

SPACE TETHERS PROGRAMMATIC INFUSION OPPORTUNITIES¹

J. A. Bonometti
Marshall Space Flight Center, MSFC, AL 35812

K. L. Frame
Gray Research, Inc., Huntsville, AL 35806

ABSTRACT

Programmatic opportunities abound for space Cables, Stringers and Tethers, justified by the tremendous performance advantages that these technologies offer and the rather wide gaps that must be filled by the NASA Exploration program, if the "sustainability goal" is to be met. A definition and characterization of the three categories are presented along with examples. A logical review of exploration requirements shows how each class can be infused throughout the program, from small experimental efforts to large system deployments. The economics of tethers in transportation is considered along with the impact of stringers for structural members. There is an array of synergistic methodologies that interlace their fabrication, implementation and operations. Cables, stringers and tethers can enhance a wide range of other space systems and technologies, including power storage, formation flying, instrumentation, docking mechanisms and long-life space components. The existing tether (i.e., MXER) program's accomplishments are considered consistent with NASA's new vision and can readily conform to requirements-driven technology development.

INTRODUCTION

Tether technologies have a tremendously wide range of applications and levels of performance that can be achieved. From simple mechanical tie-down devices as those presently used on ISS to futuristic, colossal spinning tethers that snatch up sub-orbital payloads, space tethers offer unique advantages and have been used in some form since the early days of spaceflight.¹ The first American spacewalk, by astronaut Ed White (1965), used a simple 25-foot cable as a safety tether, along with an umbilical line.² In the Gemini series alone, "tethers" were used 5 successful times including Gemini X, where it was recorded, "After the rendezvous, Collins space-walked over to the dormant Agena at the end of a 15.24-meter tether, making Collins the first person to meet another spacecraft in orbit."³ One of the more ambitious early applications was an experiment linking an Agena upper stage with a Gemini capsule using a 15.24-meter tether (Astronaut Pete Gordon had attached it during a space-walk also using a tether to cable himself to his capsule) in September 1966. The Gemini XI spacecraft tried to rotate the joined pair to generate "artificial gravity," although the attempt was only a minor success. Space cabling has been used in the Apollo, Skylab and Shuttle programs. Present day safety rules on the International Space Station (ISS) require astronaut tether cabling at all times during EVAs (External Vehicle Activities). There have been over 50 tethers or cables used in space for demonstrations, scientific research and safety over the past 40 years.⁴

In the history of tether and space cable technology, the dazzling potential for their use in space created a "gold rush" like mentality in the 1980s. With the invincible attitude coming from the Apollo Program success as well as a host of triumphant robotic missions, NASA attempted many exceedingly bold engineering challenges, including fielding its first reusable Space Shuttle in record time. The new field of electrodynamic tethers was pushed to the forefront of space research with many of the first flight experiments being very large and expensive demonstrations of the technology. This was unprecedented, since the most basic plasma physics data was not conducted in sufficient depth.⁵ The technology was, and still is, clearly understood to work. It

¹ Approved for public release; distribution is unlimited.

was acclaimed in such reputable documents as the National Commission on Space.⁶ However, the lack of fundamental data and practical experience made good design and operation of such devices awkward. Minor system engineering discrepancies, as well as human error, caused two of the prominent missions to end in mishaps.

The first mission accident was on TSS-1 and was triggered by a bolt hastily added before launch without sufficient oversight. Unfortunately, the bolt head extended into the motion envelope of the deployers' winding mechanism. On orbital deployment, the mechanism jammed when it reached the bolt. The second was TSS-1R where a plasma discharge burned through the tether itself.⁷ Proper understanding of what kind of current could be generated in the space environment would have enabled proper system design and safeguards. As it was, the TSS-1R was invaluable for space plasma physics. It is only now, some 10 years later, that the high current phenomena observed at the break is generally considered understood.⁸ Dr. Nobie Stone has recently exploited this knowledge and tested a new device that promises much higher performance than conventional hollow cathode plasmas contactors. Its success has led to further assumptions that near perfect vacuum operation (i.e., beyond the ionosphere) of electrodynamic tether propulsion is possible. This concept has tremendous implication on the design and operation of the Momentum eXchange Electrodynamic Reboost (MXER) tether system since the reboost time can be vastly extended (i.e., the reboost arch can be nominally extended to 30 degrees) and the power requirements can be limited to a relatively narrow range (i.e., ~10% of peak power).⁹

The regrettable high-profile flight glitches badly damaged the reputation of electrodynamic tethers making it difficult to sustain research (e.g., now hitting an all-time low funding level within NASA), despite overwhelming successes before and after them. Condemning tethers as an unviable technology based on past experience is equivalent to believing solar sails do not produce thrust in space because the two most recent attempts were unsuccessful, due to launch vehicle failures.¹⁰ Even the official NASA accident records and "lessons learned" archives document that tethers are completely viable. The TSS-1R Mission Failure Investigation Board's first observation was "The tether failure is not indicative of any fundamental problem in using electrodynamic tethers."¹¹ In comparison, most other research areas progress with many small physics experiments and the data scrutinized for sometime before the next test. For example, ion engines were investigated over a 30-year span, mostly small ground tests, before a main propulsion flight demonstration was made on Deep Space 1 mission (launched on October 24, 1998 and ending on December 18, 2001). Thus, the best path back to full development for tethers may be a series of smaller experiments, to build a database and, just as importantly, a successful reputation.

The first of several possible small flight experiments will be the MAST CUBESTAT launch whose goal is to generate a valid orbital debris history on a multi-line tether.¹² It will be a major victory for the technology if the objective is achieved. This can help validate micrometeorite debris codes, which have been suspect for use predicting the long, but slender, dimensions of a space tether. Two previous tether flights have utterly different results in regards to space debris lethality. SEDS-2 broke in just 4 days on orbit. It is uncertain why, but some debris modelers believe it was a micrometeorite, while other material specialists suspect the extreme susceptibility of Spectra to atomic oxygen (AO) significantly compromised the material after the four days exposure.¹³ The completely opposite outcome has been found on the TiPS experiment launched in June, 1996. This tether remains unbroken in orbit, well past its expected lifetime. It is extraordinary luck or the first indication that the debris models are not accurate under particular circumstances. A key factor should be mentioned regarding all the previous tether flights; they were all single bundle elements. Some had sleeve wraps or coatings, but none were multi-stranded configurations designed for long life in orbit. As with the SEDS-2 flight, exposed Spectra is now considered unacceptable for tether applications. New materials, coatings and manufacturing make future tether experiments significantly more reliable.

RECENT TETHER DEVELOPMENT AT NASA

Recent efforts at NASA have gained a wealth of knowledge in tethers. There are eight contracts managed by the In Space Propulsion Technologies Projects Office that are focused on the development of the Momentum exchange Electrodynamic Reboost (MXER) tether.¹⁴ The MXER application is one of the most demanding space tether concepts that is technically viable. It requires transformation of commercially available materials, processes and components into a survivable (nominally 10 years) strength tether capable of tip accelerations on the order of 20 m/s² (nominally 1g to 3g). In setting the engineering design goal for MXER, it has been possible to achieve subsystem components that would easily meet the requirements of many other tether applications. Only the large sub-orbital rendezvous momentum exchange concepts demand materials or systems beyond the MXER project goals.¹⁵ Reboost for ISS, Low Earth Orbit (LEO) electrodynamic tugs, end-of-life drag tethers, and almost all lunar transportation concepts require only a fraction of MXER's strength, survivability and complexity.

Since 2003, the In-Space Propulsion Program has funded tether research applicable to the MXER Tether. Four contractors were selected through a peer review process to develop three MXER subsystems: strength tether, propagator code, and catch mechanism. Lockheed Martin Space Systems (LMSS) was tasked to investigate coatings for the strength tether and to develop preliminary designs and fabricate two catch mechanism engineering models. STAR has been developing the algorithms for propagating a fast-spinning tether like a MXER Tether. Tennessee Technological University (TTU) has also developed some propagation algorithm along with two catch mechanism designs and engineering units. Finally, Tethers Unlimited (TUI) was originally tasked to develop some of the design software for a MXER Tether and manufacturing of survivable strength tethers.

The strength tether development, a combined effort with shared data between TUI and LMSS, objective was to develop a high specific strength multi-strand tether with atomic oxygen (AO) and ultraviolet radiation (UV) resistive coatings. The multi-strand configuration reduces the risk of a tether severe from micrometeoroid debris and the coatings reduce the degradation of tether strands associated with exposure to the harsh space environment of AO and UV. TUI made considerable progress in the area of manufacturing process including automating the process of yarn twisting, transfer of yarn to braider bobbins, and braiding the tether from the bobbins.¹⁶ LMSS made remarkable progress on developing coatings and the coating process for the multi-strand tethers. LMSS investigated multiple coatings with one coating, aluminum/alumina coating, performing well when exposed to AO and UV.¹⁷ When submitted to the simulated space environment, the sample gained mass instead of losing it.¹⁸

The propagator code also made incredible breakthroughs within the propagation and prediction algorithms developed by STAR. This development predicted that a fast spinning tether, like MXER, could predict the tip of the tether one-orbit-prior within three meters. Although the MXER Tether design is ~100 km long tether spinning tether that causes ~3 m of creep/day, the accuracy and prediction is made available due to the fast spinning and makes it act as a stiff member.

The most advancement of the MXER subsystems has occurred in the catch mechanism development between LMSS and TUI. Before these contracts began, only one concept had been conceived with no analysis to support. Between TUI and LMSS, nearly one-hundred concepts were derived, engrained into a genealogical structure, and analyzed. The concepts were down-selected to approximately four with LMSS building two and TUI building one. LMSS's first concept was the PatTrap, an iris-like concept that contain two semi-circular "jaws" that would close on a payload boom while centering the load mass. The second engineering model built by LMSS was a Stringged Array w/Probe, a square structure with intersecting cables that allows a probe to puncture through the strings and grapple with a hook. TUI's catch mechanism concepts remained mostly within the iris family, and their engineering model to NASA was the Modified Iris, a square aperture held open by solenoids that allows a boom to penetrate the plane and trigger the closure of the aperture around the boom. All concepts were tested at TUI's High Bay facility in Cookeville, TN.

Additional work within MXER has been performed by SBIR/STTR contractors. The In-Space Office had three Phase II SBIRs and two Phase II STTRs related to MXER in FY05. Tethers Unlimited had a SBIR research the overall MXER design and also an STTR developing the previously mentioned MAST Cubesat. Triton Systems worked under a SBIR researching advanced materials for the MXER conductive tether.¹⁹ Orbitec won a STTR and developed technology towards another small tethered flight experiment, TESSX, that involves a spinning tether. And finally, SRS Technologies won their Phase II SBIR for work on a grid-sphere anode applicable to tethered flights such as MXER. These research programs will be ending in roughly six to nine months. It is unfortunate no follow-up work is planned.

CATEGORY DEFINITIONS

Generally, the term tether has been used for all space applications of long wire-like connectors. However, it appears prudent to distinguish between some general categories using consistent classical definitions. After all, the only physical definition in the Webster's Collegiate Dictionary states "1: something (as a rope or chain) by which an animal is fastened, so that it can range only within a set radius"! The three categories that should help foster the implementation of such technologies into NASA's Exploration Initiative are Cables, Stringers and Tethers. All are considered extremely long compared to its cross-section, are flexible (i.e., a tight bending radius without degradation) and have tensional strength, but essentially no compressive strength.

Cables are defined here as a single line, conventional wire-type lines. They are normally single purpose connectors, such as, a safety harness for an astronaut, actuation cable, communication or power connector. They are commonly, and without deliberation, used in spacecraft design (i.e., low risk) and are usually much shorter than either stringers or tethers. Cables generally use existing materials and methods, but improvements made through the space program, readily enter the market place.

The term Stringers is a less commonplace term, but has a long history in engineering, particularly in civil engineering such as, in suspension bridge design. Stringers are defined here as structural lines or components, almost always in tension when used. Little or no electrical power is transmitted along the stringer and loads are neither dynamic nor excessive. They are usually a major component to the design or subsystem and can be multi-line or single strands. Lengths are on the order of the vehicle size or slightly larger. Examples are: boom stiffeners (i.e., to control buckling of a long beam); formation-flying spacecraft; sunshield structures. These uses are less commonly seen in spacecraft design than cables, but not unknown and are considered low to moderate risk. The development for space applications requires some modifications or improvements of existing commercial products. Long life in the harsh space environment might require some advancements and mass reduction is desirable. Technology spin-off applications and high-volume commercial fabrication is expected.

Space Tethers encompass "transportation" applications in spacecraft. These are often large components (e.g., dominating the vehicle size) and more influential on the entire architecture being designed. Many aerospace engineers and managers consider them medium to high-risk endeavors. Examples range from the Agena/Gemini spacecraft spinup, to ISS electromagnetic reboost, to MXER and up to the lunar elevator (author note: this should not be confused or related to the space elevator, as popularized today for Earth orbit access, a concept that has questionable technical or economic merit). They commonly would be multi-strand, survivable components and usually incorporate other subsystems such as deployment mechanisms, attachment devices, diagnostics, plasma contactors and power supplies. They also could see high current, voltage or dynamic loading. Many of the early space experiments (i.e., TSS-1, SEDS-1, PMG, SEDS-2, TSS-1R) attempted to demonstrate tether operations with more stringer or cable like hardware implementation. However, tethers are defined here as substantially different than cables or stringers. Fabrication engineering development will be much greater for long life in space; strength to weight ratios will be near the present day material limit (with reasonable implementation safety factors); continuous lengths will exceed 10s of kilometers

(if not longer); and commercialization of the exact space product will be unlikely due to cost (although products with de-rated performance are anticipated to be marketed).

MEETING EXPLORATION REQUIREMENTS

The Exploration Initiative began, as stated by the President's Commission to make recommendations on implementing the vision, "On January 14, 2004, President George W. Bush announced a new vision for America's civil space program that calls for human and robotic missions to the Moon, Mars, and beyond."²⁰ On September 19, 2005, NASA rolled out its plan to achieve the President's announcement with the emphasis on a lunar return as a national goal.

The details generated from 18 months of study only gives a barebones outline of the requirements and implementation strategy to achieve the stated objectives. Significant gaps exist between the stated goals and what is known of the execution instructions. Many of these can be bridged with the infusion of cables, stringers or tethers throughout the planned architecture. In some cases their implementation is the only viable technical solution to be successful. The commission's first recommendations (cited in the report's Recommendation 3-4) include creation of a new NASA organization, "...a research and technology organization that sponsors high risk/high payoff technology advancement while tolerating periodic failures."²¹ It continues in a new section heading, "The successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs." Later, under the report's Finding number 7, it states, "The ability to create new capability for humans and machines beyond low-Earth orbit will require scientific and technological advances. This includes research to develop... access planetary surfaces and locations in free space, and to operate effectively once there..."²² There are over 20 references calling for enabling, new or advanced technologies and it is clearly understood that these will be mandatory, as it stresses over ten times the need for a sustainable approach.

There is little in real "technical detail" in the report, but it does give an unprioritized, and admittedly incomplete, list of 17 enabling technologies that include these five relative to cables, stringers and tethers:

- Advanced structures – extremely lightweight, multi-function structures with modular interfaces, the building-block technology for advanced spacecraft.
- Formation flying – for free-space interferometric applications and near-surface reconnaissance of planetary bodies.
- Extravehicular activity systems – the spacesuit of the future, specifically for productive work on planetary surfaces.
- Automated rendezvous and docking – for human exploration and robotic sample return missions.
- Planetary in situ resource utilization – ultimately enabling us to "cut the cord" with Earth for space logistics.

The three base technology classes will be discussed below with the largest attention given to tethers, as they are the most broad and influential technologies to sustainable exploration.

CABLES

Cables will continue to be useful during in-space extravehicular activities (covered in the third bullet above), both human and robotic. On planetary surfaces, where the need to traverse the steep slopes of lunar craters in search of hydrogen, or Mars' landscape where canyons larger than the Grand Cannon are exceedingly common, cables undoubtedly are a simple, reliable and lightweight technology to utilize. A variation of rendezvous and docking is a cable-based architecture, in which a cable is imbedded in a flexible metal extension boom or Bi-stem. This new and innovative design approach allows for lower mass docking rings and mechanisms, due to its inherent control authority over the two spacecrafts. Conventional rendezvous mating

requires long times to slowly match orbits precisely. This uses a fair amount of propellant, particularly with large spacecrafts. Besides the mass penalty, contamination and collision issues make conventional docking very difficult, as illustrated with the failure of NASA's DART mission in April 2005 and the damage to the Mir space station in June 1997.²³ The Bi-stem approach keeps both spacecraft in completely separate orbits, while very "low-inertia objects" make the crucial, initial contact. The boom can be as long as 100 meters (a boom on each craft affords a 200 meter safety distance). Astro Aerospace has successfully deployed in space booms as long as six meters (e.g. Hubble Space Telescope) and have tested even longer ones on the ground. Each can be pivoted at the base and controlled either manually or by simple feedback algorithms for completely automated, electrically powered, rendezvous. A straightforward socket connection or other mechanism automatically locks the boom to the other spacecraft or to its extended boom. Once connected, the spacecrafts can be pulled together by retracting the cable. Gravity gradient forces will naturally help to align the spacecrafts and a second, or even third boom, can be quickly added for positive control and alignment during the final docking (Figure 1). Since there are both compressive and tensile forces present, overshooting or undershooting the velocity limits of the final docking hardware are eliminated. This permits final docking devices that neither have to compensate for large spatial misalignments, nor for an unexpected high impact load.

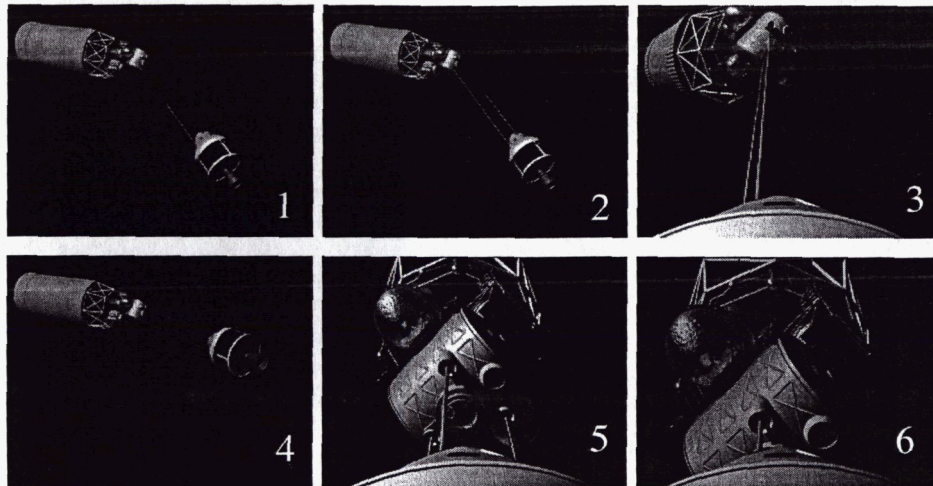


Figure 1: Boom Rendezvous Docking Sequence

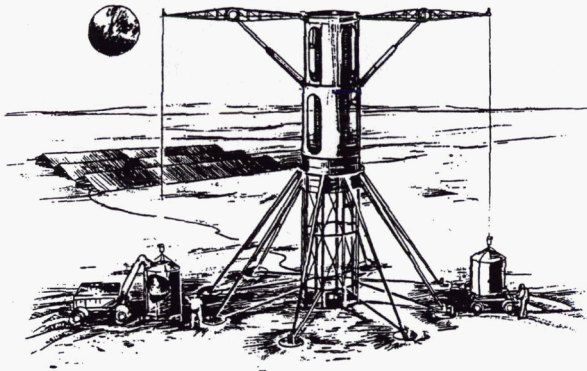
STRINGERS

The first two enabling technologies from the President's Commission report are specific examples of stringer technologies. Structures that use tension members, as the key support elements have inherent mass advantage. Steels, polymers and other common tension member materials are almost always higher in specific strength (GPa tensile/kg) when compared to their use in compression or to other common compressive materials that generally tend to suffer from higher density. Stringers can be dynamically shortened or lengthened and effortlessly connect or disconnect, thus providing multi-functionality and modularity. Formation flying spacecrafts can be readily stabilized in position by interconnecting stringers, held under tension by centrifugal forces with the constant expenditure of propellant (reducing both mass and contamination issues).²⁴

TETHERS

Tethers have a role in transportation to and from the moon, L1 and L2, or other locations. They are particularly suited to support in situ resource utilization architectures. Typical in situ space depots will require a large percentage of lunar propellants to be used for transport to a space staging point (i.e., fuel depot) such as L1²⁵. The cost of production on the moon will be

very high and could start to rival ETO costs (costs also assumed to continue to edge down as time and launch rates increase). Therefore, an architecture that uses a substantial amount of propellant from the lunar surface is unacceptably inefficient and risks cancellation. There are a variety of lunar-based tether systems that can eliminate or drastically reduce propellant demands for supporting space-based outposts, staging areas or refueling stations. A tether-sling appears to be the smallest and easiest to implement, and can support lunar operations, even before the first batch of lunar propellant is produced for orbit operations.^{26,27} As seen from Figure 2, the sling consists of a fixed tower, a rotating hub, the tether arms and a power supply. Unlike an electromagnetic catapult, a comparatively massive and complex structure, the sling can be timed to release into a wide range of trajectories and the sling's acceleration rate can be reduced by allowing more time for spin up (e.g., the catapult requires high rates to prevent excessive lengths). The energy required for orbit is supplied from the electrical power source and the momentum is gained from the moon itself. Many versions of the sling can be envisioned including: counterweighted single tether arms; multiple tethers on the hub; payloads traversing a



continually spinning hub (as compared to a spin-down/reload approach); solar or nuclear power supplies; a range of sizes (generally designs scale linearly). The applications vary from transporting raw lunar materials to be processed at L1 (LEO or L2); supplying the counter-mass for a lun-a-vator type structure; or even sending payloads directly to an earth-entry return.²⁸ The slings could be designed to relocate as propellant sites are explored, given that they are light and easily packed devices.

Figure 2: Zubrin's Lunar Surface SlingShot

The other immediate and high impact space tether is the Momentum eXchange Electrodynamic Reboost (MXER) tethered system. MXER can have a dramatic effect on launch costs using current technologies. It operates by capturing a payload at the tether end and imparting energy and momentum from the MXER elliptical orbit. The tether tip's counter-rotating velocity is subtracted from its orbital velocity at perigee to precisely match the payload's orbit velocity. This provides a brief period where a suitable (i.e., one that affords some margin of error in space and timing) catch mechanism can connect the payload to the tether. One half rotation later, the payload is released to its new trajectory and the MXER tether "drops" to a new orbit with reduced apogee. In order to restore the lost orbital energy and enable the next payload transfer, MXER reboost is achieved through the Lorentz force, induced by driving electrical current through a section of conducting tether, while moving in the presence of the Earth's magnetic field. The current must only flow "up" the tether or the force generated to increase MXER's orbital velocity will be identically balanced by a force generated in the opposite direction. This is achieved by using plasma contactors in the ionosphere or expelling ions at altitudes or times when free electrons are not readily available (i.e., beyond the ionosphere, during night times, etc.). Substantial work has been funded to analyze the design and provide needed data on subsystems and components. A full description of the latest MXER operational parameters can be found in a design paper by Sorensen²⁹. The capture and release mechanism has been experimentally demonstrated on the ground at Tennessee Technical University. Orbital propagation codes, space survivable tether materials, flywheel-based power subsystems, plasma contactors and general systems engineering have been started with significant progress made to date.

Beyond the tether sling and MXER concepts, there are four other groups of tethers for space transportation: Lunar elevator concepts; spinning tethers, whose tip comes close to the lunar surface (i.e., Moravec's Rotovator modified for lunar operation); electrodynamic tugs or

ElectroDynamic (ED) tethers; and suborbital Earth momentum exchange tethers. The elevator concepts are practical structures, even with today's materials (contrasting to Earth-based concepts that are unrealistic)³⁰. On the moon, there is no atmosphere to contend with, the gravity is significantly less, there is plentiful and easily accessible counter-mass material (i.e., by way of lunar slings), orbital debris and radiation belt degradation are not a factor, and beyond the L1 point, the Earth's gravity is advantageous. These factors reduce the strength and survivability requirements and make the concept practical. The various implementations of the lunar elevator might include how and where (if at all) it is attached to the moon; how the payload moves along the tether (rollers, electromagnetic rail, periodic attachment points, etc.); where and what is the counter-mass (bulk lunar materials, a long tether with space debris at the end, a large space station at L1, etc.); and how is the tether fabricated and deployed (tether launched from Earth, materials from the moon, construction from the L1 point outward in both directions, a tether "box" or "tube" structure, etc.).

Spinning tethers might be possible for pickup and delivery of materials and equipment on the lunar surface. These may have timing, placement and payload size limitation. Implementation of the classic Moravec Rotovator³¹ will be more practical than at the Earth (i.e., heating of the tether as it swings through the atmosphere and its large size dictated by Earth's high gravity field), but it will also be limited at where and how it can be employed. A momentum exchange tether orbiting the moon could be synchronized with a (or several) MXER tether(s) in earth orbit as suggested by Hoyt.³² In most spinning tether cases the orbital mechanics may limit the trajectory flexibility and timing opportunities. Therefore, these may be implemented much later in a lunar architecture, once large bases are established and transportation can be specifically tailored to them.

The ED tether group has many varied designs and utilization concepts. They are very interesting for near-earth operations, but the Moon's lack of magnetic field precludes use much beyond GEO. Tugs performing plane change operations are particularly attractive since such maneuvers are normally propellant mass prohibitive using conventional rockets. ED operations are inherently more power efficient as compared to ion engine systems. Typical power densities for ion engines are on the order of 10 to 20 kilogram (mass of entire power processing unit, solar cells and thruster assembly) per kilowatts (energy into the orbit). Electrodynamic tethers are 25 to 100 kilogram per kilowatts. This is due to little or no ionization, thermal, or conversion losses and since the momentum is being obtained from the earth (i.e., pushing against the earth's magnetic field) and not from the rocket exhaust gases. Common uses include cyclic tug payload transport to and from LEO to GEO, drag makeup for satellites or other large assets (i.e., ISS) in LEO, and deorbit of space debris.³³

Similar to MXER, which uses tether electrodynamic propulsion, suborbital momentum tethers impart energy and momentum to a spacecraft and then require replenishment before the next operation. Suborbital operation is, technologically, a substantially more difficult endeavor since it requires a bigger tether, greater counterbalance mass, more delta-v imparted to the payload, better timing and possibly atmospheric drag/heating.^{34,35,36} As it replaces more and more of the delta-V imparted by the booster rocket, launch vehicle size and cost is exponentially reduced. This multiplication factor precipitates from the rocket equation itself! For the largest suborbital tethers, the upper stage could be eliminated (saving manufacturing expense and additional mass) and a true Single-Stage-To-Orbit (SSTO) rocket made possible. Again, this tether-type group most likely would be implemented much later in a lunar architecture as extremely routine, safe and inexpensive transportation is sought.

FUTURE WORK

The existing MXER development contracts will continue to investigate their objectives for approximately six more months. Some of this effort will be devoted to maturing subsystem component technologies for separate spin-off applications. Using the Canfield joint as a thruster platform and/or CEV solar array applications are principal candidates. The GRC flywheel power system study conducted during FY06 will be helpful to MXER and other tether-based propulsion

schemes, as well as supporting lunar sling designs. Stringer and tether materials research is expected to be sponsored during the next year. This will pick up from the recent MXER work on tether fabrication and testing. Less technically aggressive tether prototypes are expected to be produced which should have less programmatic risk. These will most likely apply to ISS reboost, formation flying, and lunar sling applications. A private venture by Bigelow Aerospace Inc. may also hold tether development opportunities in the next few years. As previously stated, there are hopes of a successful Tethers Unlimited MAST CUBESAT flight experiment set for early 2006. In addition, another small tethered satellite experiment by either DOD (conceivably the Naval Postgraduate School, Air Force or DARPA) or NASA within three years is also a possibility.

SUMMARY AND CONCLUSIONS

Two primary themes are recapitulated; the first being NASA's existing tether program's technical progress and the second is the review of the new exploration initiative's uses of such technologies. In doing so, an academic review and categorization of the technology is presented. The categorization theme identifies three classes or groups of flexible tension materials as they are used in space applications, which are Cables, Stringers and Tethers; although in colloquial terminology the term tether is used interchangeably. Each group was defined and specific examples cited for robotic or human space missions. The groups differed in performance parameters, risk and economic impact. The salient details are summarized in Table 1 below. From the study, conclusions can be made that incremental steps are probable to the infusion of the technology into existing and planned space activities. There is not a need to develop and build a single enormous propulsion infrastructure before benefits can be gained from material and process improvements. This is consistent with NASA Administration's mandate that it will only fund requirements-driven technology development. Even if low-cost space transportation, based upon tether technologies, is not explicitly kept on the 'grand' exploration roadmap, cable and stringer hardware will be used and relied upon in many near-term space applications. The prospect of technology spin-offs into the economy, beyond Government space applications, is highly considered.

Table:1 Category Characteristics Summary

Technology Parameter	Cables	Stringers	Tethers
Length	Nominally short (1m-10m)	Short to Long (1m to 100m)	Very Long (100m to 100km)
Strength-to-weight Ratio	Low (~Steel)	Low to Medium (~Kevlar)	Low to Medium (~Aluminum to Zylon)
Dynamic Loads	Low level	No	In Some Applications
Electrical Conductor	No	No	Likely (1- 100 Amps)
Single or Multi-lines	Single	Both	Multi-lines
Material Development	None Required	Little to None	Survivability Coatings
Commercialization	Yes	Likely	Primarily NASA
Development Risk	Little	Some	Higher in Most Cases
Exploration Application	Yes	Possible	Unknown - Necessary for Sustainability

The cable, stringer and tether hardware and development work conducted to date, particularly from the recent MXER tether program, has been highly productive. It has produced new products and subsystems such as the boom rendezvous and docking approach. The potential growth to larger transportation systems, most prominent being the lunar sling, is the best

way to ensure a sustainable lunar architecture. The knowledge of flexible tension members, in whatever particular space application, will be utilized; therefore some level of research and development is warranted by NASA.

ACKNOWLEDGMENTS

The work described in this paper was funded in whole or in part by the In-Space Propulsion Technology Program, which is managed by NASA's Science Mission Directorate in Washington, D.C., and implemented by the In-Space Propulsion Technology Office at Marshall Space Flight Center in Huntsville, Ala. The program objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing cost, mass or travel times.

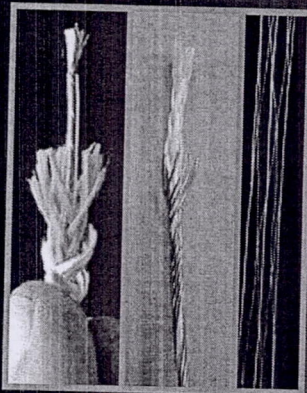
The authors wish to acknowledge important contributions by the MXER contractors, which include Bruce McCandless of Lockheed Martin Space Systems, Dan Gramer of Orbitec, Dr. Nobie Stone of SRS Technologies, Jerome Pearson of Star Technology and Research, Dr. Steve Canfield of Tennessee Technological University, and Robert Hoyt of Tethers Unlimited,

REFERENCES

1. Cosmo, M. L. and E. C. Lorenzini, **Tethers in Space Handbook**, Smithsonian Astrophysical Observatory, MSFC Grant NAG8-1 160, 3rd Edition, (December 1997).
2. Cortright, E. M., **Apollo Expeditions to the Moon**, NASA SP-350, Scientific and Technology Information Office, NASA, Washington, DC (1975).
3. Rumerman, J. A., **Human Space Flight: A Record Of Achievement, 1961-1998**, NASA History Division Office of Policy and Plans, NASA Headquarters Washington, DC 20546 Monographs In Aerospace History Number 9 (August 1998).
4. Carroll, Joseph A., **Guidebook for Analysis of Tether Applications**, Final Report on Contract RH4-394049 with the Martin Marietta Corporation, (March 1985).
5. Stone, N. H., **TSS-1 Mission: Science Presentation**, Presented to Tethered Satellite Systems Applications Review Team, (May 1993).
6. Paine, T. O. et al., **Pioneering the Space Frontier – An Exciting Vision of Our Next Fifty Years in Space**, The Report of the National Commission on Space, (1986).
7. Szalai, K., **TSS-1R mission failure investigation board: Final report**, NASA, (1996).
8. Stone, N., Private communications, (Sep 2005).
9. Stone, N. H., **Development of a Solid-Expellant Plasma Contactor (SOLEX): Harnessing the TSS-1R Tether-Break Physics**, JANNAF (Dec. 2005).
10. Isachenkov, Vladimir, **Russian Space Agency: Solar Sail Launch Failed**, Associated Press, www.space.com/missionlaunches/ap_solarsail_fail_050622.html, (22 June 2005).
11. Messor, P., **Tethered Satellite System 1 Reflight (TSS-1R) Failure**, NASA Lessons Learned Information System, Database Entry: 0566, <http://llis.nasa.gov/llis/llis.html>, (20 May 1996).
12. Hoyt, R., Slostad, J., and Twiggs, R., **The Multi-Application Survivable Tether (MAST) Experiment**, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-2003-5219 (July, 2003).
13. Finckenor, Miria M., Vaughn, Jason A., and Watts, Ed, **Changes in Polymeric Tether Properties Due to Atomic Oxygen**, 42nd AIAA Aerospace Sciences Meeting, AIAA-2004-0322 (Jan. 2004).

14. Sorensen, Kirk F., **Conceptual Design and Analysis of a MXER Tether Boost Station**, AIAA 2001-3915 (2001).
15. Forward, R., and Hoyt, R., **Hypersonic Airplane Space Tether Orbital Launch System**, AIAA Paper 99-4802, (1999).
16. Hoyt, H. P., Voronka, N., Slostad, J., Frank, S., Newton, T., and Barne, I., **Development of Space-Survivable High-Tenacity Tethers**, JANNAF (Dec 2005).
17. McCandless, B., Marshall, L., Kustas, F. M., and Lytl, W. B., **Design Concept for a Reusable/Propellantless MXER Tether Space Transportation System**, JANNAF (Dec 2005).
18. Gittemeier, K. A., Hawk, C. W., Finckenor, M., Watts, M., **Atomic Oxygen Effects on Coated Tether Materials**, 43rd AIAA Aerospace Sciences Meeting and Exhibit, (Jan. 2005).
19. Gavrin, A., Blizzard, K., and Gonyer, R., **Materials for the Advancement of MXER Tether Design**, JANNAF (Dec 2005).
20. Paine, *ibid.*
21. Paine, *ibid.*
22. Paine, *ibid.*
23. Holliman, J., Aaron, B., Dougherty, J., ***Mir at half power after collision***, CNN, <http://www.cnn.com/TECH/9706/25/mir.collusion.4p/>, (June 25, 1997).
24. Penzo, P., **A survey of Tether Applications to Planetary Exploration**, AAS 86-206, page 71 in *Tethers in Space*, Vol. 62, *Advances in the Astronautical Sciences*, AAS (1986).
25. Pearson, J., **Low-Cost Launch System and Orbital Fuel Depot**, 37th International Astronautical Federation Congress, AIAA Paper IAF-86-128, (October 1986).
26. Muller, R. M., **The Slinger: An In-Orbit Booster Facility**, AIAA 86-2175, (1986).
27. Landis, G., A., **Analysis of a Lunar Sling Launcher**, JBIS, Vol. 58, (Sep/Oct 2005).
28. Hoyt, R. and Uphoff, C., **The Cislunar Tether Transport System Architecture**, 2nd Lunar Development Conference, (July 2000).
29. Sorensen, K. F., **Design and Analysis Procedures for a MXER Tether Facility**, JANNAF (Dec 2005).
30. Pearson, J., Levin, E., Oldson, J., and Wykes, H., **The Lunar Space Elevator**, IAC-04-IAA.3.8.3.07, 55th International Astronautical Congress, (October 2004).
31. Moravec, H., **A Non-Synchronous Orbital Skyhook**, *Journal of the Astronautical Sciences*, Vol. 25, No. 4, (1977).
32. Hoyt, R. P., and Forward, R. L., **Tether Transport from Sub-Earth-Orbit to the Moon... And Back!**, International Space Development Conference, (May 1997).
33. Pearson, J., Carroll, J., Levin, E., Oldson, J., and Hausgen, P., **Overview of the Electrodynamic Delivery Express (EDDE)**, AIAA 2003-4790, (July 2003).
34. Zubrin, R., **The Hypersonic Skyhook**, *Journal of the British Interplanetary Society*, Vol. 48, No. 3, (March 1995).
35. Penzo, Paul, **A Low Earth Orbit Skyhook Tether Transportation System**, AAS 87-436, (1987).
36. Pearson, J., **Spaceflight Applications for Rotating Structures in Space**, Presented at the AIAA Annual Meeting, Baltimore, MD, (May 1982).

JANNAF



SPACE TETHERS PROGRAMMATIC INFUSION OPPORTUNITIES

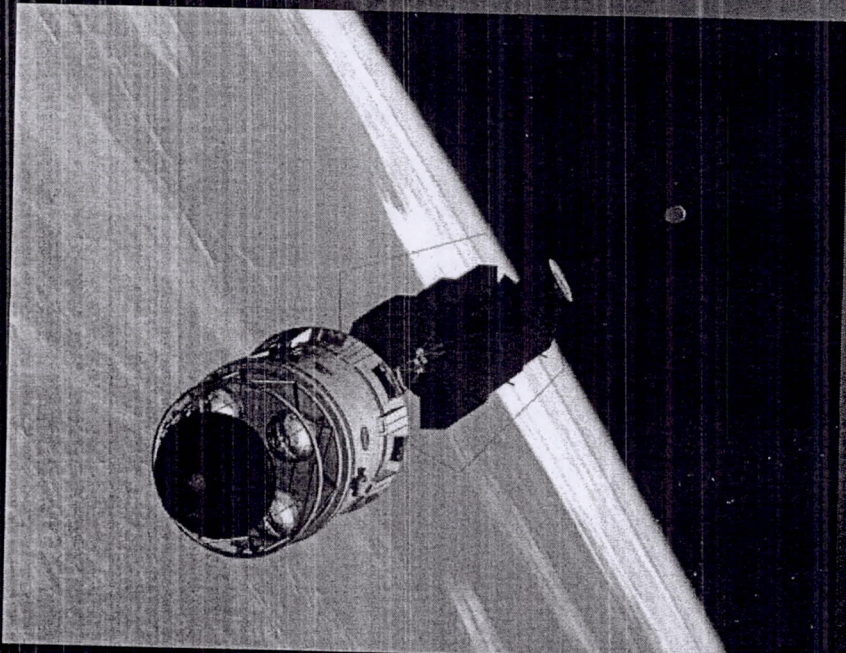
Dr. Joseph Bonometti

Marshall Space Flight Center, MSFC, AL 35812

Kyle L. Frame

Gray Research, Inc., Huntsville, AL 35806

December 7, 2005





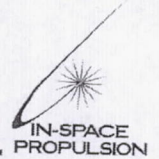
Outline



- ◆ **Old Tether History**
- ◆ **MXER Tether Project Accomplishments**
- ◆ **State of the Technology**
 - What went wrong?
 - Overcoming perceptions
 - Engineering terminology
- ◆ **Fulfilling Exploration Needs**
- ◆ **Future Work**
- ◆ **Conclusions**



Early Space Tether Implementation



- ◆ September 1966, Gemini XI generates "artificial gravity" in space
- ◆ An Agena upper stage was linked with the Gemini capsule using a 15.24-meter tether (Astronauts Richard Gordon and Pete Conrad).

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.



History

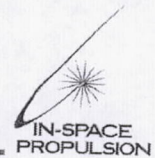


- ◆ **Tethers, cables, and stringers have been used since the earliest days of spaceflight.**
- ◆ **Gemini incorporated cables five (5) times, including the first American spacewalk by astronaut Ed White (1965).**
- ◆ **Solar array deployments (Hubble & ISS)**
- ◆ **Yo-Yo despin devices (Mars Pathfinder)**

- ◆ **Tether experiments**
 - More than sixteen tether missions have flown since 1967
 - Synopsis of four relevant missions:
 - SEDS-1: Full deployment of 20km non-conductive tether
 - SEDS-2: Full deployment of 20km non-conductive tether
 - TSS-1R: Deployed 19.6km of conductive tether; demonstrated propulsion capabilities of ED tethers
 - TiPS: 4km non-conductive tether on orbit since 1996



Synopsis of Major Tether Missions



Successful Missions

SEDS-1

Launched March 29, 1993 on Delta 7925/GPS-31

- ◆ Successful deployment of a 20-km tether
- ◆ Open-loop control law

PMG

Launched June 26, 1993 on Delta 7925/GPS-39

- ◆ Successful bi-directional ED operation
- ◆ Max current of 300 mA
- ◆ Deployed to full 500 meters using a spring ejection

SEDS-2

Launched March 9, 1994 on Delta 7925/GPS-36

- ◆ Successful deployment of a 20-km tether
- ◆ Tether severed after 3.7 days of deployment
- ◆ Attached tether stabilized in vertical position

TiPS (Tether Physics and Survivability) sponsored by NRO
Launched June 20, 1996

- ◆ Tether designed to expand slightly after deployment
- ◆ Successful deployment of 4 km of non-conducting tether
- ◆ 1000-km orbit is in high-debris region
- ◆ Survivability of the tether has significantly surpassed lifetime expectations (5-sigma)

Semi-successful Missions

TSS-1

Launched July 31, 1992 on STS-46

- ◆ Successful Initial Deployment and Dynamic Stability
- ◆ Recovery from Dynamic Upsets & Slack Tether
- ◆ Near retrieval from 276 m was nominal
- ◆ Deployment halted because of interference from a misplaced bolt

TSS-1R

Launched February 22, 1996 on STS-75

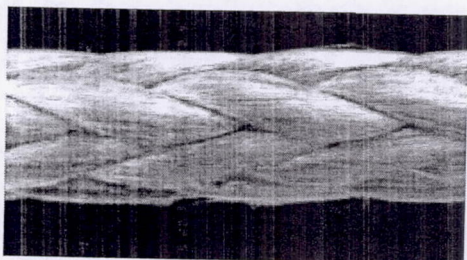
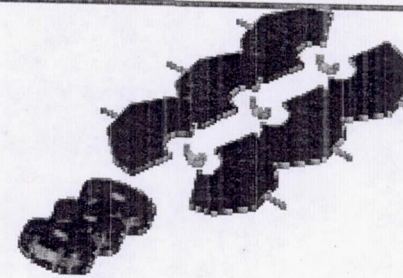
- ◆ 95% of Tether Deployed (19.7 km of 20 km)
- ◆ TSS Successfully "Closed the Circuit" and demonstrated Superior Current Collection Capability
- ◆ Power generation and thrust also demonstrated
 - Voltage of 3.5 kV and current of 480 mA were observed
- ◆ Tether severed by plasma arcing due to outgassing of tether
- ◆ Severed tether demonstrated safe orbital separation at a rate of 675 km per orbit



The MXER Team's Accomplishments

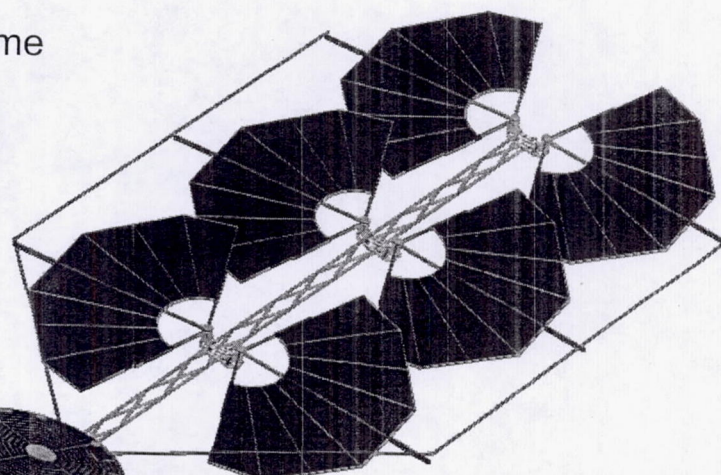
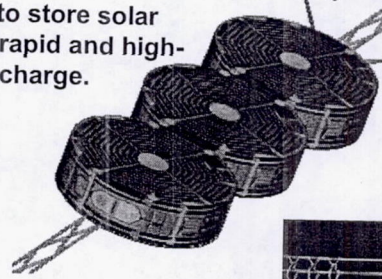


- ◆ **Successful Catch Mechanism Design**
- ◆ **Dynamics Propagator and Design Code Breakthrough**
- ◆ **Survivable tether designs and coating approaches**
- ◆ **Maturation of the MXER System**
 - Layout, mass & volume quantified
 - Solar tracking breakthrough
 - Flywheel based power system optimized for the first time
 - Understanding and flexibility in operations/sizing

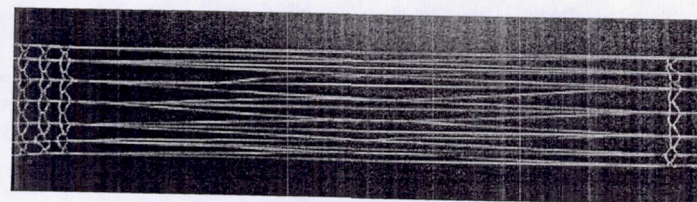


High-strength Zylon coated with aluminum oxide to survive exposure to atomic oxygen.

Flywheels to store solar energy for rapid and high-voltage discharge.



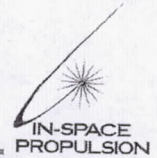
Solar arrays that can fully track the Sun while the tether rotates—without slip rings!



Sample of interconnected multi-strand Zylon tether that can survive numerous cuts from debris.

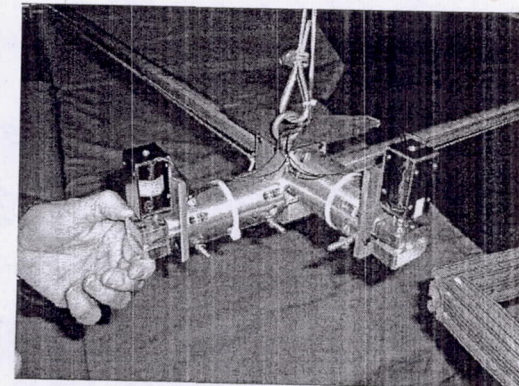
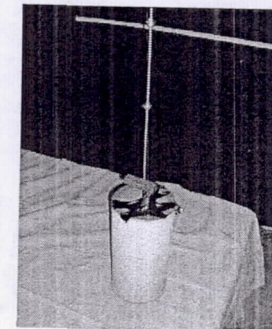
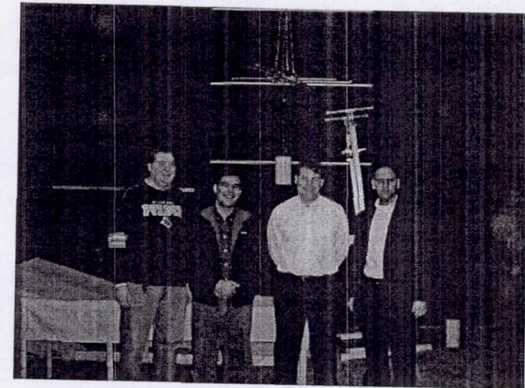


Synopsis of Recent Tether Development



Catch Mechanism Development

- ◆ Work performed and competitively awarded under NRA process to Tennessee Technological University and Lockheed Martin Space Systems
- ◆ More than thirty (30) capture concepts were developed, proposed, and analyzed.
- ◆ Capture concept genealogy and naming system developed to organize and characterize each concept
- ◆ Performed trade study using engineering team's formulated criteria
 - Four concepts were selected for additional analysis
 - QuadTrap concept selected for fabrication.
- ◆ Laboratory/bread-board testing and demonstration initiated through the following activities:
 - Design construction and testing of Payload Launch System
 - Design and constructing of the representative payload – based upon scaled mass and added gyros to stabilize the payload during launch
- ◆ Completed design and fabrication of prototype QuadTrap capture mechanism with instrumentation.
- ◆ Fabricated two additional breadboard catch mechanisms (Umbrella Probe, Double Bear Trap) and tested in the same manner as the QuadTrap.
- ◆ Initial correlation of test data with capture mechanism dynamic model
- ◆ Spin-off technologies such as Canfield joint & bi-stem boom rendezvous
- ◆ Hugely successful free-flyer testing with QuadTrap
 - Autonomous testing
 - Additional accelerometers



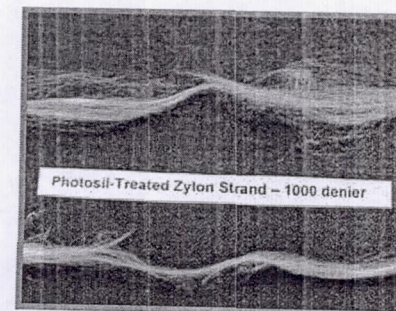
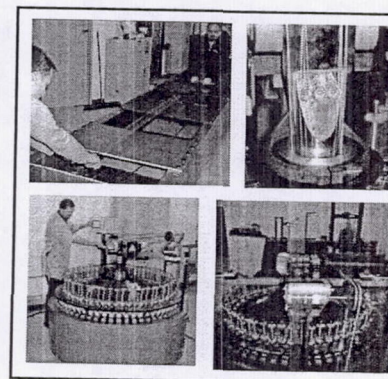
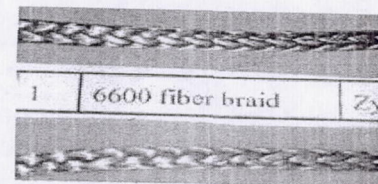


Synopsis of Recent Tether Development



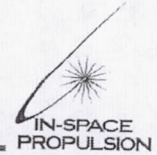
Strength Tether Development

- ◆ Work performed and competitively awarded under NRA process to Tethers Unlimited and Lockheed Martin Space Systems
- ◆ Delivered samples of Zylon yarn and braided materials treated with three different atomic oxygen-resistive coatings (PhotSil, Metallized, Aluminum-Alumina) for testing in the NASA/MSFC AO facility. The Aluminum-Alumina (Al/Al_2O_3) coating showed most promising coating to resist AO degradation. An additional small sample of M5 coated with Al/Al_2O_3 was delivered and tested in the MSFC AO chamber.
- ◆ AFRL/MLBT completed production dopes of PBO mixed with silsesquioxanes and spun it into fibers.
- ◆ Concepts for multi-strand and tape tether designs for Zylon and Spectra were defined
- ◆ Single-strand tether with predicted break-strength rating for MXER (222,000 N)
- ◆ Conducted tensile strength testing of Hoytether structures at TUI
 - Secondary strands added strength to the Hoytether structure
 - Zylon in a Hoytether configuration consistently exceeded the theoretical tensile strength
 - Initial tensile tests of Hoytether structures with cut lines
 - Pulled to 50% of theoretical strength
 - Began cutting individual segments
 - Appears the structure is maintaining strength following several cuts
- ◆ Gained data for costs associated with coating tethers with PVD deposition, TOR, and Modified C-MAG PVD coatings.
- ◆ An initial top-level investigation of thermal modeling was performed.
- ◆ Initial mandrel bend tests on coated tethers indicated that most coating tethers did not have bending issue did not experience some coating removal



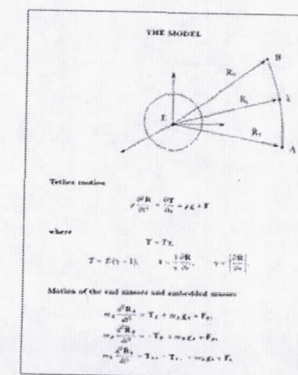
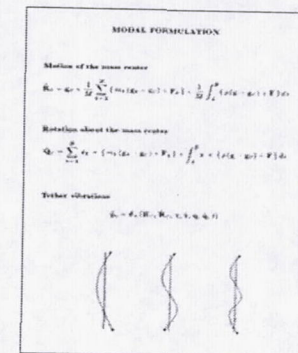
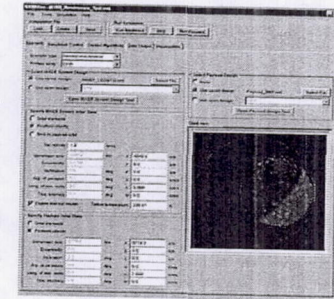


Synopsis of Recent Tether Development



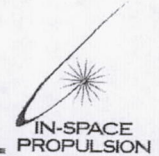
Propagator Code Development

- ◆ Work performed and competitively awarded under NRA process to Tethers Unlimited, Tennessee Technological University, and Star Technology and Research Inc.
- ◆ Four analytical models developed to considered tether dynamics
 - Continuum model using inertial-frame-based coordinates and finite difference (FD) solver
 - Continuum model using relative-orbit-based coordinates and finite difference (FD) solver
 - Continuum model applicable to multi-noded tether system, inertial-based coordinates, finite difference solver
 - Continuum model derived via Hamilton's principle, generalized coordinates and and finite difference (FD) solver
- ◆ Three classes of computational ODE algorithms were implemented:
 - Runge Kutta (single-point explicit)
 - Adams-Bashforth Moutlon (multi-point explicit)
 - Gear Methods (multi-Point implicit)
- ◆ Models for initial conditions developed, providing closed-form solution for initial rotational state.
- ◆ The equations of motion separating the motion of the mass center, rotation about the mass center, and tether vibrations, were defined to allow effective simulation of gravitational perturbations.
- ◆ Applied the theory of pendular motions for space tether systems to the MXER simulation problem and decomposed the motion into three components:
 - Orbital motion of the mass center
 - Quasi-rigid rotation about the mass center
 - Tether oscillations about of the quasi-rigid line of the tether.



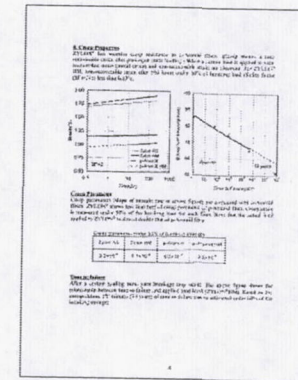


Synopsis of Recent Tether Development

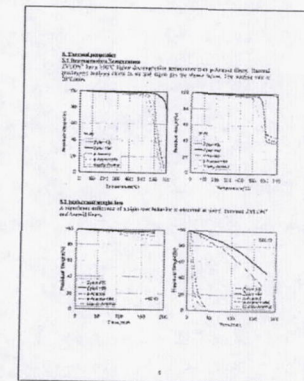


Propagator Code Development

- ◆ Derived equations for determining eigen-forms and eigen-frequencies of a rapidly rotating tether system which led to the equations for excitation of eigen-forms under small perturbations. Preliminary results predict an accuracy within 1-m (one orbit prior to catch) with the ability to be produced on a PC
- ◆ Completed three alternative numerical formulations for evaluating governing tether pde: finite difference on inertial coordinates, rigid-body relative coordinates, finite element approximations on rigid-body-relative coordinates.
- ◆ Completed computer implementation of two additional integration routines: implicit routine (gear method) and explicit, time-step adaptive (adaptive RK 7-8).
- ◆ Completed multi-stage process of model validation defined through the "Model Validation Matrix."
- ◆ A polynomial series expansion was adopted to represent the gravitational perturbations on a finite length tether system.
- ◆ Determined the effects of perturbations on the rendezvous accuracy caused by the following:
 - Creep in the tether material
 - Tether mass variation (sublimation, outgassing, meteor damage, other causes)
- ◆ Creep in tether was determined to be significant in propagation code development. It was determined that MXER tethers will creep (lengthen) of at least 2.5 m/day.
- ◆ Determined that isothermal mass loss is not significant factor in fast-spinning tethers.
- ◆ Began using MXER design code in support of MXER design.



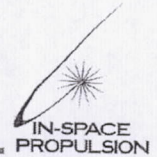
Creep Properties



Thermal Properties



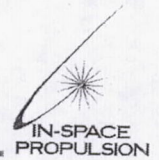
What Went Wrong



- ◆ **Space tether use was recognized early at high levels of decision-making**
- ◆ **It was rushed too fast**
 - Basic physics was not understood
 - High profile/expensive systems were flown first
 - Mishaps soured enthusiasm and brought about mistrust of the technology
 - No mandate to 'slug through' the incubation period
- ◆ **Suggest that the community go back to basics**
 - Fundamental science and engineering data gathering
 - Small/inexpensive flight experiments
 - Validation of codes
 - Niche opportunities
 - Education
- ◆ **Suggest looking at what we do in a different light to better communicate how "tethers" fit in space...**
 - i.e., overcoming The Fear Factor!**



Overcoming Perceptions



- ◆ **Do not lump all “tethers” into one category**
 - Not standard engineering practice
 - If one has a failure/problem, the other areas are less affected
 - Offer different levels of technology risk to potential customers/managers
 - Demonstrate a stepped approach for technology development and enhancements
 - Show commercialization and spin-off technologies early
- ◆ **Advance the tether technology one small success at a time**

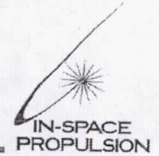
And remember what the definition of a *tether* is to some people:

“Something (as a rope or chain) by which an animal is fastened, so that it can range only within a set radius”



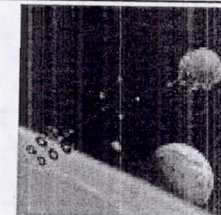
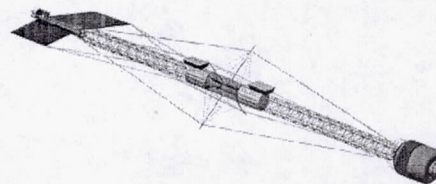


Engineering Nomenclature



Three categories of space flexible tension members

Technology Parameter	Cables	Stringers	Tethers
Length	Nominally short (1m-10m)	Short to Long (1m to 100m)	Very Long (100m to 100km)
Strength-to-weight Ratio	Low (~Steel)	Low to Medium (~Kevlar)	Low to Medium (~Aluminum to Zylon)
Dynamic Loads	Low level	No	In Some Applications
Electrical Conductor	No	No	Likely (1- 100 Amps)
Single or Multi-lines	Single	Both	Multi-lines
Material Development	None Required	Little to None	Survivability Coatings
Commercialization	Yes	Likely	Primarily NASA
Development Risk	Little	Some	Higher in Most Cases
Exploration Application	Yes	Possible	Unknown - Necessary for Sustainability



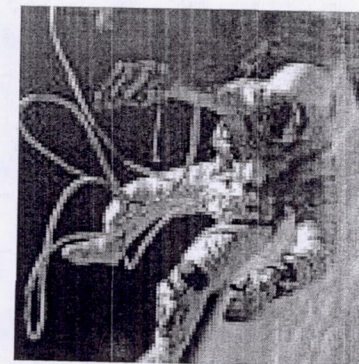
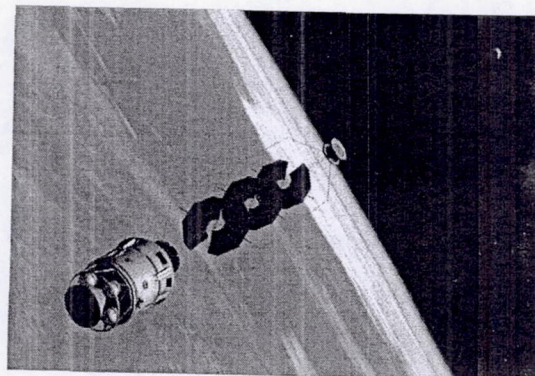
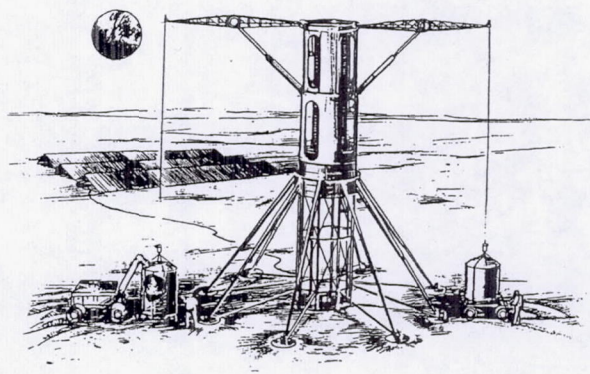


Meeting Exploration Requirements



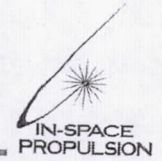
From the 17 enabling technologies included from the President's commission report:

1. Advanced structures – extremely lightweight, multi-function structures with modular interfaces, the building-block technology for advanced spacecraft. S, T
2. Formation flying – for free-space interferometric applications and near-surface reconnaissance of planetary bodies. S
3. Extravehicular activity systems – the spacesuit of the future, specifically for productive work on planetary surfaces. C
4. Automated rendezvous and docking – for human exploration and robotic sample return missions. C
5. Planetary in situ resource utilization – ultimately enabling us to “cut the cord” with Earth for space logistics. T

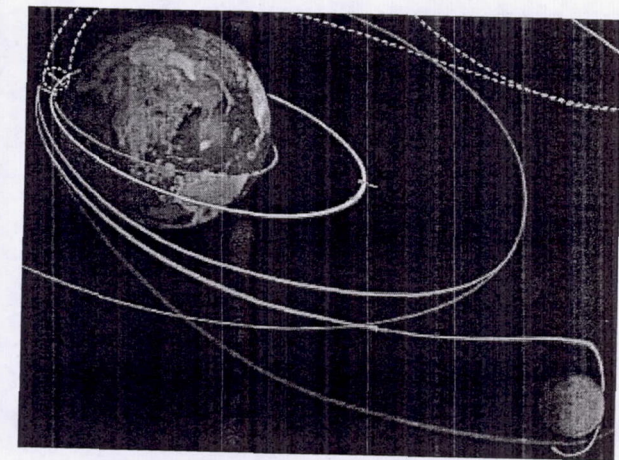
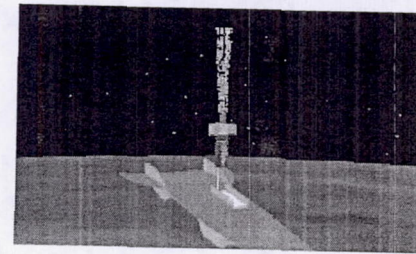
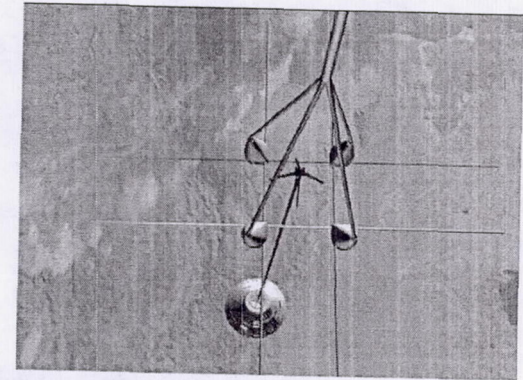




Future "Lowering the Cost" Options

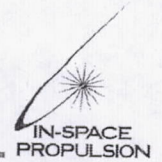


1. Single MXER to throw supplies to: GTO, Lunar supplies, L1, etc.
2. Larger MXER to transport heavy cargo to Mars/planetary injection
3. Man-rated MXER for Lunar outbound trip
4. Advanced-MXER capable of dipping into the upper atmosphere for a suborbital catch
5. Momentum Exchange tether at the Moon to Catch and return payloads from Earth MXER (continuously recouping momentum) if practical
6. Rotating tether picking up payloads from the lunar surface if possible

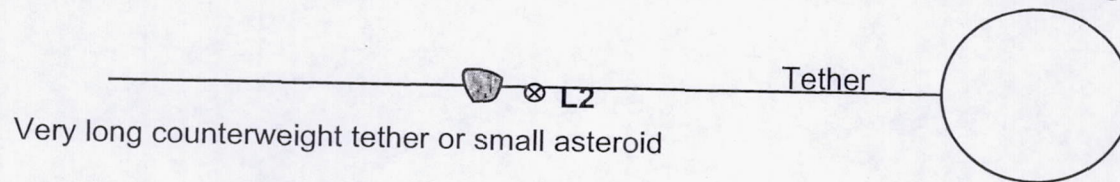




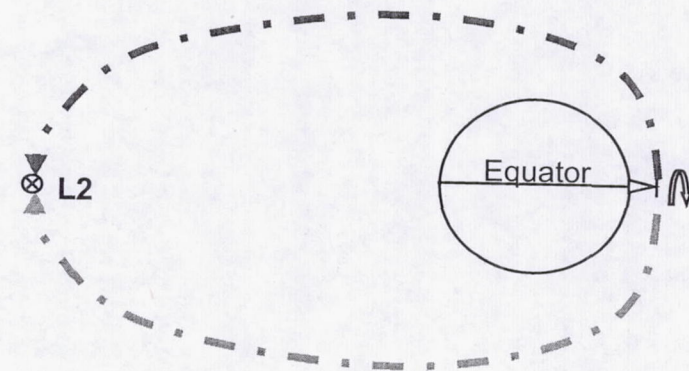
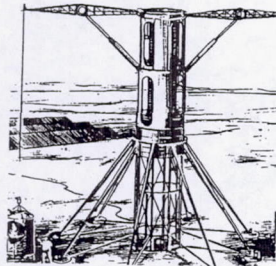
Future "Lowering the Cost" Options



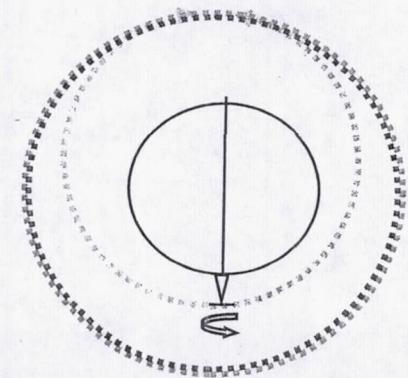
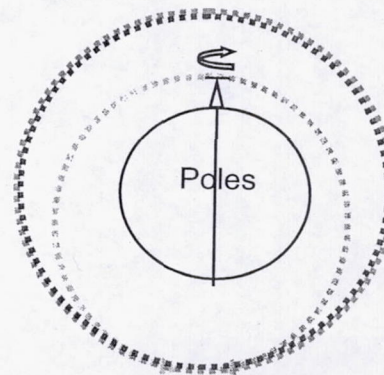
7. 'Lun-a-vator' or space elevator for the moon using an asteroid



8. Moon Surface Slingshot on equator



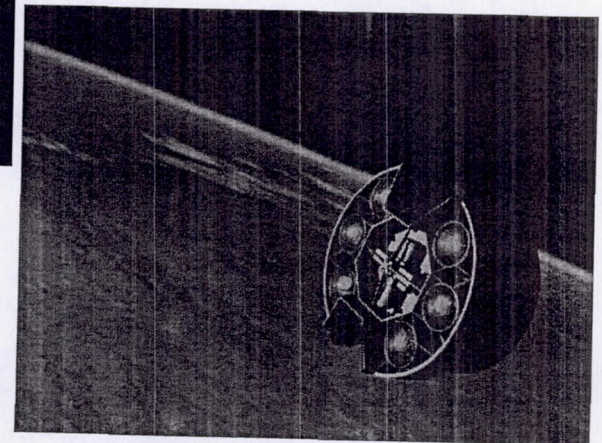
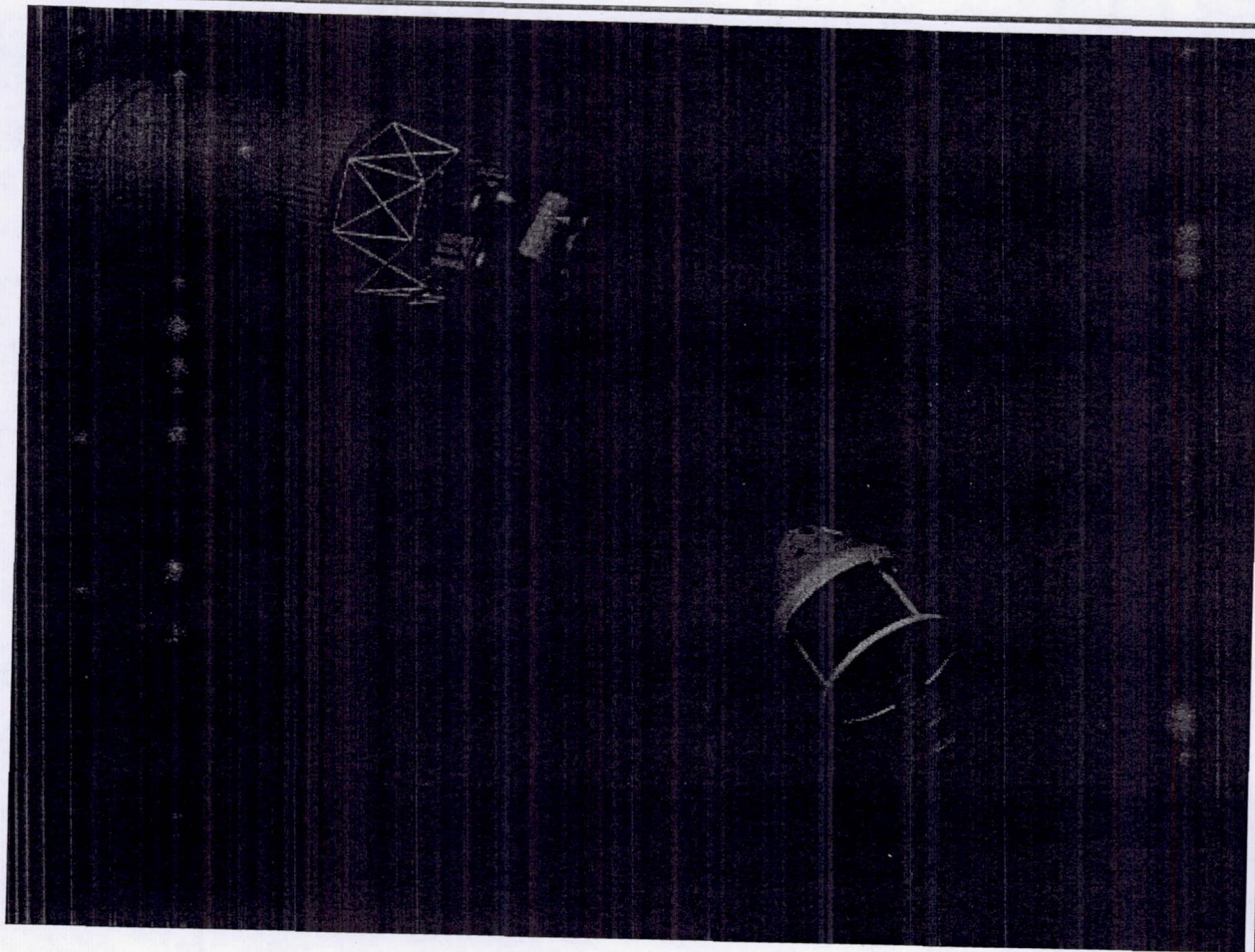
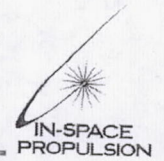
9. Surface slingshot on the two poles of the moon



10. Tethers at Mars and on Phobos

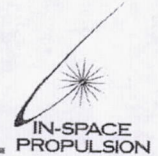


Rendezvous and Docking Video





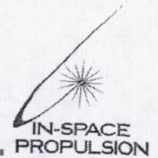
Future Work



- ◆ **There are roughly 6 more months for the existing EPT MXER contracts (options are available if future funding is found)**
- ◆ **Emphasis on maturing subsystem components for other applications:**
 - Canfield Joint for thruster/solar array and communications tracking
 - Flywheels and modified bi-stem boom for ISS thruster platform
 - Stabilization and ED reboost for ISS or Bigelow habitat
 - Terrestrial tethered power generation
- ◆ **Lunar exploration activities:**
 - Cables/stringers for surface crater mobility
 - Lunar sling
 - Lunar elevator
- ◆ **Small flight experiments and applications**
 - MAST
 - DoD satellite propulsion
 - Bigelow stabilization



Conclusions



- ◆ **NASA's existing MXER tether project accomplishments:**
 - Catch mechanism developed to TRL 3 from almost nothing
 - Dynamics code development scheme that radically reduces processing time and accuracy
 - Further refinement of survivable tether structures, particularly the Hoyt structure
 - Initial aluminum/alumina coating work on Zylon begun
 - Power system mass/volume reductions with initial flywheel designs
 - Basic Java design code developed for MXER
 - MXER design evolution and refinement (including 30 days or less reboost time, single US launch, tracking fully resolved, packing volume quantified, overall system operation and lifetime options identified)
 - Multiple spin-off technologies
- ◆ **Exploration Initiative's use of flexible tension materials appears necessary for a sustainable architecture**
- ◆ **Categorization theme identified 3 classes or groups for space applications:**
 - Cables: short, single-strand, low-tension applications using common materials
 - Stringers: short to long, single or multi-strand, medium-tension applications using common materials
 - Tethers: long, multi-strand, high-tension applications using best available materials & coatings
- ◆ **Recommend many incremental steps to further the use of such technologies in space**