example shown in Figure 21.

A third mass can be located at the orbital center of the space station-platform system. An acceleration level of close to 10^{-8} g can be obtained for sensitive space processing and life science experiments. This dual platform system constitutes a three-mass gravity gradient stabilized constellation and is shown in Figure 22.

A promising application of a tethered platform is in the area of remote sensing, particularly photographic stereoscopic coverage from space of land areas.

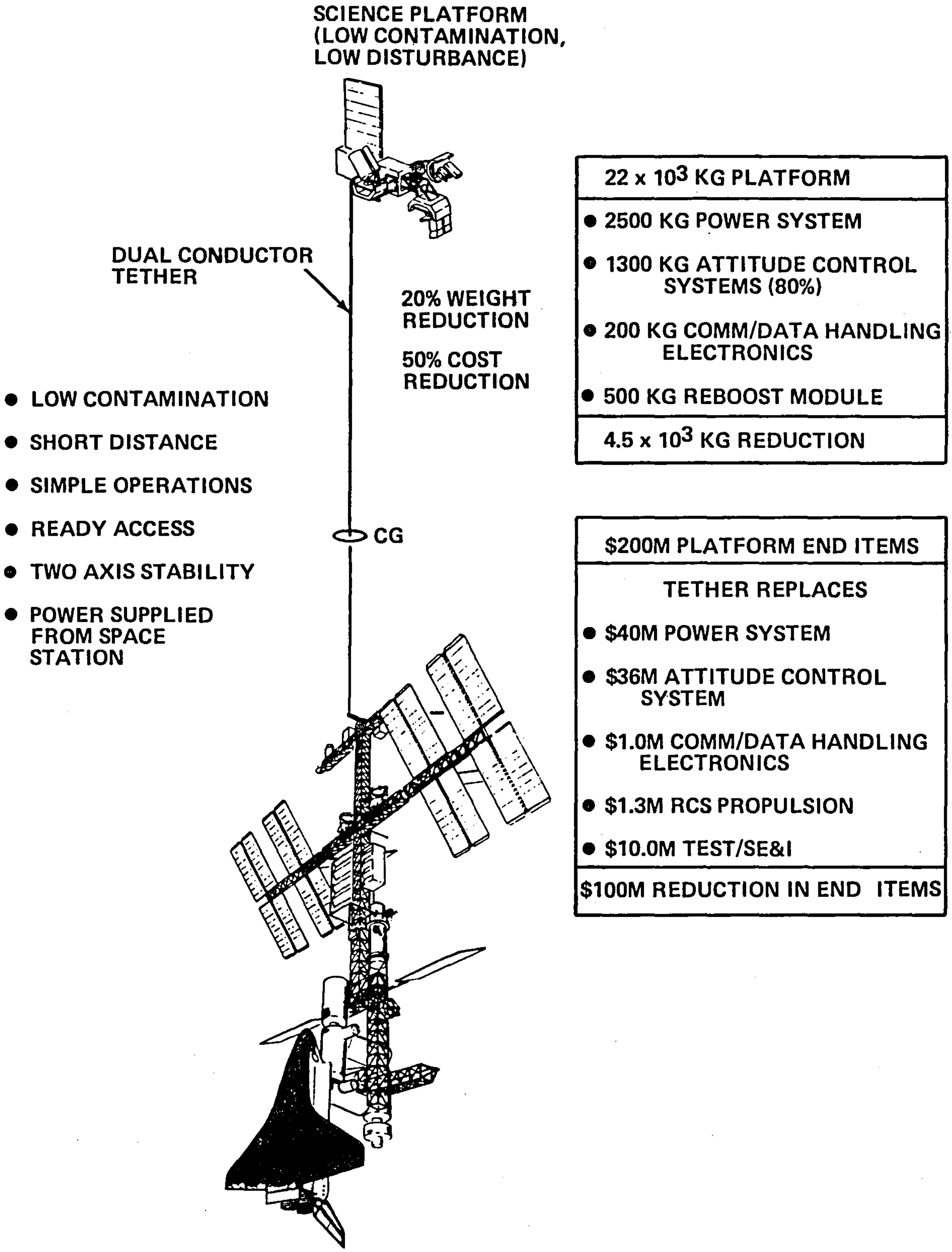


Figure 21. Tethered platform benefits.

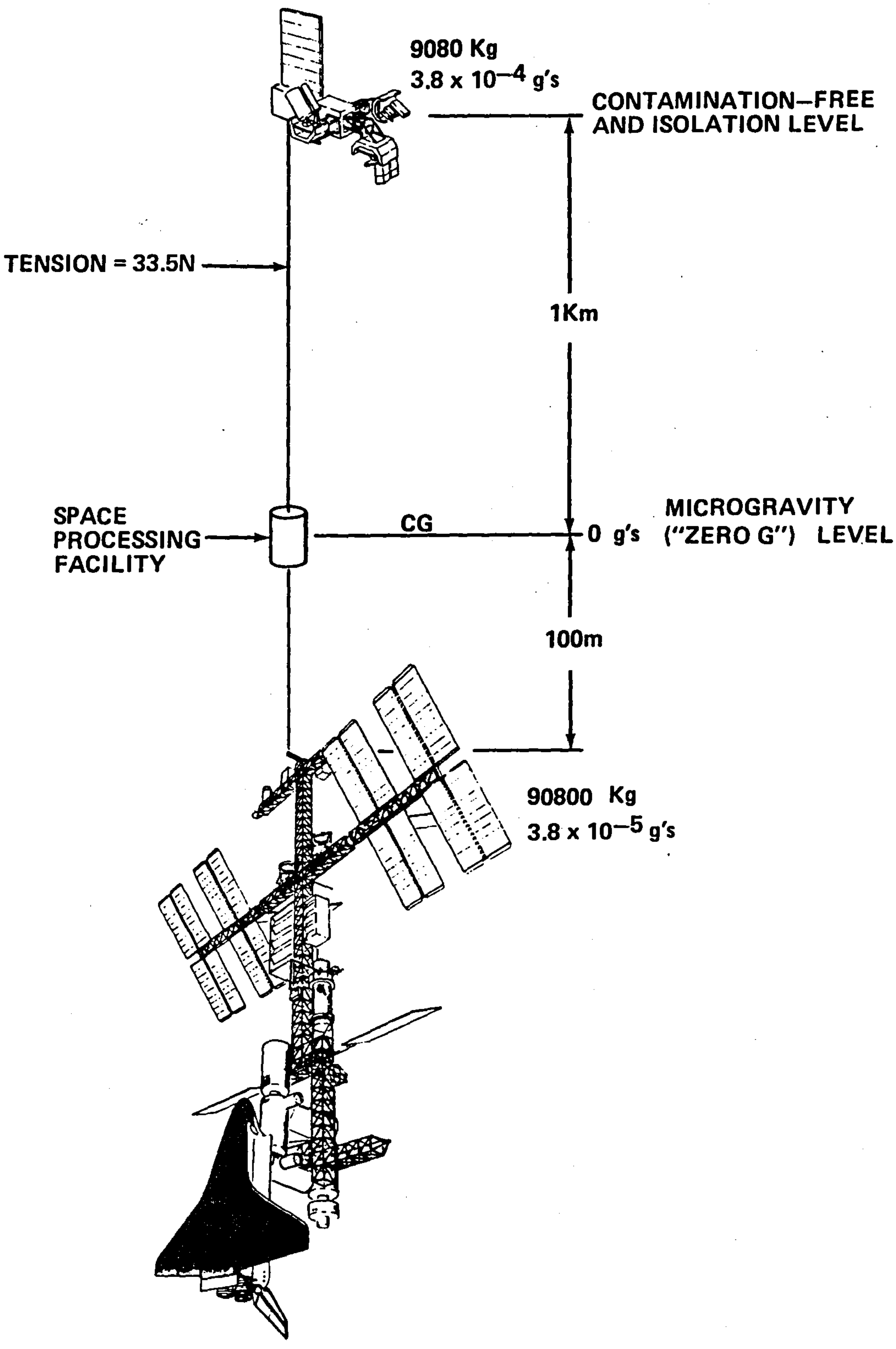


Figure 22. Tethered microgravity facility.

3.0 SPECIFIC ROLES OF TETHER ON SPACE STATION

The present ground rules for all tether applications to space station are summarized in Table 4.

TABLE 4. SPACE STATION GROUND RULES

- Nominal mass — 250,000 kg
- Nominal orbit — 500 km, 28.5 deg inclination
- Nominal angular momentum — 1.309055×10^{16} kg-m^2/sec
- Allowable orbital excursion due to tether operations — 250 to 300 n.mi. desired*
- Nominal orbit stationkeeping intervals — 90 days or less
- Conduct tether launch, orbiter deployment, and other tether transportation operations to minimize orbit stationkeeping propellant
- Space station altitude at shuttle revisit — 250 to 270 n.mi. desired

* These limits may be exceeded on specific tether transportation missions, but planned space station momentum balance operations will limit the time of excursion.

The specific beneficial roles of tethers on the space station, as described in the following sections, can be summarized as follows:

1) Tethers can regulate the space station's orbital angular momentum budget by deploying spacecraft or payloads up and down at preplanned intervals. These operations are described in section 3.1 of this report.

2) Tethers can regulate the space station's energy budget by using an electrodynamic tether for power and thrust generation thus converting orbital into electrical energy and vice versa. This is described in section 3.2 of this report.

3) Tethers can solve problems of undesirable environmental effects originating at the space station by using tethers to place certain science and applications platforms at a fixed distance from the space station. This is described in section 3.3 of this report.

4) Tethers can reduce the risks of certain space station operations by moving docking and propellant transfer operations away from the space station at the end of a tether. This is also described in section 3.3 of this report.

5) Tethers can support a broad range of scientific research by deploying a series of instrumented platforms in various tethered configurations from the space station. This is described in section 3.4 of this report.

3.1 Tethers as Regulators of the Space Station Momentum Budget (By J. Harrison)

3.1.1 Tethered Shuttle Deployment Coupled with Tethered OTV Launches

3.1.1.1 Introduction

The roles of tethers and their usefulness to alter the orbital positions of bodies in space has been discussed in section 2.2. Martin Marietta [8] has studied the application of a tether to deploying shuttles and OTVs from the space station, and developed a system concept with the benefits of using it, given in terms of propellant savings. As explained earlier in section 2.2, these tether operations will result in altitude changes to the deploying system, i.e., the space station, as well as to the deployed system, i.e., the shuttle or OTV. Since the space station prefers no altitude alterations, increases that result from downward deployments must be offset later by equivalent decreases brought about by upward deployments. The shuttle and the OTV serve nicely in this role since the shuttle is a downward and the OTV an upward deployment.

Martin Marietta's tether concept consists of the tether itself, the deployer, and a system at the end of the tether that interfaces with the shuttle or the OTV.

The estimated average annual propellant savings are about 26,000 kg over the 10 year time span between 1991 and 2000 (44,000 kg during the last 6 years due to the addition of OTV flights). These savings are from the shuttle, OTV, and space station orbital maneuvers that are done using a tether rather than the customary propulsion devices.

3.1.1.2 Energy/Momentum Exchange

The principle of tethers when applied to transportation problems involves the conservation of angular momentum as discussed in section 2.2. In simplistic language this means that the loss of angular momentum in the lower body is equal to the gain in the upper one. So, the loss of shuttle angular momentum, when it is lowered from the space station on a tether, is equal to the gain in angular momentum by the station, causing the station to move to a higher altitude. Angular momentum (h) can be computed from several equivalent expressions as follows:

$$h = mrv = mr^2\omega$$

where

m = mass

r = radius vector

v = velocity normal to r

ω = angular velocity .

The space station angular momentum at a 500-km altitude and for a 250,000-kg mass has been calculated to be 1.30906×10^{16} kg-m^2/sec [8]. Using a 65-km long tether to deploy a shuttle from the space station, which represents a change in r in the above expression of 47 km for the shuttle and 18 km for the space station, and with masses on the order of 100,000 kg for the shuttle and 250,000 kg for the station gives, according to equation (1), a momentum loss of 6.99×10^{13} kg-m^2/sec by the shuttle and, of course, an equivalent gain by the space station. These results correspond to an initial orbital altitude for the shuttle-station combination of 500 km and a final altitude of 185 x 453 km and 518 x 629 for the shuttle and space station, respectively.

The energy released by the motor/generator system, that is driven by the deployer as the tether reels out has been computed to be 153 kWh. This deployment occurs over a 4 to 6 hr period.

Similar calculations have been made for the OTV launch and the results for both are given in Table 5. The final space station orbital altitude for the OTV launch is 377 x 483 km.

TABLE 5. MOMENTUM AND ENERGY VALUES FOR SHUTTLE AND OTV TETHER DEPLOYMENTS

	Shuttle	OTV
Momentum Gain/Loss (kg-m^2/sec)	6.99×10^{13}	6.69×10^{13}
Deployment Energy (kWh)	153	366
Retrieval Energy (kWh)	11	29
Initial Orbit (km)	500 x 500	500 x 500
Final Orbit (km)	185 x 453	633 x 1482
Tether Length (km)	65	150
Mass (kg)	100,000	35,000

Each tether launch of the shuttle or the OTV will result in a displacement of the space station from its nominal 500-km altitude. For shuttle launches this raises the station an average distance of 74 km and for OTV launches it lowers it by about the same amount.

The atmospheric drag and OTV effects both contribute to a space station loss of altitude, as can be seen in Figure 23. The drag effects are much less than the OTV effects (OTV launches begin in 1995) so if the frequency of OTV launches occurs as estimated in the mission model (an average of about 11 each year through 2000) and the tether is used to assist in these, the space station orbit will be lowered to unacceptable levels.

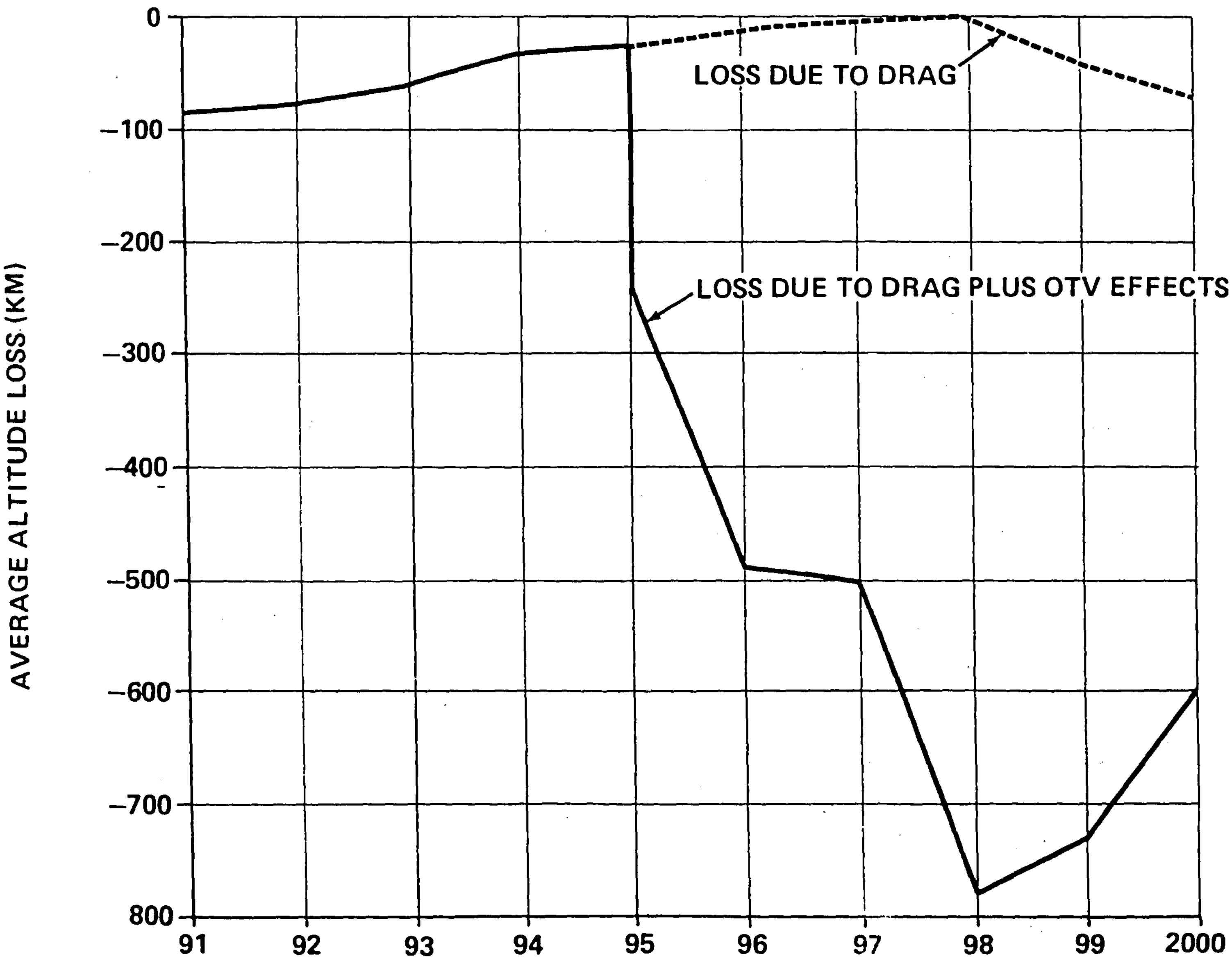


Figure 23. Space station average altitude loss each year due to drag and tethered OTV launches.

Since permanent space station altitude changes, either up or down, are unacceptable some practical means must be found to avoid them. Martin Marietta has proposed a momentum balance concept for the station that is attained by successively alternating the tether launches of shuttles and OTVs. In this concept the station losses in momentum and altitude from an OTV launch are later recovered with a shuttle deorbit using the tether.

Twenty shuttle launches over a 6-year period from 1995 to 2000 are needed to off-set the 69 OTV launches planned during this time. The length of the tether is also a factor in determining the number of launches as can be seen in Figure 24 where, for example, in 1998, 12 flights are needed to offset the 784-km drop that otherwise will occur and the tether length for eight of these is 65 km and for the other four is 42 km.

3.1.1.3 Deployer System

The major components of the deployer system, other than the tether itself, are (1) the reel, (2) the motor/generator, and (3) the level wind mechanism. The entire system weighs 11,000 kg.

The reel holds 150 km of tether material on a central hub that is 0.3 m in diameter and 3 m in length. The outer diameter is 2.5 m. The reel is made of aluminum. The tether weighs 6000 kg.

During deployment, the rotating reel can be used to drive an electrical generator that provides 56 to 122 kW for a 4 to 6 hr duration and generates 153 kWh (shuttle deployment) of electrical energy. Retrieval of the tether after release of the OTV or the shuttle will be done using a 52-kW electrical motor to drive the reel and the electrical energy needed over a 4 to 6 hr period is 29 kWh (shuttle release). Table 5 gives the corresponding OTV values. During deployment the payout speed of the tether is controlled by varying the current drawn from the generator.

The electrical energy from the generator is dissipated by a special radiator. The radiator consists of a high-temperature electrical resistor bank that converts electrical energy to thermal energy and radiates this energy to space. The size of the radiator is 1 m in diameter and length.

The level wind mechanism is a device that moves or translates back and forth along the length of the reel, e.g., in an axial direction, and winds the tether on the reel during retrieval to form a level surface as each layer is added. This insures that a snag-free deployment occurs.

3.1.1.4 Tether

To carry-out these operations a 150-km long tether (65 km for the shuttle deorbit) with a diameter of 10 mm will be used. The tether is made of Kevlar 49 with a Teflon jacket and has a breaking strength in tension of 40,000 N and a weight of 40 kg/km. In determining the tether diameter, a safety factor of 2 is used and as many as 100 reuses are planned. The maximum tether tension during the shuttle and OTV operations are equal to about 17,000 N. The tether can be cut at either end in the event an emergency arises. The tether is not tapered.

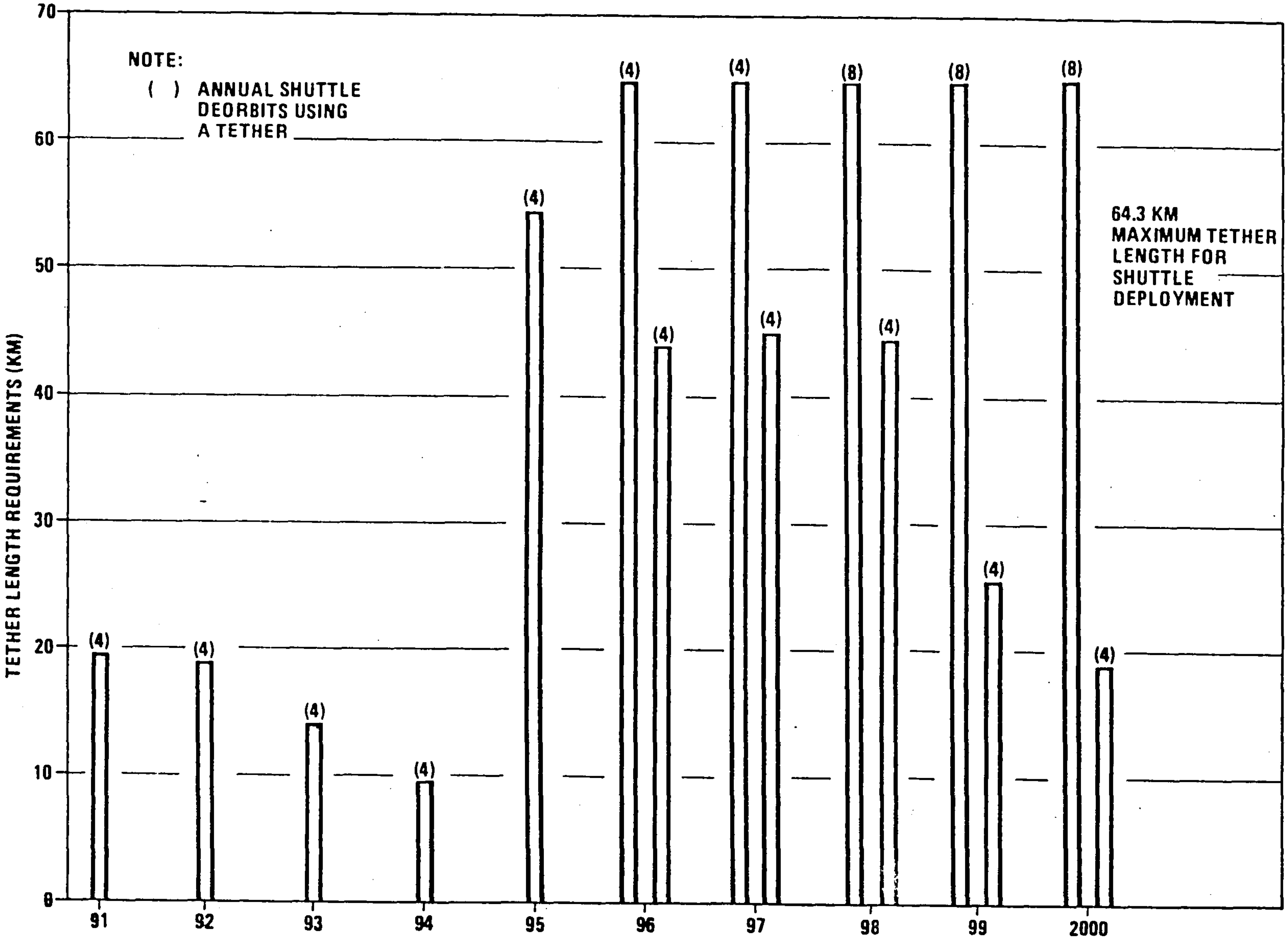


Figure 24. Annual shuttle deorbits required using a tether to maintain space station altitude at 500 km.

By way of comparison, the tether recommended for the Tethered Satellite System mission one (TSS1) is 20-km long and has a diameter of 2.5 mm and a unit weight of 6.9 kg/km. It has a stranded Nomex core, 10 twisted strands of No. 34 AWG copper wire to carry the electrical currents since TSS1 is an electrodynamic mission, Tefzel for insulation, braided Kevlar 29 for strength, and finally an outer jacket of braided Nomex for protection from atomic oxygen. Kevlar 29, the load carrying member, has a breaking strength of 1800 N.

Currently Kevlar is the principal material proposed for tether operations mainly because of its relatively high strength to weight ratio and its high modulus of elasticity. It is however subject to degradation by atomic oxygen and therefore must be protected by a jacket.

3.1.1.5 Shuttle Interface Module (SIM)

The shuttle deboost from the station requires an interface module between the tether and the shuttle to attach the two and to transfer OMS propellants from the shuttle to four storage tanks. A system concept, for such a module or system, called SIM for Shuttle Interface Module, has been developed by Martin Marietta [11]. The SIM is a semi-circular shaped structural member that attaches to the shuttle bay as shown in Figure 25 with four spherical tanks located on the structure to store the 3000 kg of OMS propellant that is scavenged from the shuttle during deployment (45 kg per km of deployment).

The SIM weighs 1400 kg and is designed so as to avoid obstructing the shuttle payload bay envelope. The payload bay doors cannot be shut while SIM is attached. After the shuttle has been lowered 65 km, it is released and SIM is hauled by the tether back up to the station for reuse after the OMS propellants are transferred to the station.

The SIM will have a grapple fixture in case some unforeseen emergency occurs and it must be jettisoned and later retrieved by an OMV or perhaps by the shuttle. Furthermore, for routine handling by the shuttle and station RMS systems, a grapple fixture is needed. For control of both orientation and position during retrieval, a cold gas propulsion system is needed. Other design features required are a quick disconnect device that is remotely controlled to separate the tether from the SIM in an emergency; retro reflective cubes for tracking during retrieval by the station; a structural provision that permits it to berth with the space station; and finally, a data system for command/control from the station.

3.1.1.6 Payload Interface Module (PIM)

A companion to SIM is needed for payload operations with a tether and Martin Marietta has developed a Payload Interface Module or PIM (Fig. 26) for these operations. Its design is tailored mainly to handle OTV launches from the station. No weight and size for PIM have been determined but approximate values are 500 kg (the OTV weight is 35,000 kg) and 1 m for the diameter and length of the cylinder shaped body. PIM will attach to the OTV near the OTV engine.

Two major differences between the PIM and SIM are the absence of propellant tanks on PIM and the addition of a structural device on PIM to mate with the OTV grapple fixture. But like SIM, the PIM will have its own grapple fixture, propulsion

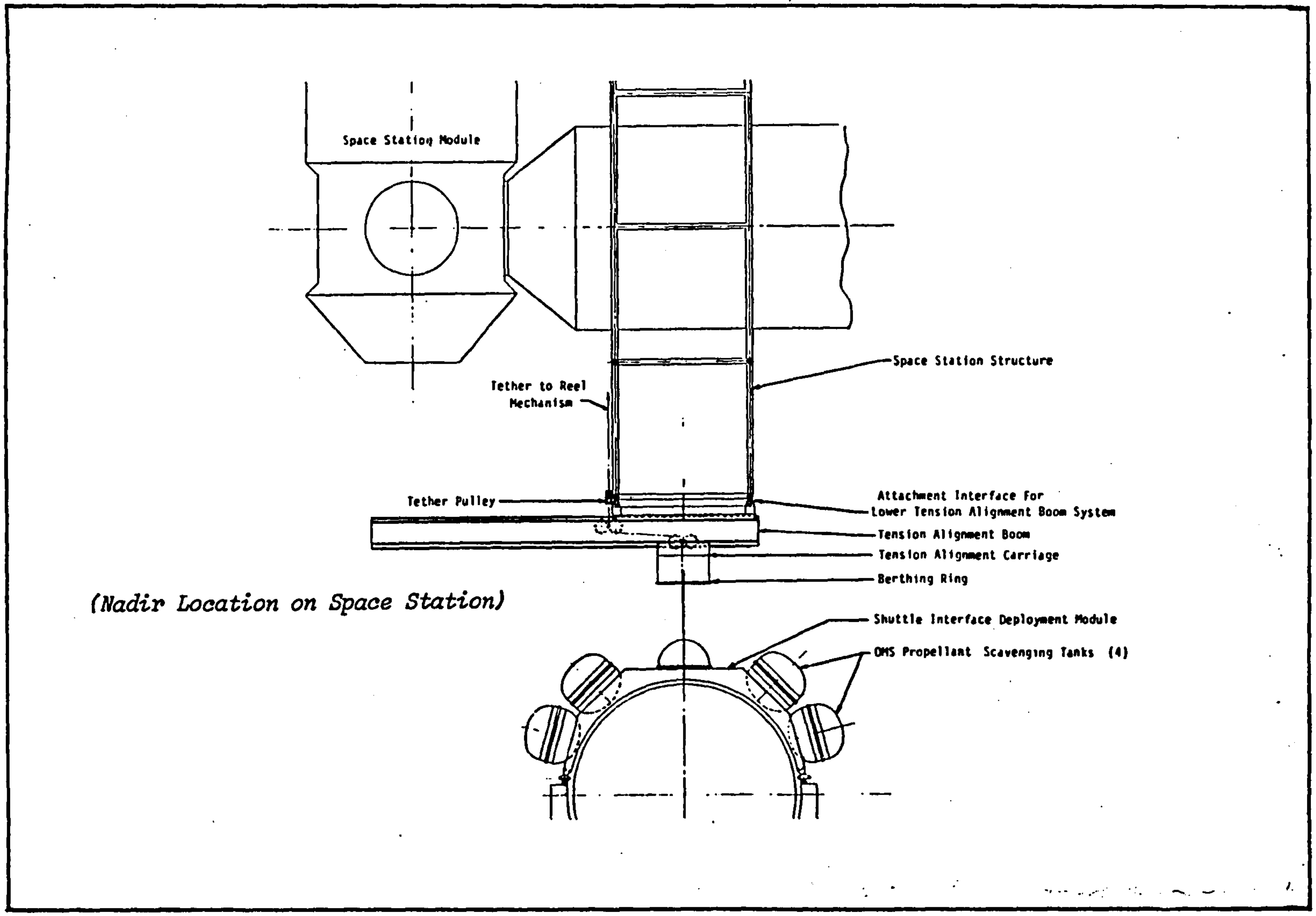


Figure 25. Shuttle tether deployment system [8].

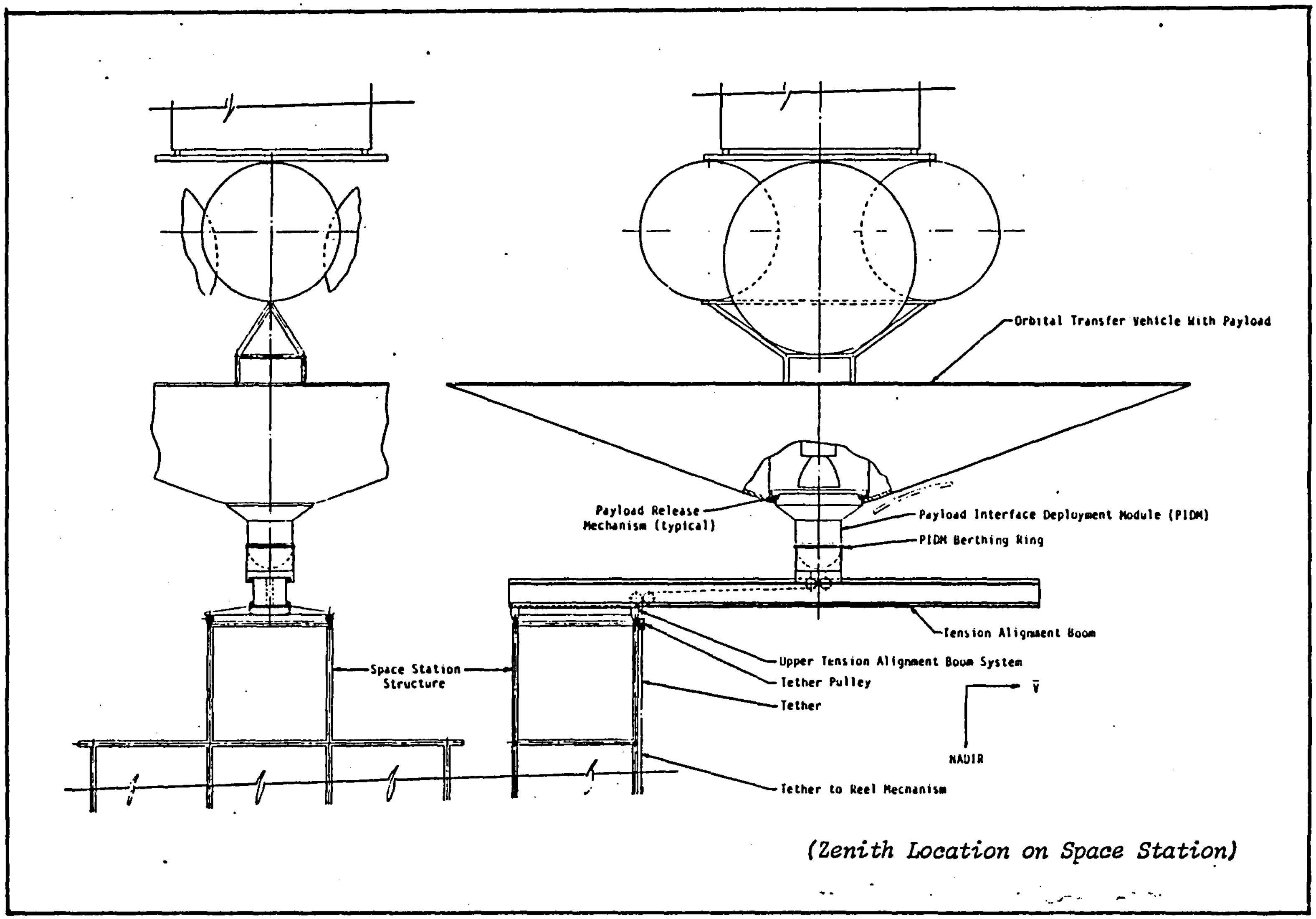


Figure 26. OTV tether deployment system [8].

system, remotely-controlled quick disconnect device, retro reflective cubes, structural provisions for berthing with the station, and a command/control data system.

Operationally, mating of the PIM to the OTV will occur at the space station; then it will be placed above the station structure with the station's RMS and released. The PIM propulsion system will move it and the OTV away from the station a distance of about 1/2 km where gravity forces will take over and further separate them by a distance of 150 km. At this point the OTV is released from the tether — at an equatorial crossing — and begins its first engine firing to take it to geosynchronous orbit. This upward OTV deployment using a tether drops the space station from a circular orbit of 500 km to a 483 x 377 km elliptical orbit and raises the OTV to a 633 x 1482 km elliptical orbit before the burn.

3.1.1.7 Results

The shuttle deployment from the space station at a 500 km circular orbit to an elliptical 185 x 453 km orbit (the shuttle burn in preparation for reentry occurs from this apogee altitude) results in shuttle propellant savings of 3000 kg or about 65 percent of the propellant normally required. The OTV propellant savings, corresponding to the conditions discussed already, are 2000 kg or about 8 percent of normal requirements.

Furthermore, the space station requires approximately 2500 kg of propellant annually, averaged over 10 years, to maintain a constant 500 km altitude and this station keeping job can be accomplished by periodic tether boosts that result from deorbits of the shuttle adding to the propellant savings already mentioned.

The benefits of these reductions in propellants must be weighed against the increases in complexity and weight of the systems involved. The tether system proposed for the station weighs 11,000 kg (this includes a 6000 kg tether) and the SIM/PIM combination adds another 1900 kg making a total of nearly 13,000 kg.

So, at the expense of this extra weight the capability exists to save 3000 kg for each shuttle visit to the station and 2000 kg for each OTV launch, plus the 2500 kg savings annually from station keeping requirements. These savings correspond to full length tether deployments, i.e., 65 km for shuttle and 150 km for the OTV. If these numbers are multiplied by the annual shuttle and OTV activity at the station as predicted by NASA mission model [2], the savings become more impressive. For example, the model calls for four shuttle visits a year to the station in the years 1991 to 1994. After each visit, the shuttle deorbit via the tether can raise the space station 70 km or so to its original orbit. The station altitude losses in these years (Fig. 23) are due to atmospheric drag and the tether lengths for shuttle deorbits, needed to offset these losses, are shown in Figure 24. The yearly propellant savings ranges from about 10,000 kg (1991) to 5000 kg (1994) with an annual average of 7000 kg (Fig. 27). Notice that the savings are split about equally between the shuttle OMS propellant and the space station keeping propellant. Since the tether lengths required (Fig. 24) are less than 65 km, each deorbit gives less than the 3000 kg savings mentioned earlier.

In 1995 the OTV-space station activity commences and the mission model predictions [12] for 1995 to 2000 gives an average of about 11 OTV missions each year resulting in propellant savings of 15,000 kg annually on the average and an added 25,000 kg savings annually from the shuttle visits that will occur (according to the

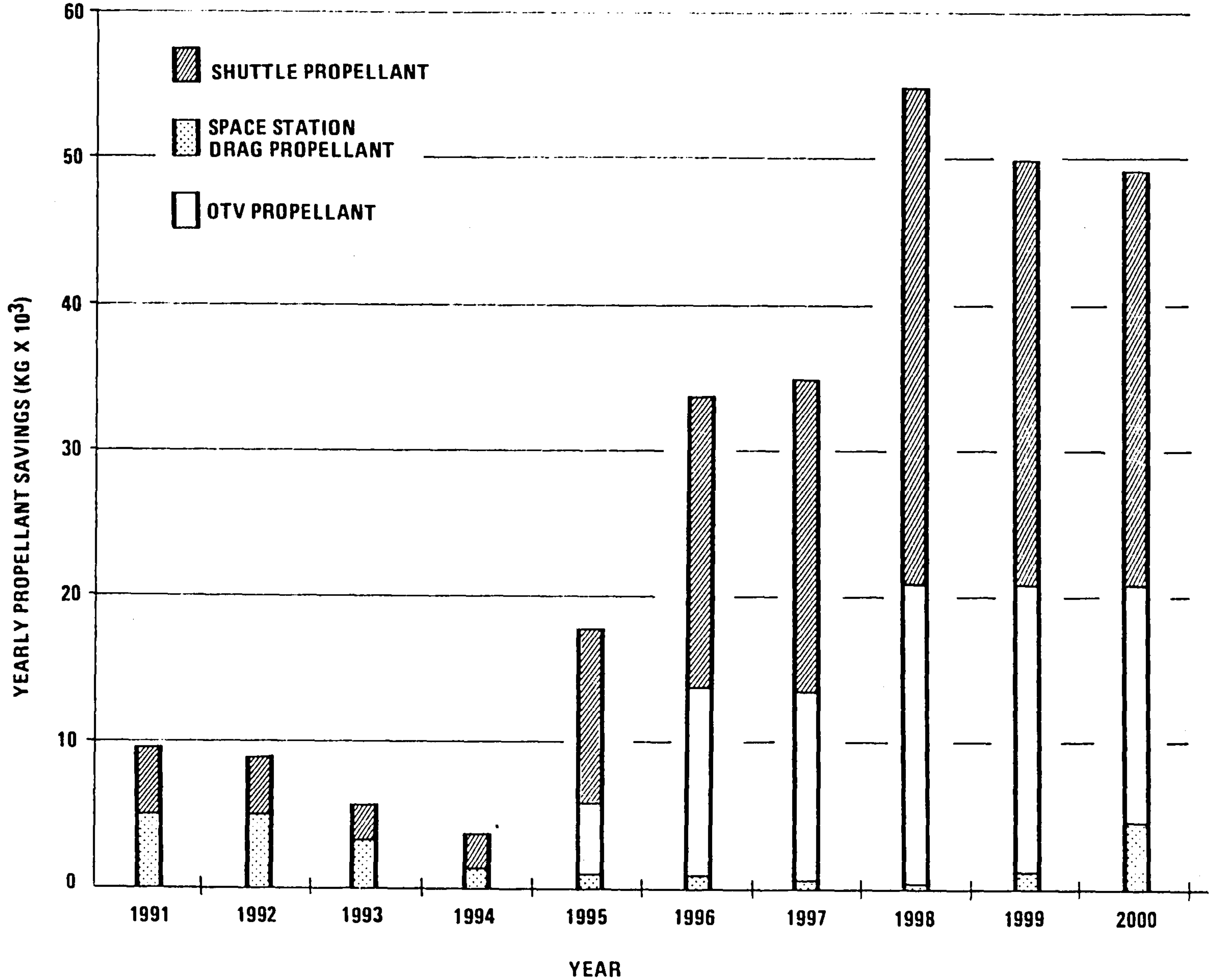


Figure 27. Tether benefits in terms of annual propellant savings.

mission model) and are used to boost the station back to its 500 km altitude after each OTV launch, and after drag losses which mainly occur in 1999 and 2000. Again, since not all of these flights involve a full length tether (65 km for shuttle and 150 km for OTV), the savings are not always 3000 kg and 2000 kg for each shuttle and OTV flight, respectively.

So, the propellant savings possible from the use of a tether to augment the shuttle and OTV operations at the space station, as outlined in the NASA mission model, for the years 1991 to 2000 are 7000 kg annually during the first four years and 40,000 kg annually during the remaining years. These are average values and they equate to an average of 26,000 kg annually over the full decade.

Using a space transportation cost of $4400 per kg gives an annual savings of $110 million. Or looking at the benefits from another standpoint, if the shuttle payload capacity is assumed to be 29,000 kg then the 26,000 kg savings amounts to an extra eight to nine shuttle flights available during the decade for jobs other than hauling propellants to the space station.

3.2 Tethers as Regulators of the Space Station Energy Budget

3.2.1 Electrodynamic Power/Thrust Generation (By William O. Nobles)

Electrodynamic tether systems can be considered for a variety of performance objectives. This includes (1) use of the tether to convert electrical power into thrust for orbit boosting, (2) the two-way conversion from electrical energy to orbital mechanical energy and vice-versa which provides a method to use the orbital energy as an energy storage medium, and (3) the use of the tether as an auxiliary power system which converts orbital mechanical energy into electrical energy in a single mode. The Concept E studied during Phase I was the dual mode energy storage concept.

The results from the recent studies indicated some fundamental difficulties with the dual mode energy storage concept. The most telling was the realization that the system would always require a full scale back up of conventional design for contingency situations. In addition, the mode switching transition of the tether, which must occur twice per orbit, will significantly reduce the operational fraction of the orbit period that can be devoted to either the thrusting or generating mode.

New insight gained from recent studies led to the realization that an electrodynamic tether auxiliary power system could provide a method to beneficially use the angular momentum available to be scavenged from the shuttle deorbit by converting it to electrical energy for use on the station.

Assumptions were made as to the practical sizing of such a system and a system design logic sequence developed. These assumptions and logic steps are described in the following paragraphs and the resulting tether described. It should be kept in mind that this is an example and that selecting other design requirements such as power level or overall system efficiency will result in variations on the tether design. The intent during this study has been to develop a design approach for the tether power system, and to apply it to develop a typical example.

3.2.1.1 System Design Requirements

The system design requirements selected for use in developing the concept are as follows:

1) Deliver 25 kW of conditioned power to the space station power bus on a full time duty cycle.

2) No more than 5 percent of system power to be dissipated in the tether.

3) Capable of operating at a reserve power level of up to 75 kW delivered to the space station bus. (Power loss in the tether will increase during reserve power operating intervals).

4) Tether angles with respect to the vertical are not to exceed 0.1 radian at maximum (75 kW) reserve power levels.

A mass of 250,000 kg was assumed for the space station and an end mass for the tether system of 500 kg.

3.2.1.2 Tether Power Dissipation

The fraction of total system power dissipated in the tether is determined by the ratio of tether resistance to the total resistance in the circuit. This includes the net resistance of the ionospheric current path, the contact resistances of the tether ends to the ionosphere, the resistance of the station power processing circuitry and the resistance of the tether.

This ratio has been designated K_T, with the defining relationship:

$$K_T = R_T/R \quad ,$$

where R_T is the resistance of the tether and R is the total resistance of the circuit.

Treating the tether power system as a direct current system, the value for K_T also defines the ratio of power in the tether to the total system power

$$K_T = P_T/P_S \quad ,$$

where P_T is the power dissipated in the tether and P_S is the total system power.

A simplified circuit for a tether of resistance R_T and induced voltage E_T in series with a load resistance R_L is shown in Figure 28. This plot shows the changing ratio of power in the load, P_L, to total system power, P_S, as K_T is varied. At the point where the values of R_T and R_L are equal, the value of K_T is 0.5 and R/R_T is 2. This is the impedance match condition for maximum power in the load for a given tether. This is shown by the lower curve P_L with maximum value of 0.25 at $R/R_T = 2$.

The value for P_S at this point is 0.5 of the short circuit power level. As the value of R/R_T is increased the fraction of the power dissipated in the tether, K_T, decreases. The design point used for this concept is a $K_T = 0.05$ or R/R_T of 20. At this point the system power has decreased to 0.1 of the value at the impedance match point ($R_T = R_L$), but the power in the load has only decreased to about 0.2 of the value at maximum. This plot illustrates the point that a given tether design can be operated at an increased power level above the selected design point. The penalty is an increased fraction of the system power will be dissipated in the tether.

Using the design criteria of 25 kW at a K_T of 0.5 and the reserve power level of 75 kW, the plot indicates that the point on the abscissa where the value of P_L has increased by a factor of 3 is at approximately 6.5 and the corresponding value of K_T at this point is 0.15. Operating at this reserve power level would cause 15 percent of the system power to be dissipated in the tether.

In order to be able to operate at both the design and reserve power levels, both the power conditioning circuits and the tether angle constraints must be designed for the reserve levels of 75 kW. These considerations will be applied at the appropriate points in the design process.

3.2.1.3 System Efficiency

Using a definition of system efficiency, ϵ, where

$$\epsilon = P_B/P_S \quad ,$$

P_B is the power delivered to the system bus, and the P_S is the total power in the system. P_S is equal to the rate of decrease in orbital mechanical energy due to the drag effect of the electrodynamic tether. Note that $P_L = P_B$ + parasitic power loss, where the parasitic power losses include the plasma contactors at each end of the tether, the efficiency loss in the power conditioning circuit and loss due to ionospheric heating.

The plot of these relationships against the K_T value is shown in Figure 29. In this figure efficiency of the power conditioning circuit is designated as "e," the resistance of the ionosphere plus contact resistance as R_I, and the induced voltage of the tether as E_T. The terms K_1 and K_2 are the respective power loss terms for the plasma contactors at the upper and lower ends of the tether. The tether is assumed to be deployed upward from the space station and that plasma contactors are used to provide a low resistance contact to the ionosphere. These contactors have been assumed to require power to operate as a linear function of the current in the system. As the tether voltage increases with a longer tether, the current will decrease for a given power level. This gives the family of lines for various voltage levels of the tether, E_T.

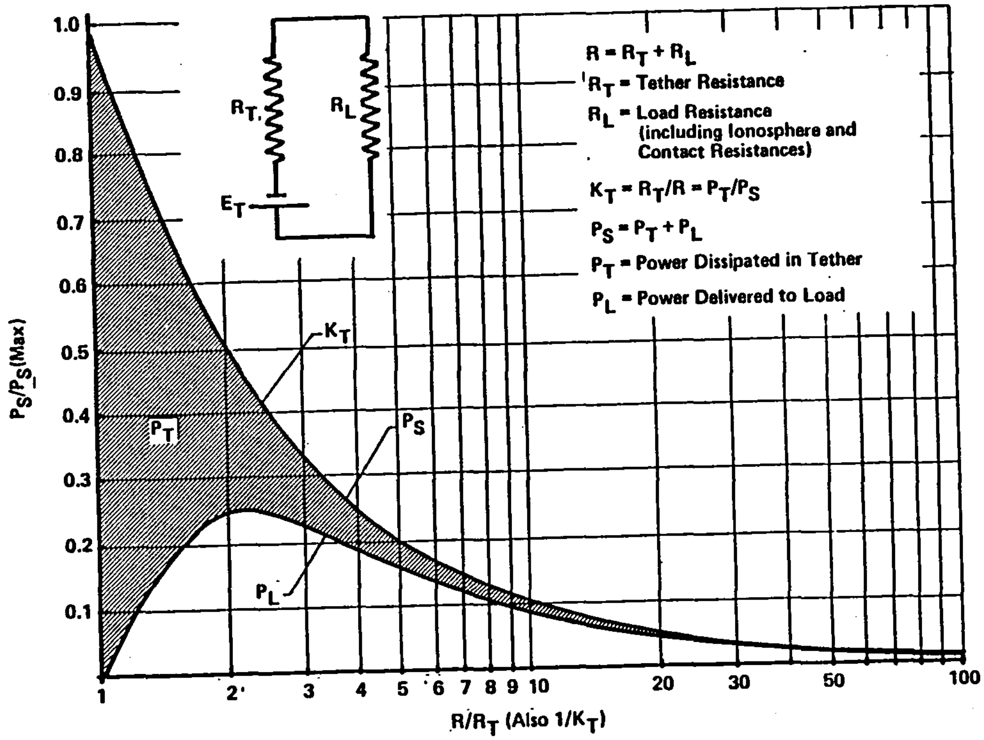


Figure 28. Load power as a function of K_T.

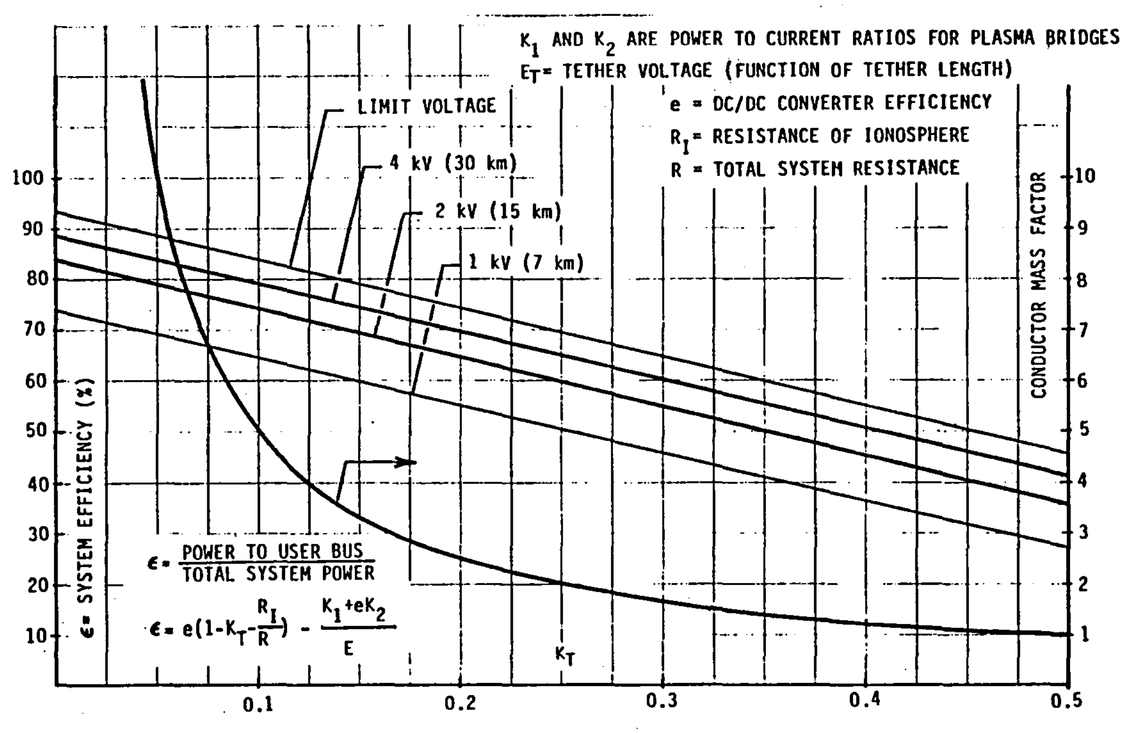


Figure 29. System efficiency as a function of K_T and tether voltage.

To produce this figure, values were assumed:

K_1 = 50 W/electron ampere,

K_2 = 150 W/ion ampere,

e = 94 percent .

The approximate tether lengths corresponding to the plotted values of E_T are based on an induced voltage of 133 V per kilometer of tether.

Figure 29 also shows a plot of the increase in conductor mass as a factor times the conductor mass required at a K_T of 0.5 (or the impedance match condition where $R_T = R_L$). As can be seen the tether mass required at $K_T = 0.05$ is 10 times the mass at $K_T = 0.5$.

A reasonable target range for the design power for this system is assumed to be between the two inner (heavy line) curves for E_T (2 to 4 kV). At a K_T of 0.05 the resulting system efficiency ϵ is in the range from 79 to 83 percent. At the reserve power level where $K_T = 0.15$ the resulting system efficiency range is 69 to 74 percent.

The important consideration to keep in mind here is that the significance of this system efficiency level is related to how the mechanical orbit energy is to be replaced. If it were to be replaced by a conventional propulsion system on the station, the specific impulse of the propellant used and the costs of transporting it to orbit drive the concept to keeping the system efficiency as high as practicable. On the other hand, if the orbital mechanical energy is replenished by a tethered de-orbit of the shuttle from space station, then the incentive to operate the system at high efficiency is significantly reduced because of the amount of mechanical orbital energy available from the shuttle deorbit operations.

If the system were to be operated in the mode where the orbital mechanical energy is replaced by a propulsion system, then the system efficiency relates to the amount of propellant required to replenish the orbital energy. For the reference space station this relationship is shown in Figure 30. The ordinate shows the mass of propellant required per kWh of energy delivered to the space station bus. The family of curves are drawn for a range of system efficiencies at 50 percent, 60 percent, 70 percent and 80 percent. The vertical bars indicate typical values of specific impulse, I_{sp}, for 3 types of propellant that have been considered for use on space station.

Another comparison which can be made is with an open cycle fuel cell where a typical conversion factor is 0.45 kg of oxygen/hydrogen fuel per kWh of electrical energy generated. The plot in Figure 30 shows that an equivalent fuel to energy ratio for the tether system is 0.13 kg/kWh for an 80 percent efficient tether system using hydrogen/oxygen as the propulsion system. This is improvement in the ratio of fuel to energy produced by a factor of 3.5. While this is an impressive factor, it is not really relevant as open cycle fuel cells are not under consideration for space station.

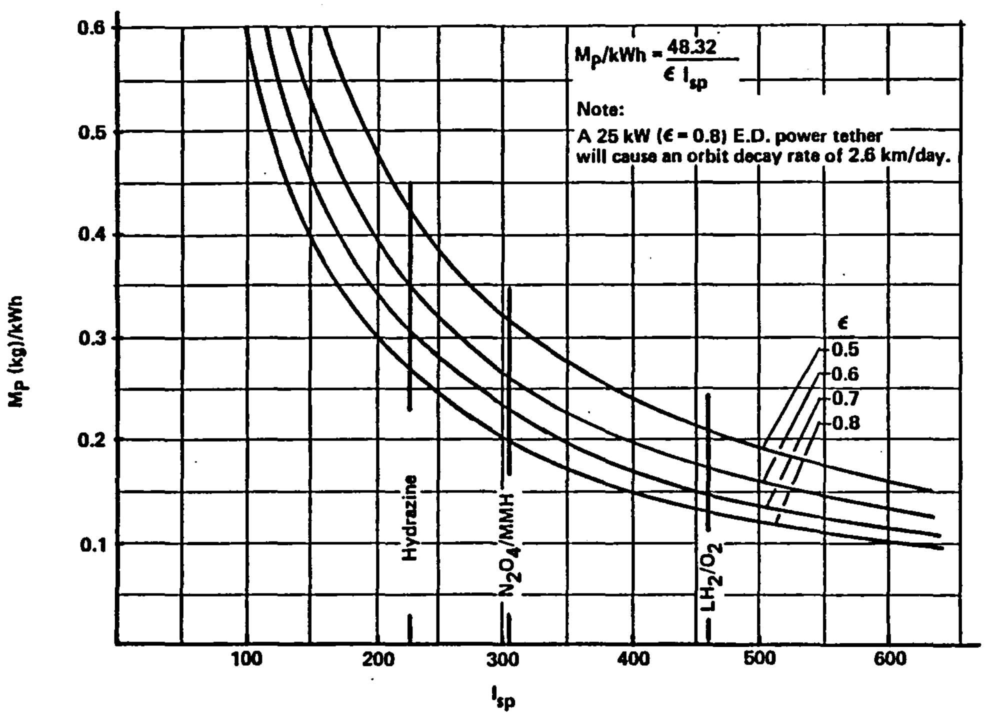


Figure 30. Reboost propellant required as a function of I_{sp}.

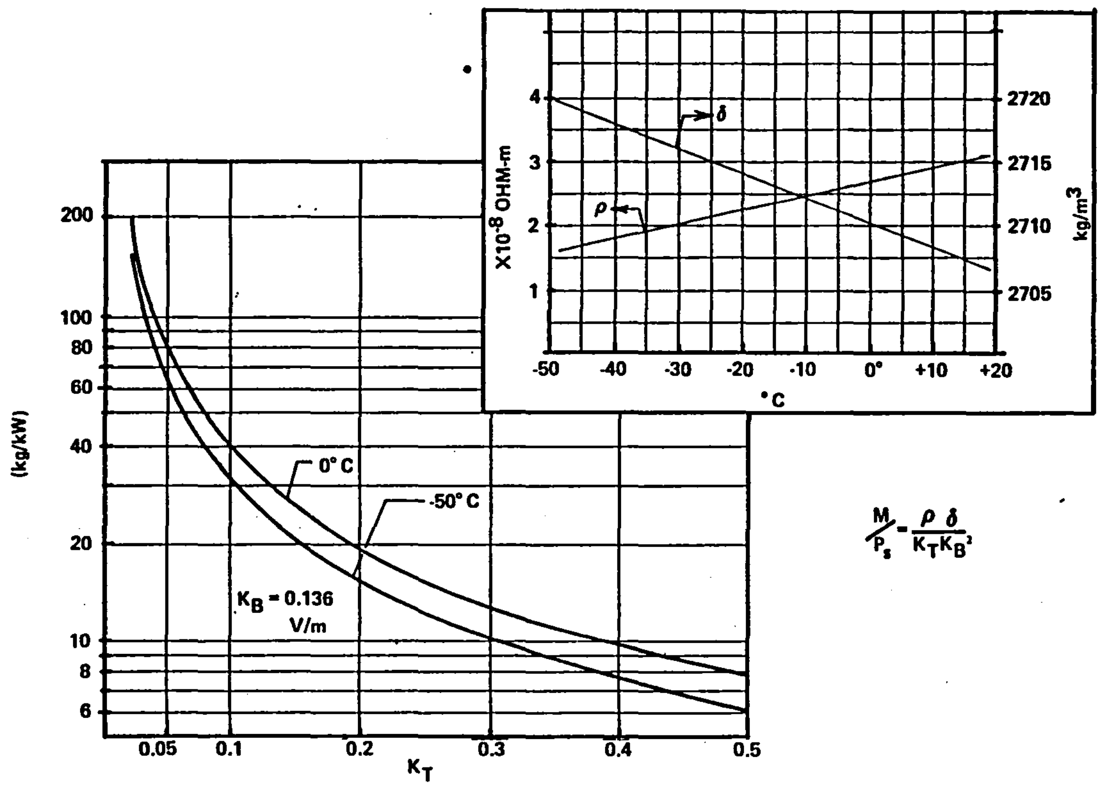


Figure 31. Mass to power relationship for an aluminum tether.

A more meaningful comparison would be to compare the amount of drag makeup propellant required to maintain the orbit altitude of a solar array sized to produce an average bus power of 25 kW. Using the fact that the baseline power system for the space station is sized at 100 kW, and that the integrated drag of the resulting articulated solar arrays and radiators contribute about 56 percent of the total space station drag, it can be estimated that increasing the baseline power system by 25 percent to 125 kW would cause a resulting increase in the drag of about 14 percent. Next, using an estimated average value of 5500 pounds per year for orbit maintenance propellant, this 14 percent increase in drag would require an additional 770 lb of propellant per year. This translates to 0.0016 kg of propellant per kWh of solar array electrical energy.

One additional piece of information is the conversion efficiency of orbital energy (measured in terms of orbit altitude) into electrical energy. This relationship is given on Figure 30. A tether system operating at 80 percent efficiency and a power delivered to the bus of 25 kW will cause the altitude of the space station to decrease by 2.6 km per day. This in turn translates into about 29 days of operation at this 25 kW power level for each full length (64 km) tether deorbit of the shuttle from space station. The corresponding time at 75 kW is 8.4 days.

The point to be made from the preceding paragraphs is that the justification for an electrodynamic tether auxiliary power system rests on the fact that the angular momentum to be converted into electrical energy is derived from the tether deorbit of shuttle. If the angular momentum were to be furnished by a propulsive reboost of the space station, it would require about 40 times the propellant required for an equivalent solar array power system. (Assuming use of a hydrazine propulsion system with an 80 percent efficient electrodynamic power tether system.)

3.2.1.4 System Power Levels

The system power levels (P_S) are given by dividing the bus power by the system efficiency at the selected operating point. Using a system efficiency of 80 percent at the design power level (25 kW) and an efficiency of 70 percent at the reserve power level (75 kW) gives the corresponding system power levels:

P_S (Design Level) = 31.25 kW

P_S (Reserve Level) = 107.14 kW

These are the relevant power levels that will be required for the subsequent steps of system design.

3.2.1.5 Conductor Mass

The expression for conductor mass as a function of system power is:

$$M/P_S = \rho\ \delta / K_T\ K_B^{\ 2} \quad ,$$

where

ρ = resistivity (Ohm meters)

δ = density (kg/m^3)

$K_T = R_T/R_S$

K_B = volts/unit length (m) of tether .

Evaluating the product of $\rho\delta$ over a wide range of temperatures for aluminum and copper, it is found that the value of the product for aluminum is slightly over one half that for copper over the temperature range. This indicates that for a given power level an aluminum tether will weigh only a little over half one made of copper. Based on this information, aluminum was selected as the preferred conductor material for this design concept.

The term K_B is a measure of the electrodynamically induced voltage generated per unit length of the tether. It depends primarily on the orbit altitude and inclination. The value for K_B varies significantly over an orbit depending on the position in orbit and on the position of the plane of the orbit with respect to the earth's tilted magnetic dipole field. The value of K_B ranges from a minimum of 120 V/km to a maximum of 219 V/km. A value of 136 V/km was selected for the plot in Figure 29. While not at the extreme low end of the range, this value will insure system operation at 80 percent efficiency or better most of the time. For the intervals when K_B drops below 136 V/km, the K_T will increase to 0.08 and the efficiency will drop to about 76 percent.

A plot of the ratio of conductor mass (for aluminum) per kWh as a function of K_T and for two temperature values is shown in Figure 31. Also shown in this same figure is a plot of the values of resistivity and density as a function of temperature for the selected aluminum conductor material.

Using this relationship, one can estimate the mass of tether required to operate at a K_T of 0.05 and a design power level P_S of 31.25 kW. Using an estimated operating temperature of 10°C gives a value of 82 kg/kW or a reference tether conductor mass of 82 x 31.25 = 2562 kg. This is called a reference mass because it is the mass that would be required if the tether were a solid conductor. To obtain the estimated total mass of the tether, one must add an allowance factor for the helical wind of an actual stranded cable and another for the insulation required. Using a factor of 1.07 for the increase due to helical winding effects and a factor of 1.03 for the insulation gives an estimated actual tether mass of 2824 kg.

This value of 2824 kg will be used to calculate tether length in the following sections. It should be kept in mind that this is an approximation based on estimated allowance factors. Any final design for the tether will require recalculation using more precisely determined values for these allowance factors.

3.2.1.6 Tether Length Determination

Once the mass of the tether and the outboard tethered satellite are known, the minimum length of tether required to maintain the tether angles within the specified range (less than 0.1 radian) can be determined. The need for this angle constraint is illustrated by Figure 32. Here two cases are shown. Both cases are operated at the same system power level which produces an electrodynamic drag force, F_D. This value for F_D is the same for both cases. In case 1 a constraint has been applied to keep the tether angle θ_1 less than 0.1 r. This means that the tension force T_1 in the tether must be greater than 10 F_D. This in turn will reduce the off-set dimension of a tension alignment boom required to keep the tension force aligned with the space station center-of-mass. For Case 1 this alignment offset is shown as 30 ft.

For Case 2 the tether angle constraint has been relaxed to 0.4 r. Now the tension force, T_2, need only be 2.5 F_D. However, in order to keep the tension force aligned to the space station center-of-mass an off-set of 126 ft is required. The final selection of an angle criteria for the tether needs to be determined by more detailed trade studies. For the purpose of developing this design concept, an angle criteria of 0.1 r was chosen as a reasonable criteria to be used.

The relationship of the tether tension, T; the mass of the station, M_S; the total mass of the system, M; the system power level, P; the angle of the tether at the station, θ_S; and the orbital velocity, V, is shown in Figure 33.

Using the values:

M_s = 250,000 kg

M = (250,000 + 2824 + 500) kg = 253,124 kg

P = 107 kW

θ_S = 0.1 r

V = 7613 m/sec .

The resulting value for the tension is:

T = 139 Newtons .

Using this value for the tension, the tether length can be calculated. The relationship is given by:

$$T = (3\,\mu/R_o^3)\,(M_1\,M_2/M_1 + M_2)\,L \quad ,$$

where

T = tether tension (139 N)

$\mu = 3.992 \times 10^{14}$ N M^2/kg

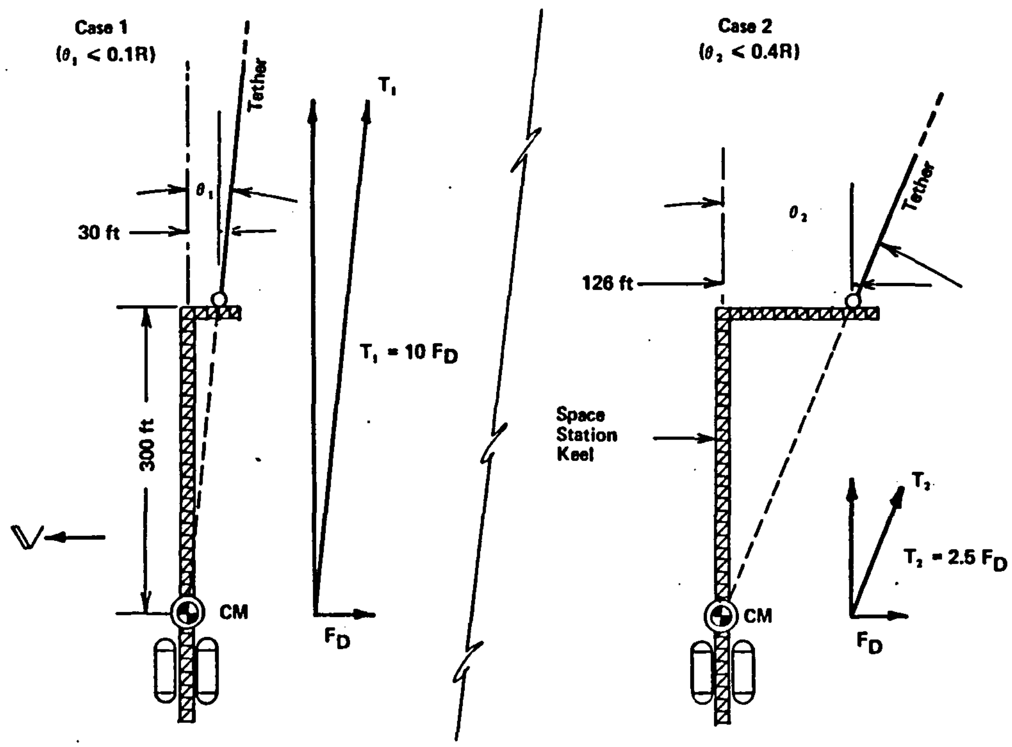
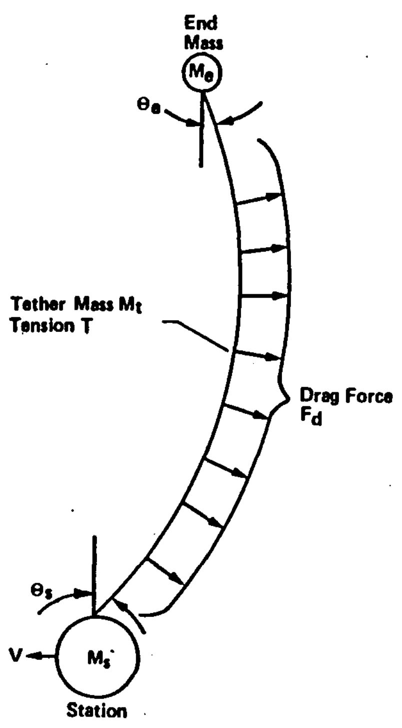


Figure 32. Tether tension constraint.



- Total Mass $M = M_e + M_t + M_s$
- In Equilibrium Condition the Drag Force F_d Must Act on Each Element in Proportion to its Fraction of Total Mass.

  $F_d = F_e + F_t + F_s$

  Using the Relation $F_d = \frac{P}{V}$

  $F_e = \frac{M_e}{M}\frac{P}{V}$; $F_t = \frac{M_t}{M}\frac{P}{V}$; $F_s = \frac{M_s}{M}\frac{P}{V}$

- Note That the Drag Forces on the End Mass and Station are Applied by the Horizontal Component of the Tether Tension "T".

  $F_e = T \text{ Sine } \Theta_e$ and $F_s = T \text{ Sine } \Theta_s$

  $\Theta_e = \text{Sine}^{-1} \frac{F_e}{T}$ $\quad \Theta_s = \text{Sine}^{-1} \frac{F_s}{T}$

- Substituting for F_e and F_s, and Using Small Angle Limits

  $\Theta_e = \frac{M_e}{M}\frac{P}{VT}$ or $\frac{M_e}{M}\frac{F_d}{T}$

  $\Theta_s = \frac{M_s}{M}\frac{P}{VT}$ or $\frac{M_s}{M}\frac{F_d}{T}$

- Solving for T

  $T = \frac{M_S}{M}\frac{P}{V\Theta_S}$

Figure 33. Tether angle relationships.

R_o = orbit radius (6.871×10^6 m)

M_2 = mass of space station (250,000 kg)

M_1 = sum of end mass + tether mass/2, 500 + 2824/2 = 1912 kg

L = minimum tether length required (m) .

Solving for L = 19.8 km as a minimum required length. For the design concept a length of 20 km has been selected.

3.2.1.7 Tether Voltage Considerations

The electromotively induced voltage in the tether, E_T, is given by the vector scalar product:

$$E_T = B \times V \cdot L \quad ,$$

where

B = geomagnetic field vector (Tesla)

V = orbit velocity - earth rotation component (m/sec)

L = tether length (m) .

A useful value is the voltage per unit length of tether which is given by E_T/L. This is the same as the term K_B used in Figure 31. The variation of E_T/L is a complicated function of altitude, inclination, position in orbit, and the position of the orbit plane with respect to the geomagnetic field. For purpose of the concept development, the values have been calculated at extremes to define the maximum to minimum range of induced voltages. These calculations were based on a tilted offset dipole model of the earth's field.

$$E_T/L = 113 \text{ V/km (minimum)}$$

$$= 207 \text{ V/km (maximum)} \quad .$$

These values apply when the tether is in a vertical orientation and straight. In the actual case as power is generated by the tether, it will assume a bowed configuration (Fig. 33) which will reduce the projected vertical length of the tether, and thus, the voltage. Effectively, it will appear as though the field strength is decreased with increasing power levels.

In order to make allowance for this tether bowing effect, the voltage range will be derated by a factor of 0.95. This is an estimated derating value and is used here primarily as a place holder in the system design logic.

Using these derated values, the minimum, median and maximum voltages for the 20 km tether are:

E_T (min) = 2147 V

E_T (median) = 3040 V

E_T (max) = 3933 V .

3.2.1.8 Current Considerations

In order to operate the system at a constant power level, the input impedance of the power processing circuit will need to be varied to maintain the system current in a reciprocal relationship to the changing voltage of the tether.

For the specified levels of design power (25 kW) and reserve power (75 kW), the corresponding levels of system power are 31.25 kW and 107.14 kW (see section 3.2.1.4).

The current range for design level is then:

I (max) = 14.6 A

I (median) = 10.3 A

I (min) = 8.0 A .

The current range for reserve level is:

I (max) = 49.9 A

I (median) = 35.2 A

I (min) = 27.2 A .

It should be noted that if the system is operated at a constant power level, the drag force on the tether caused by power generation is constant and the dynamics of the tether should stabilize into an equilibrium configuration for each selected level of power operation.

Unfortunately this situation is complicated by the presence of forces on the tether which are out of the orbit plane. This will be discussed in more detail in section 3.2.1.12.

An approach to the design of the power processing circuits was developed for the electrodynamic tether concept studied in Phase I. This concept seems viable for use on this concept as well and will not be repeated here. The concept uses solid state circuitry based on a series resonant inverter topology currently under development. The system is built up of modular units to allow sizing to any particular requirement and for overall system reliability. The requirement to operate at the reserve power level for the system means that the power capacity of the processing circuitry must be proportionately increased over the design level. This would be accommodated by an increased number of modules available to be bought on line when the system power level is to be increased above the design level of 25 kW.

The operating efficiency of these power processing units has been estimated at 94 percent and was the basis for use of this efficiency value in the calculation of the overall system efficiency (see Section 3.2.1.3).

3.2.1.9 Electrical Potential Considerations

In order to design the necessary electrical insulation for the system, the electrical potential levels at various locations must be understood. These potential levels are mapped over the tether system in Figure 34.

The tether is indicated as a series of distributed voltages and resistances which sum to the values V_T and R_T. The next circuit element is the space station power processing system with a voltage drop V_S and impedance R_S. Next is the space station plasma contactor with voltage drop V_{C2} and impedance R_{C2}. Next is the ionospheric circuit path with voltage drop V_I and impedance R_I. Finally, to complete the circuit path, is the tether end plasma contactor with voltage drop V_{C1} and impedance R_{C1}. The node points in the circuit are at the ends of the tether and the interface between the station power processor and the plasma contactor. The ionosphere plasma potential is identified as V_o and is shown as the reference potential on the potential plot in the lower portion of Figure 34. Referring back to section 3.2.1.2 and Figure 28, the load resistance R_L used reappears in this circuit where

$$R_L = R_S + R_{C2} + R_I + R_{C1} \quad .$$

The voltages around the circuit must sum to zero.

$$V_T + V_S + V_{C2} + V_I + V_{C1} = 0 \quad .$$

The potential plot is shown for four cases of system operation.

Case 1 is with the power converter open circuited. Here the space station will rise to almost the full tether potential with respect to the ionosphere. This is based on the assumption that the plasma contactor at the top end of the tether will keep the tether potential close to V_o at the node point.

Case 2 is the best approximation to the design case. The potential at the station end drops by the amount IR_T and the voltage drop across the power conditioning circuit is near maximum. The point here is that for low values of K_T (i.e., 0.05) the potential difference across the tether insulation at the station node will essentially be at the full tether potential.

Case 3 shows the situation where $K_T = 0.5$, or the load resistance, R_L, is equal to R_T. This is the impedance match condition where one-half of the system power is dissipated in the tether. Here the maximum potential drop across the insulation is a little less than half the full tether potential because of the IR drop in the tether itself.

Case 4 is shown for completeness and illustrates the condition that would exist if the power processing circuit were completely shorted.

The conclusion here is that the system must be insulated to withstand the maximum voltage generated by the tether. This includes the space station installation and the station end of the tether. The potential drop across the tether insulation will decrease linearly with distance from the station. This would indicate that the tether insulation thickness could be varied along the length of the tether with the greatest thickness on the inboard end.

3.2.1.10 Tether Construction

A proposed approach to construction of the tether is shown in Figure 35. A bunch stranding concept is used to permit the required resolution in adjusting the conductor cross section to the desired value and to provide flexibility in the cable.

An inner wrap of polished foil is shown as a reflective surface to provide low absorptivity to radiation. A metallic foil was used to avoid any differential voltages between this layer and the tether conductor. Further thermal analyses may indicate that this layer is not required.

The outer insulating portion is made up of multiple wraps of a Kapton film tape which is coated on both sides with a heat sealable FEP Teflon. This construction method will permit the long continuous application of insulation by a wrapping process during manufacture and a graded thickness capability by the number of wraps applied. The insulation will be heat fused after application. The Teflon also provides an outer surface with good resistance to erosion from residual atmosphere effects (e.g. atomic oxygen).

Using a rated breakdown voltage of 3kV per layer, it has been assumed that two layers of the tape wrap would be adequate over most of the tether length and with the inboard region going to three or four layers.

This construction method would also be compatible with on orbit repair in event the insulation were damaged by handling or by micrometeorite impact.

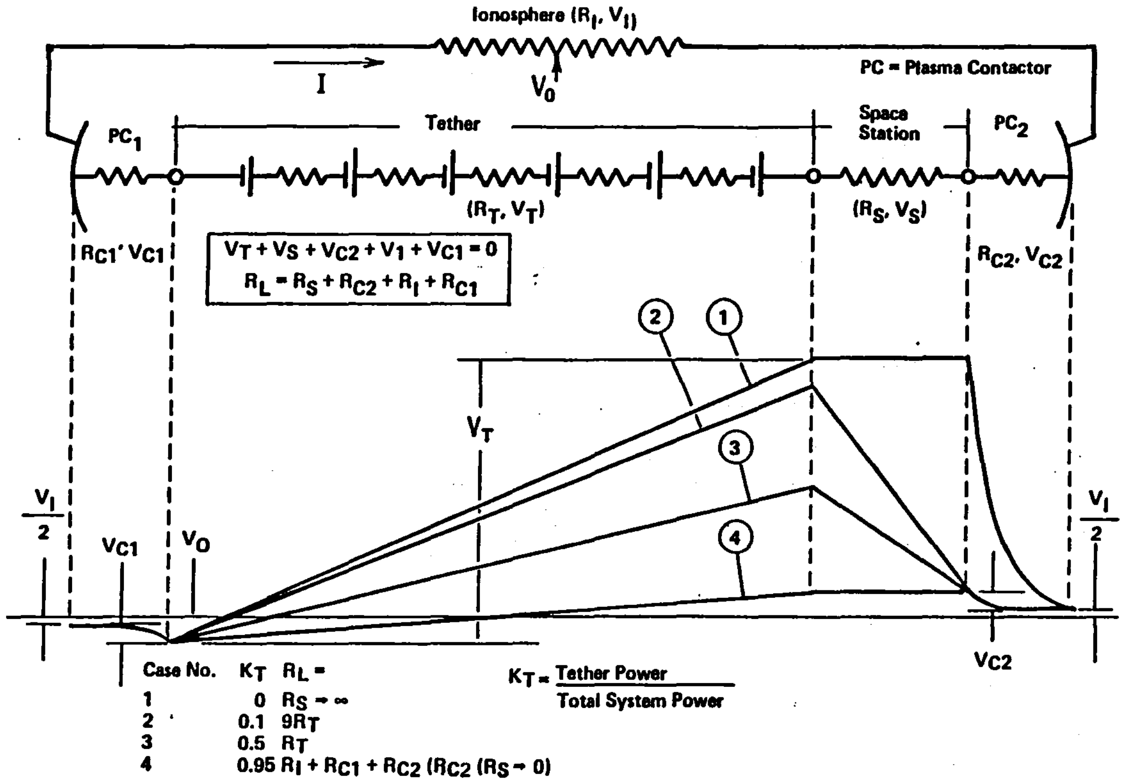


Figure 34. Potential map for an electrodynamic tether system.

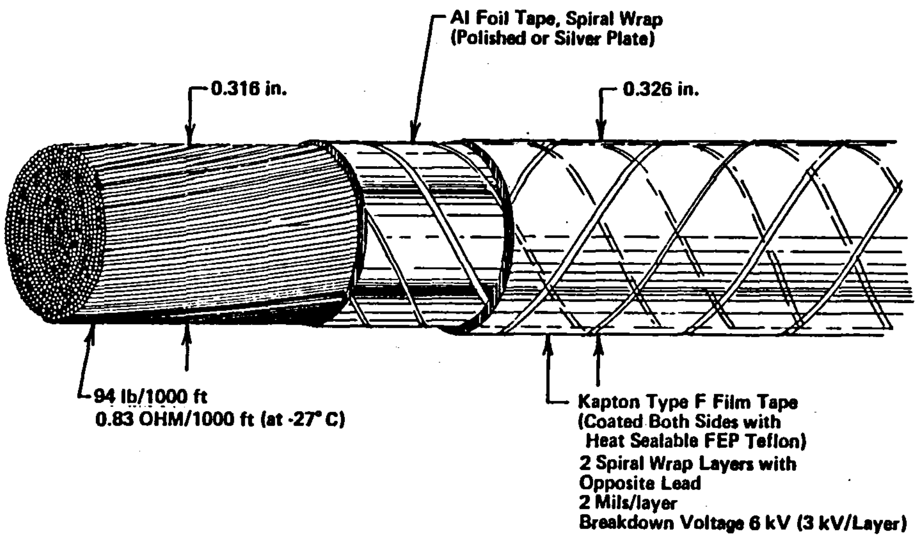


Figure 35. Tether construction using a bunch stranding.

3.2.1.11 Tether Temperature

Using values of absorptivity of 0.15 and emissivity of 0.85 for the tether surfaces gives equilibrium temperatures for the eclipse and sunside temperatures for the design power (25 kW) of:

Eclipse = - 80°C

Sun Side = - 40°C .

And for the reserve level power (75 kW):

Eclipse = -12°C

Sun Side = +8°C .

The actual operating temperatures should range between these extremes during an orbit. No analysis has been performed on the effects of this temperature cycling on the proposed construction method.

Further study may indicate that higher operating temperatures would be preferable for materials considerations. This should be achievable by designing for increased absorptivity and decreased emissivity values for the tether surface.

Recall that for the original estimate of tether conductor mass a temperature of +10°C was used. With the temperature range for the design level power identified above (-40 to -80°C), the tether is over designed and the K_T actually achieved should be less than 0.05. However, for the reserve power case (+8 to -12°C), the design should be near optimum.

3.2.1.12 Cross Track Libration Effects

Due to the 28.5 deg inclination of the space station orbit, the tether cuts across the magnetic field lines at other than the optimum 90 deg angle when crossing the equator. This effect is further accentuated by the 11 deg tilt of the earth's dipole field with respect to the earth's axis. The angle between the orbital velocity vector and the horizontal component of the magnetic field vector ranges over 90 ± 28.5 ± 11 deg. The 28.5 deg component varies through a cycle per orbit and the 11 deg component through a cycle per earth rotation.

A time plot of the effects of this angle variation on the magnitude of the cross track forces on the tether is shown in Figure 36.

In order to generate a system power of 31.25 kW (25 kW design level), the in-plane component of the electromagnetic drag force on the tether must be 4.1 N. The out-of-plane or cross track component will vary as the plot shown on Figure 36. The effect of this forcing function will be to drive the cross track libration of the tether.

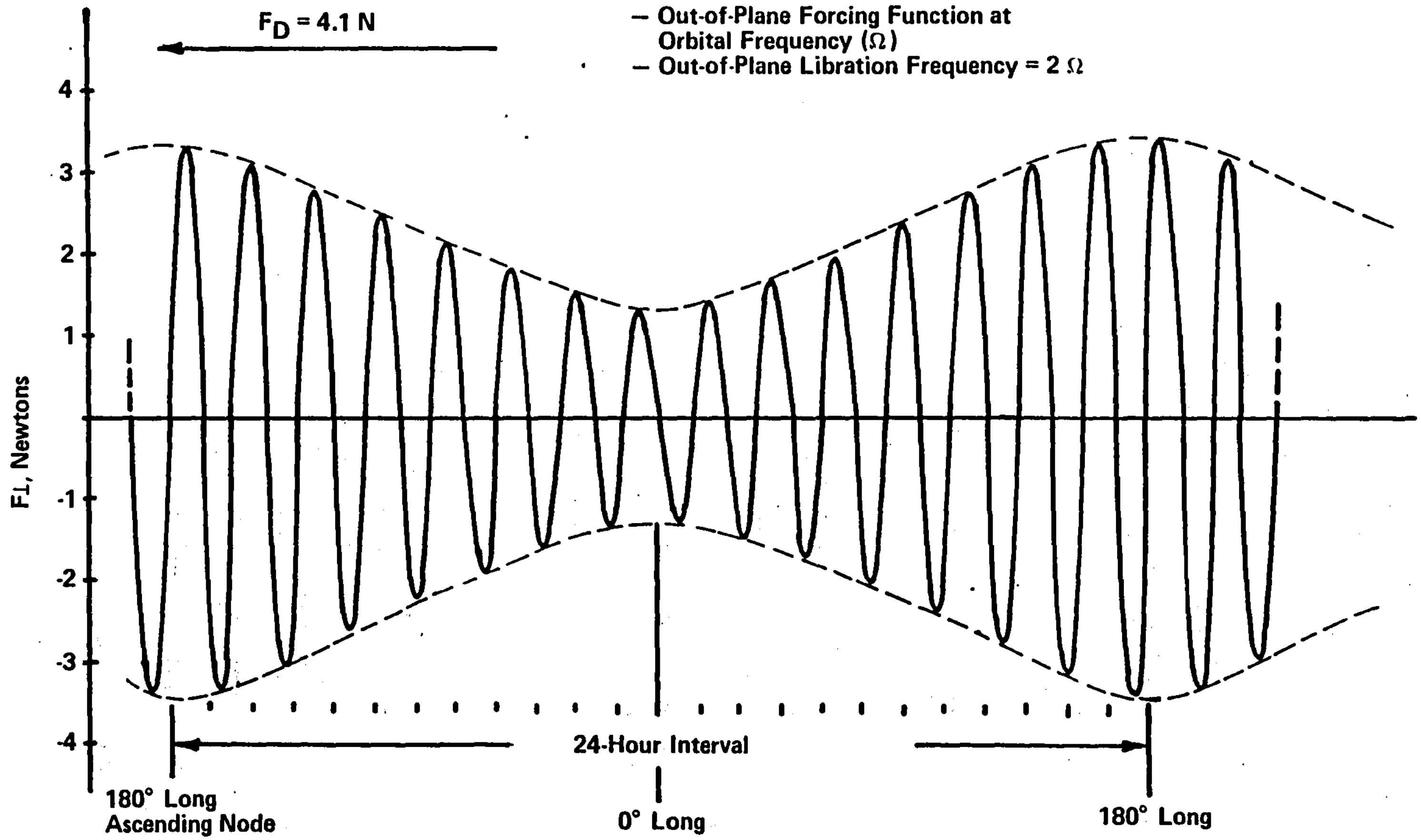


Figure 36. Variation with time for the cross track component of tether force.

The natural frequency for tether libration in the cross track mode is two times the orbit frequency while the forcing function varies at the orbit frequency. The resulting dynamics of the tether have not been analyzed. The initial assumption has been made that the angular displacement of the tether from vertical would be in phase with the forcing function which would indicate that the tether would be vertical at the high latitude portion of the orbit. If this assumption is confirmed by further analysis, this is a fortuitous development since the cross track libration angles in combination with the magnetic field dip angle have an exaggerated effect on the tether voltage developed at high geomagnetic latitudes. For the most extreme case when the Earth dipole is tilted 11 deg toward the orbit, the geomagnetic dip angle is almost 60 deg down from the horizontal. Under these extreme dip angle conditions, a cross track libration angle of 6 deg would cause an induced voltage variation factor of 1.15 to 0.81.

This area of cross track libration is recommended as an area for further study and simulation. The dynamic behavior of the tether is a result of interaction of the geomagnetic field, the tether dynamics and the power generated. High fidelity computer simulations are a necessary tool to scope the integrated effects of these forces on the tether. A capability for extended run times, which integrate the effects over multiple Earth rotations, will probably be required.

3.2.1.13 Tether System Characteristics

The tether characteristics resulting from the concept design development are summarized in Table 6.

TABLE 6. CONCEPT DESIGN DEVELOPMENT TETHER CHARACTERISTICS

Conductor material: Bunch stranded aluminum wire cable
Insulation: Multiple layers of heat sealable Type F Kapton tape
Length: 20 km
Conductor mass: 2741 kg
Total tether mass: 2824 kg
Mass/Length: 141.2 kg/km
Conductor diameter: 0.78 cm
Tether diameter: 0.83 cm
Tether voltage range: 2147 to 3933 V
Current range at design power: 8.0 to 14.6 A
Current range at reserve power: 27.2 to 49.9 A
Temperature range at design power: -40 to -80°C
Temperature range at reserve power: +8 to -12°C
Tension at space station end: 139 N (31 lbs)
g level induced on station: 6×10^{-5} g
Tether end mass: 500 kg
Space station mass: 250,000 kg
Tether reel size: Length 2 m; core diameter 0.5 m; outside diameter 1.1 m.

3.2.2 Electrodynamic Power Generation Coupled with Tethered Orbiter Deployment

(By J. Harrison)

3.2.2.1 Introduction

Power generation using an electrodynamic tether lowers the space station to unacceptable altitudes making periodic boosts necessary. One way of accomplishing these boosts is via a shuttle deployment from the station using a tether following the schemes outlined already in section 3.1.1.2.

This electrodynamic tether-shuttle combination is analogous to the OTV-shuttle combination discussed earlier where the angular momentum exchange principle is used to see-saw the space station up and down, e.g., up using a tether deployment of shuttle and down from use of an electrodynamic tether to generate station power.

3.2.2.2 Electrodynamic Tether-Shuttle Tether Deorbit Combination

The generation of 25 kW of electrical power from a 20 km electrodynamic tether deployed upwards from the space station will decrease the station altitude 2.6 km per day, averaged over a year, or about 80 km each month. This loss in altitude must be overcome by subsequent reboosts.

The nominal station altitude is 500 km with excursions permitted up to 575 km and down to 460 km giving a total range of 115 km. So, a monthly boost of 70 to 80 km seems necessary if the station is to be kept near its nominal altitude.

The customary way of achieving these boosts is to use the station propulsion system and the propellant requirements per kWh are in Figure 37. If we assume that the electrodynamic tether delivers 25 kW, that the overall system efficiency (ε) is 80 percent, and that the station propulsion system has an I_{sp} of 230 sec, then from Figure 37 the propellant requirement is 0.275 kg/kWh. If the tether operates continuously for a year (219,000 kWh) the propellant required for these periodic boosts is 60,000 kg.

Of course, these periodic boosts can also be accomplished by deorbiting shuttles from the station, just as was proposed earlier to handle the station altitude losses due to atmospheric drag and OTV launches. The same methods and tether system (weight is 13,000 kg) can be used and, as already stated, each shuttle deorbit using a full length tether, e.g., 65 km, will give about a 70 km boost to the station.

According to the NASA mission model [2], there will be sufficient shuttle traffic at the space station in the 1990's to accommodate these monthly boost requirements.

So, by making use of the tether to deorbit shuttles the 60,000 kg of propellant needed annually for the station propulsion system can be saved. Furthermore, the 3000 kg of OMS propellant normally needed for a shuttle deorbit can be saved — since monthly deorbits will occur this amounts to 36,000 kg annually. The total annual savings, therefore, is 96,000 kg.

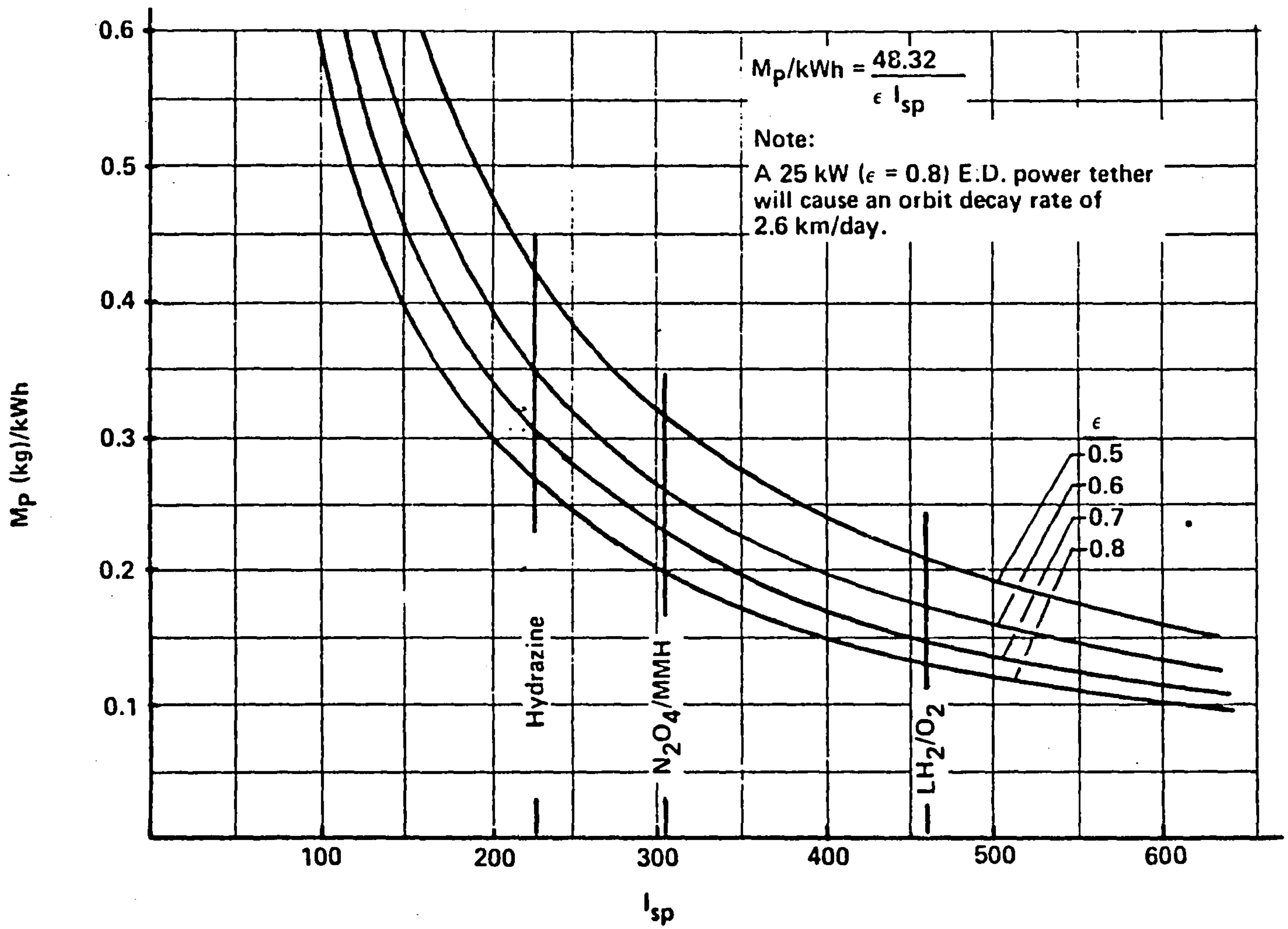


Figure 37. Propulsion system and propellant requirements.

3.3 Tethered Platforms as a Solution to Incompatibility of Space Station Functions

(By K. Kroll)

3.3.1 Tethered Platform Characteristics

In the previous sections of this report, the tether applications talked about could be used on a space station without adversely affecting or only temporarily affecting functions currently planned for the space station proper. On the other hand the use of a tether for the deployment of platforms will have a definite and more permanent impacts on the space station. To justify the expense and effort involved in minimizing these impacts, these tethered platforms will require some substantial advantages. The basis for these advantages can be found in the characteristics of tethered platforms, which are distributed, like beads on a string, along a gravity gradient stabilized tether oriented along the Earth's local vertical.

In integrating the various functions of a space station system, a fundamental problem has been to balance the requirement for compatiblity of the desired functions and accessibility to the space station support facilities. The result has been to split these functions between the space station proper and free-flying platforms. Tethered platforms can be viewed as an intermediate location for these functions. Tethered platforms have the free-flyer advantage of remote location to reduce functional incompatibility; however, tether platforms do not have to worry about maintaining active control of a free-flying formation and have far greater access to the facilities of the space station proper. The tether, as a structure, fixes the position of the platform relative to the space station, while providing a guide and reaction surface for a device which crawls along the tether. The use of such a crawler should allow easier logistics and manned access for the tethered platform than a free-flying platform. Utilities such as power and communications may be routed through the tether itself. Orbital maintenance can be performed at one location for the entire tethered system. It is estimated that 20 percent of the weight and 50 percent of the cost of free-flying platforms can be avoided with tethered platforms (Fig. 21). Compared to platforms on the space station proper, the use of tethered platforms will allow the space station to expand or change configuration much more readily. A tethered platform shares with a gravity gradient stabilized space station the attribute of naturally having the Earth and space sensors oriented in the proper respect to the Earth.

One of the primary reasons for having tethered science and applications platforms is the separation provided from hazards and other detrimental factors. A constant hazard will be the contamination of sensitive surfaces like waste and water dumps, attitude decontrol thruster, and reboost firings. Separation using tethers is implemented in three ways. First, the contamination source is moved away from the space station where the sensitive surfaces are presumed to exist. Second, the sensitive surfaces are tethered away from the space station where the contamination source is presumed to exist. Third, the tether is used to separate the tethered platforms that have sensitive surfaces from those that have contamination sources. The first two cases will be prevalent when only a very few platforms are in the tethered system. Consideration can be given for the strength of the contamination source and the sensitivity of the surface. The most sensitive surfaces may be tethered in one direction from the space station, while the strongest contamination source is tethered in the other direction. Thus a gradation of surface contamination sensitivity and source strength can be provided.

A constant detrimental factor for many functions will be the vibration resulting from the conduct of other functions. A tether can act as a low bypass filter in the lateral direction; however, the characteristics of a tether in the axial direction currently are not known. However, tether materials development, such as weaves with inherent damping, may result in less vibration transmission in the axial direction. Therefore, a tethered platform can expect at least some reduction in the vibration transmitted from other functions. Care must be taken to insure that disturbances originating with the tethered system are minimized. Such disturbances could be the sudden shift in system center of gravity due to docking or release of vehicles, libration of the tether, elliptical orbits, and expansion/contraction in the tether due to changes in temperature with day/night transitions.

Another reason to separate functions is to avoid the emissions of other functions. A large radiation source may be separated for the safety of men or to avoid interference to other functions. Alternatively, sensitive functions, such as sensing operations or communications, can be separated from the sources of interference, which could be electromagnetic or gravitational in nature.

Potentially catastrophic, but unlikely, hazards would be a collision with a free-flying vehicle or an explosion. The exact circumstances and results of these hazards are hard to predict. However, a tether can separate the most likely location for a collision, such as near a docking module, away from men and valuable equipment. If an explosion should occur on a tethered platform the separation provided by a tether would reduce the number of fragments hitting other hardware. If sufficiently catastrophic, either of these hazards would result in the disruption of the tether system, but it is preferable to sacrifice the integrity tether system for other more valuable considerations, such as the safety of the crew.

As a large structure, a tether allows for the location of functions remote from the space station proper. The primary advantage of remote locations is the ability to disperse functions to reduce crowding. This allows the number of platforms or modules to be increased. The actual number of functions on the space station will probably not be increased, but the specialization of each platform may. Different countries or companies could have their own platform increasing the confidentiality of their work. Each platform could be specialized to a particular application, thus reducing interference among applications which can occur on multi-application platforms. The reduction in crowding would also increase the angular field of view for those functions where interaction with the outside is important. Similarly, approaches and departures for proximity operations would be clearer, except along the vertical which is occupied by the tether. Also, the reduction in crowding will help to prevent awkward configurations that result from adding hardware to an already crowded location, such as the space station proper.

The ability to have locations remote from the space station proper will allow more than one location to be used simultaneously or sequentially. These multiple locations could be used for the same function, measuring or using different environments and getting different view angles. If these multiple locations are used simultaneously, some of the time dependence of free-flying platforms can be avoided. In addition, multiple locations can also be used for complementary functions. Examples are a lens and a sensor or an active environmental stimulation with passive observation at different locations.

If something off the space station is of interest, a remote location can be used to probe an otherwise inaccessible region. There are various reasons why a region may be considered inaccessible. The performance penalty to the space station or space shuttle may be too great for either to operate in that region. A closely related concern is the safety of operating in these regions, since any breakdown in equipment or unknown environmental anomalies could be disastrous. The location may pose a direct hazard to people or equipment. Examples of these hazards would be a higher probability of collision with debris or the natural radiation present in the Van Allen belt.

Remote locations offer other advantages. The distance to an area being observed can be reduced to increase resolution. Similarly, a remote location can be used to get past a region that interferes with observation. A related example from World War One was the tethering from a dirigible of a observer below the cloud layer. The tether can release a free-flyer at a desired location, assuming the velocity change is not the important parameter. A tether can also access a remote environment that is different from the one around the space station.

As described in previous sections, a fundamental property of tethers is that any location off the system center of gravity will have a velocity different from that required for an orbit along the same path. This will cause any object released from the tether to separate from the rest of the tether system. This characteristic provides the ability to dispose of a platform when advantageous. Of course, if the platform is not at the end of the tether, prior special arrangements must be made to insure disposal of only the desired platform. There are a couple of reasons for disposing of a platform. First, a platform may be disposed of to avoid the effects of an extremely hazardous situation, such as an explosion, assuming it can be discovered in time. In this case, disposal would extend the separation properties of tethered platforms. Second, a platform may be disposed of because it has performed its function, but it is not worth retrieving for reasons of remote location, safety, or damage sustained. Platforms that could fit this description are atmospheric probes and a nuclear reactor.

A tether can maintain its shape and attitude relative to the Earth because a gravity type force, which is proportional to distance from the system center of gravity along the Earth radial, produces a tension away from the system center of gravity. For a static vertical tether, this gravity has an acceleration equal to 3.81×10^{-4} g per kilometer of tether length from the tether system center of gravity. This gravity can also be used by the tethered platforms to facilitate their functions, while maintaining microgravity at the center of gravity. An acceleration as low as 10^{-8} g is available at the center of gravity [8].

What follows is a description of different types of tethered platforms that use the above characteristics. Tethered propellant depots have been studied in a substantial amount of detail; however, most applications have not been studied in such detail. So the amount written about each item does not necessarily reflect the relative usefulness of each platform type. In addition, some of the platform applications are purely speculative at this time. The most important thing to draw from a description of these platforms is how a tether can facilitate each application.

3.3.2 Propellant Resupply Depot

A propellant resupply depot can use several characteristics fo tethered platforms. The low gravity present off the center of gravity can be used to separate and position the gas and liquid phases, making fluid transfer easier. The positioning of the different phases is called fluid settling. The separation of the propellant depot from the space station and other tether platforms will reduce the contaminating effect that leaked or vented propellant will have on any sensitive surfaces. The reduced crowding inherent in the remote location of the tethered depot will allow the placement of a hanger at the tethered depot much more readily than on the space station proper. Finally, the tethered depot can be disposed of if an imminent catastrophic emergency, such as an overpressure, is detected early enough.

The advantages to fluid transfer of settling fluid using a tether can be compared to using zero gravity techniques, where the distribution of the liquid and gas is not well known [9]. In performing fluid transfer, the object is to transfer only the liquid; therefore, a means must be developed to acquire only the liquid for transfer. As on the Earth, a settled liquid can have the liquid positioned directly over the supply tank outlet, insuring it is the only phase transferred. The zero gravity techniques would be to use a bladder to separate the two phases or to use a screen which would block gas from going into the outlet. For some propellants these techniques work very well, but for other propellants, especially cryogens, the use of bladders is infeasible or there is some uncertainty in the performance of screens. When filling a nonvented receiver tank, any gas in the tank or boiloff produced during the fill will be compressed, raising the pressure. The fluid transfer can be slowed or stopped if this pressure rises too high. As on Earth, a settled liquid can have gas positioned over the tank vent, allowing gas to be vented during tank fill, so preventing the pressure rise. Since in zero gravity liquid will normally be at the vent, the zero gravity technique is to vent any gas in an empty tank prior to fill and to condense any boiloff with a spray of subcooled liquid. This technique has a number of difficulties. First, a transfer of any remaining propellant from the receiver tank to a holding tank is required, increasing the complexity of the operation. Second, the vented gas is much harder to recycle to the supply tank; therefore, gas and any residual liquid in the receiver will be dumped overboard increasing contamination concerns. Third, the fill efficiency when condensing gas is unknown at this time. To control the fluid transfer operation and to plan resupply of propellant from the Earth, the quantity of liquid in a tank must be determined. As on Earth, settling allows the quantity of liquid to be gaged by determining the liquid level and relating it to the liquid volume. No comparable technique is available in zero gravity, primarily due to the lack of knowledge of liquid distribution. All existing techniques either do not have the accuracy of level sensing or have problems with accumulation of errors.

To insure a fluid is settled, the nondimensional Bond number (Bo) should be at least 50. This Bond number is a direct function of the fluid density, the acceleration level, and the square of the tank radius; while being an inverse function of the fluid surface tension coefficient. Therefore, for a given fluid and tank size, the minimum acceleration, and corresponding tether length, can be determined. Assuming that cryogenic propellants have a tank diameter of 4.2 m to fit in space shuttle payload bay and storable propellants have a tank diameter of 1.7 m to fit side-by-side in the shuttle payload bay, Table 7 can be derived for the minimum acceleration and corresponding tether length from the center of gravity to settle the fluid.

Settling the fluid allows more transfer methods to be considered than would be normal in zero gravity. The primary difference is that a vapor return line is possible from the receiver tank to the supply tank (Fig. 38), because liquid is settled away from the tank vents. This line allows venting of the receiver tank without dumping the gas overboard (where it would be a contamination hazard), eliminates the need to resupply pressurant for the transfer, and provides an equalizing pressure on the supply tank. However, a method is needed to provide the transfer work.

TABLE 7. STATIC TETHER LENGTH FOR PROPELLANT SETTLING
(Bo = 50)

Fluid	Gravity (10^{-4} g)	Tether Length (m)
Oxygen	0.12	32.3
Hydrogen	0.27	71.3
Nitrogen Tetroxide	1.30	342.0
Monomethylhydrazine	2.74	719.0
Hydrazine	4.71	1235.0

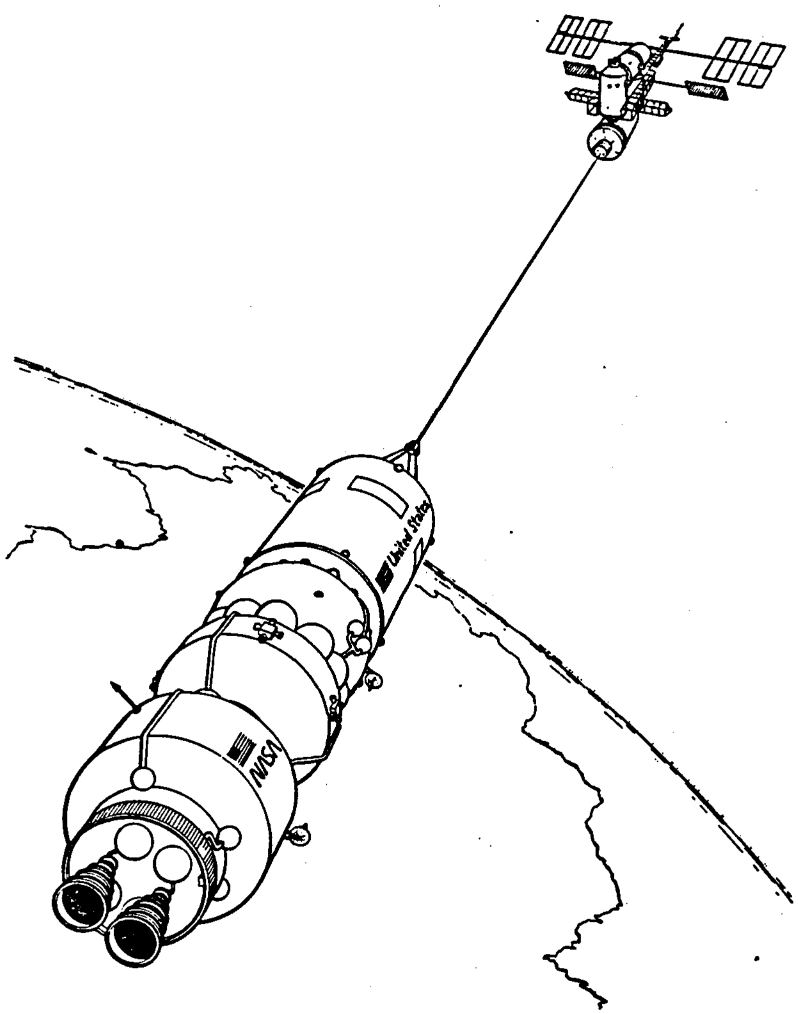


Figure 38. Simplfied schematic of fluid transfer system.

The Tethered Orbital Refueling Study [9] examined the options and recommended the following methods. A compressor in the vapor return line was chosen for cryogenic propellants because of the availability of extra gas and the limited pressure available at a pump. A pump in the liquid transfer line was chosen for storable propellants, because pressure at the pump was no problem and additional gas was not readily available. As a backup, either propellant type could use the highly reliable gravity feed method; however, this would require a considerable amount of time to fill the receiver tank. A possible fluid transfer concern is that the initial start of the transfer could impart an impulse into the system that reduces the tension on the tether; however, calculations indicate that a tether length sufficient for settling is enough to overcome the acceleration due to the initial impulse of a typical fluid transfer.

The small size of a vent line can result in a Bond number less than that required for fluid settling. If this parameter is the only consideration, any liquid getting into the vent would stay there, blocking the flow of gas into the vent. This Bond number is based on a balance between the hydrostatic pressure of the liquid and the gas pressure below the liquid required to hold it up. However, if an equal gas pressure is available at the top, such as the open line of a vent, the liquid will drop out. An example is taking your finger off the top hole of a straw filled with water. Complications can develop if bends in the vapor return line provide traps for liquid. If liquid does get trapped, the liquid will have to be forced, either way, through the line to clear it. The best way to avoid these problems is to insure that liquid does not get into the vent. If the tank sees zero gravity, liquid will get into the vent; therefore, the valve closing the vent must minimize the volume seen by the liquid to reduce the chances of it getting trapped. Even though the fluid is settled during transfer, fluid slosh and the jet from the liquid inflow can cause liquid to cover the vent. Special baffling will probably be required to disperse the inflow jet; while liquid slosh will have to be controlled. If the danger of covering the vent is too great during fill, alternating the venting and filling of the receiver tank may be required.

As discussed in the preceding paragraph, slosh control will be a requirement; not only to prevent the covering of the receiver tank vent, but also to prevent the uncovering of the supply tank outlet. Sloshing is a type of pendulum motion with kinetic and potential energy constantly being exchanged. To limit the slosh motion from a single disturbance, the potential energy capacity of the tanks must be maximized. This can either by done by increasing the acceleration level with more tether length and/or by increasing the height change of the liquid center of mass for a given angle of slosh. This height change is increased by choosing a tank shape which is narrow at the bottom and wide at the top. To prevent multiple disturbances from accumulating slosh energy, the liquid motion must be damped, usually with baffles. For a cryogenic propellant depot, the Tethered Orbital Refueling Study recommended a tether length of a little less than 1 km and ring baffles.

The tether length required to settle propellants also provides separation for hazard clearance. The major hazard is leaked or vented propellant which can constitute a contamination concern, especially for the storable propellant. An individual calculation to determine the required tether is needed for each propellant, sensitive surface, contamination efflux magnitude, and efflux duration. A calculation has determined that any surfaces at the superfluid helium temperature can not face a propellant depot without causing unacceptable contamination, even for a tethered cryogenic depot on a 1 km tether [9]. A small constant leak can be just as bad as a large, short duration vent of propellant. A zero gravity depot will require an overboard dumping of fluid. An explosion is unlikely, because fluid designs have a high level of redundancy to prevent overpressure and because the low pressure of space will not sustain a detonation of two propellants mix. If an explosion did occur, the distance from the space station provided by the tether would reduce the probability that a fragment would hit the space station proper. A puncture of a tank by debris can cause an impulse to be imparted to the system; however, much of the gas expelled would not have an impulse because of non-propulsive vents in the surrounding debris shield. A tether will limit the effects of the impulse that is produced. If this impulse is uncontrollable or if an explosion is imminent, the depot can be disposed of before the situation becomes critical.

Figure 39 shows the latest cryogenic propellant depot arrangement. This is a small depot holding 100,000 lb of propellant, equivalent to two Centaur loads, and capable of being launched in a single shuttle flight, totally filling the payload bay. Notice that this depot has conically based tanks for slosh control and remote manipulators to handle the OTV. The combination of the OTV and the attached payload would be a very bulky item to ferry from the space station to the depot. The OTV is being resupplied in an acceleration orientation opposite the thrust orientation, because of the need to allow room for the payload. This positioning of the OTV would obviously prevent the attachment of a tether to the bottom of the depot and complicate the fill and plumbing of the OTV. Planning for the OTV has determined that a larger OTV is preferred, requiring a doubling of the depot propellant quantities. In addition, current planning for basing an OTV on the space station requires the addition of a large hanger, which would result in a substantial lateral shift in the space station center of gravity and substantial modification of the space station. Combining a hanger with two of the tethered propellant resupply depots (Fig. 40) would prevent this shift and would eliminate the depot problems discussed above.

Many of the characteristics and considerations expressed for a propellant resupply depot will also apply for any facility that requires the storage and transfer of liquids. However, it must be understood that the large volumes inherent in propellant applications facilitate the use of a low gravity for settling. Other applications which use a small quantity of liquid may require substantially larger tether lengths to settle liquid. Therefore, zero gravity techniques may be preferable for these applications.

3.3.3 Low Gravity and Microgravity Laboratories

Low gravity and microgravity laboratories can use several tethered platform characteristics. The low gravity laboratory will primarily use the gravity produced by a tether when off the center of gravity to study and facilitate various processes. The microgravity laboratory can use the separation provided by a tether to reduce disturbances seen by the laboratory, allowing processes to be subject to only extremely low accelerations. Multiple locations can be used to combine the low gravity and microgravity laboratory, because gravity is continuously variable along the tether.

The microgravity laboratory can be accommodated in three ways (Fig. 41). The first arrangement is to keep the microgravity laboratories planned for the initial space station on the space station proper when a tether is added. This arrangement has several advantages. The configuration and operations of the space station do not have to be changed radically. The direct interaction between men and the experiment can continue as planned for the space station and as now performed on the space shuttle mid-deck. And the location of the center of gravity will be controllable by

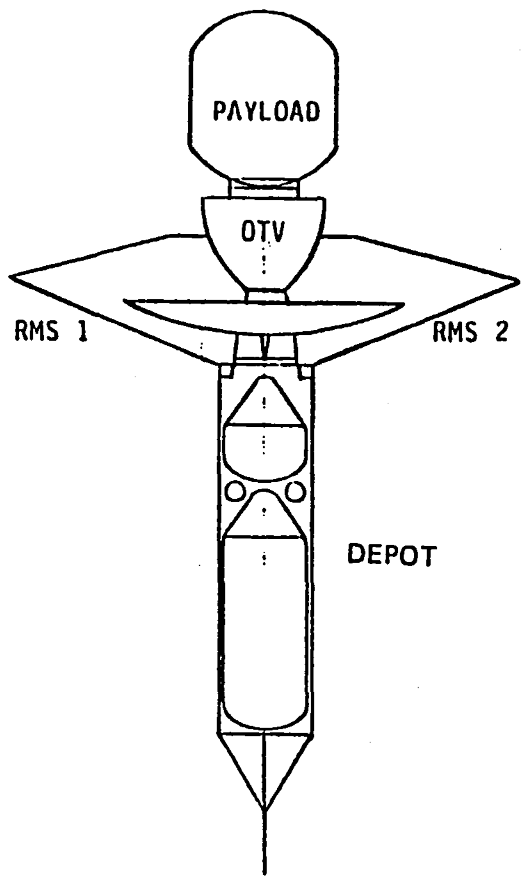


Figure 39. Small cryogenic propellant depot.

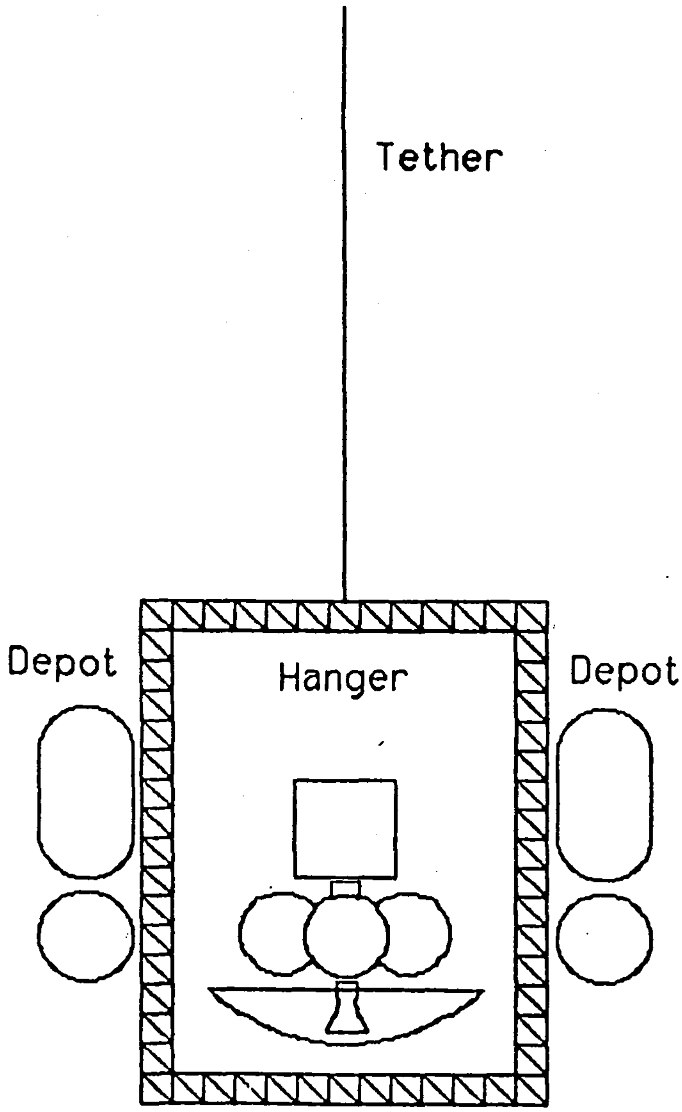


Figure 40. Tethered OTV hanger/depot.

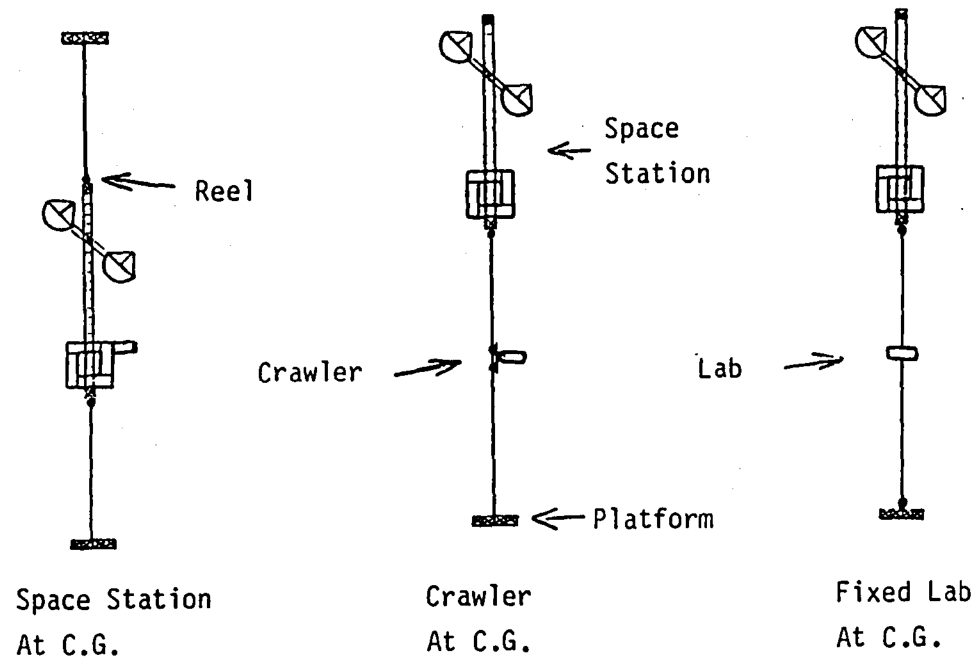


Figure 41. Micrograyity laboratory accommodations.

varying the upper and lower tether lengths, allowing a lower gravity gradient disturbance to the process being investigated. However, men will still be a major source of disturbances.

The second microgravity laboratory arrangement also has many advantages. This arrangement would be to have the laboratory on a crawler that seeks the tether center of gravity, allowing the microgravity laboratory to be also the low gravity laboratory and reducing some of the problems with balancing a tether system for positioning of the system center of gravity at the space station proper. Instead of direct interaction with a man, control of experiments would be by remote control, reducing the disturbances induced by a man. In fact, disturbances would be reduced to an extremely low level, 10^{-8} g [8], because the tether would substantially reduce the disturbances transmitted to the laboratory, while minimizing the gravity gradient acceleration seen by the laboratory. The primary disadvantage of this arrangement is that the microgravity modules planned for the initial space station probably could not be used.

The third microgravity laboratory arrangement is very similar to the second. This arrangement would have the laboratory fixed to the tether, with the positioning at the center of gravity performed by varying the tether length. The primary advantage of this arrangement is that a crawler would not have to be developed; however, a crawler will probably be needed for other reasons.

Classical microgravity platforms usually have a gravity level specified for their operating range. These gravity levels, however, are usually transitory and uncontrollable, while a tethered low gravity laboratory can develop a constant and controllable gravity. A tethered platform mounted on a crawler can vary its gravity levels, with a constant direction, by varying its distance from the tether system center of gravity. If this platform has access to the center of gravity, the range of its gravity levels could include what is normally considered microgravity. Thus a tethered low gravity laboratory can investigate processes with gravity and time as variables.

Compared to a centrifugal facility on the space station proper, a tethered low gravity laboratory would have a relatively large volume at a particular gravity level without the problems a centrifugal facility would have with coriolis forces and gravity gradient. The tethered laboratory uses a system which enhances attitude control, while a centrifugal laboratory adversely affects attitude control. In addition, the tethered laboratory would have better quality of gravity, because the tether would not transmit some of the space station disturbances, which would be seen by a centrifugal facility. However, a tethered laboratory can only deliver up to 10^{-1} g. Otherwise, the two facilities share the characteristic of gravity level being controllable and having a fixed direction.

The primary purpose of a low gravity laboratory is to examine various physical and biological processes. Among the biological processes that could be examined are the growth of plants and animals, and medical research, required to understand the effect gravity has on the cardiovascular, skeletal, and vestibular systems. Examples of physical processes that could be examined are crystal growth, fluid science, chemical reactions, and simulations of conditions on a low gravity body, such as asteroids, to examine natural processes, such as meteor impacts. A recurrent theme of research will be to determine the gravity level at which the gravity force starts to have an effect. Once this threshold is reached, the question will be if relations developed on Earth are valid in the low gravity regime.

A low gravity laboratory could also be used to research space operation that may involve low gravity. An example is research into using a low gravity force to shape a large area in the manufacturing of a large structure. The force should not be large enough to damage a fragile structure. Another example is again the use of the laboratory to simulate low gravity body conditions, but this time examining manned mobility operations and equipment, such as extraterrestrial materials extraction equipment.

3.3.4 Sensor Platforms

Sensor platforms take advantage of several tethered platform characteristics. The tethered platform characteristic of remote locations will be usable in all the ways mentioned in section 3.3.1. Especially valuable will be the multiplicity of locations and the increased field of view from reduced crowding. Separation from other platforms and the space station proper will reduce the risk of contamination and the detrimental effects of disturbances. All sensors will benefit from separating them from the interference of emissions due to performance of other functions on other platforms. The low gravity on a tether can be used to provide the force required to point large sensors (Fig. 42). And an expendable sensor platform can be disposed of following its use, due to the momentum transfer characteristics of a tether.

The astronomical sensor platform should be the uppermost of the permanently deployed platforms to ensure a clear field of view. This platform could be the presently planned upper sensor platform detached from the initial space station for this purpose. Since some of these sensors will probably be cooled with superfluid helium, a primary concern will be to separate these very sensitive surfaces from possible contamination sources. This will probably set the length of the tether segment from this platform to the next platform. Another important concern will be to have accurate pointing. The gravity on a tether can provide the force required for pointing either by shifting the tether attachment point in relationship to the platform center of gravity, possibly to compensate for tether swing, or by shifing the platform attachment in relationship to the sensor center of gravity. Pointing will also be helped by the tether's filtering of disturbances. Multiple astronomical platforms could be used to provide different viewing angles. Multiple locations could also be used to provide different elements of a particularly large sensor, such as a lens and the sensing element.

The Earth orbservation platform should be the lowermost of the permanently deployed platforms to ensure a clear field of view. This platform could be the presently planned lower sensor platform detached from the initial space station for this purpose. This platform will have similar considerations for contamination, pointing, and multiple locations as the astronomical platform. In addition, a position closer to the Earth can provide increased resolution. This could be a factor in determining the permanent tether length or in having this platform able to temporarily deploy farther than normal.

The space environment sensor platforms probably will be distributed along the permanently deployed tether and may be put on the end of deployable tethers to reach even farther. The use of multiple locations will provide the ability to measure properties at different locations at the same time, while reducing crowding for a better field of view. Separation from other platforms will provide some protection from interference. A temporarily deployed platform can be used to reach an inaccessible region. An atmospheric sensor platform would be a platform of this type;

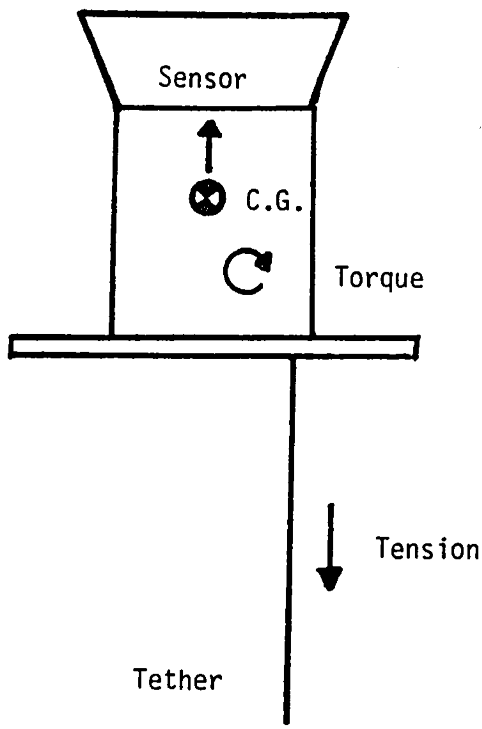


Figure 42. Sensor pointing.

however, the space station will probably be maintained at too high an altitude to deploy a tether that could reach the atmosphere. If recovery of a temporarily deployed platform is not desirable, the platform may be disposed of by cutting the tether.

3.3.5 Operations Platforms

Operations platforms take advantage of several tethered platform characteristics. The separation that a tether provides for a platform protects that or another platform from contamination and other hazards. The use of remote locations reduces crowding. And a platform can be disposed of if it threatens to become a catastrophic hazard. Most of the operations platforms described below are speculative, because the use of these platforms will depend on the results of system studies that have not yet been performed.

Utilities can be placed on an operations platform. This assumes that power and communications can be transmitted through the tether. A communications platform would be useful primarily because a remote location can improve the field of view of the antenna, while separation can result in less interference. If reconfiguration of the the initial space station is acceptable, a nuclear reactor or solar power collector can be placed on tethered platforms. A nuclear reactor platform would benefit primarily by separating other platforms from its radiation and protecting a greater volume with its radiation shadow shield. In addition, the reactor could be disposed of, into a high lifetime orbit, following the end of its life or in an emergency. This will require that the reactor platform be placed above the tether system center of gravity, preferably at the end to minimize the risk to other platforms. A solar power platform would benefit primarily by the separation from contamination sources and by the reduced crowding for movement of the collector. This platform would best be deployed upward to eliminate as much blocking of the Sun as possible by other platforms. Since heat cannot be transferred through the tether, a heat rejection utility cannot be placed on a central platform, requiring every platform to provide its own radiator panel.

If low thrust is used, a single platform can provide orbital maintenance for the entire tethered system. This orbital maintenance platform could also separate the exhaust gas from platforms sensitive to contamination. This application could be combined with another, such as a propellant depot, depending on availability of the propellant and power required by the propulsion system. A location near to the center of gravity and the large masses would minimize the disturbances induced by a given thrust level.

The remote location of a stowage platform would be convenient for bulky or massive items because of reduced crowding compared to the space station proper. These items could also be kept near the point where they are used to reduce ferrying operations.

A large space structure and construction platform would also benefit from the reduced crowding of a remote location. This location would provide separation to reduce hazards to the space station, while providing an easy means of separating the final product from the space station system, simply by releasing it.

When a tethered system is set up, the space station proper can be viewed as a tethered platform. As such, it derives all the benefits of separation from hazards and the avoidance of crowding with new functions. Similar to sensor pointing, the movement of the tether attachment point can be used to provide some active control of the space station proper's attitude. If the microgravity laboratory is off the space station proper, a small gravity can be applied to it. This gravity would settle objects in one direction, assisting in the retention of liquids, removing floating objects from the air, and providing a limited amount of traction to limit shifting of objects. This small gravity level may also have some medical benefits, of nothing else, by increasing the amount of exercise the crew performs during regular chores. An important aspect of this gravity is that the crew would not sense any coriolis or gravity gradient effects.

Some operations platforms will be required by other tether applications. Mass, such as space shuttle external tanks, may be required to be stowed for later momentum scavenging. If the microgravity laboratory is located at the space station proper, a counterweight platform, possibly composed of space shuttle external tanks, may be required to balance the tether system for proper control of the center of gravity. This platform may have additional benefits by increasing the tether system inertia, so the orbit will not change drastically with momentum transfer, and by providing a mass for an emergency orbit change with momentum transfer. The mass stowage and counterweight platforms could possibly be combined below the center of gravity if the tethered propellant depot is deployed above the center of gravity. Momentum transfer may require a platform to launch and capture vehicles. This platform would probably consist of a manipulator arm, propulsion system, and a location sensor on a temporarily deployed tether at the end of the permanently deployed tether. If an electrodynamic tether is used, a platform with an electron emitter and collector will be required at the end of the permanently deployed tether.

3.3.6 Platform Impacts on the Space Station

Using tethered platforms will have advantages, but selecting the overall tether system configuration will be difficult, because the tether applications have competing considerations. Besides the requirements for each application, there are a number of bases for selecting a tether system configuration. The tethered platforms could be arranged by sensitivity of surfaces to or sources of contamination. They could be arranged by operational considerations. They could be arranged to balance, so that the system center of gravity occurs on the space station proper. And they could be arranged to limit the effects of tether breakage. Particularly important in the development of a tethered configuration will be the arrangement of the permanently deployed tether end, because many of the applications desire this location.

Many of the tethered platform applications will be deployed permanently on the tether, because concentrating these platforms back at the space station would contradict the reason for dispersing them in the first place, allowing compatibility of the space station functions to again become a concern. As an example, the deployment of a propellant resupply depot only during transfer operations would help in performing the transfer itself and in reducing contamination from transfer operations, but at the price of increased operations time and increased contamination from persistent leaks. Many of the impacts on the space station result directly from this permanent deployment of the tether.

Tethered platforms will have a predominately favorable effect on the safety of the space station. This was mentioned previously as a characteristic of a tethered platform. However, a hazard will be added. If a tether breaks, due to impact with debris or due to degradation of the tether, the two masses will go into two different orbits, one upward and the other downward. If the tether breaks near a platform that is far enough away from the system center of gravity, it may deorbit or go into such a high orbit that the space shuttle can not reach it. To prevent large changes in orbit, the distances that a permanently deployed platform can be tethered away from the system center of gravity will be limited. In addition, the risk of a tether break is a function of tether length, so the tether lengths between the most critical platforms should be limited to reduce the risk of the break occurring there. At the very least, a tether breakage would require a means of recovering the two masses to reconstruct the system.

Another concern would be posed by a nuclear reactor. It is deployed on a tether for safety reasons, but the very reason it is separated from other platforms would restrict access to the tether beyond its location, especially for men. This would severely affect servicing of this region of the tether and momentum transfer with manned stages.

The use of tethered platforms would tend to increase, over a concentrated space station system, the orbital maintenance propulsion requirements, because a tethered system would see more drag. The drag area would be increased due to the addition of the tether area and due to the reduction of shadowing that one element would provide another on a concentrated space station system. If an atmospheric probe platform is used, it will increase the drag even more, because of a much higher gas density. The increase in orbital maintenance requirements will be less than for free-flying platforms, due to lack of shared facilities on free-flying platforms.

The use of tethered platforms will require changes to the initial space station configuration. The addition of tethered platforms would block some of the view of the planned sensor platforms on the initial space station; therefore, these sensor platforms would probably have to be moved to the ends of the permanently deployed tether. If the tethered platforms are not balanced, a gravity level greater than the initial space station requirement of 10^{-5} g can be induced on the space station proper. The attachment of only a tethered propellant depot can induce a gravity level on the order of 10^{-4} g [9]. The present philosophy for the initial space station is to have microgravity laboratory modules on the space station proper where people could get hands-on experience with microgravity processes. To maintain this philosophy will require an active control of the tether lengths and possibly a counterweight platform to place the center of gravity at the proper location. If the center of gravity location is not controlled, the microgravity laboratory will have to go to the center of gravity. This could involve moving the initial space station laboratories or designing a new one. The initial space station laboratories would probably not have the right characteristics. An example is that these laboratories require men to operate the experiments, while the new location would require the minimum ferrying of men. Therefore, having the microgravity laboratory go to center of gravity will probably involve replacing the planned laboratories with a new one. The requirement to change the microgravity experimental philosophy and to replace the planned laboratories will limit the attractiveness of the option to go to the center of gravity. A secondary consideration when inducing a gravity on the space station proper will be to insure that the hardware, such as fluid equipment, on the initial space station have the proper orientation.

To have the tethered platforms accessible from the space station, a transportation system will be needed along the tether. The use of free-flying transfer systems, such as the OMV, will entail difficult orbital transfer maneuvers, involving matching the platform altitude and phasing before performing a fast capture. This transportation system is best used for free-flying platforms. A better transportation system for tethered platforms will probably use the characteristics of a tether. The tether is a structure which can be used as a guide and reaction surface for a device which crawls along the tether. This crawler can also be the basis for movable platforms, such as a low gravity laboratory or docking platform at the center of gravity. One of the requirements of a crawler will be to have a means of getting around fixed platforms, because these will block its path along the tether. A solution may be to have a crawler along each tether segment with a remote manipulator system at each platform to transfer cargo between crawlers.

The use of tethered platforms will require the development of new operational techniques. New techniques will be required to deploy platforms, reconfigure the tether system, and replace tethers. New techniques will be required to track and control the dynamics of multiple and moving tethered platforms and to perform ferrying operations with crawlers. Questions to be answered are how are large masses and men to be handled and how are items to be transferred around platforms with mainpulator arms. Strategies will have to be developed to minimize the amount of ferrying and reconfiguration required, especially for large masses. For platform maintenance, the question of whether to bring the platform to the space station or to bring people and materials to the platform will have to be answered. If a low gravity is present on the platform, standard EVA procedures, except for a greatly reduced MMU usage, will probably have to be modified to secure the astronaut to the platform, so he will not fall. For microgravity platforms remote from the space station proper, the question of whether to use remote control of experiments or to ferry men to the laboratory for hands-on control and experience must be answered. Selection of operational techniques will relate directly with selection of the tether system configuration. For example, the location of the orbital transfer vehicle hanger will directly relate to what operational techniques are used to ferry masses and how the vehicle is to be prepared for a new mission.

3.4 Tethers in Support of Scientific Research (By W. J. Webster, Jr.)

The advent of the space station system with its components in both polar and equatorial orbit promises to revolutionize both the process of acquiring scientific data in Earth orbit and the temporal extent of such data. In astronomy, for example, the benefits of the kind of operations that are possible with the space station have been clear since Skylab [10]. The solar observations made with the ATM under direct astronaut control are still the most extensive data set on solar flares available. In terrestrial physics, the benefits of the space station system can be greatly enhanced by the addition of tether technology [1].

The greatest unknown in understanding the relationship between the terrestrial and extraterrestrial environment is the temporal structure of the uppermost (90 to 150 km) atmosphere and the spatial variations of that structure. This structure includes variations in neutral composition as well as ionic content. In the measurement of the Earth's potential fields (magnetic and gravity), the next major advance will come from gradiometric measurements. To be most effective, gradiometric measurements must be made at low altitudes (around 110 km). Earth observations, especially spectrophotometric observations, benefit from the highest spatial and flux resolution possible. For a fixed instrument aperture, the lower the altitude of measurement, the higher will be the spatial resolutions.

Current systems do not provide for extensive observations in the 90 to 150 km range. The best that can be done is to use multiple sounding rocket launches to give coverage through a time interval of interest or use a maneuverable satellite for a short (not more than 15 min at 120 km) period. As a result, the existing data base is very spotty.

The advent of the Tethered Satellite System (TSS) [11] promises to provide the means to extend the data base. As currently designed, the TSS is capable of operation at about 120 km altitude for a period of about 40 hr. This system promises to produce a quantum leap in the quality and extent of measurements at low altitude.

Although TSS will provide crucial new data in a wide variety of disciplines, as it is currently designed, it does not have the capability of operation at the lowest altitude nor is it capable of extended (i.e., weeks) operations at low altitude. Changes in the choice of tether materials promise extension to altitudes as low as 100 km at reasonable cost. The advent of the space station will allow the temporal extent required to make detailed observations of both the spatial and temporal history of the boundary of the Earth's environment.

The following paragraphs examine the scientific benefits to be expected from tethered observations based both on the space station manned platform in a low inclination orbit (28.5 deg) and the Earth Observing System platform (EOS) in a high inclination orbit (sunsynchronous polar). This discussion will address four areas of research in Terrestrial Physics:

1) Space Plasma Observations — The transition between the mostly neutral atmosphere and the mostly ionized ionosphere takes place in the region accessible to tethered payloads. Also, since most of the ionosphere activity takes place below 500 km, observation from the space station components will cover almost all regions of major interest.

2) Upper Atmosphere Observations — The structure in the uppermost neutral atmosphere is strongly influenced by many factors which vary with geographic position and time. Since the region which receives the maximum deposition of solar energy is crucial to the energy balance of the atmosphere and since this region is near the lower end of the tether accessibility, the space station will be a crucial component of the observing system.

3) Potential Field Observations — The next major advance in the understanding of the Earth's gravity and magnetic fields will come from gradiometric measurements. These measurements are best conducted at low altitude to maximize the gradient magnitudes. Also, the measurement of the crustal magnetic field is best conducted at the lowest practical altitude since the crust is a weak source of magnetism.

4) Earth Surface Observations — Conventional remote sensing observations made with fixed aperture sizes obtain their highest spatial resolutions at the lowest possible altitude. Assuming that motion compensation is possible or the detector sensitivity is high enough, valuable spectrophotometric data at a resolution intermediate between aircraft and conventional satellite data can be obtained.

Geodetic observations of the Earth require a long baseline to produce the highest accuracy in relative positioning. For the long term, repetitive coverage required, staging a tether mission from the shuttle is not sufficient. The capabilities of the space station are essential.

The following examines the scientific data which might be obtained and some of the problems involved with tethered observations using the components of the space station. Each of the disciplines described above and the typical observing systems which might be employed will be discussed. No attempt will be made to exhaust the possibilities in each field, but some of the more important possibilities will be considered. In some cases, the benefits to be obtained are well known. In those cases, more emphasis will be placed on some of the technical problems involved.

3.4.1 Space Plasma Observations

The physical characteristics of the Earth's ionosphere change both with altitude and geographic position. The altitude dependence is determined by the ionization and recombination rates which are in turn determined by the chemical composition, insolation spectrum and the magnetic field [12]. The geographic position dependence is dominated by the magnetic field and the position of the terminator [12].

Two geographic regions are of special interest. Because of the convergence of the magnetic field at the poles, the arctic and antarctic regions show intense, complex, and highly time variable ionospheric structure. Along the magnetic equator, one of the major currents in the Earth's current system, the equatorial electrojet flows in an east-west direction. Each of these regions has major activity below the expected altitude of the components of the space station. In order for them to be observed, tethers at least 100 km in length will be required [12].

The equatorial electrojet [13] flows at an altitude of between 90 and 130 km with a half-current density width of about 15 km. It is relatively confined in geomagnetic latitude and has a half-current width of about 4 deg (E-W component) centered on the geomagnetic equator. The jet has a complex current structure which, in addition to a local solar time variation, shows both meridional and latitudinal current flow. In addition, the flow of charge is irregular, depending on very high altitude winds and on the level of solar activity.

The magnetic polar regions are also regions of intense and time variable ionosphere activity [14]. In addition to an average current flow in latitude and longitude throughout the polar regions, currents into and out of the ionosphere flow along the magnetic field directions [15]. These currents, called Birkeland currents, appear to close the current loops between the outer magnetosphere. The total currents in the Birkeland flows are large (as much as 3.5×10^6 A) and the time and space variable (by a factor of two or more).

Both major components of the space station can provide extensive spatial and temporal coverage of these currents. At 28.5 deg inclination, the manned component will cover the equatorial electrojet at a wide range of local solar times and with frequent sampling of all the latitudes covered by the jet. The EOS platform in polar orbit will provide corresponding, but perhaps limited local solar time coverage, for the Birkeland currents.

For altitudes down to about 110 km, no new instrument development is required. The kind of instruments used on the Atmospheric Explorer [16] and the Dynamics Explorer satellites can be adapted to tethered observations. Below 110 km, effects due to the motions of the payload through the ionosphere may make it impossible to infer the characteristics of the undisturbed plasma with any tethered instruments.

A payload suitable for deployment from either EOS or the manned component should be capable of operations for at least days at 110 km. Positioning, with respect to the deployer, should be accurate on the tens of meters level. A telemetry line either to the deployer or TDRS will be essential to long duration operations. Table 8 summarizes the operating requirements and a potential ionospheric mapping instrument complement.

TABLE 8. SPACE PLASMA OBSERVATIONS PAYLOAD [17]

Altitude Regime: 100 to 130 km	
Position Accuracy: Tens of meters	
Altitude Knowledge: Axis orientations to within 10 deg	
Instrument Complement:	
Electron Spectrometer	
Electron Current Direction and Magnitude Sensor	
Ion Spectrometer	
Ion Current Direction and Magnitude Sensor	
Vector Magnetometer	
Vector Electrometer	
Instrument Performance:	
Electron Spectrometer	$\Delta E/E$ - 2 percent
Electron Current Direction and Magnitude	5 deg, 10^{-11} A
Ion Spectrometer	$\Delta E/E$ - 2 percent
Ion Current Directions and Magnitude	5 deg, 10^{-11} A
Vector Magnetometer	6 nt/axis
Vector Electrometer	1 mV/m per axis

3.4.2 Upper Atmosphere Observations

Because the neutral atmosphere grades into the ionosphere in a relatively smooth manner, it is difficult to separate the problems of upper atmospheric observations from those of space plasma observations. Although the bulk of the neutral atmosphere is below about 90 km, sufficient neutral species remain up to about 120 km (the end of the turbopause) that the composition, motion and distribution is a major factor in the overall structure of the atmosphere.

Two major problems which have as yet, necessarily only scant direct measurement data, are the temporal energetics of the uppermost neutral atmosphere and the global distribution and motion or the major neutral constituents. To date, the data consists of measurements from the maneuverable satellites of the Atmospheric Explorer [17] series, sounding rockets, and remote sensing (spectroscopy). Of these three data types, the remote sensing observations are, for obvious reasons, the most extensive in time. A major attack on the two problems listed above requires in-situ measurement of the neutrals. Remote sensing observations, while exceedingly valuable, are one or more additional steps removed from the physical processes involved compared to in-situ observation.

In-situ observations at altitudes as low as 93 km have been attempted with the Atmospheric Explorer C satellite. Below about 100 km, correction for the effects and the motions of the satellite through the surrounding atmosphere became difficult. Accordingly, 100 km is likely to be a lower limit [18].

In order to address the temporal energetics and the global distribution and motion, measurements of temperature, vector velocity and composition are required for an altitude range which should go as low as is feasible (about 100 km) and up to 150 km. Conventional measurements can cover altitudes above 150 km and, unfortunately, must suffice for altitudes under 100 km. Because of the nature of the energy input mechanisms, intensive coverage of both the polar and the equatorial regions is essential. In the polar regions, electrodynamic forces, joule heating and particle inputs are deposited in restricted geographic regions and result in large density and temperature excursions over small regions of the thermosphere. Accordingly, coverage from EOS, which will see each polar region once per orbit, is essential. Because the equatorial regions are dominated by atmospheric tides and insolation, the 28.5 deg inclination of the manned component is ideal for dense spatial and temporal coverage.

The operating requirements for an atmosphere observations payload are similar to ionosphere observations. Because one is concerned with the neutral component, the charged particle instruments are replaced with mass spectrometers. In order to assess the energy input, UV photometers and charged particle spectrometers are required. Because the support needs of atmosphere and ionosphere observations are similar, the two kinds of instruments could be combined into one payload. Although the two kinds are listed separately, this is not likely to be true in practice. Table 9 gives the operating requirements and instrument complement for an upper atmospheric observations payload.

TABLE 9. UPPER ATMOSPHERE OBSERVATIONS PAYLOAD

Altitude Regime: 100 to 160 km	
Position Accuracy: 150 to 50 m	
Altitude Accuracy: Principal Axis Orientation Stable to within 20 deg	
Instrument Complement:	
Mass Spectrometer	
Kinetic Temperature Probe	
Pressure Transducer	
Vector Neutral Velocity Sensor	
Instrument Performance	
Mass Spectrometer	Concentrations to 10 to 15 percent
Kinetic Temperature	0.5°K at 120 km
Pressure	1 percent at 120 km
Vector neutral velocity sensor	2 m/s per axis

3.4.3 Potential Field Observations

The gravity and magnetic fields of the Earth have been the subject of satellite observations since the beginning of the Space Age [19]. Satellite results have been of importance in understanding the density distributions of the Earth and defining the possible fluid motions of the liquid part of the Earth's core. In a more applications oriented sense, the gravity field and the crustal magnetism have been of value in a wide range of geophysics investigations.

While there are numerous potential field investigations which are best performed on or staged from the space station, this report will concentrate on two kinds of investigations which require a tether for execution: gravity/magnetic gradiometry and low altitude mapping of the crustal field. Each of the investigations requires an altitude of 110 to 120 km and, for global mapping, would best be conducted from EOS.

The crustal field at 300 km represents no more than 0.1 percent of the magnitude of the total field [20]. Since time variable fields due to magnetosphere and ionosphere currents can reach 10 percent of the magnitude of the total field, it is clear that the crustal field is a weak source which is best observed at the lowest feasible altitude. At an altitude of between 110 and 120 km, the signal strength will be sufficient to observe the finest detail possible. Below about 100 km, the screening due to plasma forming around the sensor will prohibit observation of the crustal field [21]. Table 10 gives the operating requirements and instruments complement for a crustal field mapping mission.

TABLE 10. CRUSTAL FIELD MAPPING [21]

Altitude Regime: 110 to 120 km	
Position Accuracy: 60 m or better	
Altitude Knowledge: 0.2 deg	
Instrument Complement:	
Absolute Scalar Magnetometer	
Vector Magnetometer	
Instrument Performance:	
Absolute Scalar Magnetometer	0.5 nT
Vector Magnetometer	0.5 nt/axis

Potential field gradiometry promises to provide information on these small spatial scale features of the fields which is nearly impossible to obtain by conventional means. Gradiometer observations are best conducted at altitudes where the gradient in the field is as large as is practical. Gradiometric observations of the gravity field, for example, are best conducted at the lowest practical tether altitude [22,23]. A recent conference on gravity gradiometry recommended 125 km as a goal [24].

High sensitivity gradiometers are cryogenic instruments [25,26] and accordingly would require regular servicing to maintain the cryogenics. The gravity and magnetic gradiometers could map the global fields in about 6 months. Since the gravity field is mostly stable over extended periods of time, one mapping should suffice for a time period of at least a decade. However, a remeasurement at 10 year periods might detect gravity field perturbations at the smallest spatial scales due to the motion of the tectonic plates. Since the main and magnetosphere magnetic fields are time variable, continuous observations of the global field are indicated [27]. Table 11 gives the operating requirements and instrument complement for a potential field gradiometer system.

TABLE 11. POTENTIAL FIELD GRADIOMETRY [24,21]

Altitude Regime: 120 km	
Position Accuracy: 10 to 30 m	
Altitude Knowledge: 2 arc min	
Instrument Complement	
Cryogenic Gravity Gradiometer	
Cryogenic Magnetic Gradiometer	
Instrument Performance	
Cryogenic Gravity Gradiometer	10^{-4} E $Hz^{-1/2}$
Cryogenic Magnetic Gradiometer	5×10^{-8} nT/m

3.4.4 Earth Surface Observations

Earth surface observations divides into two classes of problems. The first class contains conventional remote sensing, both spectrophotometry and broad band imaging (in primarily the visible region of the spectrum). The benefits of conventional remote sensing are well known [28]. At the lower altitude tether regime, infrared emission from the bow shock around the payload will make it difficult to observe ground emissions. Accordingly, IR remote sensing will probably be restricted to altitudes above 100 km. Visible remote sensing will be limited by the optical luminosity generated on spacecraft surfaces by atomic and molecular recombination and by emissions from the shockwave around the payload. The limiting altitude for optical remote sensing is probably around 90 km.

The second class of observations is geodesy. Geodetic observations can perform, at least in some cases, a dual function. With a sufficient number of observations, both the ground positions and the station positions in orbit can be obtained to the highest accuracy possible [23]. Tethered payloads are needed in this application because the use of perspective (i.e., viewing the ground from two altitudes) allows greater precision in ground determination. Altitude limitations on geodetic observations are similar to those of conventional remote sensing. The radar or laser signal must retain sufficient strength after a round-trip to be adequately timed and detected on reception [23,29]. In the case of beacon-based systems, plasma in the vicinity of the beacons can cause differential phase distortion of the beacon signals and thereby limit the accuracy of geodetic measurements [30].

In order to function effectively at low altitude, spectrophotometers and other imaging devices must either be very sensitive or else have extensive image motion compensation [31]. The high sensitivity is required to obtain sufficient radiometric accuracy with a very short sample time. Image motion compensation would allow a longer sample time and therefore less sensitive detectors could be employed.

Geodetic observations will not be subject to the kind of limitations that remote sensing observations must deal with. However, the requirement of a high signal to noise ratio on returned signals will set a requirement on either laser or radar power which could require a substantial power source on the tethered payload.

In conventional remote sensing, the goal of the observations is to produce repetitive images and spectrophotometry at the highest spacial resolution possible. The scientific and applications benefits to be derived from this data are well known and can be found in the Landsat 4 summary conference proceedings [28].

Geodetic observations made from space stations altitudes will allow coverages which are intermediate between conventional surveying and the kind of geodetic measurements that span continents and plates. Distance regimes from 200 to 600 km can be covered effectively by geodetic systems using the space station components as either a signal source or as a reference point [23].

Geodetic observations which can be made include: precise positioning by using multiple beacons on a tether to provide a well-known reference baseline, differential radar interferometry to obtain contour heights within an illumination footprint, differential positioning by radar or laser ranging and absolute positioning by conventional two way doppler or laser tracking.

Repetitive geodetic observations over a 200 to 500 km region are of considerable scientific and applications importance. For example, of one can obtain differential positions of an array of stations deployed in the vicinity of a seismically active fault, with a precision of 0.5 to 1 cm, repetitive observations of such an array will capture the preseismic deformation thought to be common for earthquakes of magnitude 3 or greater [31]. Tables 12 and 13 give the operating requirements and instrument complement for typical geodetic and remote sensing systems.

TABLE 12. EARTH OBSERVATIONS: REMOTE SENSING [28]

Altitude Regime: 110 to 120 km

Position Accuracy: 10 m

Altitude Knowledge: 1 arc min

Instrument Complement:

- Imaging Spectrophotometer
- Panchromatic Camera

Instrument Performance:

- Imaging Spectrophotometer: Radiometric accuracy - 0.5 percent NES (visible)
- Panchromatic Camera: Geodetic rectifications - $\leq$ 0.5 pixel

TABLE 13. EARTH OBSERVATIONS: GEODESY

Altitude Regime: 120 km	
Position Accuracy: 1 cm	
Altitude Knowledge: 1 arc mm	
Instrument Complement:	
Two pair of dual phase-locked beacons Spaceborne Laser Ranging System	
Instrument Performance	
Dual Phase-leveled Beacons	10^{-8} stability at 1.7 GHz Phase coherence of 1 percent
Spaceborn Laser Ranging System	10 pps ± 2 cm/single pulse

3.4.5 Aerothermodynamic Research (by Paul M. Siemers III)

3.4.5.1 General

The Earth's atmosphere from 90 km to 200 km provides the last aerothermodynamics frontier. This atmospheric region is taking on even more significance as man advances into space on a more routine basis with plans for a permanent presence requiring even more extensive capabilities to "fly" in and through this region. Present NASA programs which require but also can provide an understanding of the aerodynamics and aerothermodynamics of the free molecule and transition flows that exist at these altitudes are the Aeroassisted OTV, Entry Research Vehicle, and the Tethered Satellite. Each of these programs provides a unique opportunity to do flight research in the rarefied upper atmosphere. However, the Tethered Satellite Program provides, because of its capability to obtain global, in-situ, steady-state data, data, the greatest potential to:

1) Define the performance of aerodynamic shapes as a function of environmental characteristics (free molecule, transition, slip flow regimes)

2) Define the characteristics of the upper atmosphere and the global variability of properties such as composition temperature, pressure and density (Fig. 43).

Such data are required to accomplish the systematic development and verification of analytical prediction techniques required to support advance configuration designs.

These requirements have resulted in a growing need for and interest in the establishment of the technology base required to support the development of vehicles that can maneuver in the upper atmosphere while returning from orbit, as well as vehicles that can fly in the atmosphere at hypersonic speed for sustained periods of time.

This section presents the results of research studies to define the feasibility and capabilities of a tethered system to operate in the altitude range of interest and to obtain the in-situ data required to accomplish the stated research objectives.

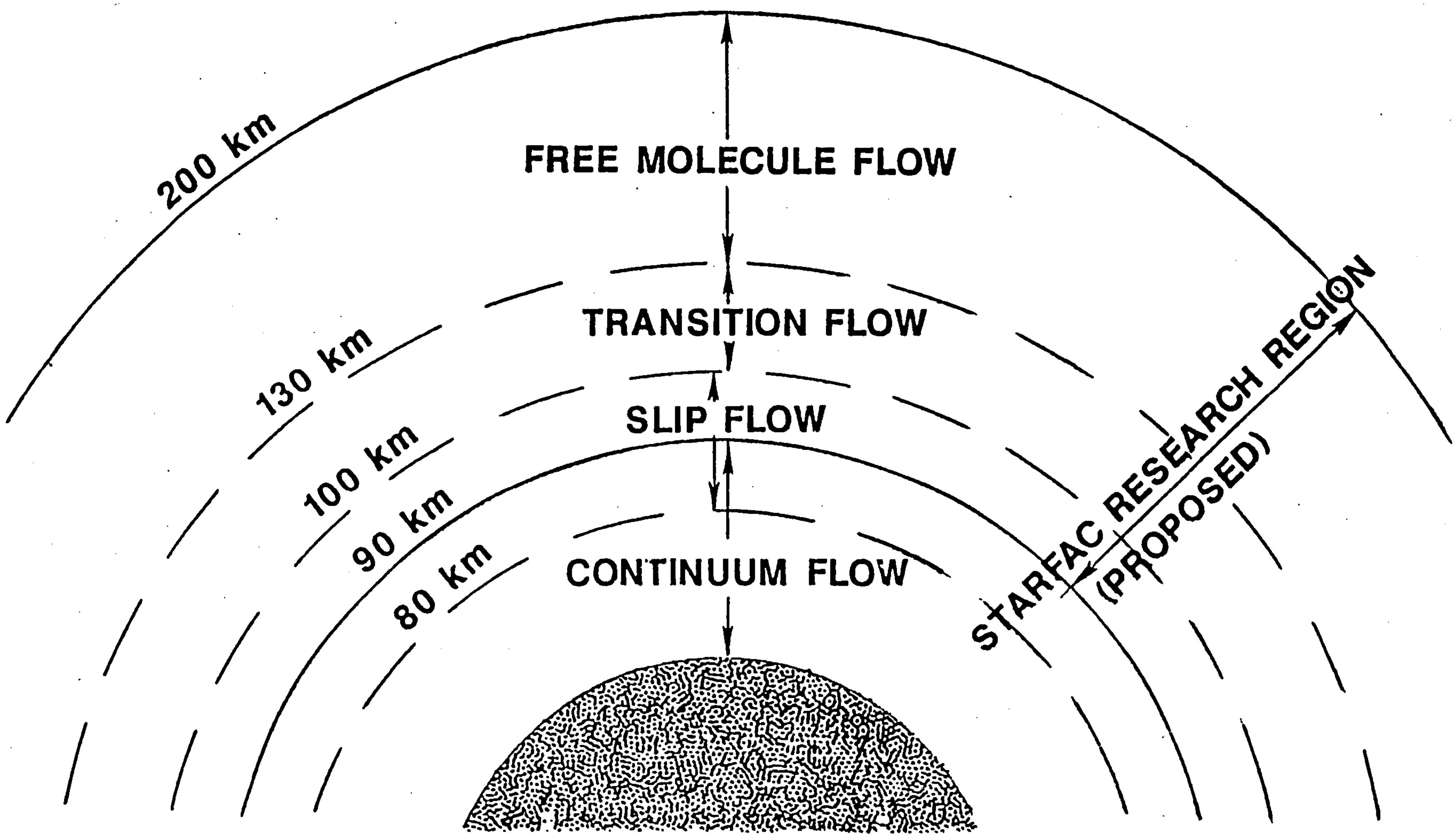


Figure 43. Shuttle tethered aerodynamic research facility.

This section describes briefly the tether simulation program, SKYHOOK, used to accomplish the feasibility simulation studies, the control law developed to accomplish the proposed missions, the simulation results, as well as the results of the instrumentation requirement studies. The results are then used to establish the feasibility of STARFAC-Phase I, i.e., utilize the base line TSS with minimum modification. Finally, recommendations are made for continued mission studies, instrumentation development, and TSS modifications that could lead to STARFAC implementation.

3.4.5.2 STARFAC Simulation Studies

In order to accomplish the feasibility and capability studies of the STARFAC-Phase I concept, utilize the base line configured TSS to accomplish upper atmospheric aerothermodynamic research, a simulation technique had to be employed that was generally accepted in the tether community. A review of available capabilities isolated the SKYHOOK program as the best program for these studies.

3.4.5.2.1 SKYHOOK Program

The SKYHOOK program was originally conceived and developed by the Smithsonian Astronautical Observatory (SAO) and evolved into a program of great generality and analytical sophistication with capabilities to analyze a broad range of tether related problems and missions. In the program, the Shuttle Orbiter and the satellite are modeled by mass points, and the tether may be lumped in part into the orbiter and the satellite or be represented independently by an arbitrary number of connected mass points. If mass points are used to represent the tether, their number increases or decreases as the tether is deployed or recovered.

With all its capabilities, SKYHOOK was not developed to accomplish system simulations at the altitudes required to accomplish the STARFAC feasibility studies; therefore, a low altitude capability and atmospheric model were added to permit program operation for STARFAC simulations. In addition, the input and output routines were simplified and modernized and the graphics output enhanced by displaying a number of quantities significant to STARFAC such as orbiter and satellite altitude and satellite dynamic pressure. Finally, a new control logic was developed and is described in the next paragraph.

3.4.5.3 STARFAC Control Law

The control law is required to deploy the tethered "wind tunnel" — STARFAC — to the target altitude and maintain it there for a length of time sufficient to obtain the desired data, nominally one complete orbital revolution. After that, the satellite may be deployed to a new target altitude or recovered. The deployment should take place expeditiously but not so fast as to cause unacceptable oscillations. In the STARFAC modified SKYHOOK program, deployment, maintenance, and retireval are accomplished by applying a programmed tension to the top end of the tether. This tension will be caused by a torque imparted by the tether reel which in turn is produced by an applied voltage.

3.4.5.4 Mission Simulations (Figures 44 through 47)

The tether system provides a controlled flight capability that allows a mission design capable of providing aerothermodynamic data in more than one of the flow regimes of interest (slip, transition, free molecule) and global atmospheric data at several altitudes. During this mission, data is obtained during orbital passes at altitudes between 125 km and 100 km in 5 km increments of altitude. The total mission time is 100,000 sec. Much of this time is consumed, however, during the deployment from 105 km to 100 km.

3.4.5.5 Feasibility Study — Summary of Results

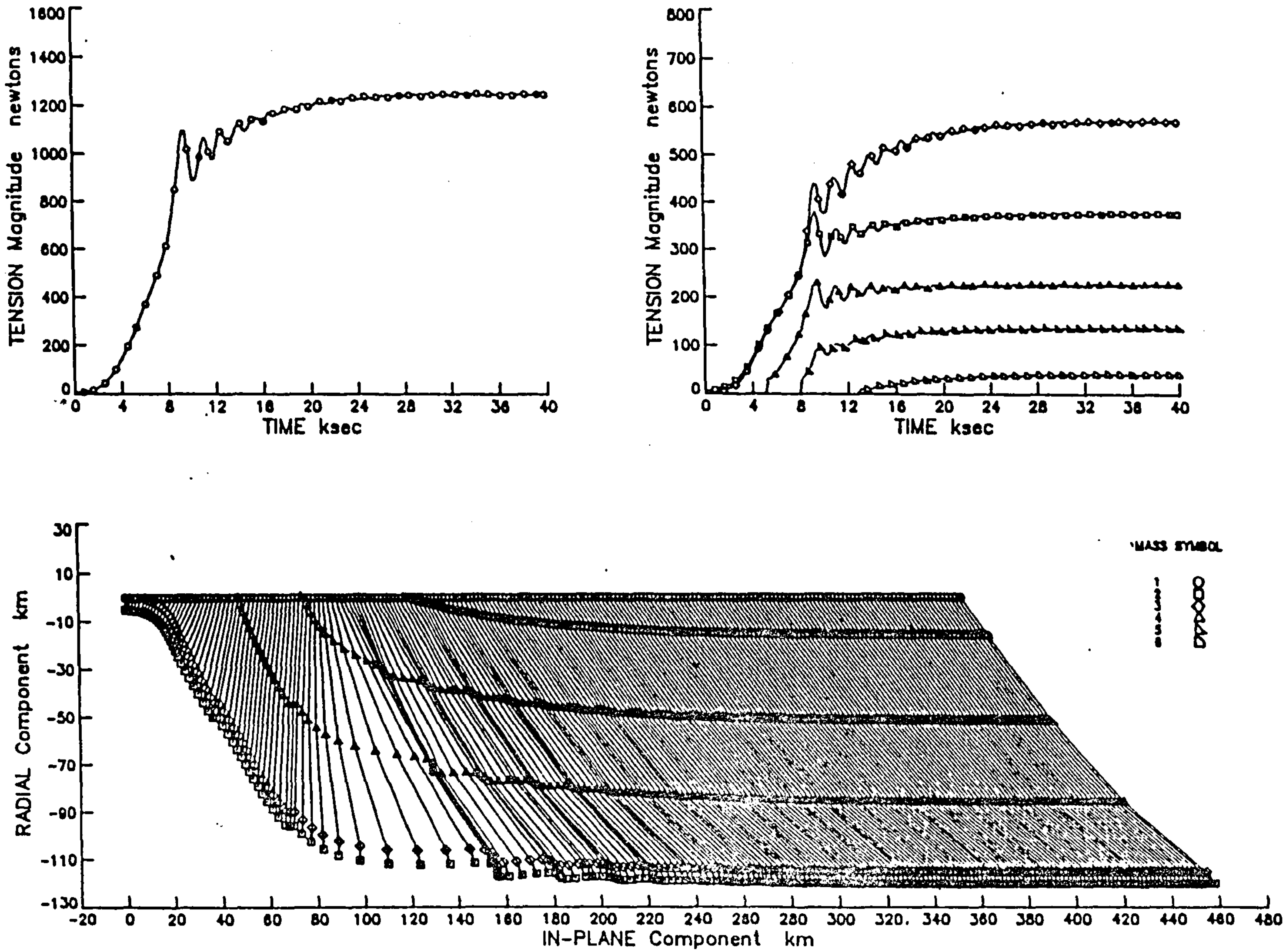
A series of simulations have been accomplished to establish feasibility and mission limits of the proposed STARFAC. These simulations have produced data which demonstrate that the deployment of a tethered satellite to an altitude of 100 km is feasible, and thereby establish the credibility of the STARFAC concept.

Finally, to accomplish any mission below an altitude of 125 km, a high temperature tether material and tether configuration must be developed.

3.4.5.6 Instrumentation (Tables 14 and 15)

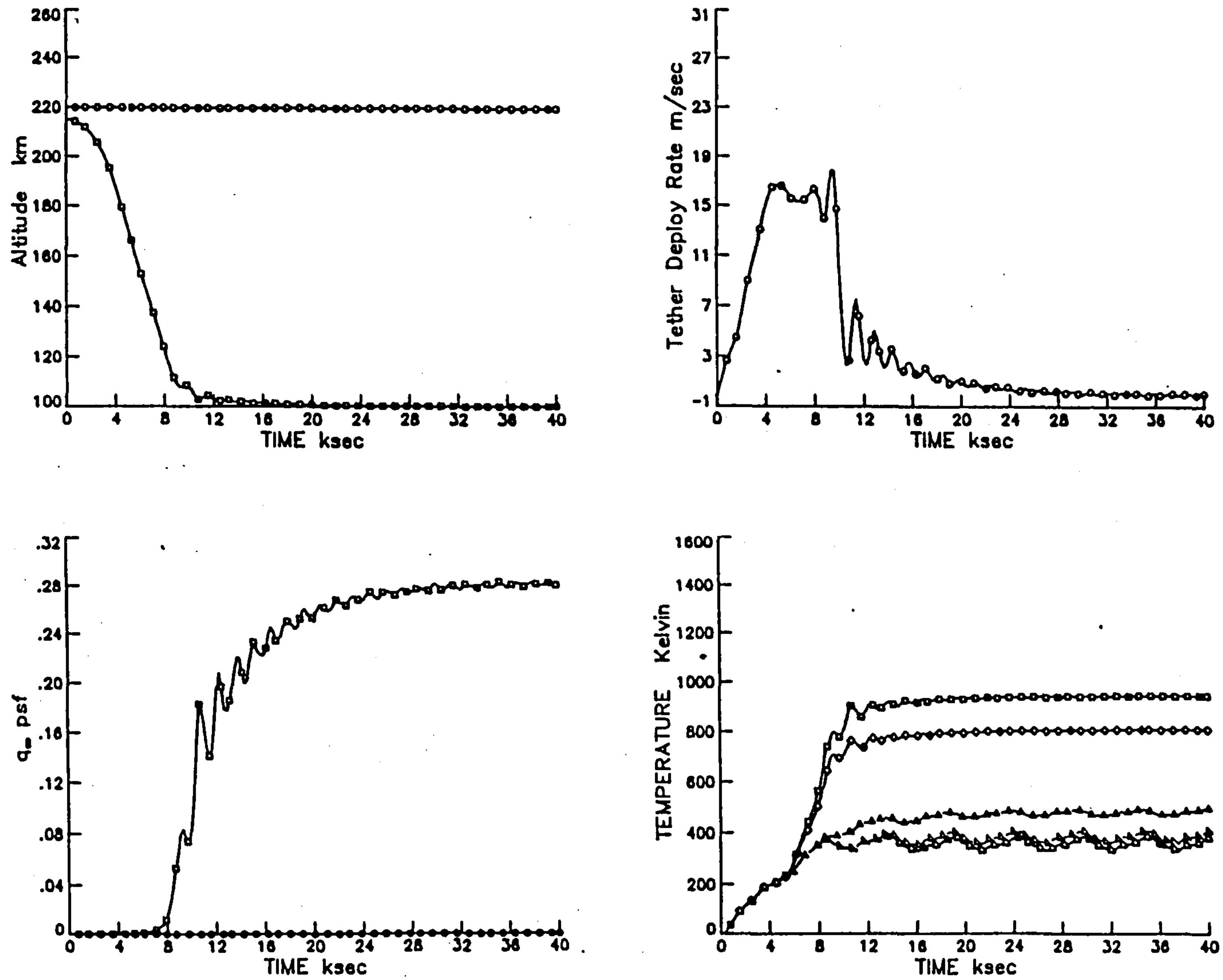
While the justification for the STARFAC program is established and the feasibility of the concept has been demonstrated, the successful accomplishment of any such flight research program is dependent on the acquisition of the required data. In the case of STARFAC, the acquisition of aerothermodynamic and atmospherid data is at altitudes between 90 km and 200 km. Such research in the rarefied upper atmosphere introduces instrumentation requirements that have not been fully addressed or solved in either ground facilities or flight systems. STARFAC instrumentation must be capable of obtaining data over a broad range of atmospheric and flight conditions and be compatible with the size of the flight system. The development of instrumentation to accomplish STARFAC research was identified as a critical supporting technology.

In order to define instrumentation requirements and to establish recommendations for development activities, a comprehensive study was initiated to define both science and engineering parameters requiring monitoring and to assess the state of the art of candidate measuring techniques. Interim results of the study have been reported [32,33,34] and are also summarized in this report. Hypersonic flight experiments to date have relied primarily on vehicle surface temperature and pressure measurements and on computer modeling to predict vehicle performance. This has obviously been successful for contemporary vehicles such as the STS; however, the development of more advanced systems requires an understanding of gas phase chemical reaction on the vehicle surface and of gas related effects on vehicle performance. Furthermore, catalytically induced gas phase interactions on the surface and exchange reactions between gas and solid phase atoms can cause significant localized heating which impacts thermal protection surface design requirements and also influences temperature dependent flight properties. Ideally, these measurements will be nonperturbing to the flow and will extend from the gas-surface interface to the edge of the boundary layer if it exists.



Satellite Ht. = 110 km

Figure 44. STARFAC mission parameters I.



Satellite Ht. = 110 km

Figure 45. STARFAC mission parameters II.

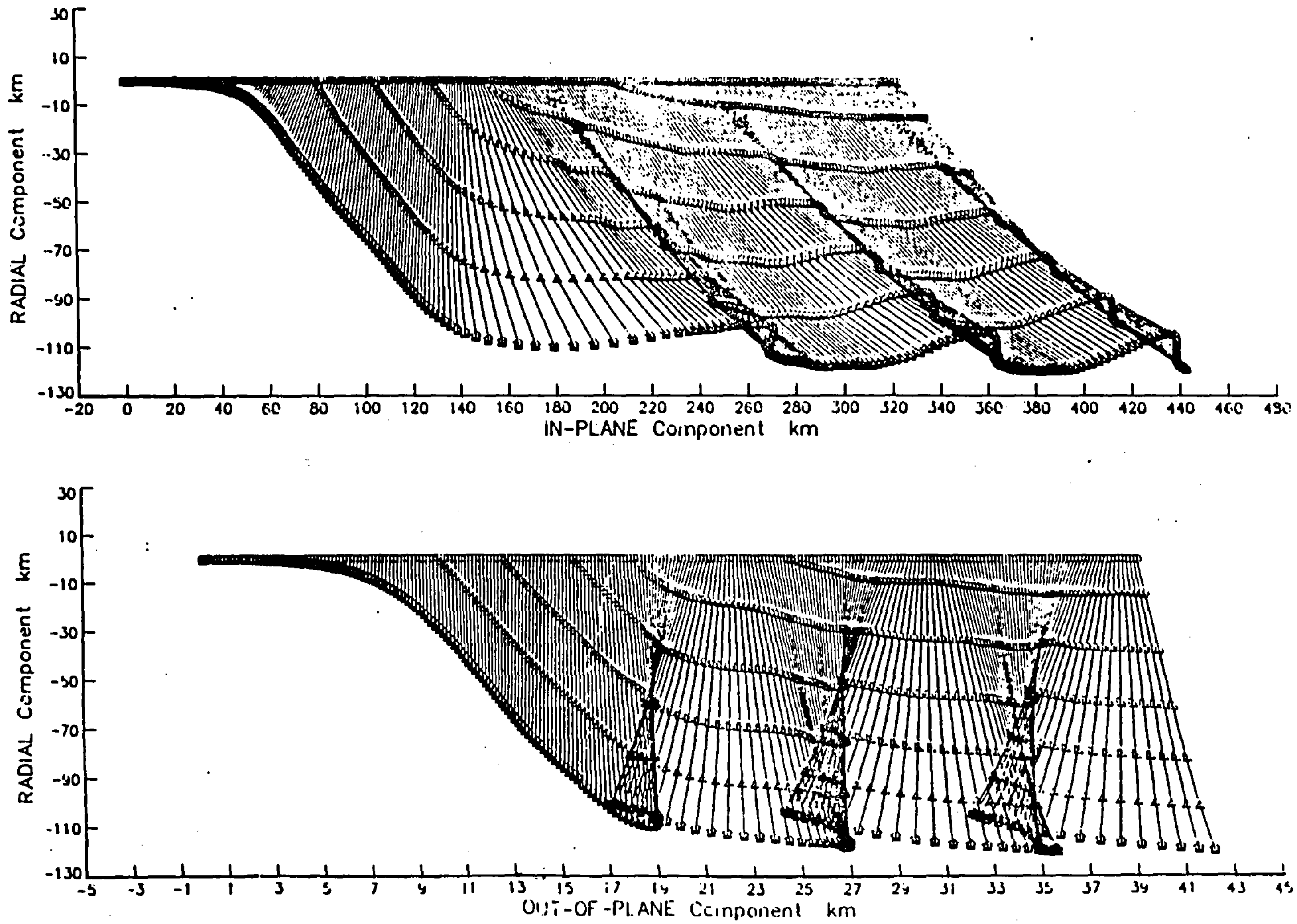


Figure 46. STARFAC inclined orbit simulations.

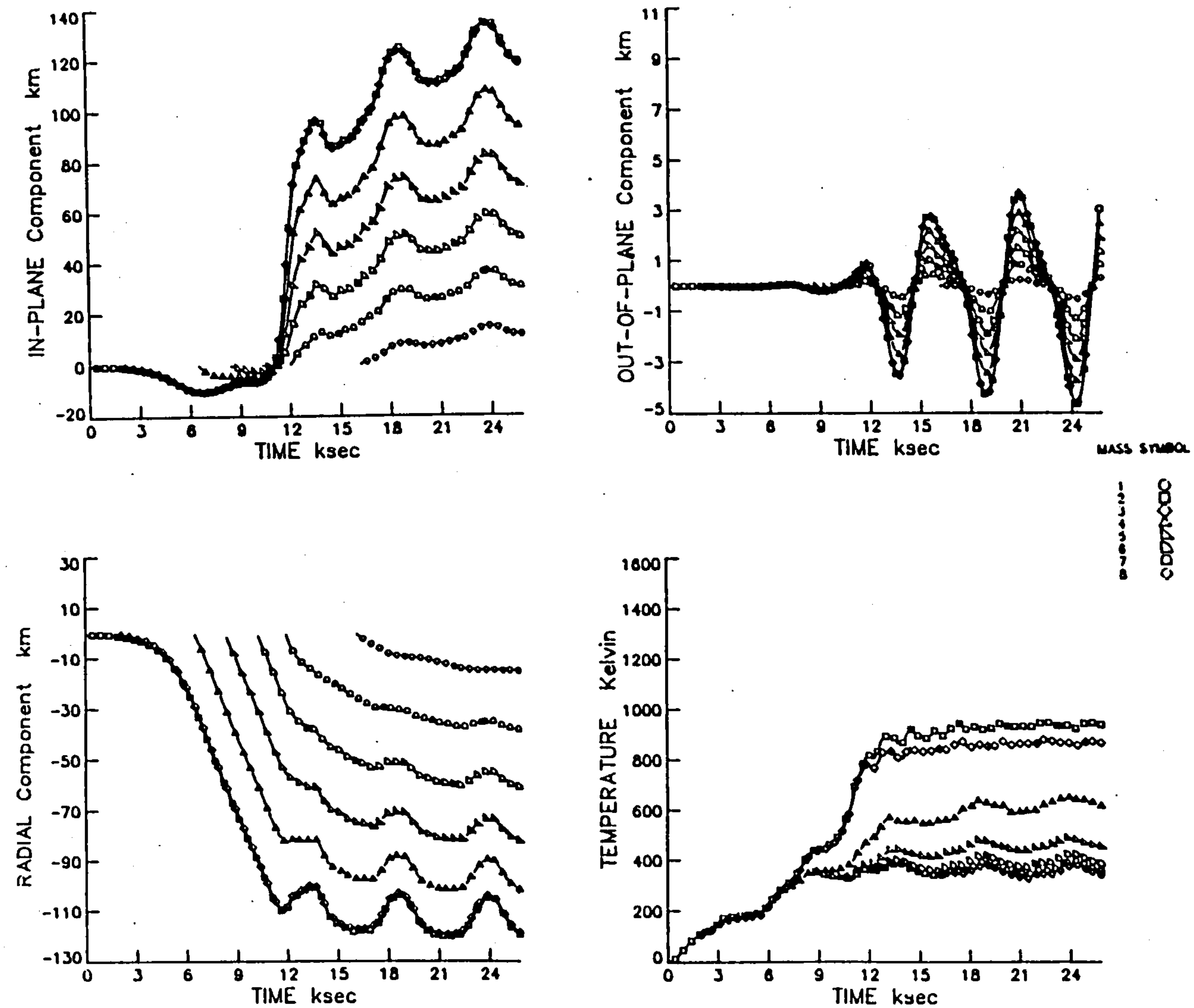


Figure 47. STARFAC inclined orbit simulations.

TABLE 14. STARFAC SCIENCE MEASUREMENTS

CURRENTLY IDENTIFIED MEASUREMENTS	CANDIDATE METHODS UNDER CONSIDERATION	PROJECTED R&D REQUIREMENTS	
		EXTENDED	MODERATE
SURFACE TEMPERATURE DISTRIBUTION	THERMOCOUPLES.		*
HEAT FLUX RATE	THERMOCOUPLES, CALORIMETERS	*	
SURFACE PRESSURE DISTRIBUTION	CAPACITANCE, VARIABLE RELUCTANCE		*
FREE STREAM GAS ANALYSIS	FREE STREAM MASS SPECTROMETER	*	
BOUNDARY LAYER GAS ANALYSIS	BOUNDARY LAYER MASS SPECTROMETER	*	
FLOW-FIELD PROFILING	RALEIGH SCATTERING, IR, LASER FLOURESENCE	*	
GAS DENSITY	PRESSURE, TEMPERATURE, MASS SPECTROMETER MEASUREMENTS		*
BOUNDARY LAYER TRANSITION	PRESSURE, TEMPERATURE MEASUREMENTS		*
WALL CATALYSIS	MASS SPECTROMETOR, TEMPERATURE MEASUREMENTS		*

TABLE 15. STARFAC ENGINEERING MEASUREMENTS

CURRENTLY IDENTIFIED MEASUREMENTS	CANDIDATE METHODS UNDER CONSIDERATION	PROJECTED R&D REQUIREMENTS	
		EXTENDED	MODERATE
TETHER TENSION	TENSIONOMETERS, ACCELEROMETERS		*
TETHER TEMPERATURE	REFLECTED ACOUSTIC WAVE PROPOGATION	*	
SATELLITE SURFACE TEMPERATURE	THERMOCOUPLES		*
HEAT TRANSFER RATE	THERMOCOUPLES, CALORIMETERS	*	
SATELLITE INTERNAL TEMPERATURE	THERMOCOUPLES, RADIOMETERS		*
DYNAMIC SURFACE PRESSURE	CAPACITANCE, VARIABLE RELUCTANCE		*
INTERNAL PRESSURE	THERMOPILE, CAPACITANCE		*
ACCELERATION (DRAG)	ACCELEROMETERS, GYROSCOPES		*
SATELLITE COORDINATES	LASER RADAR	*	
SATELLITE / STS COMMUNICATIONS	FIBER OPTICS, ELECTRONIC, LASER	*	

The measurements, which have currently been identified, include both the engineering measurements necessary for control and housekeeping of the tether system, and the scientific measurements necessary to investigate the aerothermodynamic energy and momentum transfer to the satellite. While some of these methods are well established, all are expected to require at least a moderate amount of development to meet specific STARFAC requirements.

The most difficult of the engineering measurements which have currently been identified is the determination of temperature distributions along the tether when the satellite is deployed to altitudes below 125 km. Since surface temperatures at this altitude can be as high as 900°K, a portion of the tether will of necessity be consistent with these temperatures and will probably be metal or metal composite (e.g., quartz clad high strength metal wise). The tether diameter and weight restrictions preclude the use of multiple thermocouples, and radiometry is not presently considered a viable solution. The temperature dependence of the propagation of acoustic waves through the material, when reflected from periodically spaced acoustic reflectors, is being examined as a potential measurement method. In this approach, the time between the emission of a narrow sound pulse and the reception of a portion of the reflected pulse should be indicative of the temperature of the material, although the effects of changing tension must also be considered.

3.4.5.8 Summary and Conclusions

The feasibility of tethered "wind-tunnel" concepts proposed by the STARFAC has been demonstrated, and the STARFAC-Phase I has been shown to be a viable concept to complement other flight programs proposed to obtain upper atmosphere aerothermodynamic and atmospheric data. It has been shown that STARFAC provides a significant advantage since it has the capability to obtain continuous, steady-state, data on a global basis and, therefore, produce an extensive aerothermodynamic/atmospheric data base. This feasibility demonstration has been accomplished through the modification and utilization of the tether system simulation program SKYHOOK to study tether satellite missions at altitudes between 200 and 100 km. The results of these studies have defined (1) the initial mission envelope of the STARFAC-Phase I concept: to use the baseline configured TSS with minimum modifications; (2) the need to define optimized and control laws and timelines to accomplish orbiter/STARFAC missions within the operating and safety constraints imposed by the STS; (3) the requirements to develop a high temperature tether capable of accomplishing missions at altitudes less than 125 km, and finally (4) that the incorporation of lift and/or propulsion into the tethered research-STARFAC-Phase I body may produce a potential for mission envelope expansion to lower altitudes and velocities higher than orbital.

As a result of these studies, it is concluded that the continued development of the tethered system concept and capabilities will provide an upper-atmospheric aerothermodynamic research capability not achievable from any other source.

4.0 TETHER SYSTEMS AND OPERATIONS

The accommodation of tether systems and of the associated operational requirements constitute an important element in assessing the impact of tether applications on the space station. The physical size and characteristics of these systems can vary depending on their planned usage. A simple disposable payload tether system can have a mass of a few hundred kilograms; a satellite deployer and retriever can have a mass of a few thousand kilograms; and finally, a tether system to deploy an orbiter and retrieve it can have a mass of several ten thousand kilograms. Each one of these tether deployer systems could play a role on the space station.

In the following sections these systems will be described.

4.1 Tethers (By G. von Tiesenhausen)

Obviously, the tether is the central element of any tether system. It is the link between two or more orbiting masses and, during deployment and retrieval operations it transfers angular momentum from one mass to the other. During steady state operations it causes two or more masses to move in concentric orbits. The tether is under tension at all times. Its cross section is planned to be cylindrical in shape (untapered) with a maximum deployed length of 150 km and a maximum tension of 18,000 N.

4.1.1 Tether Tension

With an assumed massless tether, the tether tension T is:

$$T_1 = 3 \times \text{Payload Mass (kg)} \times \underset{\text{(from C.G)}}{\text{Tether Length (m)}} \times (\text{Orbital Rate})^2\ (s^{-2}) \quad .$$

If the mass of the tether is included add:

$$T_2 = 1.5 \text{ Tether Mass Per Unit of Length } (kgm^{-1}) \times (\text{Length})\ (m)$$
$$\times (\text{Orbital Rate})^2\ (s^{-2}) \quad .$$

4.1.2 Tether Dynamics

If a tether is displaced from the local vertical as it occurs during deployment and retrieval, it will librate in and out of plane. Since the restoring forces on the tether increase with tether length, the libration periods are independent of length and are:

<u>In Plane:</u>

$$\text{Period} = \frac{2\pi}{\sqrt{3} \times \text{Orbital Rate}\ (s^{-1})}$$

Out of Plane:

$$\text{Period} = \frac{2\,\pi}{2 \times \text{Orbital Rate } (s^{-1})}$$

Tether length changes via the deployer system entering the dynamic expressions as damping terms; there, tether deployment is stabilizing the system while tether retrieval adds negative damping to the system and, hence, is destabilizing. Tether dynamic analysis is highly complex. A recent computer manual for this area consists of over 1200 pages. Therefore, no further discussions on this subject are provided here.

4.1.3 Tether Control

Tethers have to be controlled during deployment, station keeping, and retrieval. There are two basic approaches to libration control: tether tension and tether length rate modulation. Both are accomplished by the deployer system, one using a tensiometer, the other using a tachometer. Since, during tether retrieval, the libration angles grow rapidly to substantial amplitudes, control laws alone cannot damp these librations completely but require the assistance of thrusters located at the mass to be retrieved.

4.1.4 Tether Characteristic Velocity and Length

In order to define a figure of merit for tether materials, two significant parameters can be used; both are based on the ratio of material stress to density.

The square root of that ratio is a velocity, which interestingly is equivalent to the circumferential velocity of a rotating tether with two end masses:

$$\text{Characteristic Velocity} = \sqrt{\frac{\text{Design Stress } (Nm^{-2})}{\text{Density } (kgm^{-3})}} \quad (ms^{-1}) \quad .$$

The square root of 2/3 of that ratio divided by the orbital rate gives a length. A tether at that length will reach its stress limit by its own mass, therefore, it could not accommodate any end masses.

$$\text{Characteristic Length} = \sqrt{\frac{\dfrac{2 \text{ Stress } (Nm^{-2})}{3 \text{ Density } (kgm^{-3})}}{\text{Orbital Rate } (s^{-1})}} \quad (m) \quad .$$

4.1.5 Electrodynamic Tether Voltage

An insulated conducting tether in low Earth orbit receives an induced voltage E which depends on the Earth's magnetic field strength, the tether length, and the orbital velocity. For low Earth orbit:

$$E = \frac{150\text{–}200\ V}{m} \quad \text{(see section 2.3)}$$

4.1.6 Tether Materials

The most important criterion for a useful tether material in space is an adequate characteristic velocity and a sufficient characteristic length (see section 3.1.4).

At the same time the material must have sufficient flexibility to be deployed from a reel without coiling, and it has to withstand the space environment for days up to periods of a year or more, depending on the mission. Conducting tethers have to have a conducting part in addition to the load carrying component. Table 16 gives elements of the space environment that affect the tether material in many ways.

TABLE 16. SPACE ENVIRONMENTAL EFFECTS ON TETHER

Micrometeorites
Atomic Oxygen
Thermal Effects
Vacuum
Radiation Effects

The most critical consequence of the space environment on a tether is a reduction in tensile strength; therefore, tether material development and testing is of great importance and progressing well.

The tether material presently selected for early missions is Kevlar® with the properties shown on Table 17.

TABLE 17. KEVLAR® 29 MATERIAL PROPERTIES

Density	kgm^{-3}	1440
Tensile Strength	MNm^{-3}	3.450
Tensile Modulus	MNm^{-2}	63,000
Elongation	%	3.6
Dielectric Constant	—	3.4
Specific Modulus	m	4.5×10^{-2}
Char Point	°C	450
Melting Point	°C	614
Dernier/Filaments	—	1500/1000

A minimum structural design factor of safety of 2.0 is required. This may go up to a factor of 7 to 8 in special cases. The tether will be designed for acceptable recoil characteristics in case of a tether break.

TABLE 18. EARLY MISSION REQUIREMENTS ON A CONDUCTING TETHER

Maximum Operational Load	= 500 N
Safety Factor	= 4
Electrical Resistance	$\sim$ 0.2 - 0.02 Ω m^{-1}
Operating Temperature	= -100°C to +150°C
Insulation Breakdown Voltage	= 10 - 50 kV
Maximum Elongation	= 5 percent
Breaking Strength	= 1800 N

Future tether applications requirements for the space station are given in Table 19.

TABLE 19. SPACE STATION REQUIREMENTS ON THE TETHER

Tether Length:	For Orbiter Deployment	= 65 km
	For OTV Deployment	= 150 km
Tether Tension:	For Orbiter Deployment	$\sim$ 18,000 N
	For OTV Deployment	

Table 20 gives specific critical subjects in the broad area of tether materials and configurations which require further work.

TABLE 20. TETHER MATERIALS AND CONFIGURATION TECHNOLOGY

- Measurement and Cataloging of Tether Materials Properties
- Tether Protective Coatings
- Electrodynamic Tether Insulations
- On-Orbit Tether Repair Concepts
- High Strength Tether Configurations

The tether will generally be designed for multiple reuse for all planned tether applications at the space station. The design goal is 100 or more reuses. The Kevlar® tether will be jacketed with Teflon® for abrasion and erosion resistance.

In all applications, an emergency tether release (e.g., guillotine) at both ends of the tether is required for safety.

For certain applications, the tether can be disposed of after deployment in cases where no retrieval is required (see section 4.2.2).

4.2 Deployer and Retrieving Systems (By G. von Tiesenhausen)

There are two approaches to a tether system: (1) a combined tether deployment and retrieving system, and (2) a disposable tether payload deployment system without retrieval capability.

4.2.1 Combined Tether Deployment/Retrieval System for Space Station (3)

The system must provide the capability to alternately deploy payloads downward (e.g., shuttle) and upward (e.g., OTV). This means that deployment locations will be required at both the nadir and zenith locations on the space station centerline. Due to the vertical dimension of the station (120 m) the following option was selected: One centrally located reel system which could be alternately directed either up or down. The following description is taken from the MMC study [8].

Figure 48 shows the baseline space station with the addition of the tether deployment system equipment. In this configuration, shuttle is shown berthed at the Earth pointing or nadir end of the station prior to release for downward deployment. The OTV with payload is shown positioned on the top or zenith end of the space station prior to release for deployment upward. Centrally located on the space station structure is the dual mode main reel system. Reaching from this point to each end of the structure are separate leader tethers feeding the two deployment systems (upper and lower). A tether quick release connecting device to be discussed later is located in proximity to the reel. As one system is in use, the leader tether for the other will be disconnected.

Each end of the space station structure is equipped with a tension alignment boom. This boom translates fore and aft on the upper (or lower) end of the space station structure, and in plane with the orbit. Riding on the boom is a translating tension alignment carriage which includes a berthing ring for the Payload Interface Deployment Module (PIDM). As the payload is deployed, the translating carriage will change position as required to maintain alignment of the tether tension with the space station center of mass. This allows the space station in-plane attitude to remain vertical as the tether to the OTV or shuttle payload deviates from vertical during the deployment process. The booms are designed to accommodate up to $\pm 7°$ (slightly in excess of the 0.1 r requirement) of in-plane tether angle. Out of plane angular deviations for these missions are minimal, therefore, no out of plane alignment provisions are included.

For purposes of simplified assembly in space, the tether system has been designed in four modularized subsystems:

1) Reel drive assembly

2) Reel with tether

3) Upper tether alignment assembly

4) Lower tether alignment assembly.

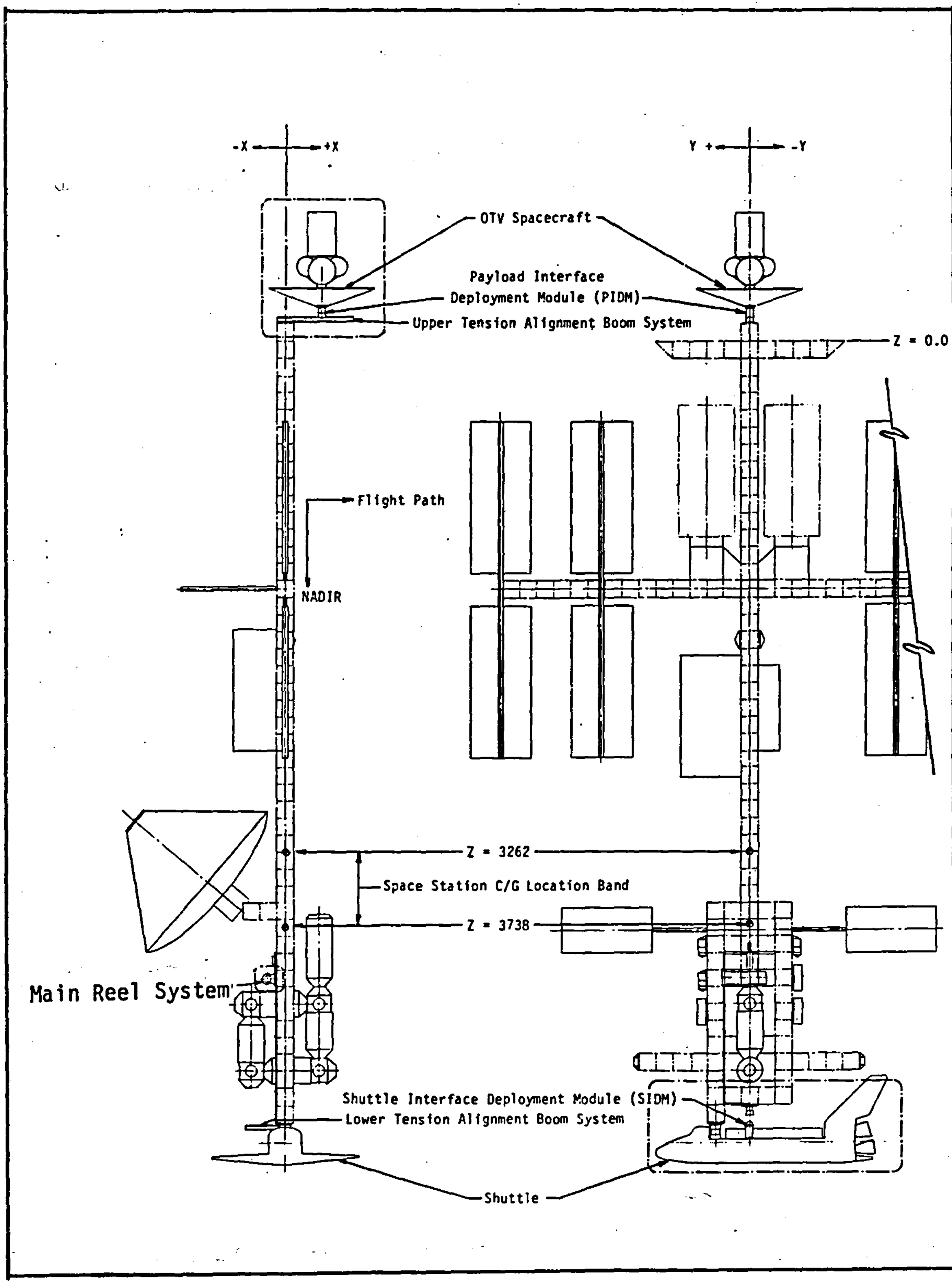


Figure 48. Space station with dual mode tether deployment system [8].

These subsystems are brought up as preassembled units to be attached to the structure by standardized fastening devices. It is anticipated that such devices will be standardized throughout space station for attachment of components. The reel module with tether will be removed and changed out as a unit for tether replacement.

The installation of the interconnecting tether between the reel assembly and the boom assemblies will be performed by EVA.

Attached to the lower end of the space station structure is a standard shuttle berthing interface. This location has been selected to position the shuttle in an ideal location for the installation of the Shuttle Interface Deployment Module (SIDM). The SIDM could also be installed onto the shuttle at other berthing locations on the space station. This SIDM attachment interface location is forward of the shuttle center of mass. This is to cause the shuttle to hang on the tether in a nose up atitude so as to avoid any danger of the tether fouling the shuttle tail structure during tether deployment and release operations. Installation of the SIDM to the shuttle will require EVA to mate the latches and to mate the OMS propellant transfer lines.

The corresponding attachment of the OTV spacecraft to the upper PIDM will be somewhat different than for the installation of the SIDM onto the shuttle. The OTV mission stack to be deployed will be transported from designated assembly and servicing areas to the upper deployment area by the space station traveling manipulator. The manipulator will place the mission stack onto the PIDM and the retention latches will be closed by remote control. After the OTV mission stack has been attached to the PIDM, which in turn is held by the alignment boom system, the manipulator can be detached and moved out of position.

The PIDM will differ from the SIDM with respect to its spacecraft interface configuration. Also, there is no PIDM requirement for an OMS propellant scavenging system. The functional requirements for on-board systems such as the propulsion system required for retrieval and communications will be similar.

Figure 49 shows the reel system assembly. The assembly is located on the trailing side of the space station structure. This system includes the reel, reel motor/generator, radiator, tether leader exchange mechanisms, tether control unit and guide pulleys (Figs. 50 and 51).

Space Station Tether System: The system is configured to be transported by the Orbiter and installed/berthed on the space station without needing any change to its arrangement.

It contains the same basic elements seen in an Orbiter-based system. The significant difference is the size and weight of the cable drum, which in the case is approximately 20,000 lb with cable. To minimize the weight of the structure for Orbiter transport, the drum bearing shaft is integrated into the cradle as the principal beam between Orbiter trunnion points. Since this beam will load the system weight into the Orbiter for both pitch and longitudinal loads, the cradle structure in general can be minimized for Orbiter flight loads in not having to provide load paths for the significant drum weight.

The deployable ASE has its own Orbiter support trunnions which will introduce its vertical loads directly into the Orbiter while its longitudinal and yaw loads will be transmitted through the fixed ASE cradle structure.

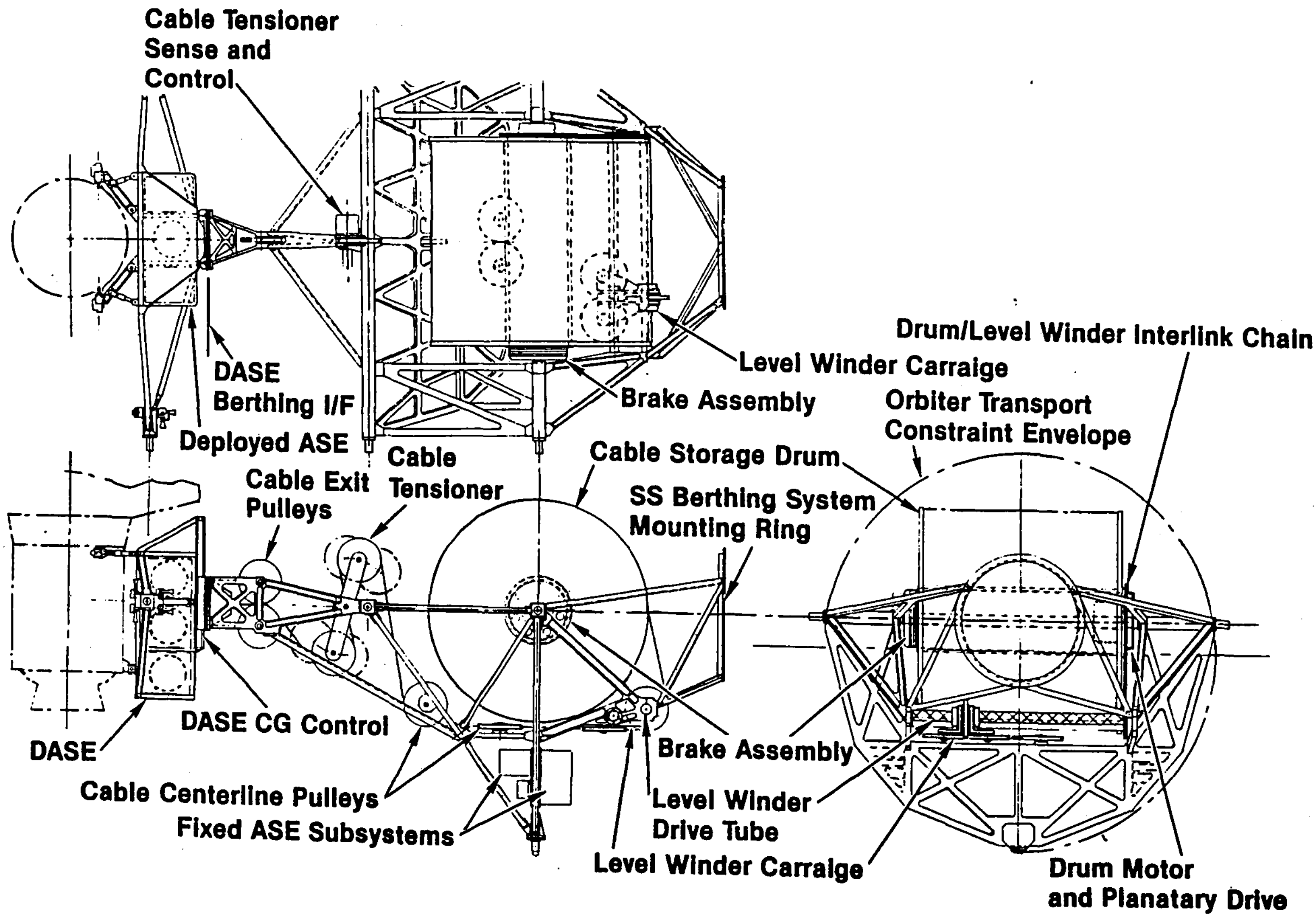


Figure 49. Space station-based tether system.

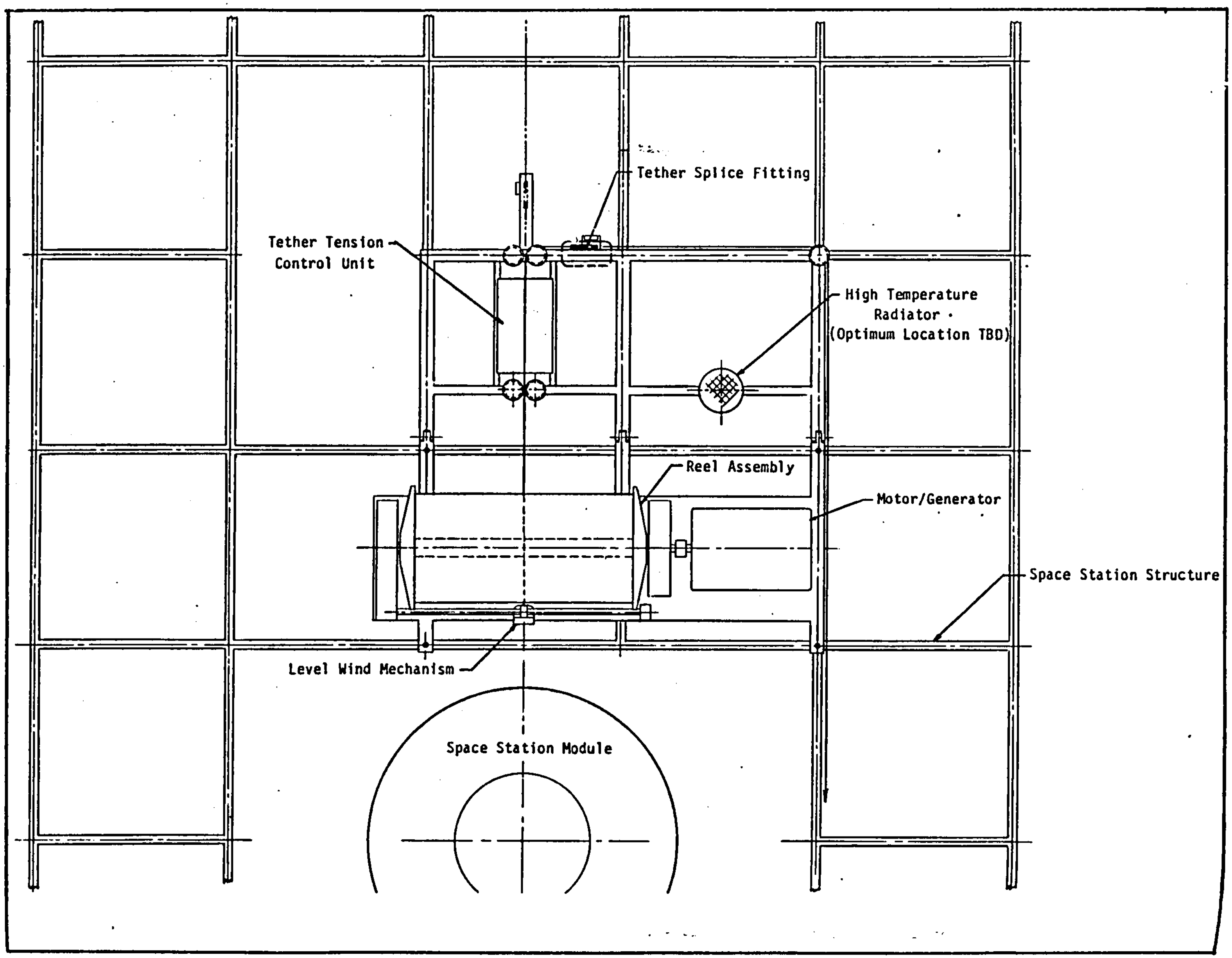


Figure 50. Tether reel system installation [8].

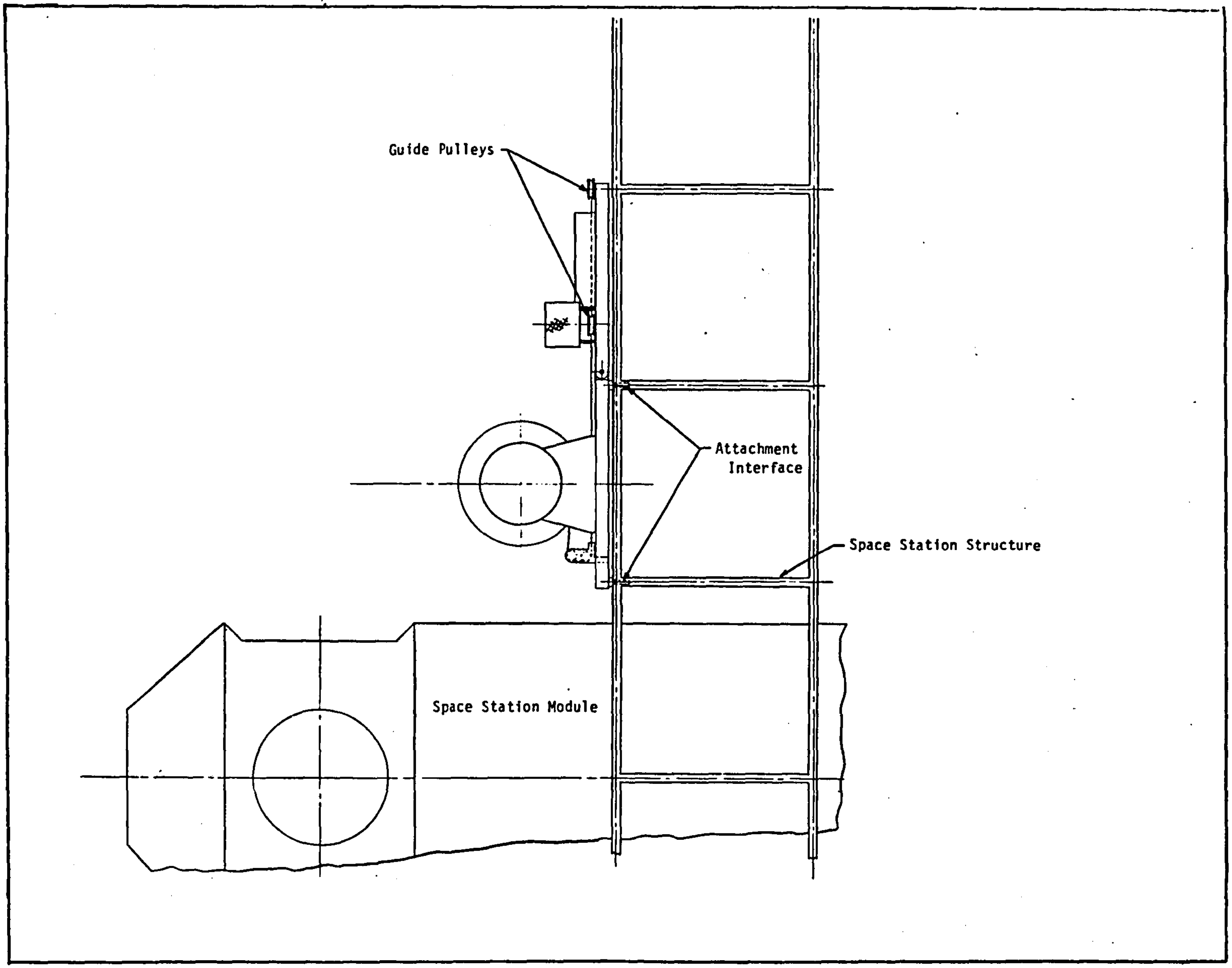


Figure 51. Tether reel system installation [8].

Reel: The reel is sized to hold up to 150 km of Kevlar® tether. The tether will be teflon jacketed to prevent long term degradation from exposure to atomic oxygen. There is adequate space for a larger capacity reel if needed.

Reel Motor/Generator: The reel motor sizing is dependent on power generated during the deployment phase and the requirement to develop adequate braking torque to halt the deployment at any stage. Depending on the amount of time available for OTV deployment, it is anticipated that the power rating of the motor/generator drive will be in the range of 55 to 110 kW.

Radiator: The radiator is a high temperature electrical resistor bank which receives electrical power from the reel drive motor/generator during deployment and converts it to thermal energy that is then radiated to space as waste heat. This radiator can be located away from the proximity of the reel system and can be placed on the space station in a location selected to optimize its view factor to space and to avoid illuminating sensitive areas with thermal radiation.

Tether Splice Fitting: Figure 52 shows a method of connecting the main reel tether to either the downward or upward tether leader deployment assemblies. Each of the leader tethers and the main reel tether are spliced to their respective connector fittings. The mating fittings connect together by a hook and pin method. To mate the two fittings, they are oriented at 90 deg to each other which allows the hook to fit over the pins. The spring plunger is then retracted allowing the hook to fall in place over the pin. When the two fittings are returned to an in-line position they cannot be separated as the hook end will bear on the opposite fitting bearing face. The assembly is designed to pass over the 12-in. diameter guide pulleys. This will occur during the first 200 ft of tether deployment when both velocities and tensions are low. Guides will be incorporated at each pulley to insure that the fitting will pass over the pulley in a flat position.

Tether Control Unit: This unit will contain tether control equipment for measuring tether velocity, tension, deployed length and a device to provide tension control at the reel during intervals of low tension operation. Tension control will be required to insure smooth rendering of the tether onto the reel.

As the tether is deployed, OMS propellant (N_2O_4 on the right side and MMH on the left side of the shuttle) will be transferred to the appropriate receiving tanks on the SIDM strong back. At any time during the deployment operation, only as much propellant will be transferred to the SIDM scavenging tanks as has become surplus to shuttle deorbit requirements. In the event of tether system malfunction or other abort situation, the SIDM could be released from the orbiter and adequate propellant would always be available on-board the shuttle to complete deorbit and reentry. Under normal conditions, 6500 lb of propellant will be transferred and retrieved to the space station for use by other systems (such as the OMV).

Figure 53 shows the placement of the OTV on the upper tether deployment system. This assembly is the same design concept as the lower tether deployment system except for increased boom length. The additional length is required because the center of mass of the space station is located closer to the lower end of the space station. The added length permits the same range of angular alignment for the tether angle during deployment.

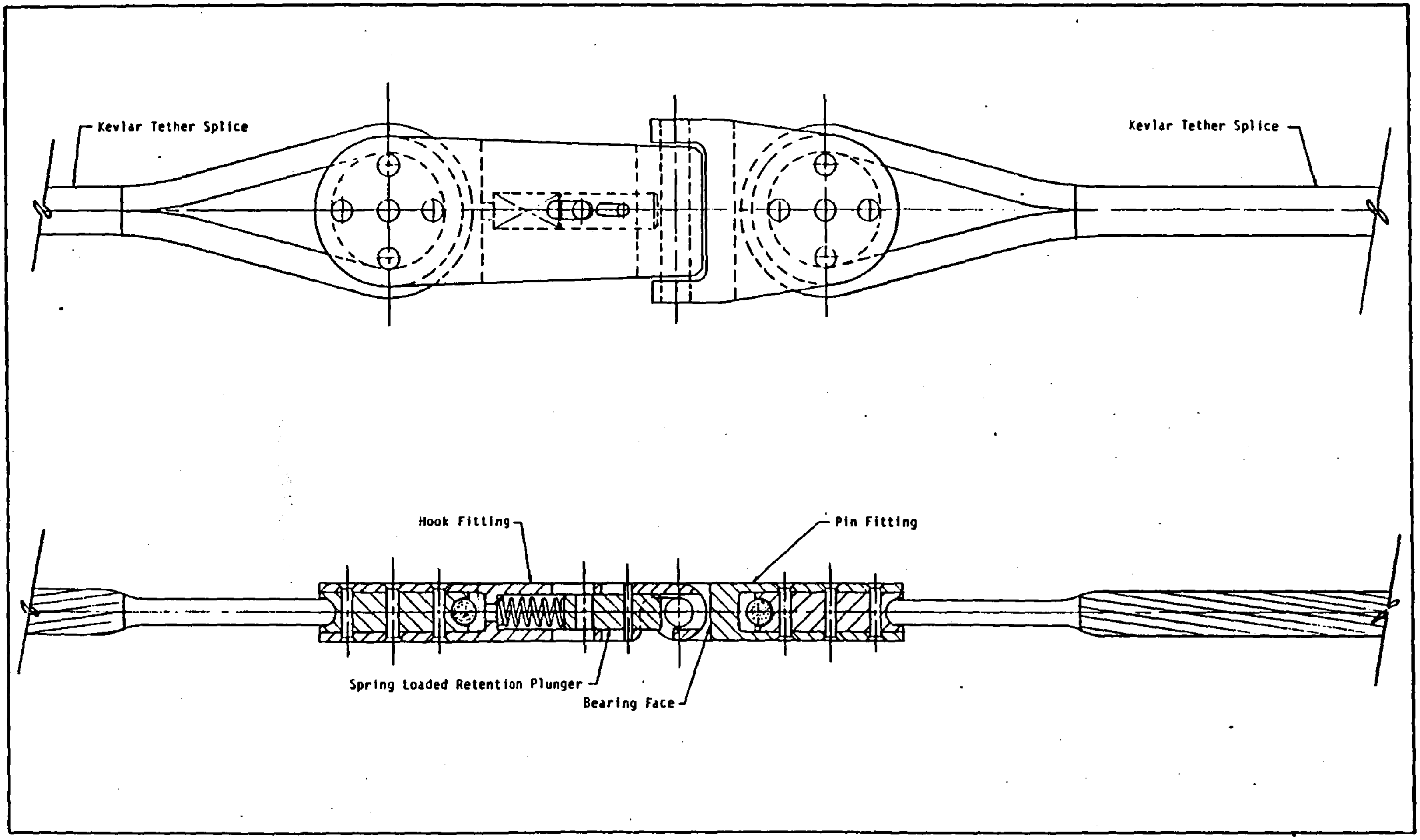


Figure 52. Tether splice fitting [8].

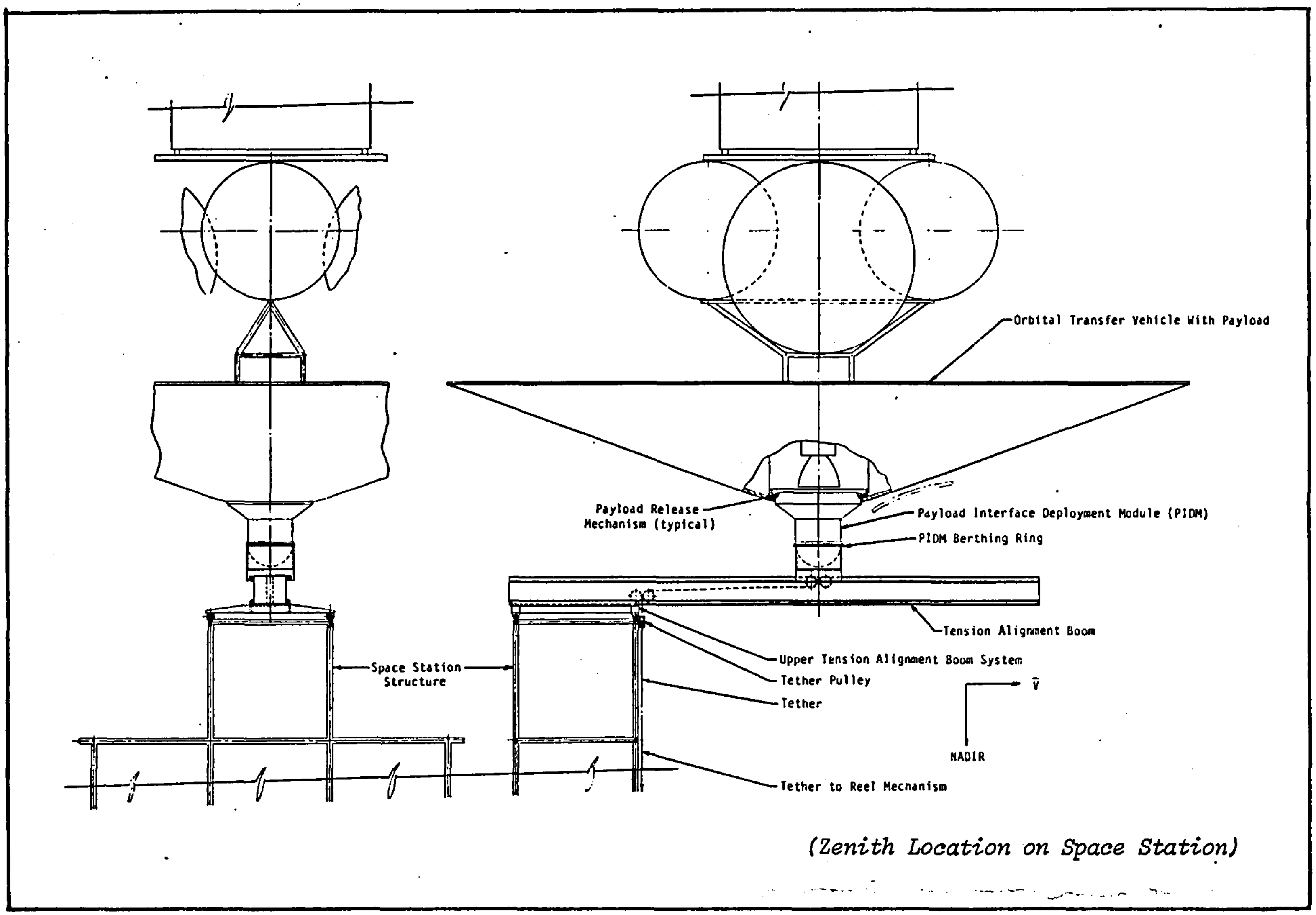


Figure 53. OTV tether deployment system [8].

The OTV will be placed on the PIDM by the space station traveling remote manipulator and latched in place. On release of the latches, the OTV will separate with the aid of in-line thrusters in the PIDM. These thrusters will control the separation until tether tension reaches approximately 4 lb at which time the gravity gradient tension forces will be used to complete the deployment process.

An analysis was made of the loads in the space station truss structure for the upper tether deployment system using a tension of 18,000 N and with the tension alignment boom and carriage at maximum excursion (14 m from center line). The resulting strain induced in the upper end of the space station keel structure caused 0.5 m of displacement from the unstressed condition. This is over a length of approximately 90 m from the space station center-of-mass to the upper deployment system. This is a preliminary estimate based on assumed characteristics of the space station structure and will need reverification. It has been deemed an acceptable effect for this study. In actuality the maximum angular displacement and the maximum tension levels will not occur at the same time and the condition analyzed is an extreme worst case.

Guide Pulleys: Pulleys will be located to direct the tether properly and will be a minimum of 12 in. in diameter and wide enough to accommodate the tether to leader interconnect fittings. All pulleys will be enclosed to prevent jamming. Enclosures for pulleys, tether and reel assembly are omitted from drawings in this report.

Additional Shuttle Docking and Deployment Elements: Figures 54 and 55 show a close up view of the shuttle berthed to the lower end of space station. This berthing location is ideally located for installation of the SIDM on shuttle from the lower tether deployment assembly. The shuttle interface station location shown will always be located forward of the shuttle center of mass resulting in a shuttle nose-up hang angle attitude at all times. The nose-up attitude angle can be controlled by shifting the SIDM location forward or aft. The SIDM attaches to the shuttle sill rails by means of the SIDM latches located on the aft end of the SIDM. The forward end of the SIDM bears on the sill bearing pads with no physical attachment. With the shuttle hanging on the tether in a nose up attitude position the SIDM latches will always be in tension and the bearing blocks in compression. When the latch pins are pulled by the pyrotechnic pin pullers, the SIDM will be pulled away by the tether tension. Installation of the SIDM onto the shuttle as shown here will require EVA.

The tension alignment boom translates on rollers attached to the space station support structure. The tension alignment carriage in turn translates on the boom tracks. Motor driven rack and pinion drives will provide the force to translate the carriage and boom and to maintain them in position. These boom and carriage drives will be controlled by the space station attitude determination system to control the in-plane attitude of space station (Fig. 56).

Figures 57 and 58 show an expanded view of the SIDM. The spherical unit on top is shaped to fit the cylindrical berthing interface on the carriage. The shape aids the final retrieval docking of the SIDM after shuttle release. Latches on the alignment carriage berthing ring will secure the SIDM to the carriage for berthing and stowage. The SIDM strong back structural section serves to transfer tether tension loads to the release latch mechanisms at the shuttle sills resulting in vertical loads only at the sill fittings.

Figures 57 and 58 also show the propellant storage tanks for an OMS propellant scavenging system. No attempt has been made to show the propellant transfer interface or disconnect fittings. The propellant tanks shown are the same size tanks as

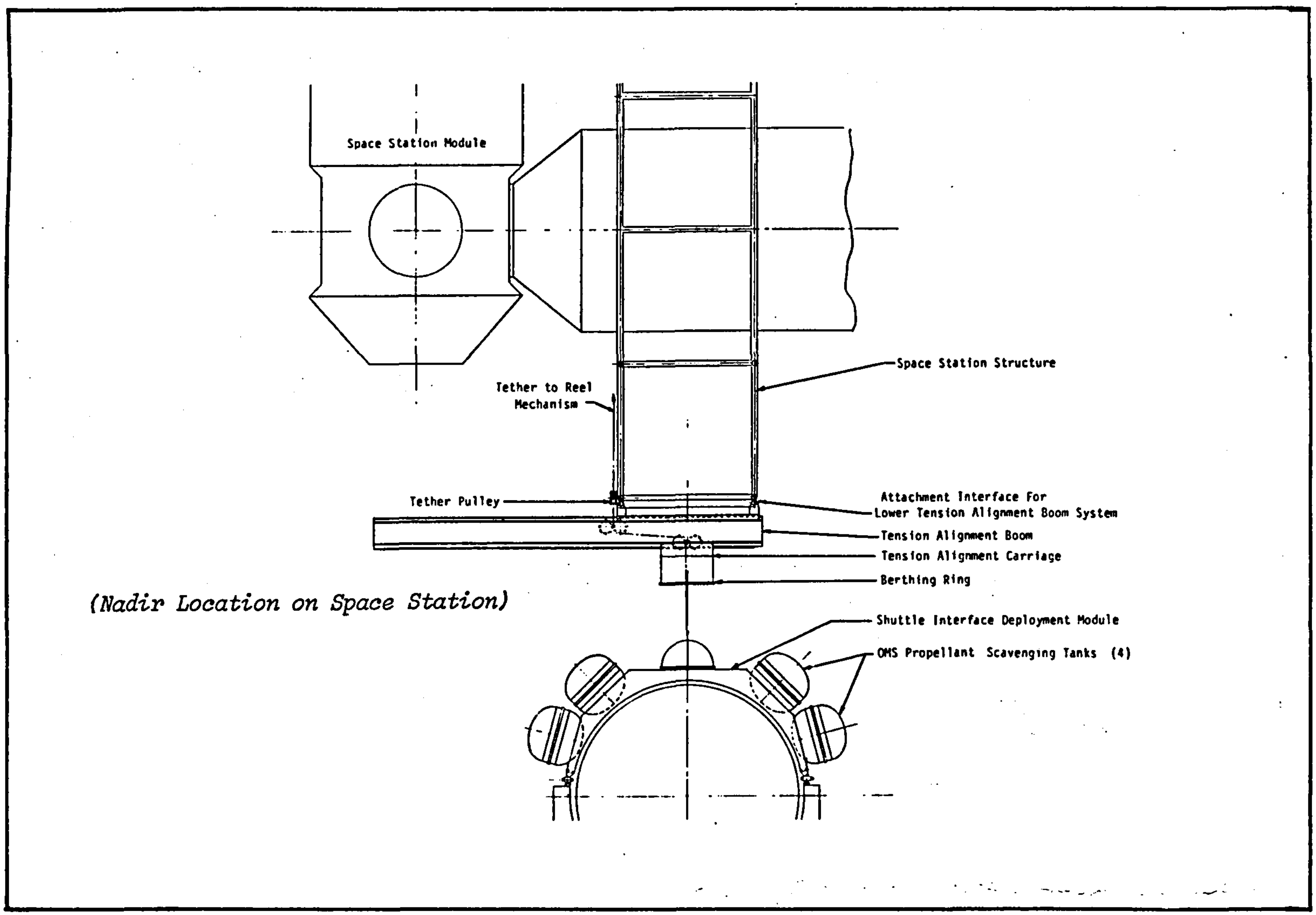


Figure 54. Shuttle tether deployment system [8].

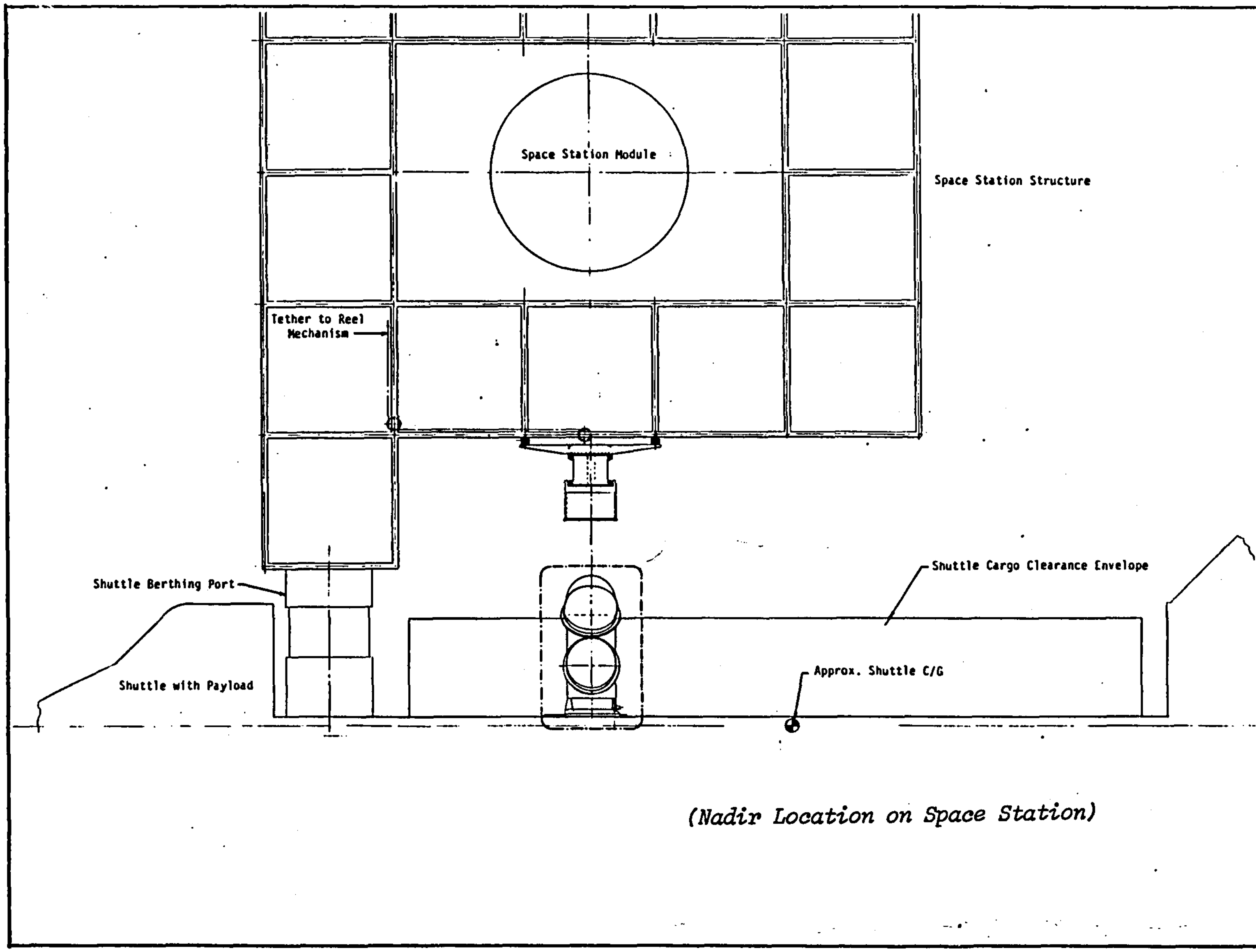


Figure 55. Shuttle tether deployment system [8].

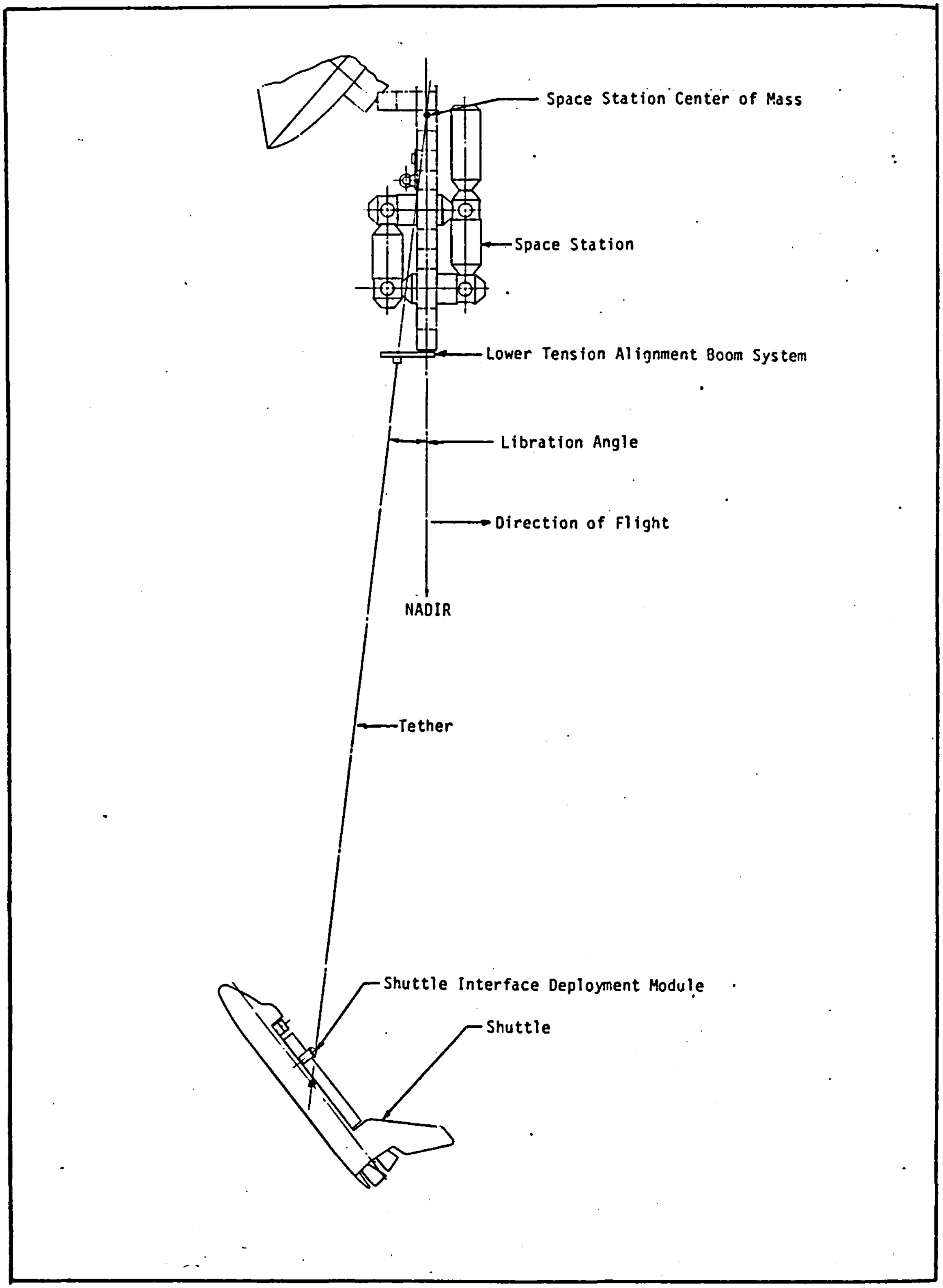


Figure 56. Space station/shuttle attitude during deployment [8].

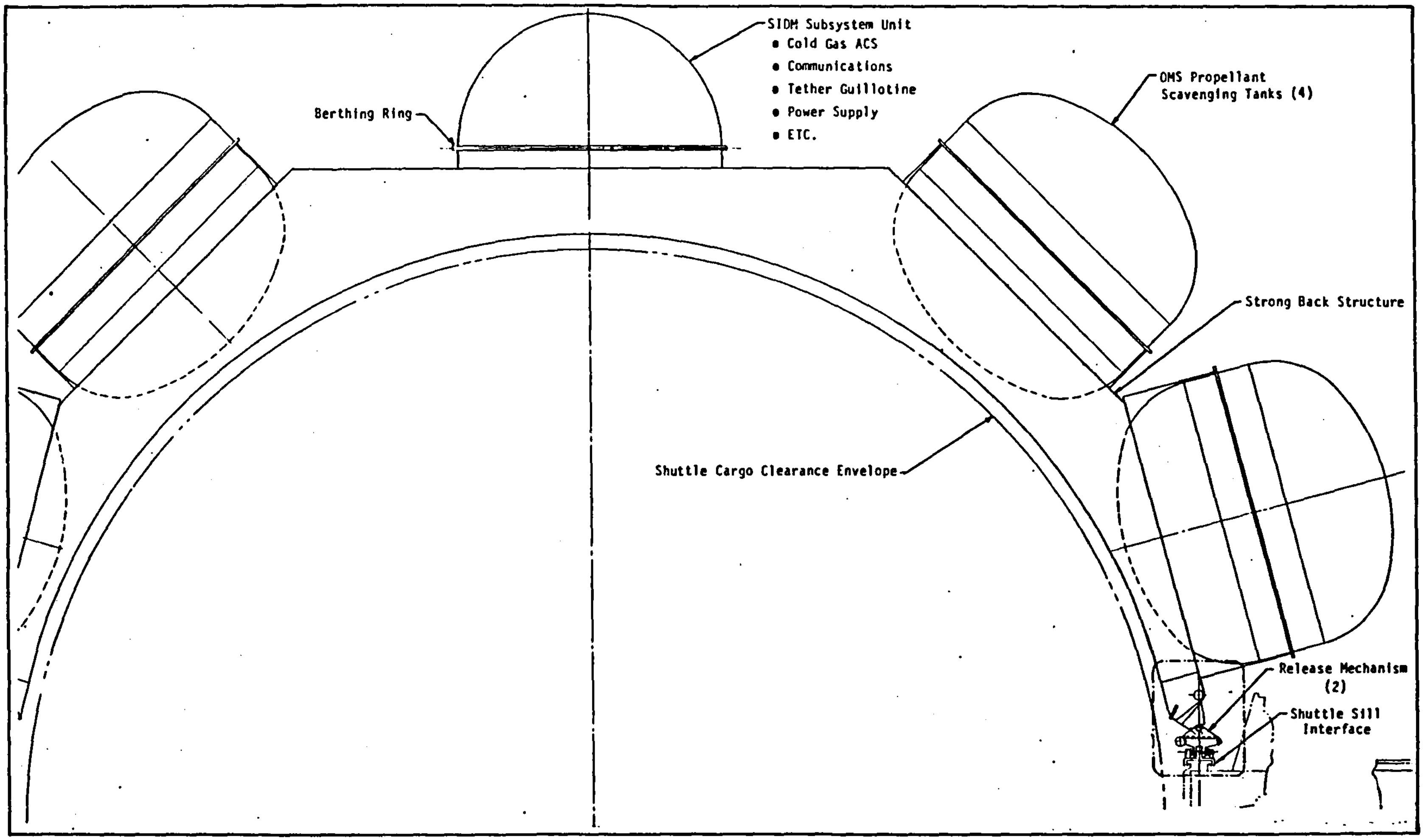


Figure 57. Shuttle interface deployment module (SIDM) [8].

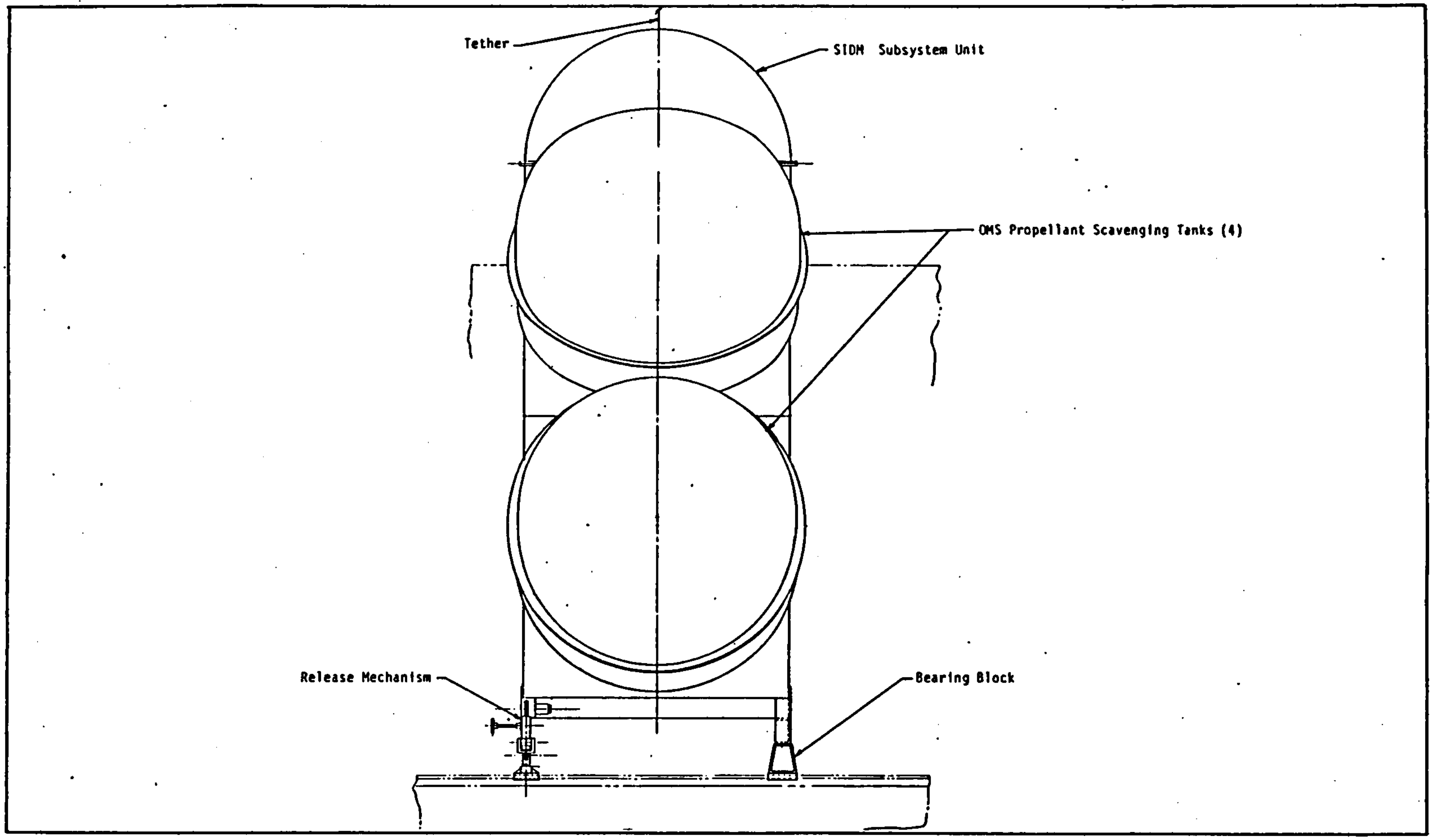


Figure 58. Shuttle interface deployment module [8], side view (SIDM).

those planned for the OMV. The total capacity of the four tanks is 3050 kg, which is an ideal sizing for this application.

4.2.2 Disposable Tether Payload Deployment System [35]

Since the retrieval of tethered payloads places the greatest demands on a tether system, requiring powerful electromotors and associated power equipment, it was only logical to consider payload requirements which involve deployment only.

The disposable tether payload deployment system:

1) Eliminates time-consuming retrievals

2) Simplifies deployer — no motor or level-winder

3) Eliminates retrieval boom and docking gear

4) Minimizes tether degradation — new tether each time.

The system will use low tension deployment and a swinging release tether operation (Fig. 59).

The orbiter deploys the payload with the RMS, lets go, and backs away with a series of small RCS burns. This drops it into a slightly lower and faster orbit and causes the tether to deploy. The range rate reaches a maximum after 45 min and then decreases to a minimum about 35 min after that, near the end of the deployment period. A second RCS burn then reduces the range rate so the tether goes taut gently.

If the tether tension were exactly zero during deployment, the range rate would be negative one orbit after deployment. However, it turns out that a tension under 2 N can modify the payload and orbiter trajectories enough to keep the range rate positive even with 25 ton payloads and 10 km tethers.

After deployment is finished and the tether becomes taut, the assembly becomes a gravity-gradient pendulum. Over the next 30 min the tension gradually increases as the pendulum approaches the vertical. The tether is released at both ends at or near the vertical. The payloads drift apart into separate orbits, with the tether in an intermediate orbit. Within a few hours to days the tether decays and reenters.

Loads increase with the swing amplitude, but for tethers providing delta Vs up to 90 ms^{-1}, the loads are less than 1 percent of launch loads even with swinging tethers. Hence, load differences should be unimportant unless boosting of very delicate fully-deployed structures is desired.

A swing amplitude near 35 deg minimizes the tether mass for a given total energy and momentum transfer. However, the mass is within 2 percent of this minimum for all amplitudes above 17 deg, so this is not a critical function.

Micrometeoroid resistance is an important issue with tethers sized for light payloads, and can be controlling if high reliability is desired. Thus, shorter thicker tethers (and swinging releases) are advantageous.

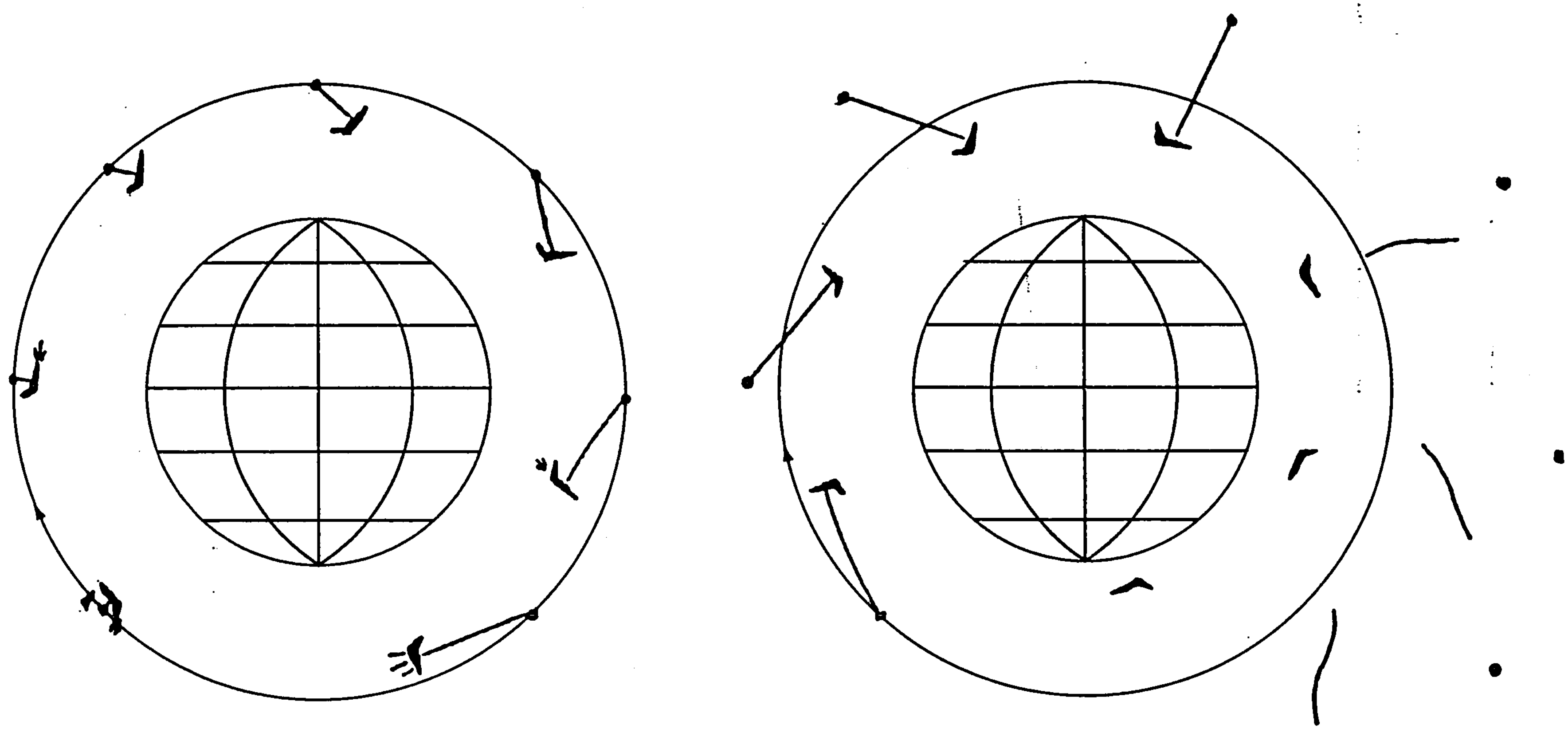


Figure 59. Low-tension deployment followed by pendulum swing and release.

Power dissipation can also be an issue if the deployer mass, volume, complexity, and cost are to be minimized. The energy to be dissipated during deployment is the gravity-gradient potential at the end of a swing. Swing angles close to 90 deg clearly have advantages.

As work on the TSS has shown, it takes considerably longer to retrieve a tether than to deploy it, particularly if there is no actively maneuverable spacecraft at the end of the tether. Cutting the tether loose eliminates this entire operation.

If there is no need to retrieve the tether, a simpler, lighter, and more compact deployer can be used. This can reduce the number of failure modes and increase the reliability of the deployment operation.

The deployable boom on the TSS deployer is primarily needed for final retrieval and docking. If tether retrieval is eliminated, no boom is needed. Proper deployer location plus minor RCS use can provide adequate attitude control for the orbiter during the operations considered here.

Degradation of Kevlar and other high-strength materials in the space environment is a serious issue. Using a new tether each time is a "brute force" approach to the issue, but it may be the most economical one: a tether intended for reuse would have to be slightly heavier, and the added cost of launching it would probably exceed the purchase cost of a new tether.

Performance is estimated for two different cases. In both cases, the assumed "baseline" shuttle performance is 65 klb to 100 n.mi. For mission altitudes over 240 n.mi., direct insertion launch is used. No OMS kits are used. The tether system is the size of a Get-Away Special, and contains 165 lb of tether 5 to 15 n.mi. long (varying with the payload). A safety factor of 3 is used.

In one case, the STS mission is to a "normal" circular orbit. The payload is boosted into a higher, slightly eccentric orbit. This orbit is assumed to be equivalent to a circular orbit that gives the same payload orbital life.

In the other case, the shuttle launches into an eccentric orbit ($e = \sim 0.01$). This has a minor beneficial effect on payload orbital life in its own right, equivalent to a 4 to 5 n.mi. boost, but a major benefit when it is combined with a tether operation.

The actual STS mission altitude is slightly lower (by 3 to 4 n.mi.) than in a nominal mission: it is only the payload which is boosted. This effect occurs on a much larger scale if an OMV is used to boost a payload: this reduces the altitude the orbiter itself can reach by about 50 n.mi. The smaller orbiter-altitude penalty of a tether system may be valuable on multi-payload missions.

Note that if the tether is severed prematurely, the net benefit of the tether scales (within 8 percent) with the tension at the time of release: if a tether breaks at one-half of its design load, about one-half of the boost is still obtained.

The orbiter payload gain by using the disposable tether deployer is given in Figure 61.

4.3 Systems Integration Requirements and Effects (By Kenneth R. Kroll)

Full scale use of tether applications is being considered for the growth space station. As a minimum, incorporating tethers on the space station will have an effect on the space station configuration and dynamics. Some of these effects have been studied for a few individual applications. This section tries to take the wider viewpoint of the integration of multiple tether applications on the space station.

A tether application can be incorporated on the space station either as an add-on to minimize impacts on the space station or as an integrated system to maximize the advantageous features of tethers. A tether application can be considered an add-on as long as it is not applied in an unbalanced way, moving the center of gravity, or as long as it does not require the use or development of space station facilities on the tether. The use of tethered platforms, because they normally do not meet these specifications, will require the tether to be considered as an integrated system. Since no tether application can be considered as an exclusive way of performing a function, the use of tethers as an integrated system should be investigated as a means of improving its competitiveness against the functional alternatives. Competitiveness can be improved by sharing costs, applying complementing functions, limiting interference among tether applications, and increasing the number of applications that would benefit from the use of tethers. The integration of tether applications will have to enhance the space station role as the primary low Earth orbit operations node.

The use of a tether on the space station will require some reconfiguration of that space station. As long as a tether application is an add-on, the amount of reconfiguration required will be minimal. Primarily, this would involve adding mounting structure, power and communications connections, and the tether equipment itself, including the tether reel and motor, tether tension alignment device (a boom or track for attitude control of the space station proper), and control electronics, to the space station. Additional provisions may have to be made for the increased tension in the space station structure and the possibility of interaction with the space plasma at the space station. Sensor locations on the initial space station may have to be moved to provide the proper location for the tether reel mechanism. If the sensors in the initial space station have their view restricted by the tether, an integrated tether system may be required with the sensors being mounted on

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Figure 60. Deployer design concept

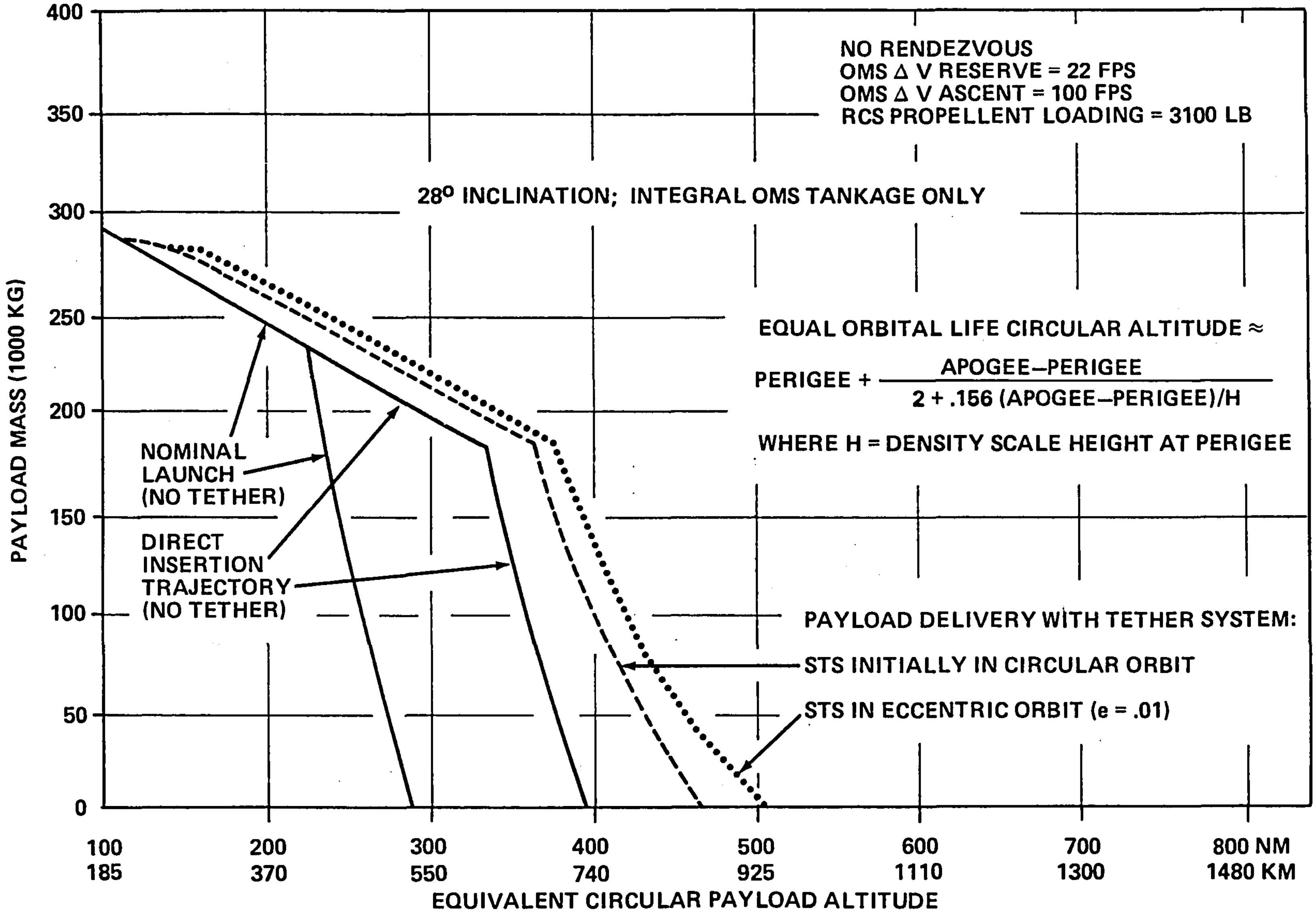

Figure 61. Benefits of GAS-Can-sized tether system to STS.

platforms at the end of the tether. Docking facilities may require reconfiguration to allow docking with the space shuttle while it avoids the tether. An integrated tether system may require the movement of all microgravity work to a location off the center of gravity, which would disrupt the arrangement of modules on the initial space station. If the center of gravity is not at the space station proper, some equipment on the initial space station may need reorientation to account for the presence of a gravity force. If momentum transfer is used, it is possible that systems on the space station proper may temporarily see fairly large gravity levels, up to 10^{-2} g [9], from two different directions. This would make the use of vane surface tension devices in fluid systems very questionable. In addition, provisions will also have to be made for dissipating the energy released by tether deployment and for supplying the energy requried for tether retrieval.

A primary consideration in the integration of tether applications on the space station will be the effect these applications have on the system dynamics. To perform the various functions of the space station, the system dynamics must be controlled. Specific concerns will be maintenance of the space station proper attitude, the prevention of interference or collision of various elements of the tether system, and the maintenance of acceleration limits. A factor may be the limits on the tether tension alignment device movement for space station attitude control, which will limit tether swing to near vertical if the device is far from the center of gravity, eliminating the option of swinging tethers for momentum transfer. The more complicated the system is, the more complicated system dynamics will be. Therefore, the use of tether applications will increase the problems with control of the system. The components of the system should have different natural frequencies. Tether motion control techniques with multiple tether segments must be investigated. An inherent motion damping should be included in the system wherever possible. Motion damping in the tether itself would be especially helpful.

The first option in integrating tethers on the space station will be to maximize the use of add-ons, such as the electrodynamic and momentum transfer applications, to minimize the overall impact to the space station. Using both these applications on the space station is highly desirable, because both momentum transfer for OTV launch and electrodynamic power can use the large amount of momentum derived from space shuttle orbiter deorbit [8]. Can these applications use the same tether to reduce costs? Using the electrodynamic tether as the momentum transfer tether would reduce the amount of momentum transfer possible, because of the tether material characteristics. The use of the electrodynamic tether as part of the momentum transfer tether may require the use of a tether crawler, tether strengthening, and/or disconnecting the electrical connections. Therefore, separate tethers will probably be required to maintain the full momentum transfer performance. The primary problem will be to prevent interference between the applications. As a minimum, this will require that only one tether be deployed from each end of the space station at a time. Side-by-side tether deployment mechanisms appears feasible; however, the tether tension alignment device should probably be a boom instead of a track to prevent interference. These add-on tether applications will result in significant space station orbit changes, which will probably eliminate the concept of formation flying with free-flying platforms. Therefore, while these applications can be considered as add-ons to the space station proper, they will adversely affect the space station system.

The second option for integrating tethers on a space station is to form an integrated tether system, which may consist of platforms that would otherwise have been free-flyers. Figure 62 is an example of a possible integrated tethered space station system. The tethered system can be a means of eliminating or reducing the

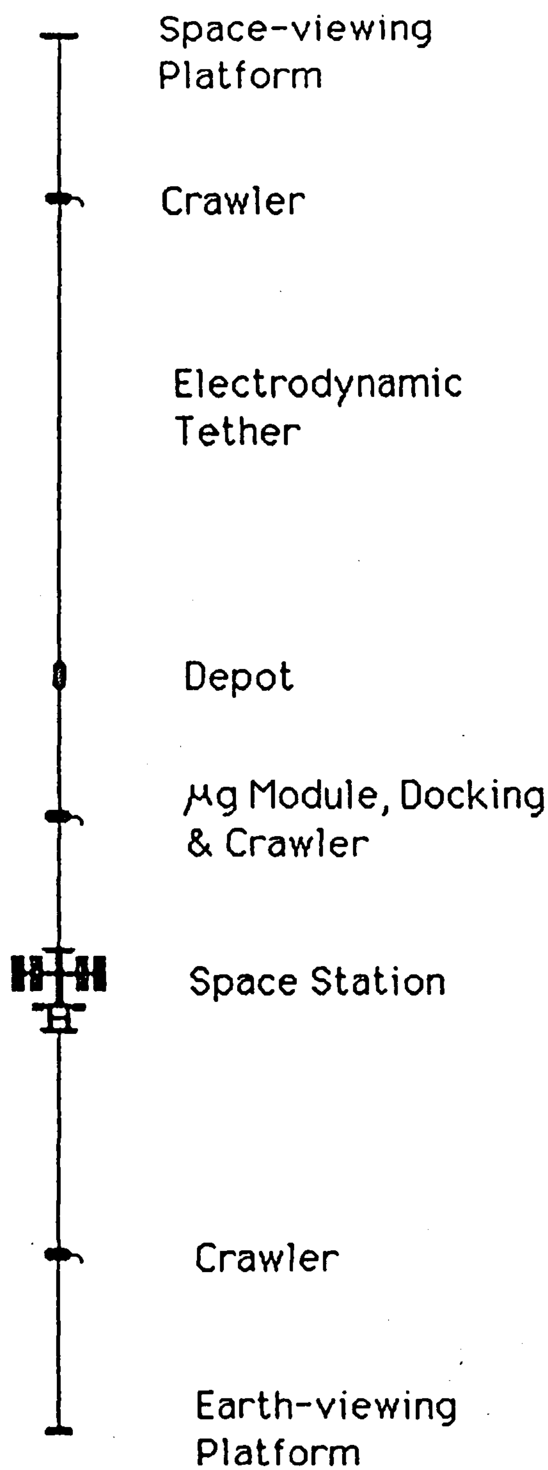

Figure 62. Tethered space station.

reasons why an individual or combination of tether applications cannot be considered as an add-on to the space station. Tether applications can eliminate concern with gravity being induced at the microgravity laboratory by balancing each other to position the center of gravity at the proper location on the space station or by making the microgravity laboratory a tethered platform. As an integrated tether system, each application would be able to share costs involved in developing and delivering the basic tether hardware and operational techniques infrastructure, and the new infrastructure required for access to space station facilities; therefore, improving the competitiveness of tethers for each application. The basic tether infrastructure would provide tethers, deployment mechanisms, and control systems. While the access infrastructure would provide for ferrying between tethered platforms and the supply of utilities such as power and communications.

Other factors deserve consideration in developing an integrated tether system. Tether applications may complement each other. An example is the use of an electrodynamic tether to supply power to the platforms. Trade-offs can be done to determine the proper location for each application which reduces interference among applications and the concern with dynamics on the space station or platforms resulting from ferrying operations. While the ability to disperse is one of the advantages of a tether, operability may determine that some of the applications should share platforms. An example would be sensors and the deployable tether hardware sharing the platform on the end of the permanently deployed tether.

4.4 Operational Requirements (By Kenneth R. Kroll)

The use of tethers on a space station will require some new and modified operational techniques. The tether is a new type of structure to be used in space. It is long, thin, and exhibits a gravity (or a velocity different than the orbital velocity) at locations of the system center of gravity. The operational requirements with a tether on the space station is the least studied of tether aspects. The primary effect has been in the control of tethers during deployment and retrieval for the tethered satellite system. This section tries to extend the consideration of operational requirements to different aspects.

The deployment or retrieval of a tether will probably require monitoring by space station crewmembers; because the control of the system dynamics during these operations will be difficult, entailing the risk of collision between the system elements. Monitoring tasks would include observing system dynamics and verifying deployment mechanism operation. This is similar to the remote manipulator system on the space shuttle orbiter which uses two crewmembers for critical operations such as berthing. If these operations required more than one shift to perform, the expense of these operations will be increased, because the number of crewmembers requiring training in this area would be increased and the amount of time available to other tasks would be decreased. Crew time on the space station will be very expensive. Once deployed, having the crew monitor the tether motion would be quite burdensome. Hopefully, because of limited tether motion when deployed, the monitoring of tether motion can be done with the computer system limiting crew involvement to when an out-of-limits alarm is set off.

Because of the different shape and velocity characteristics of a tether system, proximity operations will be changed. For approach to the system, collision with the tether will be a primary concern. Current planning for the space station is to have vehicles approach the bottom of the space station at a slow speed either at the same altitude or from below. If the vehicle misses the approach it can escape below the space station. A tether system can only be approached near the altitude of the system center of gravity or at one of the tether ends. Like current planning, a slow approach can be made at the center of gravity altitude; however, if the approach is missed, the vehicle must escape to the side of the system to avoid the tether. An approach to one of the tether ends would allow an easy escape following a missed approach, but would require a very fast docking. This docking would be more appropriately called a capture operation, because the approach would entail a slowing down from a fast to zero relative velocity at a given position for a limited time before it accelerated away. This type of approach would have to be quite precise to match the tether end position using an elliptic orbital maneuver. Overall, an approach at the system center of gravity altitude would be easiest.

A tether system will have some concerns with docking. Enough clearance must be provided around the vehicle to prevent interference between structures. This should not be a problem except for the space shuttle tail which may contact the tether. Therefore, the shuttle long axis will probably have to be displaced off the tether axis for clearance of the tail. The force of the docking will be a disturbance input into the tether system; therefore, it would be desirable to fire a propulsion system at the docking location to counteract this force. If the docking is off the system center of gravity and the vehicle center of gravity off the tether axis, a torque will be input into the docking module. This will have to be counteracted either by tether tension and a stiff structure along the tether axis or by a counterweight on the opposite side of the tether. This concern may require some special procedures to be performed before equilibrium can be established. In addition, the docking of a vehicle off the center of gravity will stretch the tether, which can result in a maximum tension load twice the equilibrium load [9]. The use of propulsive thrust or winding in the tether immediately after docking can reduce this maximum load.

When releasing vehicles from the tether system, many options exist for the release location. A primary concern will be the possibility of collision with the tether or one of the tethered platforms. A release at the system center of gravity or tether end would have the least problems. At the center of gravity, the release point would be in a central location, which would reduce ferrying requirements, but a separation maneuver would be required. At one of the tether ends, the distance from vehicle stowage locations would require the largest ferrying requirements, but a separation maneuver would not be required, this location is assumed for momentum transfer. Releasing the vehicle at its stowage location would require the least ferrying. If this location is off the system center of gravity, no separation maneuver would be required and some momentum transfer would occur. However, care must be made to insure that there is enough clearance down the tether, so the departing vehicle will not contact the tether or a tethered platform. Threfore, releasing the vehicle from an outstretched manipulator arm may be desirable to prevent contact with vehicle attitude changes. As for docking, the lateral shift in vehicle center of gravity off the tether axis may cause some operational concerns. In addition, releasing a vehicle off the center of gravity will cause the tether to recoil and possibly go slack. The use of propulsive thrust or winding out the tether immediately before release can reduce tether recoil.

Because the velocity off the system center of gravity is not at the orbital velocity, free-flying transfer vehicles will have to perform some complicated maneuvers to perform ferrying operations to different areas of the tether. An obvious option would be to reel in the tether to get to any part of the tether or a platform. Reeling in the tether can cause several problems. First, the dynamics of reeling in a tether may exceed the space station attitude or safety requirements, especially if there is a large mass on the tether. Second, reeling in the tether may violate the reason that a platform was tethered in the first place. Third, the reeling in and subsequent reeling out operation will require a large amount of time. Fourth, a reeled in platform may interfere with the space station hardware and with any docked vehicles. A preferable ferrying operation may be to travel along the tether, using it as a guide and reaction surface for a tether crawler. This option will require further investigation to determine how fast the crawler can traverse the tether without disturbing the space station dynamics too much, to determine how payloads should be loaded so as not to twist the tether too much (Fig. 63), and how payloads are to be transferred around platforms.

Orbital maintenance will cause some operational concerns. A tether system can have up to three ways of providing orbital maintenance thermal propulsion, momentum transfer, and electrodynamic propulsion. If more than one is available, an orbital maintenance technique must be developed that optimizes their use according to their characteristics. There are four considerations in their use: attitude control, orbital shape, performance, and controllability for formation flying with free-flying platforms. Thermal propulsion will be limited in thrust to prevent attitude control problems, can provide any orbital shape desired, has the least performance efficiency, and has the most controllability. Momentum transfer may require some propulsive attitude control, will tend to produce elliptical orbits, will improve the performance of both the space station and space shuttle, and has the least controllability. Momentum transfer will be tied to the orbital parameters and timetable of the released vehicles. Electrodynamic propulsion probably has the least concerns with attitude control, will tend to produce elliptical orbits, has very good performance efficiency, and has a limited controllability. Electrodynamic propulsion will be tied to the availability of power, which may be available on only one side of the Earth if solar power is used. Orbital maintenance probably will require that a thermal propulsion system be available.

A tether can be damaged or break due to being struck by fast moving debris, an accidental collision of a free-flying vehicle with the tether at relatively lower speed, and due to deterioration caused by the space environment. The use of an oversized, multi-strand tether will reduce the risks, but the tether must be inspected for accumulated damage. If damage is light, the tether may be repaired in place; however, if the damage is at an unsafe level, provisions must be made for tether replacement to ensure safe and effective operation of the tethered system. Methods for replacing the tether have not yet been developed. A possible solution would be to reel in the tether, secure any platform, detach the old tether, attach a new tether, then reel out the new tether. Similarly, instead of reducing the length of that tether segment, a type of crawler with a reel on both sides could travel along the tether reeling out the new tether while the old tether is being reeled in. The tether replacement operation should also provide the basis for changing the tether system configuration, allowing the addition or elimination of tether segments and platforms.

If a tether does break, the most immediate concern is that the broken sections of the tether will recoil towards their attachment points. Calculations have determined that the impact of this recoil is not damaging, but the tether may wrap around objects, interferring with their functions. The best way to avoid this problem is to sever the tether at each end when a break occurs. The second and more important concern is that the tether elements will be transferred into different orbits. If the section of tether away from the space station proper is only an element of an electrodynamic or momentum transfer application, the recovery of that section is probably not worthwhile. However, if the other section contains a major tethered platform,

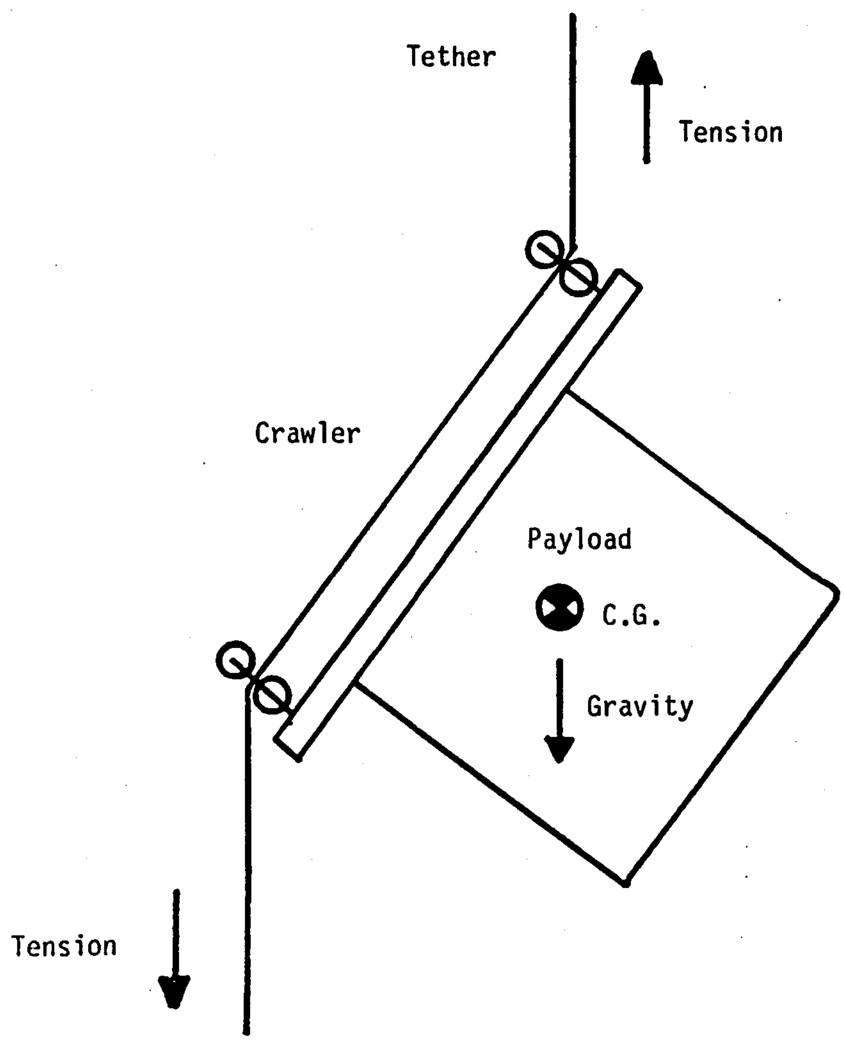

Figure 63. Tether twisting with payload on crawler.

recovery of that section will probably be mandatory. The development of a satisfactory procedure for reassembling the tether system will probably be necessary before that system can be adopted on the space station, because of the relatively high probability of breakage in the lifetime of a permanently deployed tether [__]. Each section will require guidance and propulsion to affect a rendezvous between the two sections. The means of providing the guidance and propulsion may already exist on each section or may require use of the OMV. The rendezvous location will probably be chosen on the basis of the method used to attach a tether between the sections. The primary advantage of rendezvousing at the same altitude will be the availability of time. With this type of rendezvous, one of the sections can be disassembled and then reassembled on the other section or a tether stretched between the two sections with them swinging into position following some attitude control rocket thrusting and tether damping. Rendezvousing at lightly different altitudes will probably be the fastest way of reassembling the system, but will probably require synchronized swinging of each section and the use of a tethered OMV to perform the tether attachment. Another factor that needs consideration is the transfer of a spare tether from its storage location and installation of it in the proper position.

The masses of various tethered platforms can change as they perform their functions, resulting in a change of the system center of gravity. A tethers system has the option of changing the length of tether segments to maintain desired relationships with the center of gravity. These could be either the maintenance of the center of gravity position or the maintenance of position relative to the center of gravity for the purpose of maintaining desired gravity levels. For long term changes in the center of gravity position, adjusting tether lengths is probably a desirable procedure. A harder question is if the tether lengths should be adjusted during temporary deployment of a tether application, such as for momentum transfer. A decision for this case will have to be based on the need for absolute maintenance of gravity levels by the sensitive applications on the effect that tether adjustment would have on system dynamics.

The use of tethered platforms will have an effect on the applications control philosophy on the space station. Direct control of applications by men will be limited because of the problems inherent in having to use extravehicular activity (EVA). At least three people are needed for EVA activity, two performing the EVA itself and one observer or activity coordinator inside. The preparation time for an EVA is long. And the time on station is limited. If a gravity level is present, astronauts will have to be secured to prevent falling. Remote control will consume more time to do the task itself and does not have the same range of capabilities as men, but overall takes less manhours than with EVAs and still allows some flexibility of operations. Autonomous control is the least flexible, but does not require manned control. The use of tethered platforms will probably expand the use of remote control over what is planned for the initial space station.

5.0 TETHER APPLICATIONS TO STATION PLANNING (By Georg von Tiesenhausen)

The very large number of potential tether applications to space missions, the great diversity of approaches to tether utilization, and the wide spread of the various states of development between the numerous ongoing tether projects requires an efficient approach to planning, a comprehensive planning structure, and a dedicated organization to carry out, support, and implement the planning agendas. All of these factors are in existence and active since 1983.

5.1 Planning Organization

In 1983 the Director of Advanced Programs in the Office of Space Flight, Ivan Bekey, established a Tether Applications in Space Inter-Center working group. Presently, this organization represents seven NASA Centers and has eight members. Each Center is responsible for near term and long range planning within a specific, established category or area of tether applications. These categories are shown in Table 21.

TABLE 21. TETHER APPLICATION IN SPACE CATEGORIES

Tethered Transportation
Tethered Spacecraft Constellations and Platforms
Electrodynamic Interactions of Tether System
Electrodynamic Tether Components
Tether Technology and Test
Science and Applications
Gravity Utilization Through Tethers
Advanced Concepts Development

The evolution of tether applications within the planning framework is divided into three areas:

1) Study planning

2) Technology planning

3) Demonstration mission planning.

Figure 64 shows the planning organization structure and the areas covered by the different Center representatives.

The working group meets several times annually to update and expand the individual project plans for each category as the projects progress. The resulting updated overall program plan, which represents an integration of the various individual project plans, is then formally presented to the NASA Program Offices. Based on this comprehensive plan, the next year's activities are then scheduled and funded. The planning goals of the organization are depicted in Figure 65.

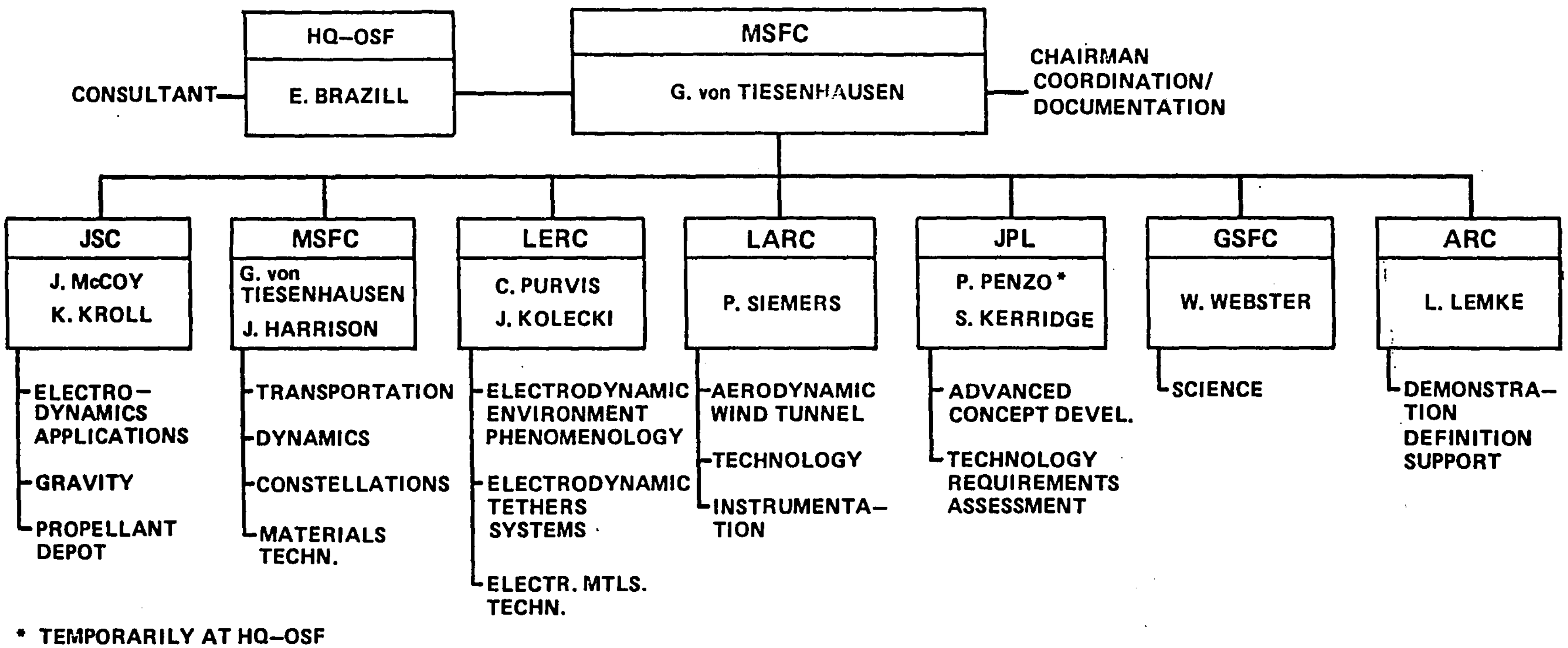

Figure 64. Tether applications working group.

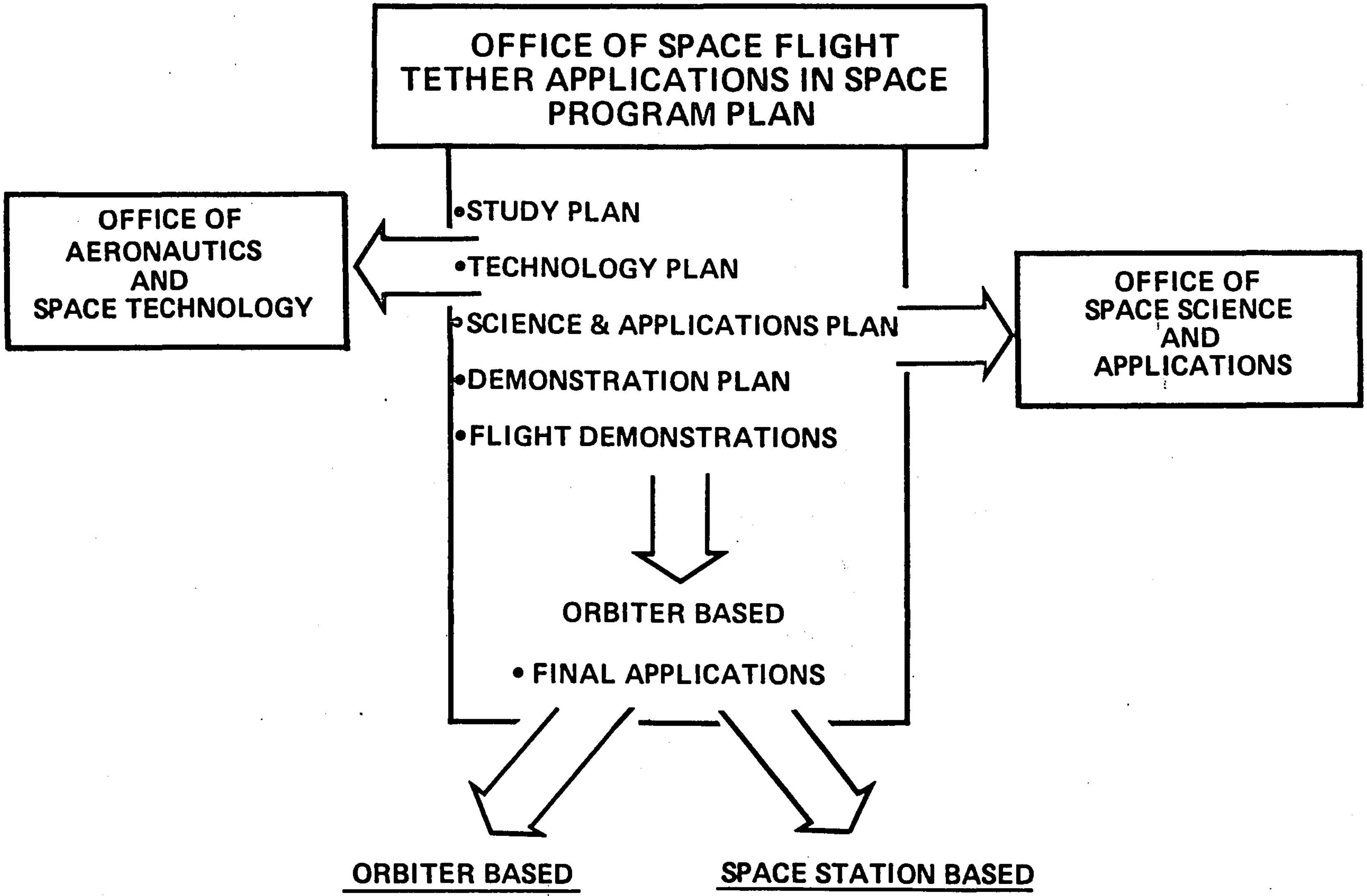

Figure 65. Planning goals.

The study planning generally proceeds through the following four phases:

1) Theoretical and engineering feasibility and technology requirements

2) In-depth analysis of promising candidate applications

3) Engineering design and cost/benefit analysis of selected applications

4) Demonstration mission definition of selected applications.

The demonstration mission developments are not included and follow separate, individual plans and procedures.

The technology planning consolidates technology requirements of all major tether concepts under study. To date the following critical technology areas have been defined:

1) Tether materials and configurations

2) Tether applications engineering instrumentation

3) Tether applications science instrumentation

4) Tether system dynamics/orbital mechanics simulation

5) Atmospheric/aerothermodynamic technology

6) Hollow cathode technology

7) Tether applications critical component technology.

These technology task areas were documented and have been brought to the attention of the appropriate NASA Program Office for implementation.

The demonstration mission planning resulted in the evolution toward a number of feasible and practical early demonstration mission candidates. The prime criteria in selecting these early demonstrations are:

1) Capability of fulfilling flight objectives

2) Affordability

3) Simplicity

4) Maximum use of available payload hardware with minimum modifications, e.g.,

   — Available instrument carriers (e.g., XSAT, SPARTAN, PDP, others)

   — Available reentry vehicles (e.g., GE-SRV, others)

5) Minimum development time ($\sim$2 years).

5.2 Efforts to Date

Three years of effort have resulted in remarkable progress in the evolution of promising tether applications in space, particularly to the space station. The efforts are directed by NASA's Office of Manned Space Flight, Ivan Bekey, Director of Advanced Programs.

The following industries, institutions, and NASA field centers have been participating in research and development of these applications.

Industries:

- Martin Marietta Aerospace
- Ball Aerospace Company
- McDonnell Douglas Corporation
- Boeing Aerospace Corporation
- Control Dynamics Company
- Energy Science Laboratories
- Analytical Mechanics Associates
- S-Cube Corporation
- Materials Concepts Incorporated

Institutions:

- Smithsonian Astrophysical Observatory
- University of California - San Diego
- University of Utah
- University of Alabama - Huntsville
- Stanford University

NASA Field Centers:

- Marshall Space Flight Center
- Johnson Space Center
- Goddard Space Flight Center
- Langley Research Center
- Lewis Research Center
- Ames Research Center
- Jet Propulsion Laboratory

The results of these efforts as they apply to the space station were summarized in this report.

Other results were:

1) Understanding of tethered constellation dynamics and the boundaries of constellation stability. One-dimensional, multimass constellations including movable masses were found to be most practical and beneficial.

2) Quantification of benefits using tethered momentum transfer between spacecraft and payloads.

3) Quantification of expected performance parameters of electrodynamic tethers.

4) Engineering design of most promising tether applications as basis for cost analyses.

5) Development of analytical tools like simulation programs of tether behavior for specific applications.

5.3 Program Plans Through 1991 (Fig. 66)

Present tether applications planning has covered the time span from 1983 to 1989 with goals reaching into the 1990's. Each year has been assigned a specific theme representing a subsequent step in the evolution toward specific tether applications to the space station. These annual themes are in addition to continuing efforts on past themes which sometimes take more than a year to cover or which cover new concepts that became known since the original effort began.

The orbiter will be the basis for initial concept flight demonstrations. Emerging successful candidates then become the subject for space station based final systems demonstrations.

Thus, NASA's tether applications in space program planning and implementation activities proceed in a logical and well structured approach toward the realization of tethers for increased economy and capability of our future space station activities as outlined in Reference 11.

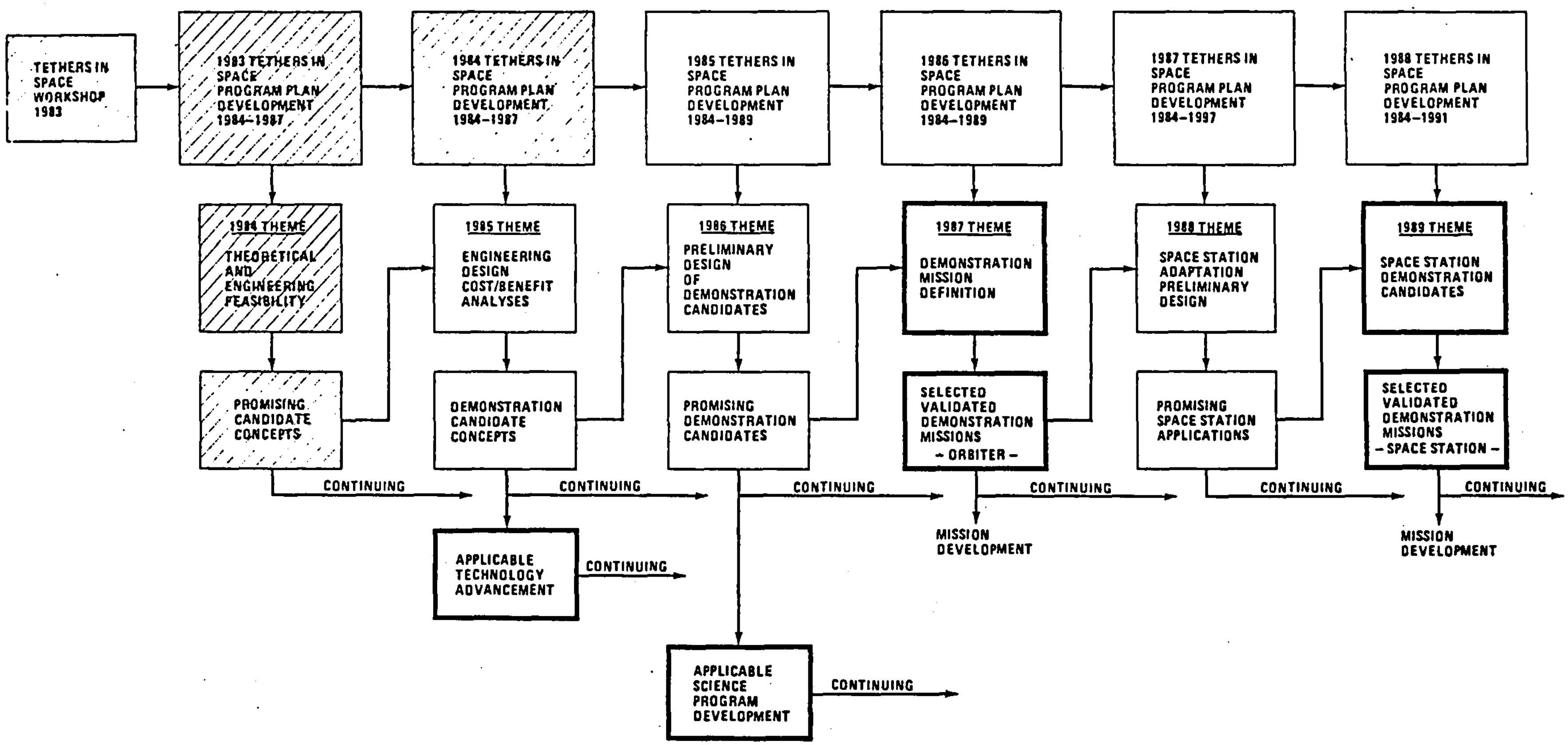

Figure 66. Overall program planning approach for tethers in space.

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APPROVAL

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By Georg von Tiesenhausen, Editor

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