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TETHERS IN SPACE – BIRTH AND GROWTH OF A NEW AVENUE TO SPACE UTILIZATION

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Advanced Systems Office
Program Development

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16. ABSTRACT

This report traces the evolution of the ideas of tether applications in space from its origin in the last century past a dormant period of sixty-five years to the mid-seventies. At that time as a consequence of major revival efforts, NASA entered into serious investigations of the theoretical and practical feasibility of a large number of tethered concepts in space. These efforts culminated in the establishment of the Tethered Satellite System Project now at NASA in the advanced development phase.

The report describes NASA's 1983 extensive planning efforts, first, through a Tether Applications in Space Workshop which generated additional concepts and provided overall assessments and recommendations to NASA, and then through a NASA inter-center Tether Applications in Space Task Group which generated a four-year program plan in the areas of further studies, technology, work and science and applications of tethers in space.

Finally, the report offers an outlook into the future of tether applications that may approach some of the goals of the early visionaries.

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1.0 INTRODUCTION

It is interesting to recognize that almost all of our past, present, and planned future spaceflight concepts and missions and most of their technical elements have been thought about, conceived, and predicted in some way or another many decades, sometimes almost a century ago, by profound visionaries. All these prophets were modest men who in their daily lives performed rather down-to-Earth work like teaching (Tsiolkovskii, Goddard, Oberth), city utility maintenance (Hohmann), car racing (Valier, Opel), and others. Most of today's space mission planners have knowingly or unknowingly drawn from these early, often long-dormant, ideas which became alive when their time had come. One of these early visions from about ninety years ago whose time has come involves a rather unusual element of space transportation. We have to understand that in those days rockets into space were believed to be centuries away in the future; however, the human urge to leave Earth and to enter space was rather strong in the minds of a few. What more natural way was there than to think of a tall tower reaching into space and to use it to mechanically move up into the unknown.

This report will trace the evolution from these early thoughts to today's concepts and projects involving very long structures – tethers – and describe their expected beneficial utilization in almost all areas of space flight in the near and far future.

2.0 VISIONARY STRUCTURAL SPACE ACCESS CONCEPTS

It seems to be in the nature of human conceptualization that radically new ideas usually involve their most advanced applications, omitting the many beneficial, small steps of the rocky path of an evolutionary engineering development. In the following we shall review the most significant advanced tether concepts, many of which exceed the realm of practical application. It is also interesting to note that several advanced tether concepts have been re-invented a number of times. In the following an effort was made to trace the first publication of each of these concepts.

2.1 Dreams of Earth and Space

The earliest report available on terrestrial access to the weightless environment of space by mechanical means was described by Tsiolkovskii in 1895 [1]. In this fascinating report he considers, among countless other things, ways in which an environment without terrestrial gravity could be created (Fig. 1). He proposed an equatorial tower reaching beyond geostationary altitude. He said: "Upon ascending such a tower, gravity decreases gradually, not changing direction; at a distance of 34,000 verst (1 verst = 3500 ft) gravity is totally eliminated. For that reason at a still higher altitude it is displayed with a force directed away from the critical point; the direction is reversed so that a man's head faces Earth."

He continues elsewhere in his report and proposes to apply this to other planets as follows: "On this second similar planet stood a tower of an extreme height, the ends of which were thin, much as a spindle, and without any means of support. We walked beneath this castle in the air, wondering

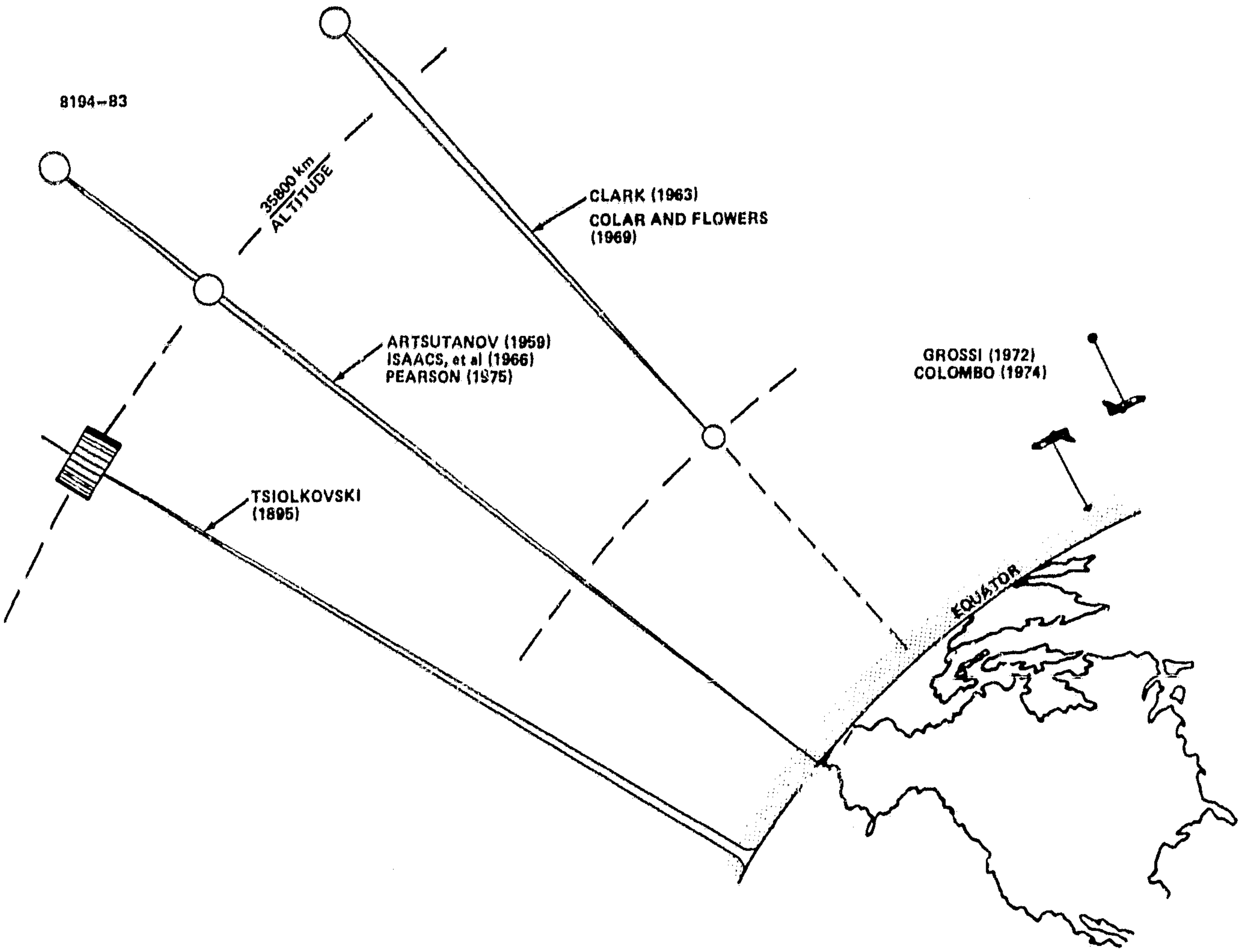

Figure 1. Early orbital tower and skyhook concepts.

why it did not fall on our heads. The point is that the top part aspires to fly due to the centrifugal force; while the lower part pulls in the opposite direction. The form and placement is such that the equilibrium is invariable observed."

2.2 The Heavenly Funicular (Artsutanov)

Sixty-five years passed after Tsiolkovskii's idea when the Russian engineer Y. N. Artsutanov [2] generated an idea in 1960 which can be considered a reversal of Tsiolkovskii's tower. Instead of erecting a tower on Earth pointing toward space he conceived one "anchored" in space and pointing toward Earth, touching and being connected to the Earth's surface at the equator (Fig. 1). A cable would be deployed up and down from a geostationary satellite, the lower one would be secured to the Earth's surface while the outer cable would carry a ballast so the center of gravity would be maintained in the geostationary orbit.

Artsutanov was also the first one to be concerned about the required strength of the cable material and the first one to calculate a cable of constant stress along its length according to LVOV [3]. The purpose of this "funicular" was to serve as a cosmic elevator. He calculated a balanced lift energy system where the work obtained from launching payloads from the outer part would equal the energy demand to lift the payload up the inner part. The lifting speed would be about 1000 km/hr and result in a transportation capacity of 12,000 tons a day (LVOV) [3].

2.3 The Sky-Hook (Isaacs, et al.)

While Arthur C. Clarke seems to be the next in line of reviving Artsutanov's funicular in 1963 [4], he appeared to have not pursued this any further.

In 1966, Isaacs, et al., published their well-known brief paper on "Satellite Elongation Into a True 'Sky-Hook' " [5]. It is interesting to note the "Science" editors' and reviewers' reservations for publishing this paper. The prime concern of this paper was the tether material question. The authors conclude that the required theoretical strength of the cable material is more than two orders of magnitude greater than that of available engineering materials. The authors, though, realize that practical applications may be possible on the moon's farside, Jovian moons, or Mars where the acting forces would be greatly reduced (Fig. 1).

2.4 Low Altitude Geostationary Satellite (Collar and Flower)

In 1969 Collar and Flower [6] suggested a very long tether connecting a satellite located beyond the geostationary distance with another satellite positioned at a relatively low altitude such that the center of gravity was located at the geostationary distance (Fig. 1). The use of this lower passive communication satellite would involve greatly reduced power to maintain signal strength in communications. The authors, of course, were concerned about the tether materials problem and considered aluminum and graphite whiskers, glass and carbon fibers, and others.

The authors appear to be the first to assess meteorite damage to tethers and conclude that a 0.2 mm tether of 50,000 km length would be severed by a micro-meteorite in about 1 hour. Temperature effects by the lower satellite's and the tether's passage through the Earth's shadow would result in tether length (and lower satellite altitude) changes of about 40 km under favorable dynamic conditions.

2.5 The Orbital Tower (Pearson)

In 1975 Pearson [7] picks up Artsutanov's idea (Fig. 1) and provides a good assessment of critical issues involved; particularly, he is the first to analyze some of the tether dynamics including tidal force effects and traveling waves along the tether. He calculates that the tower material deployment would require 24,000 flights of a super-shuttle with 30 times the payload of the present orbiter.

Two years later, in 1977, Pearson extended his concept to lunar applications [8] (Fig. 2). This includes lunar satellites at the libration points L_1 and L_2 attached by tethers to the lunar surface. These satellites would launch lunar payloads throughout cislunar space and, in forming lunar halo orbits, would provide continuous communication with the lunar farside (Fig. 3). Material for a lunar base could be supplied from Earth without landing vehicles.

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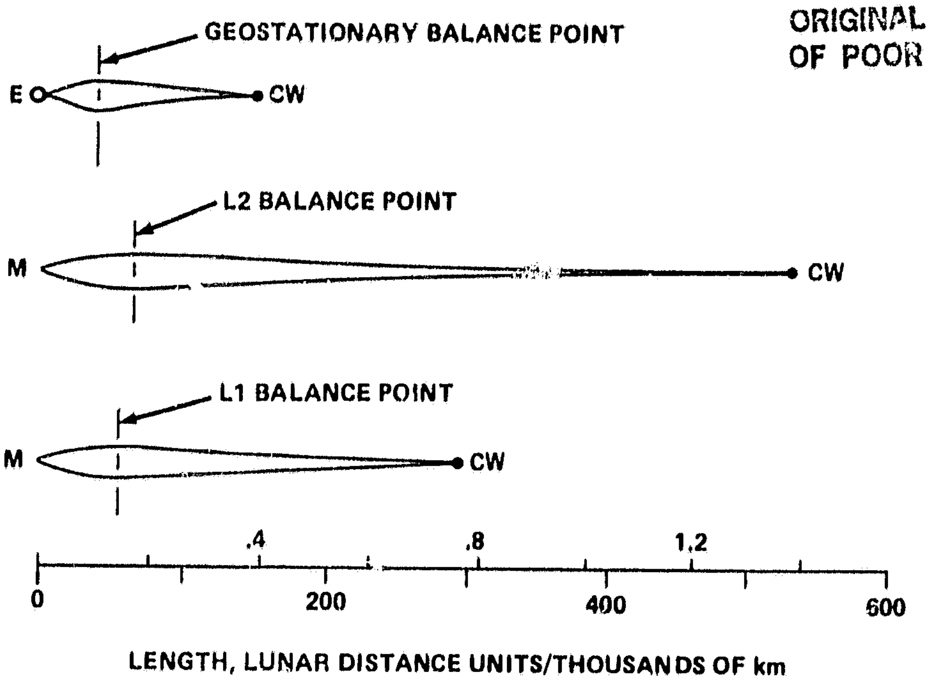

Figure 2. Anchored lunar satellites compared to the anchored Earth satellite [8].

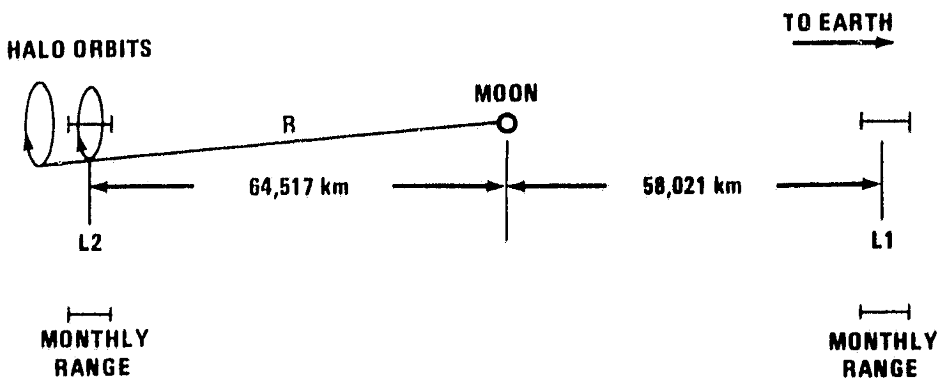

Figure 3. Lunar halo orbit for farside communication [8].

2.6 The Space "Necklace" About the Earth (Polyakov)

As a special advanced tether concept we shall consider Polyakov's "necklace" which he published in 1977 [9] (Fig. 4). His concept consists of several equally-spaced "funicular" (Artsutanov) reaching from the equator beyond geostationary altitude with payload carrying elevators going up and down, or being launched from the far end. Between the funicular beyond geostationary altitude, various stations are located and interconnected in a circular fashion by tethers, thus forming a ring around the orbit. This ring is fastened to the funicular and the complete configuration forms a stable equilibrium.

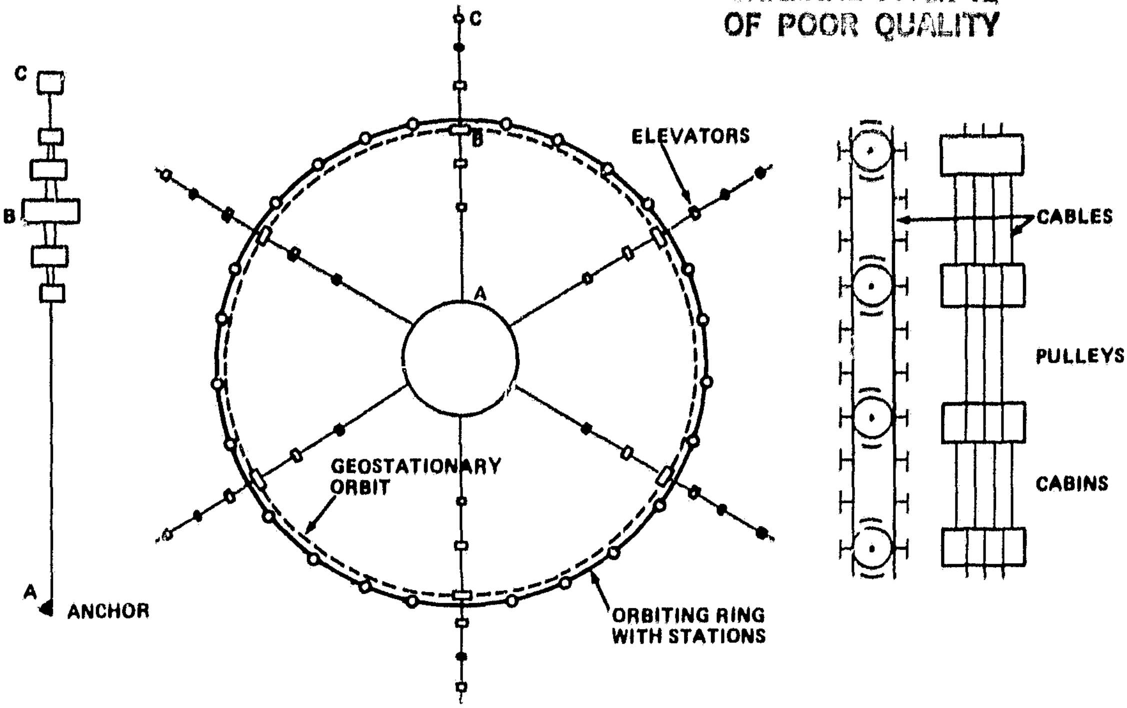

Figure 4. Space necklace (Buckminster Fuller, 1951; G. Polakov, 1977; A. C. Clark, 1977).

2.7 The Non-Synchronous Orbital Skyhook (McCarthy/Moravec)

This last advanced concept shall conclude the very great variety of past, grandiose tether applications. This is a wheel tether based on an idea by Artsutanov [10] in 1969 and described in more detail by Moravec [11] in 1977 (Fig. 5). A satellite in low circular equatorial orbit has two long tethers deployed in opposite directions. The system rotates in the orbital plane in the same sense as the Earth rotates. The tethers touch the Earth's surface during each rotation such that the velocity of the lower tether end cancels the orbital motion of the cable carrying satellite. The system acts like two spokes of a wheel rolling on the equator. The Earth touching tether can lift about 2 percent of its own mass at each contact in an optimum configuration and could launch it at over 13 km/sec from the outer end to Mars or Venus.

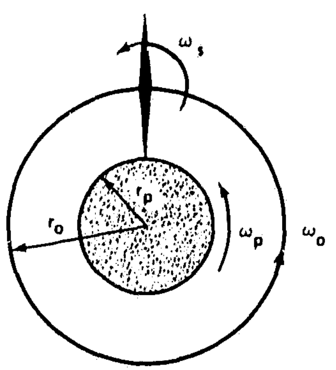

Figure 5. Orbital Skyhook (Y. Artsutanov, 1969; McCarthy/Morevac, 1977).

3.0 EVOLUTION TOWARD A TETHERED SATELLITE SYSTEM

There is a large step from the far-reaching advanced concepts of the visionaries down to those concepts that are not only possible with the technologies of today and the near future but that also show potentials of profound technical and economical benefits and improvements to a great variety of presently planned space missions as compared to alternative approaches. This does not detract from the value of these prophetic concepts because some of those may be considered as distant goal setters that provide direction for future developments.

3.1 Initial, Sporadic Tether Activities and Studies

In September and November of 1966 the Gemini XI and XII spacecraft together with the Atlas-Agena D spent stage performed the first two tether in space application experiments (Fig. 6) [12]. The idea originated according to D. L. Lang (NASA/Johnson Space Center) with the late Richard P. Gilooley.

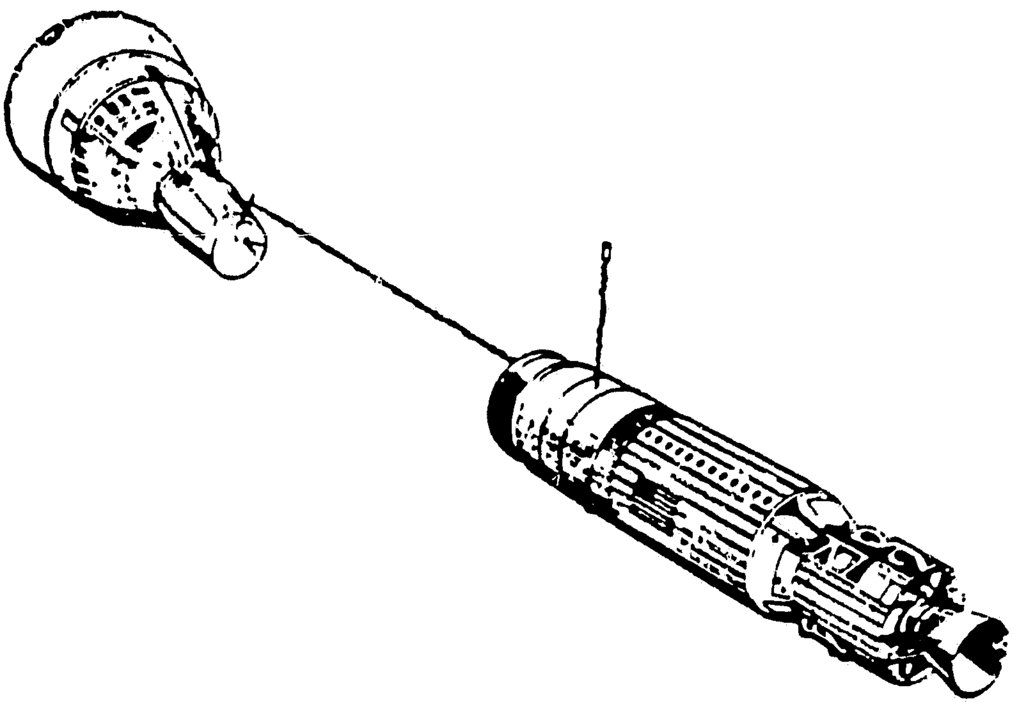

Figure 6. Gemini spacecraft/target-vehicle tethered configuration.

Basically, two modes of tethered space vehicle operations were explored in the Gemini program. One mode of operation consisted of intentionally inducing an angular velocity in the tethered system by translational thrusting with the spacecraft propulsion system. The other mode involved tethered, drifting flight during which the effect of gravity gradient on the motion of the system was of interest. These two modes of tethered vehicle operation were completely successful and verified the analytical assumptions and calculations.

In 1972, Analytical Mechanics Associates, Inc., updated a Marquardt Corporation study of 1963 on the rescue of stranded astronauts with a tether. During the Skylab studies in 1967 tethers were considered in connection with the Apollo Telescope Mount. All these sporadic, uncoordinated, individual efforts were of value in their own narrow field of interest but lacked an overall goal orientation.

3.2 Convergence of Efforts

It was not until the early 1970's that systematic efforts began to investigate the complex dynamics of long tethers in space, their utilization for a wide spectrum of scientific and operational applications, and the critical technologies associated with their use.

Among the first to investigate tether dynamics and tethered spacecraft motions were Eads and Wolf [13] in 1972. They studied selected problems dealing with orbiting tethered body systems and developed a relative motion orbit determination program. They analyzed the effects of gravity gradient and orbit excentricity and of oscillations and rotations on tether forces. An apparent first attempt was made to define types of control actions needed for an accurate placement of tethered masses.

The first practical application of an orbiting tether was developed by Grossi in 1972 in the form of an orbiting antenna to generate Ultra Low Frequency (ULF) emissions by stimulating natural micropulsations in the plasma medium. This wire was to be 20 to 100 km long and to be excited by a Shuttle-borne transmitter.

Radiophysics measurements on a long wire radiator by means of a tethered subsatellite was first proposed by Grossi in 1974. Additional experiments with magnetometers and gravity gradiometers were suggested by Colombo. This research culminated in a formal report published in 1974 [14]. A patent was granted to both Colombo and Grossi in 1978 on "Satellite Connected By Means of a Long Tether to a Powered Spacecraft."

This paper was followed in the same year by a report by Colombo, et al. [15], which constituted a major milestone in tether analysis and applications. It was this report that initiated NASA's own in-house efforts in this area. Colombo and his colleagues Gaposchikin, Grossi, and Weiffenbach proved the great potential of a Shuttle-borne tethered satellite of contributing significantly to the scope of scientific investigations by the Shuttle orbiter. This paper proved that a tethered satellite system ("Skyhook" system) was practical in that it defined in a preliminary way, a system with a subsatellite deployed 100 km below the orbiter at an altitude of 110 km with either a stainless-steel rope or a special wire alloy with high strength/high temperature characteristics. The considerable scientific potential in the areas of atmospheric and magnetospheric science experiments as well as in gravity-gradient measurements is outlined here for the first time.

Shortly after this key report was published, a complementary paper by Dobrowolsy, Colombo and Grossi (1976) discussed the electrodynamic interaction of long conducting tethers in near-Earth orbit [16]. A first analytical approach was developed to evaluate these electrodynamic interactions affecting a conductor moving in the ionosphere. Computer models were developed for the distribution of the induced potential along the tether and the resulting current.

From now on NASA activity in tether applications in space increased rapidly, primarily due to the considerable internal and external promotional efforts of Ivan Bekey of the Office of Spaceflight at NASA Headquarters. The first tether tension control law for tethered subsatellites deployed along the local vertical had been developed by Rupp [17] of NASA's Marshall Space Flight Center in 1975. An uninterrupted sequence of analytical and design work began. In addition to Smithsonian Institution's and Marshall Space Flight Center's efforts, theoretical tether dynamics studies using computerized models were performed by the European Space Agency, Aeritalia, McGill University, the University of British Columbia, Martin Marietta Aerospace Division, Ball Aerospace System Division, Control Dynamics Company, and others.

These studies have served to define tether behavior during deployment, station keeping, and retrieval operations in addition to defining control laws necessary for operating tethered satellites.

In 1982 Harvard Observatory launched a 40 km altitude balloon with a tethered payload deployed to a distance of 12.5 km and proved the successful mechanical reel deployment and retrieval of very long tethers from a free-flying vehicle.

All these theoretical studies and practical techniques culminated in an effort where this knowledge would be the basis for one single system: the Tethered Satellite System. The result will be a system that can achieve 100 km deployment distances with new tether materials, control laws, and the supporting subsystems. This system has become an official NASA project.

4.0 THE BROAD FIELD OF BENEFICIAL TETHER APPLICATIONS IN SPACE

4.1 General

The ongoing Tether Satellite System project which is targeted for implementation in the later years of this decade is but one of the large number of uses of tethers which open up entirely new avenues of space utilization by using the space environment and the forces acting in space as the primary means to accomplish their objectives. Very quickly it became obvious that the tethered satellite system was only the beginning. Since 1979 a whole spectrum of tether applications has been generated by many individuals. M. Grossi and G. Colombo of the Smithsonian Astrophysical Observatory and Ivan Bekey of NASA's Office of Spaceflight became the prime movers within NASA toward tether applications in space. They were joined by industry, academia, and NASA Centers who in concert conceived an ever increasing family of concepts, a process which is still continuing.

The following tether application categories have been established and are under investigation:

4.2 Electrodynamic Interactions of Tethers (Fig. 7)

A conducting, insulated tether orbiting the Earth interacts with the ionospheric plasma and with the Earth's magnetic field. This generates a voltage potential the effects of which can be used for power, propulsion and for generating very low frequency radiation of electromagnetic waves.

The potential to generate power requires that a low impedance current path be created which collects electrons from and returns them to the ionospheric plasma. One method of creating this path includes the collection of electrons on a conducting sphere (Fig. 8) carried as the tether payload, transmission of current along a conducting tether, and ejection of electrons near the Shuttle with an electron gun. The load exists in series along the conduction path. An experimental package to generate power by this method is scheduled to fly on the first Shuttle/tether mission (TSS 1) in 1987. The payload is being designed and built by Aerilalia (Italy), the remainder of the package is being designed and built by Martin-Marietta (USA), and the effort is being coordinated and managed by the Marshall Space Flight Center [18].

Utilization of tether for propulsion requires that the current be reversed in direction and generated by an on-board source of energy. The generation of ULF and ELF communication waves requires that a modulated current be applied to the tether.

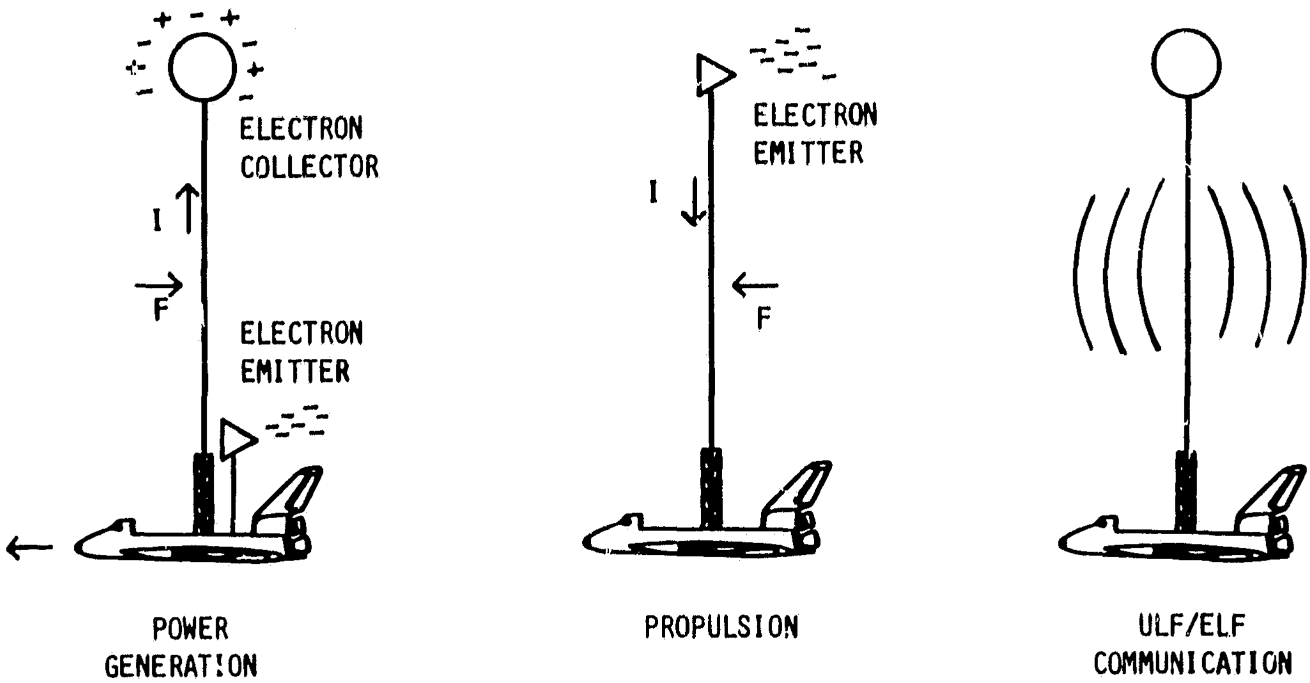

Figure 7. Electrodynamic tether technology applications.

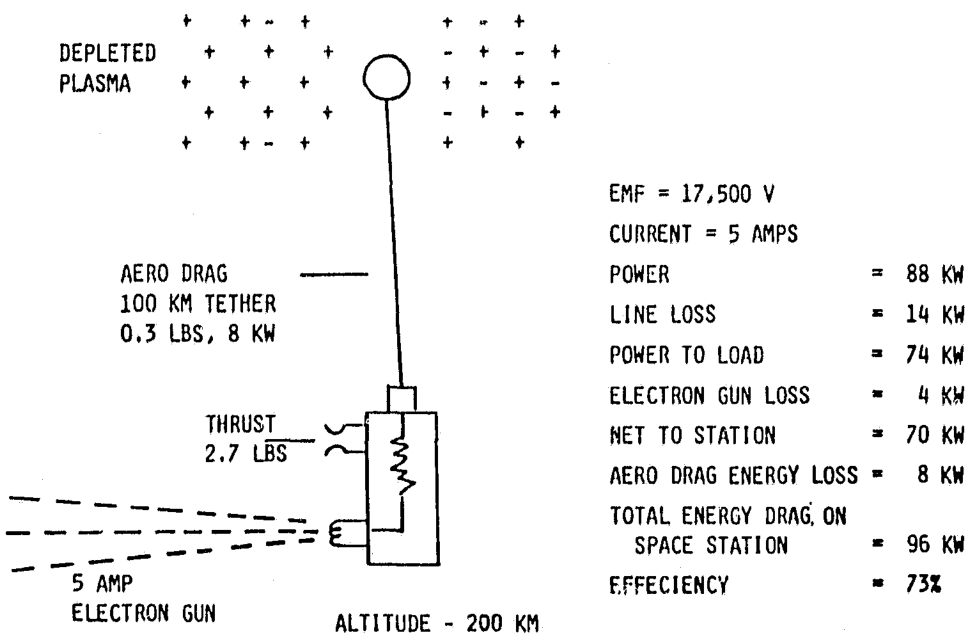

Figure 8. Electrodynamic tether – operating characteristics.

The electrodynamic tether can be used in a great variety of ways. It can provide peak power to an orbiting spacecraft supplementing solar arrays and on board batteries. It can be used as a practically unlimited energy storage system for example for a space station. The electrodynamic tether would supply needed power during the dark part of orbit. Solar array will provide required power during the daylight part of the orbit and in addition provide power to the tether thus creating a forward force that will boost the orbit, thus storing energy in the form of altitude gain. A preliminary assessment of this application indicated that approximately 40 percent of the mass and about 25 percent of the cost of the power system could be saved by the use of an electrodynamic tether system.

4.3 Tether Applications To Transportation

Tether applications to transportation may be classified in the following general categories:

1) Angular momentum exchange – applications in which tethers are used to effect favorable angular momentum exchange between spacecraft/payloads, spent stages, etc. (Figs. 9 and 10).

2) Remote operations – tethers used to move objects to more favorable vantage points for observation, sensing, etc.

3) Forcing systems – use of tethered objects to interact with natural media (atmosphere, magnetic field, etc.) and thereby produce desirable forces on the overall system (Fig. 11).

A good example of a quite beneficial angular momentum exchange operation involves the tethered deployment of an orbital transfer vehicle into a higher altitude. In addition to the initial altitude gain which depends on the tether length there is the orbital excess velocity of the vehicle. Both factors result in a net propellant saving or payload gain as compared with conventional methods.

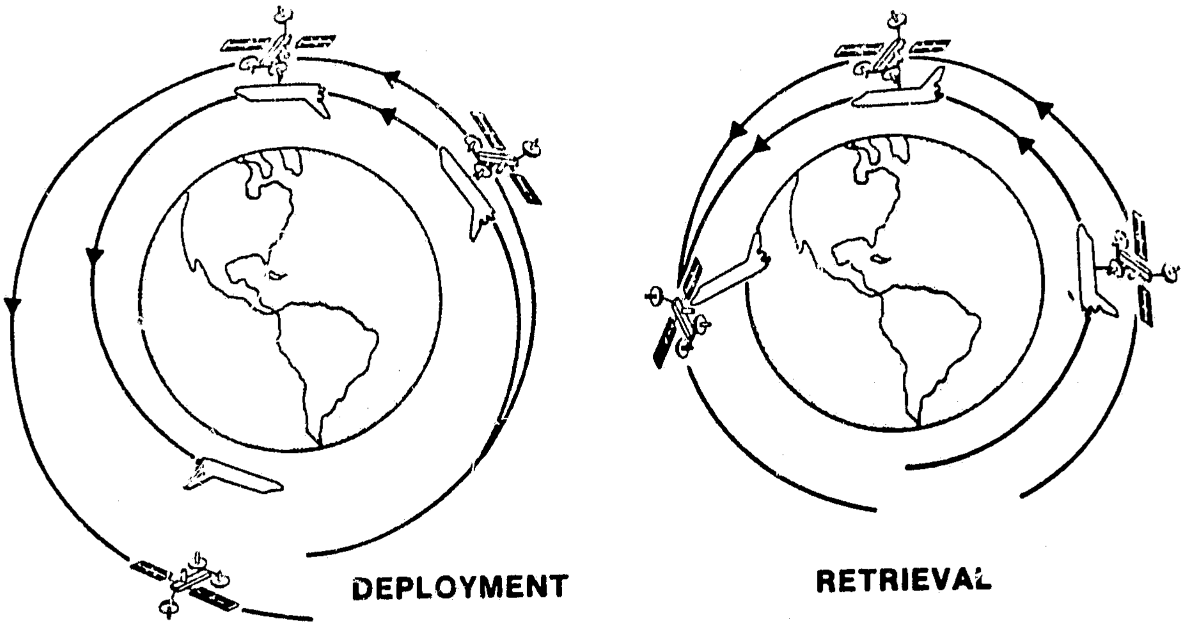

Figure 9. Angular momentum exchange.

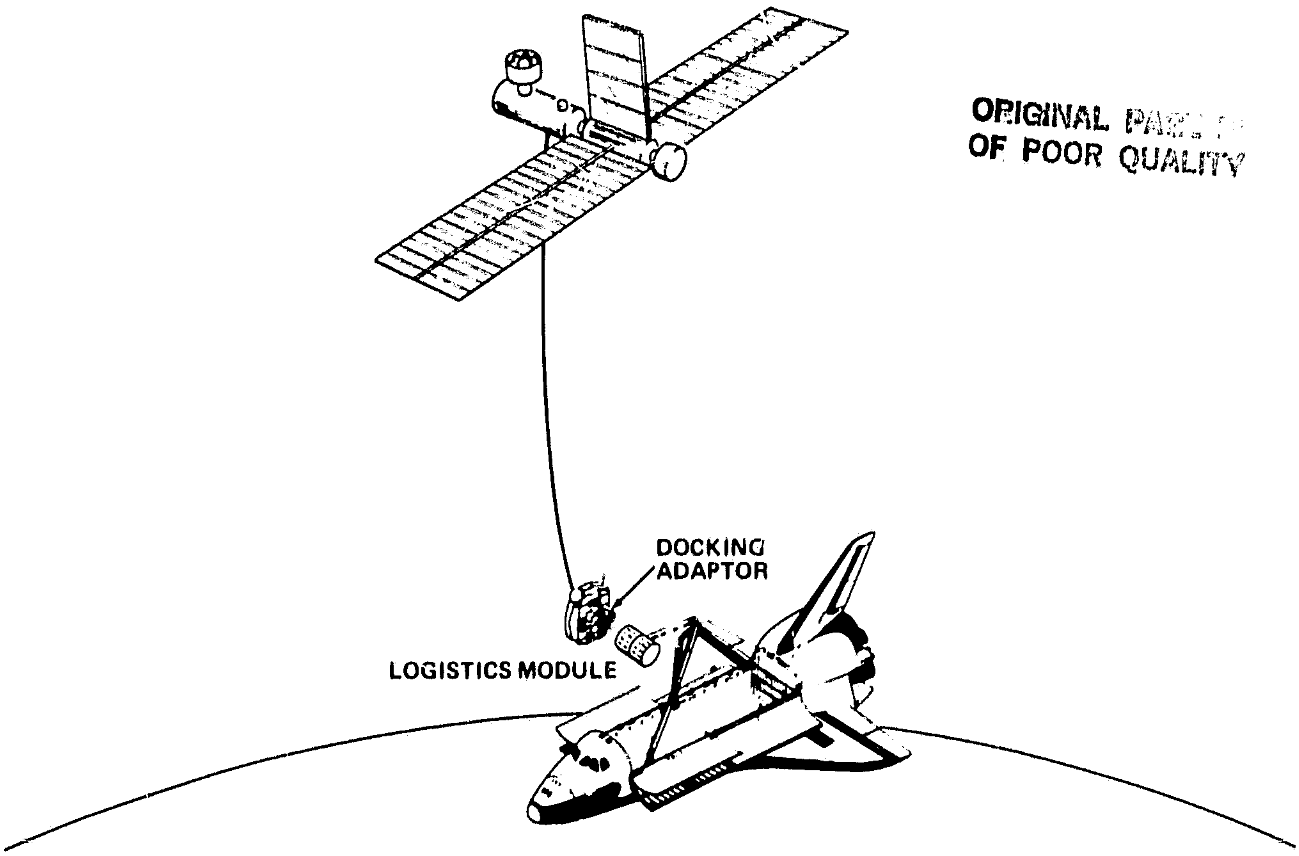

Figure 10. Remote docking – payload transfer.

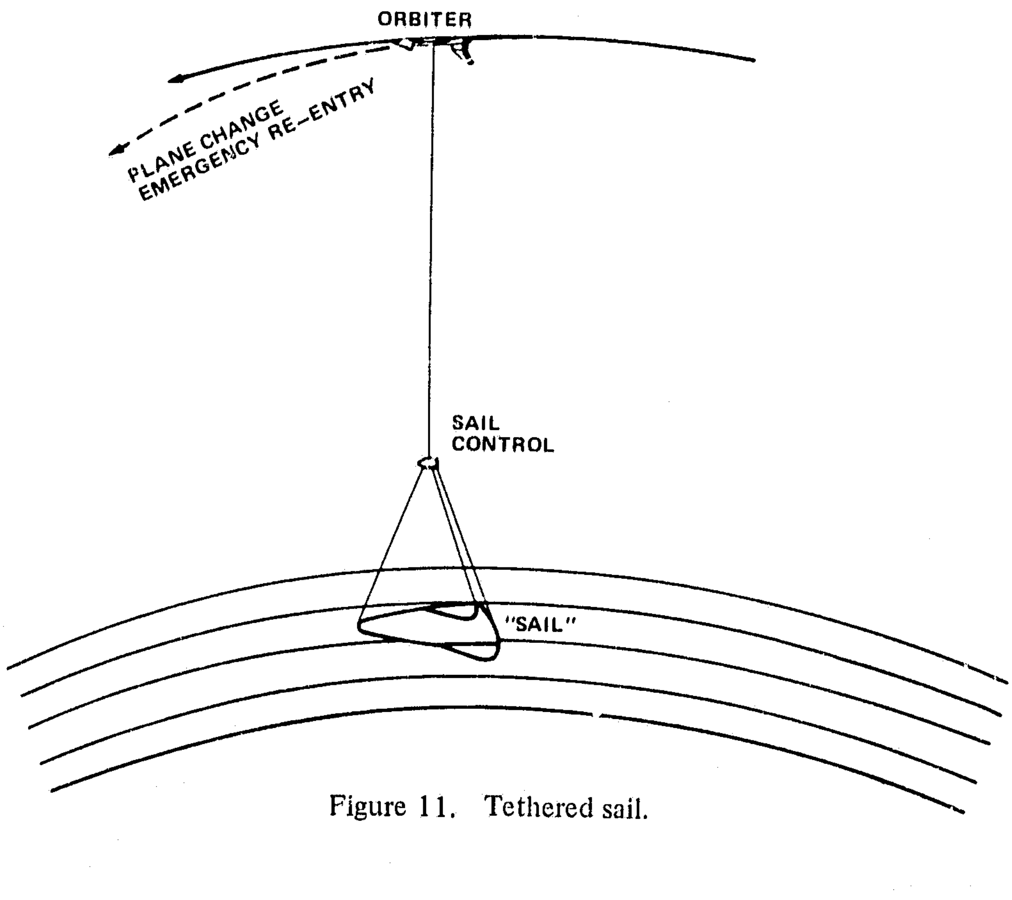

Figure 11. Tethered sail.

Another example is the orbital boost applied to a space station by deploying the Shuttle orbiter or external tank on a tether downward (Fig. 9). A promising operation is also a tether deployed remote docking adaptor which could rendezvous with and retrieve a payload from the orbiter cargo bay. This would eliminate docking of the orbiter with the space station (Fig. 10).

A tether application not yet under study is the tethered atmospheric sail which, if under proper control, could apply lateral force vectors to the orbiter allowing a gradual plane change if so desired (Fig. 11).

Overall, research is primarily directed to extend our knowledge and understanding of the theoretical and technical feasibility, behavior, technical and operational risks, technology requirements and overall costs and benefits as compared with conventional propulsive means.

4.4 Tethered Spacecraft Constellations

A constellation is a tethered configuration with at least three separate tethered masses. This definition is important since all other tether configurations have two masses.

A great variety of possible spacecraft constellations is possible (Fig. 12). Ongoing studies will show which ones are practical and beneficial.

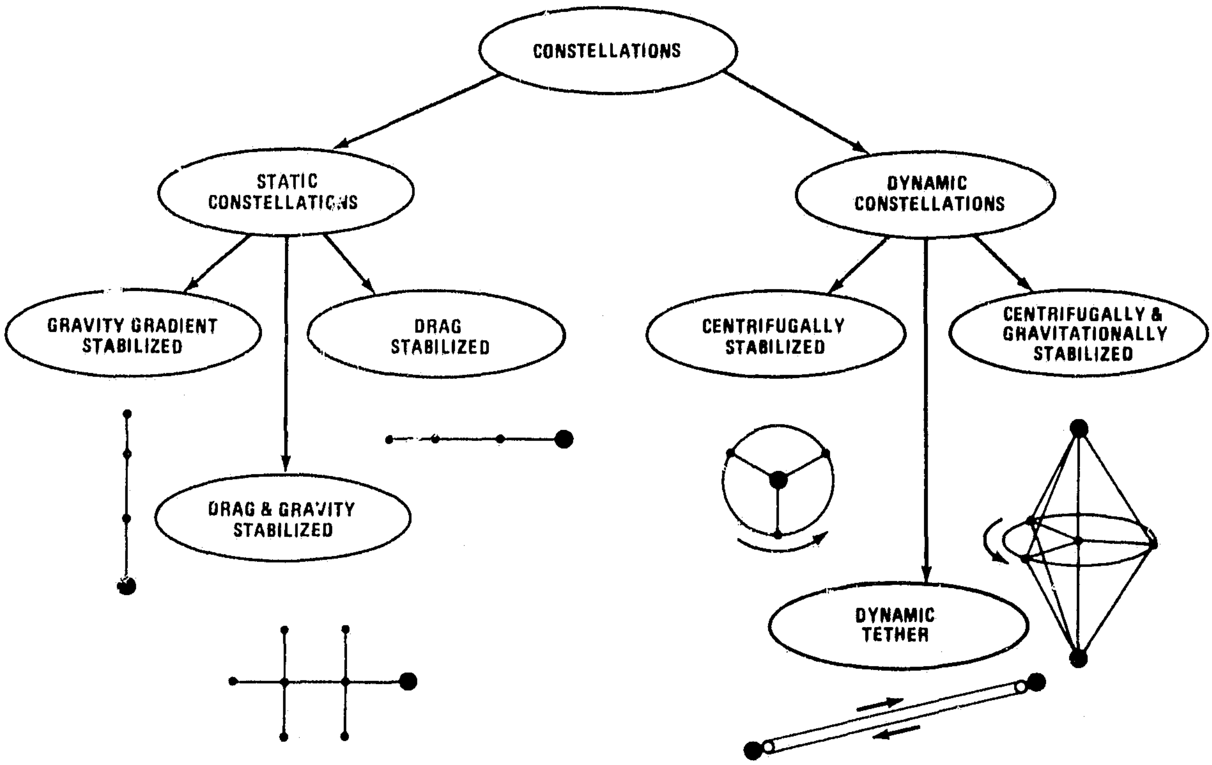

Figure 12. Tethered constellations.

Gravity gradient stabilized constellations have great value in measuring various gradients in space, e.g., magnetic fields and plasma density gradients and compositions. Drag stabilized constellations are expected to derive their stability from drag differences between forward and rearward tethered spacecraft. This concept will be studied in the near future together with constellations using a combination of gravity and drag forces for stabilization.

In contrast to these static constellations, NASA is investigating various dynamic concepts. Rotationally-stabilised constellations have similar characteristics as described in Section 4.5.b. A combination of rotationally- and gravitationally-stabilized concepts has been under investigation and has quite limited margins of stability. An interesting tether concept is the dynamic tether which runs between spacecraft over pulleys. The continuous momentum transfer keeps the masses apart. Certain dynamics problems need solutions in this concept.

4.5 Gravity Utilization Through Tethers

4.5.a. Gravity Gradient Stabilized Tethers

Any mass that is deployed by a tether from a spacecraft shifts the system's center of gravity out of the spacecraft along the direction of the deployed tether. Consequently, any points along the tether outside the center of gravity are subject to gravity gradient forces. These forces are quite different from so-called "artificial gravity" because they depend entirely on the presence of a central gravitational field. Artificial gravity is generated by a rotating system anywhere in space.

Gravity gradient forces depend on tether length and the magnitude of the tether end masses (Fig. 13). The gravity acceleration level, of course, depends only on tether length.

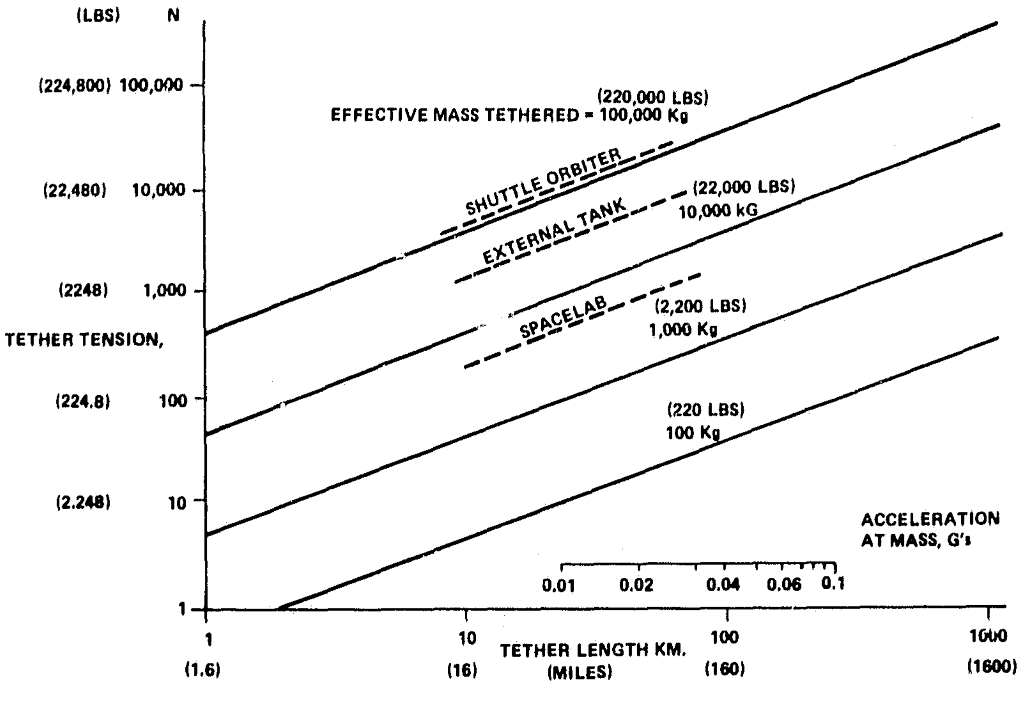

Figure 13. Gravity gradient forces.

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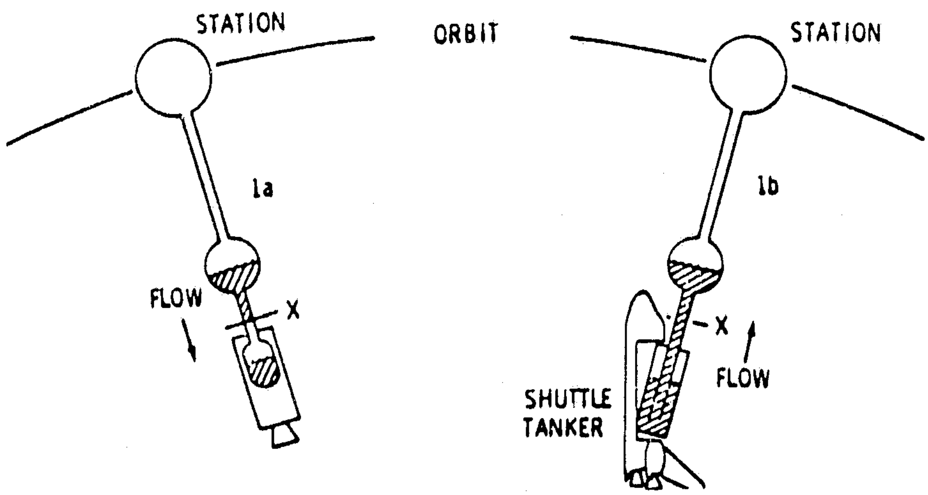
The generation of these small gravity levels with a gravity gradient stabilized tether is of considerable scientific and technical interest (Table 1). An application of great promise is the storage and transfer of propellants between spacecraft and tethered fuel depots (Fig. 14).

TABLE 1. TETHERED SATELLITES GRAVITY UTILIZATION CATEGORIES AND EXAMPLES

CATEGORY	EXAMPLES
SCIENCE	ANIMAL/PLANT GROWTH, CRYSTAL GROWTH, FLUID SCIENCE, SIMULATIONS IN CHEMISTRY/PHYSICS
TECHNOLOGY	FLUID STORAGE, ATTITUDE CONTROL SIMPLIFICATION, OTHER SUBSYSTEM ENHANCEMENTS
MEDICAL	STUDY/REDUCE EFFECTS OF ZERO–G ON HUMANS. INVESTIGATE MEDICAL PRODUCTS/SERVICES IN LOW G
HABITABILITY	IMPROVE MAN'S PRODUCTIVITY AND COMFORT BY PROVIDING SOME LEVEL OF GRAVITY
OPERATIONS	ORBITAL REFUELING, INSTRUMENT/ANTENNA FARMS, TETHERED TMS FOR SPACECRAFT RETRIEVAL



1a. Station/Tethered Dewar Loading OTV
1b. Station/Tethered Dewar Loading from STS Tanker

Figure 14. Tethered propellant concepts.

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4.5.b. Rotation Stabilized Tethers

These are true artificial gravity systems as compared with gravity gradient systems. The advantage of rotating systems is the capability of generating much higher force fields with relatively short tethers than is possible with gravity gradient systems where tether masses may exceed the attached payload masses above a few hundredths of a g force.

An interesting fact is that the artificial gravity force becomes highly variable in low Earth orbit if the tether rotation rate is near the tether's orbital rate, resulting in fluctuations of the force magnitude between zero and some positive and negative maxima (Fig. 15). This range, therefore, is unsuitable for low gravity experiments that require constant forces. A gravity gradient tether would be a solution in these cases.

Since rotational tether systems are inertially stable, care must be taken in their use in connection with a spacecraft with a different mode of stability, e.g., Earth oriented.

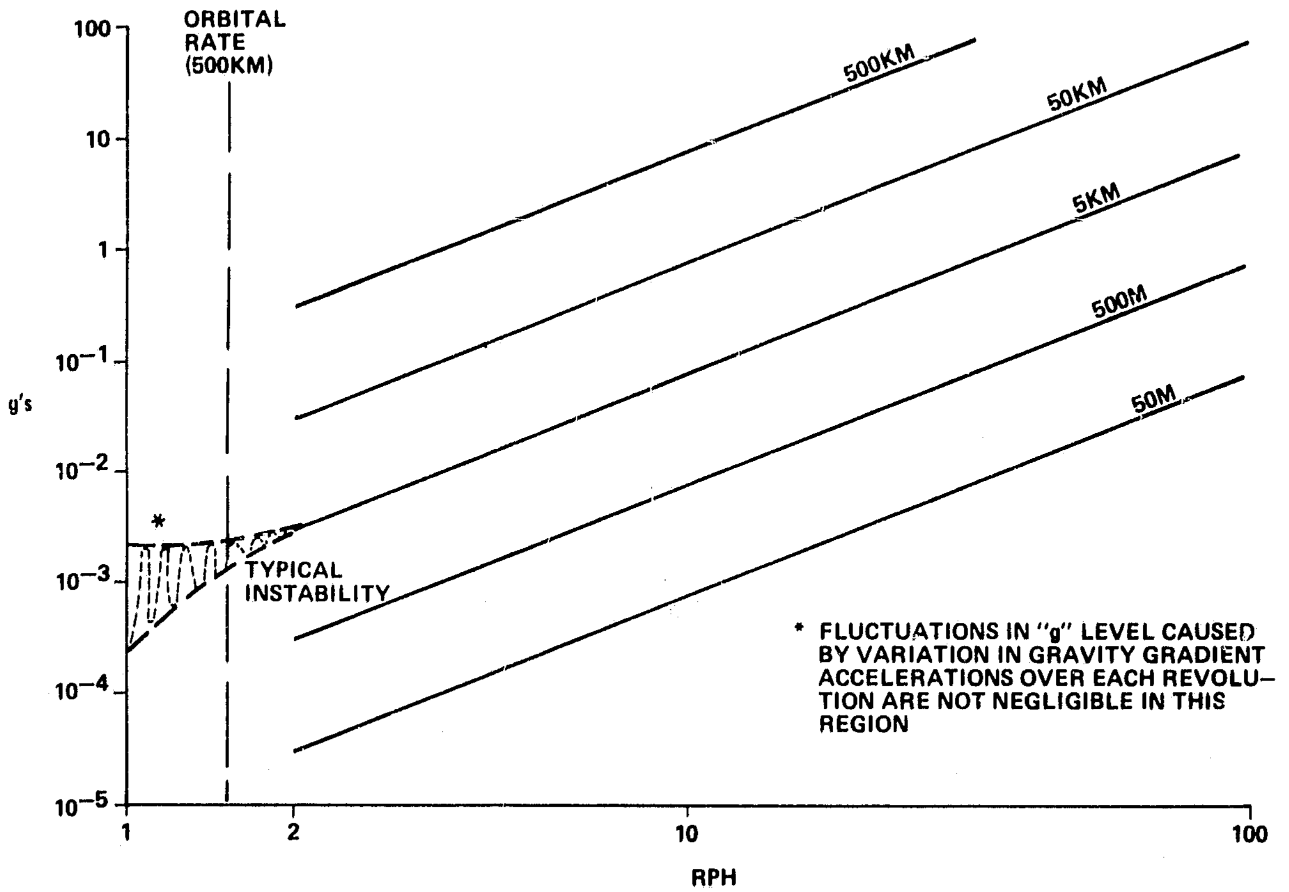

Figure 15. Tethers for artificial gravity.

4.6 Tethered Test Facilities and Technology

This tether applications category covers all tether missions which utilize the outer atmosphere (90 to 200 km) as either a test bed for the thermal stability of structures and materials or as a hypersonic "wind tunnel" facility to test aerodynamic models. These applications appear to be economically quite superior in comparison with equivalent ground-based facilities. The indicated altitudes (Fig. 16) are atmospheric areas from slip flow through transition flow to the region of free molecular flow. All projects requiring accurate configuration aerodynamic performance data will benefit from these tests.

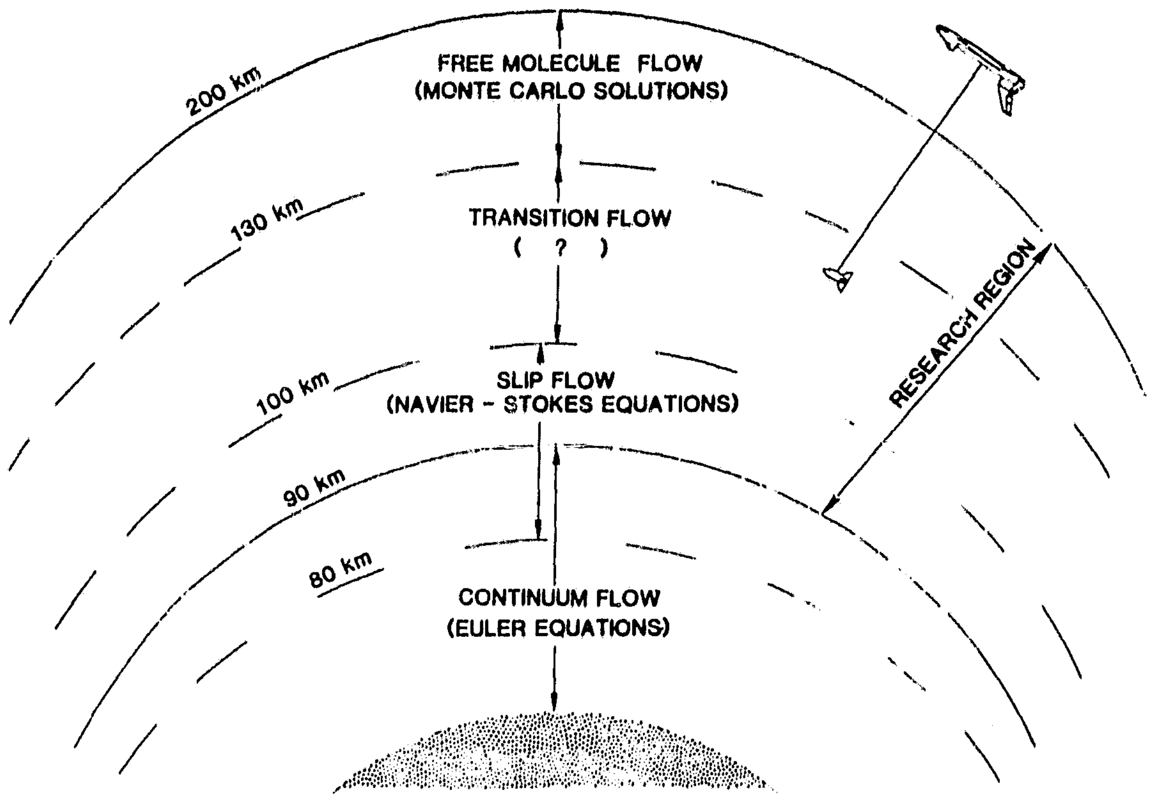

Figure 16. Aerodynamic research regions.

The tether technology work covers the various dynamic simulation capability requirements, engineering instrumentation, and tether materials research.

4.7 Present NASA Tether Application Studies

NASA's present studies in tether applications are based on two major efforts that took place in 1983. One was an Applications of Tethers In Space Workshop in the summer of 1983 and the other was the development of a four-year NASA Program Plan on tether applications by an inter-Center NASA Task Group. The 1984 NASA efforts in this area are based on the recommendations of these two sources (Table 2).

TABLE 2. TETHER APPLICATIONS IN SPACE – PRESENT STUDIES

ELECTRODYNAMIC INTERACTIONS	TRANSPORTATION	GRAVITY UTILIZATION	CONSTELLATIONS	TECHNOLOGY AND TEST
DYNAMIC STABILITY AND POWER/DRAG GENERATION	SELECTED TETHER APPLICATIONS IN SPACE	TETHER ORBITAL REFUELING	SELECTED TETHER APPLICATIONS IN SPACE	SHUTTLE TETHERED AEROTHERMODYNAMIC RES. FAC.
EMERGENCY PEAK POWER GENERATOR	TETHER PAYLOAD RELEASE ORBITAL PUMPING			TETHER APPLICATIONS AND TECHNOLOGY REQUIREMENTS ASSESSMENTS
ENVIRONMENTAL INTERACTION MODEL	TETHER ASSISTED SSUS			ROLES OF TETHERS ON AN EVOLVING SPACE STATION
	TETHER DYNAMICS ANALYSIS			
	DISPOSABLE TETHER P/L LAUNCH			

5.0 ISSUES AND PROBLEMS OF TETHER APPLICATIONS

There are two classes of issues and problems associated with tethers in space. First, the long tether in space is the only element of space systems that is entirely and irrevocably dependent and functionally relying on the natural forces acting in space: gravitational and plasma interactions and drag and the complex variations of these forces. These are the causes of certain system issues and problems. Secondly, tethers in space are only stressed in tension and therefore are the most efficient structural elements possible, resisting imposed stresses with the minimum quantity of material. However, this fact makes tethers environmentally vulnerable. A 1 mm diameter tether 100 km long has a projected area of 100 m^2, large enough to be damaged by meteorites over extended periods of time. These are tether materials issues and problems.

5.1 Systems

Primary systems issues and problems lie in the areas of tether stability, dynamics, and operations. For instance the configuration stability of certain constellations using drag stabilization is poorly understood at present. General stabilization problems occur during deployment and retrieval of individual constellation elements. Individual simulation models must be developed for each constellation configuration.

The issues associated with tether dynamics and control laws are being addressed at present and continued updating and expansion of the computer programs can be anticipated. A significant systems issue is the impact of potential tether operations on a space station, particularly if we anticipate multiple tether applications. Different attitude requirements between stations and tethers must be studied. One of the primary system problems to be addressed is the mass of the tether deployment system and the tether mass itself because these masses enter into almost every trade-off with propellant and other savings in comparisons with conventional means of achieving any desired goals.

5.2 Technology

Since the stress on a tether depends on its length, the size of the end masses and its orbital altitude, the tether must have a high strength and a low density – that is a high strength-to-mass ratio. By dividing the allowable material stress by its density multiplied by the gravity acceleration one obtains a figure of merit for tether materials, the critical length of a tether as shown in Figure 17. Going above 250 or so kilometers of tether length in low Earth orbit requires tethers of constant stress or exponentially tapered tethers to accommodate heavier masses. Present tether applications will utilize protectively coated Kevlar 29 for non-conducting tethers and a metallic core with insulation for conducting tethers.

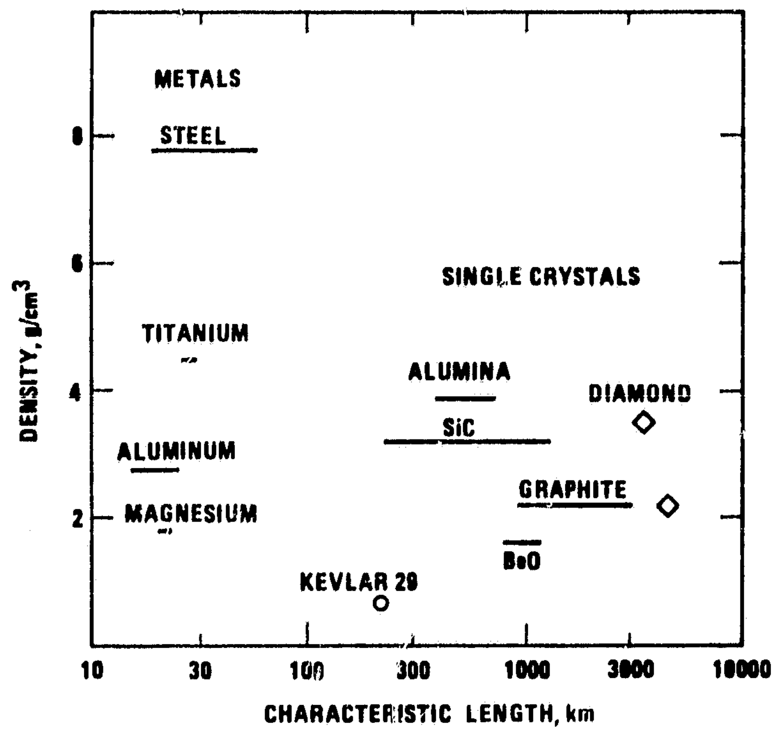

Figure 17. Characteristic length versus density for various materials (adapted from Reference 7).

Other critical technology issues are tether dynamics and the associated required control laws. The dynamic behavior of long tethers within a gravitational field is quite counter-intuitive. Therefore, each considered tether application requires very carefully developed dynamic algorithms and computer simulations in order to understand its behavior. This is especially critical in tether constellations in general and in special cases where stability is expected to be achieved by both gravity gradient and atmospheric drag forces. Much work needs to be done in this area.

A summary of presently recognized issues and problems of the various tether application categories is given in Section 6.1, Tables 3 and 4.

6.0 TETHER APPLICATIONS IN SPACE PLANNING

6.1 Tether Applications Workshop Results

In the summer of 1983 about 150 representatives of government, industry, and academia participated in an historical workshop on tether applications. Existing and new applications were discussed analyzed, evaluated, and assessed. The results of these deliberations were carefully documented [19] and a summary of the findings is shown in Table 3. A special working group on science and applications came forth with recommendations summarized in Table 4.

TABLE 3. WORKSHOP PANEL SUMMARY APPRAISALS OF CONCEPT CATEGORIES

CATEGORY / PARAMETERS	ELECTRODYNAMIC INTERACTIONS	TRANSPORTATION	CONSTELLATIONS	GRAVITY UTILIZATION	TECHNOLOGY AND TEST
•FEASIBILITY •COST BENEFIT POT. •OPERATIONAL POTENT.	EXCELLENT FEAS. GOOD COST BENEFIT POTENTIAL GOOD OPER. POT.	HIGH: P/L BOOST, OTV BOOST ORBITER DEBOOST MEDIUM: ET DEBOOST ORBITER DOCKING P/L BOOST (UPPER STAGE)	FEASIBLE IN LEO COST BENEFITS AND OPERATIONAL POTENTIAL IS CONSIDERABLE	EXCELLENT GOOD COST BENEFIT POTENTIAL GOOD OPER. POT.	EXCELLENT FEASIBILITY OF TETHERED "WIND-TUNNEL PROJECT"; GREAT COST BENEFIT AND OPERATIONAL POTENTIAL
•PRINCIPAL TECHNOLOGY REQUIREMENTS	TETHER MATERIALS HIGH VOLTAGE TECHN. ENERGY STORAGE PLASMA CONTACTOR ULF/ELF COMMUNICATION	TETHER MATERIALS TETHER DYNAMICS	NEW SIMULATION MODELS AND CONTROL LAWS	RELIABLE DOCKING & TRANSFER MECHANISMS MALFUNCTION PLANNING ORBIT CORRECTIONS MAINTAINING DESIRED MICROGRAVITY	TETHER MATERIAL DYNAMIC MODELING
ISSUES: •DESIGN •PERFORMANCE •OPERATIONAL	POWER VARIATIONS OVERALL IMPEDANCE RADIATION LOSSES RADIATION DETECTABILITY	UPRATED TETHER HARDWARE PASSIVE DEPL./RETR. USER ACCEPTANCE	STABILITY DEPLOYMENT PROCEDURES MASS EXCHANGE OVERALL LACK OF UNDERSTANDING	FLUID STORAGE TANK DEPLOYMENT DYNAMICS TETHER PLUS ROTATION DYNAMICS MAINTENANCE	IMPROVED SATELLITE TRACKING SYSTEM REMOTE TSS OPERATION
CRITICAL ENGINEERING QUESTIONS	COLLECTION BODY EMITTER PROPERTIES	SYSTEMS DEFINITION	MASS MOVEMENT ALONG TETHERS	NONE MENTIONED SEE "TECHNOLOGY REQUIREMENTS"	GENERATION OF AN ENGINEERING DYNAMIC MODEL
•REQUIRED PROOF OF CONCEPT TESTS	PLASMA CONTACT DEVICES WAVE EMISSIONS & PLASMA PARAMETERS PLASMA WAKES AND DRAG EFFECTS CHARGE EMISSION	NOT DEFINED	TSS DERIVATIVE MISSION CG CONTROLLED ELEVATOR FREE FLYING DEPLOYER-PALLET-END MASS EXPERIMENT	SPACE STATION EXPERIMENTS	IN SITE ENVIRONMENTAL DATA NEEDED
PRIORITY BENEFITS ALTERNATIVES •PRODUCTIVITY •NEAR TERM APPL.	EXCELLENT SCIENCE NO ALTERNATIVES HIGH PRODUCTIVITY EXCELLENT NEAR TERM APPLICATIONS	EXCELLENT EFFICIENCY OVER ALTERNATIVES NEAR TERM APPLIC. TO BOOST SATELLITES	BENEFITS, PRODUCTIVITY AND APPLICATION UNKNOWN AT PRESENT	PRIMARY APPLICATION TO SPACE STATION	KEY TO ALL APPLICATION BENEFITS AND PRODUCTIVITY NEAR TERM EFFORTS REQUIRED

6.2 Tether Applications Program Planning

Based on the detailed results of the tether applications workshop, a working group representing six NASA Centers, developed six individual project plans for each tether applications category which then were integrated into an overall four-year program for the Office of Spaceflight (Fig. 18). NASA activities are following this plan since the beginning of this year.

TABLE 4. WORKSHOP PANEL ON SCIENCE AND APPLICATIONS APPRAISAL SUMMARY

	AERONOMY	GEODYNAMICS	REMOTE SENSING
EXPLOITATION OF EXISTING SYSTEMS	TSS INSTRUMENTATION DIFFERENT INCLINATIONS DIFFERENT LOCAL TIMES DIFFERENT SEASONS POLAR ORBIT	TSS BELOW AND ABOVE ORBITER MAGNETOMETER BOOM GRAVITY GRADIOMETER PRECISION ALTITUDE	TSS WITH OPTICAL INSTRUMENTS AT LOW ALTITUDE SPECTRAL AND SPATIAL MEASUREMENTS
EXISTING SYSTEMS WITH MULTIPLE PAYLOADS	MEASUREMENTS OF COMPOSITION CHANGES SEVERAL SATELLITES ON A STRING MASS SPECTROMETERS, WIND DIRECTION, DENSITY, IONISATION	MULTI-SPACECRAFT TETHER GRAVITY AND MAGNETIC FIELD GRADIENTS UPWARD AND DOWNWARD MEASUREMENTS	IDENTICAL INSTRUMENTATION ON ORBITER AND SATELLITE MEASUREMENTS AT DIFFERENT VIEWING ANGLES
LOWER ALTITUDE MEASUREMENTS	MEASUREMENT OF MOST IMPORTANT PROCESSES BETWEEN 90 AND 130 Km ALTITUDE	GLOBAL OBSERVATIONS IN LOW ALTITUDE	GREATLY IMPROVED RESOLUTION BY LOW ALTITUDE SENSING
TETHERED AUTONOMOU MULTIPLETS	LONG DURATION MEASUREMENTS. PLANETARY ATMOSPHERES ROTATING TWO SPACECRAFT ABOUT CENTER OF MASS.	PLANETARY MAGNETIC FIELD MEASUREMENTS	———
SUB-TETHER	MEASUREMENTS OF VERTICAL STRUCTURE OF ATMOSPHERE	———	———

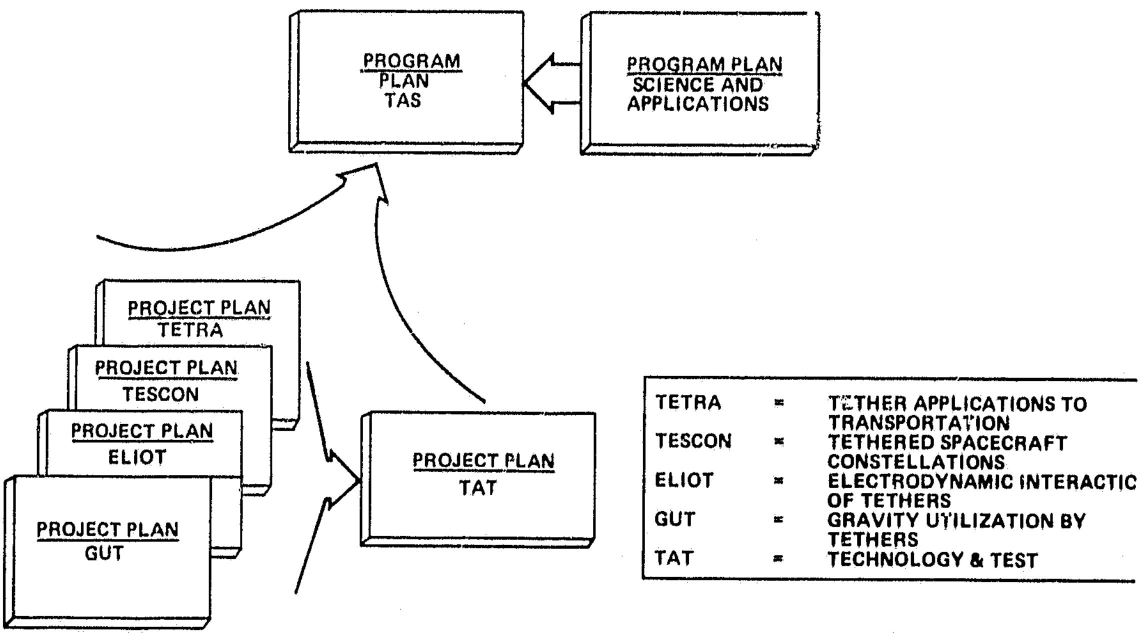

Figure 18. Tether applications program plan development.

7.0 THE PROMISE OF TETHERS IN SPACE

The major contribution of the early and recent visionaries on the use of long tethers in space is the recognition that movement in space is possible without rockets, that the large reservoir of energy residing in the ionosphere can be tapped by tethers, and that multiple spacecraft at different altitudes can fly with a common orbital period if joined by tethers. The present NASA efforts directed by the Office of Spaceflight constitute a well coordinated and structured approach to demonstrate the most promising tether applications during the next ten years. The potential benefits in form of mission cost reduction, improved operational mission efficiency, and particularly, the expansion of mission scenarios are already being recognized in several application categories (Section 4.0).

Since the number of tether applications in space appears almost limitless and since the only constraints are tether materials and the laws of nature and of economics, it is hard to predict where the main inroads of tethers are going to occur. There are, however, certain areas that show great promise for the future and present priorities bear this out. The following criteria established these present priorities:

1) Needs or special benefits

2) Tethers are the only way to accomplish the tasks or there are equivalent alternatives

3) Relative quantity of knowledge or results gained

4) Feasibility of near-term application.

According to these criteria we have:

Priority I: Electrodynamic Interactions

- o Provides maximum potential benefit in the power generation mode
- o Alternative approaches appear less efficient and productive
- o Near-term applications have already been initiated (TSSI).

Priority II: Technology and Test; Tether Applications to Transportation

These two categories seem to be next in line and of equal significance. The areas of tether materials and of dynamic simulation technology will remain of fundamental importance across different categories of tether applications for some time. The utilization of tethered aerodynamic models and of tethered momentum transfer modes have no equivalent alternatives and have near to mid-term applications.

Priority III: Tethered Spacecraft Constellations, Gravity Utilization Through Tethers

Constellations so far are the least understood concepts and involve great complexity in their dynamic behavior. Therefore, no near-term applications and benefits have been established. More than any other concept, constellations require several years of analysis and simulation in order to establish their merits. Gravity utilization in the area of microgravity seems to be deficient in useful applications and cost benefits at this time. This category can ride on the coat tails of other gravity gradient stabilized concepts in order to establish its usefulness.

The few examples provided here must suffice because the potential promises of tethers in space seem almost endless. Tethers will give space missions a new perspective and will generate a whole new area of technical developments within NASA covering a multitude of disciplines. Presently, we are in the birth phase of tethers, the next ten years will begin their growth phase leading to a long term evolution of new possibilities in space (Fig. 20).

In addition to the mentioned future plasma propulsion systems, tethers will enable space stations to maintain their altitude by deploying the logistic shuttle orbiter on a tether rather than letting them depart directly. Gravity gradient stabilised Earth observation stations, artificial gravity manned planetary missions using rotating tethered spacecraft, planetary atmospheric and surface probes using tethers and interplanetary rotating solar sail vehicles are some of the endless future applications of tethers in space.

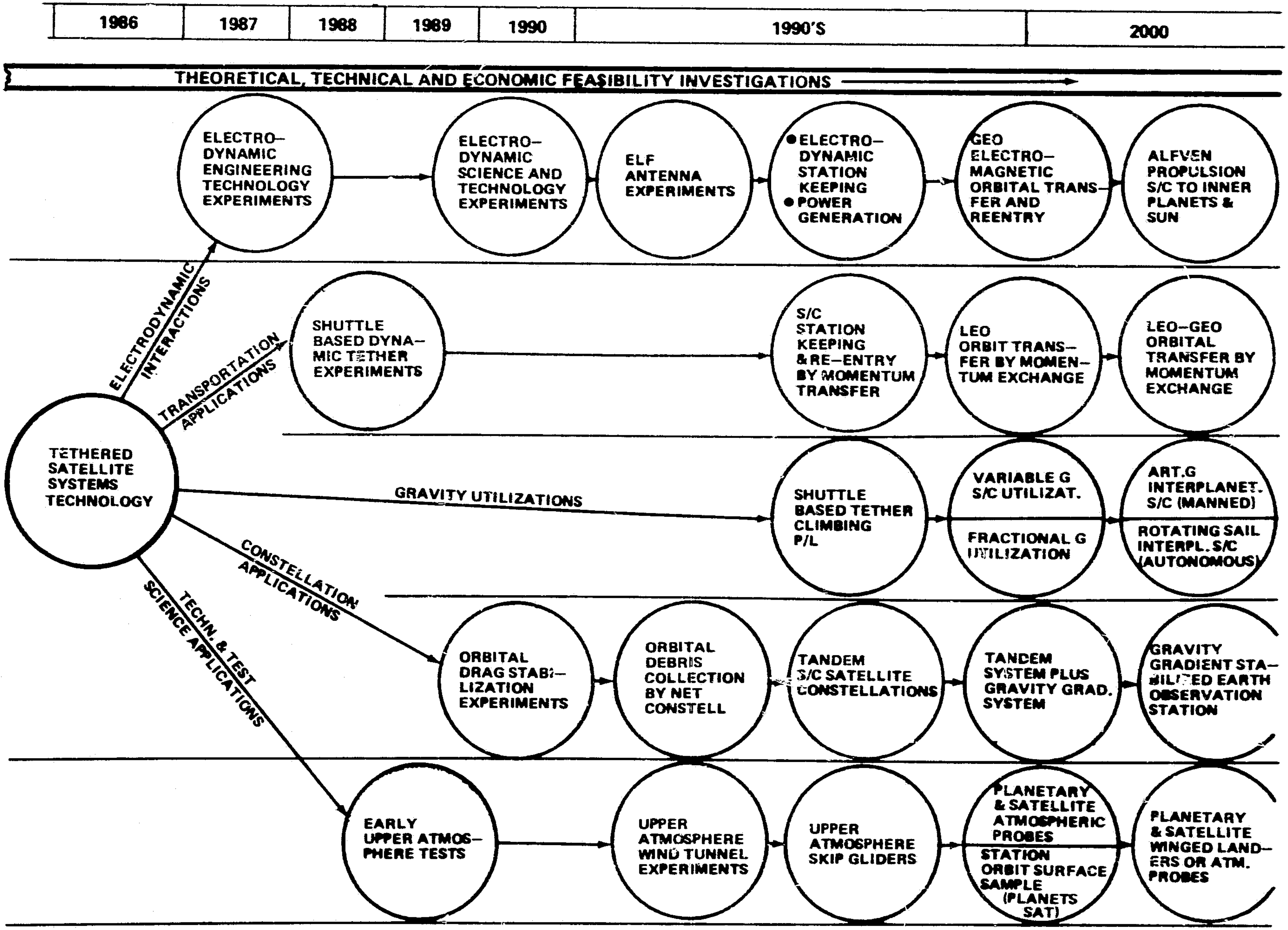

Figure 20. The evolution of tether applications in space.

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APPROVAL

TETHERS IN SPACE – BIRTH AND GROWTH OF A NEW AVENUE TO SPACE UTILIZATION

By Georg von Tiesenhausen

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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