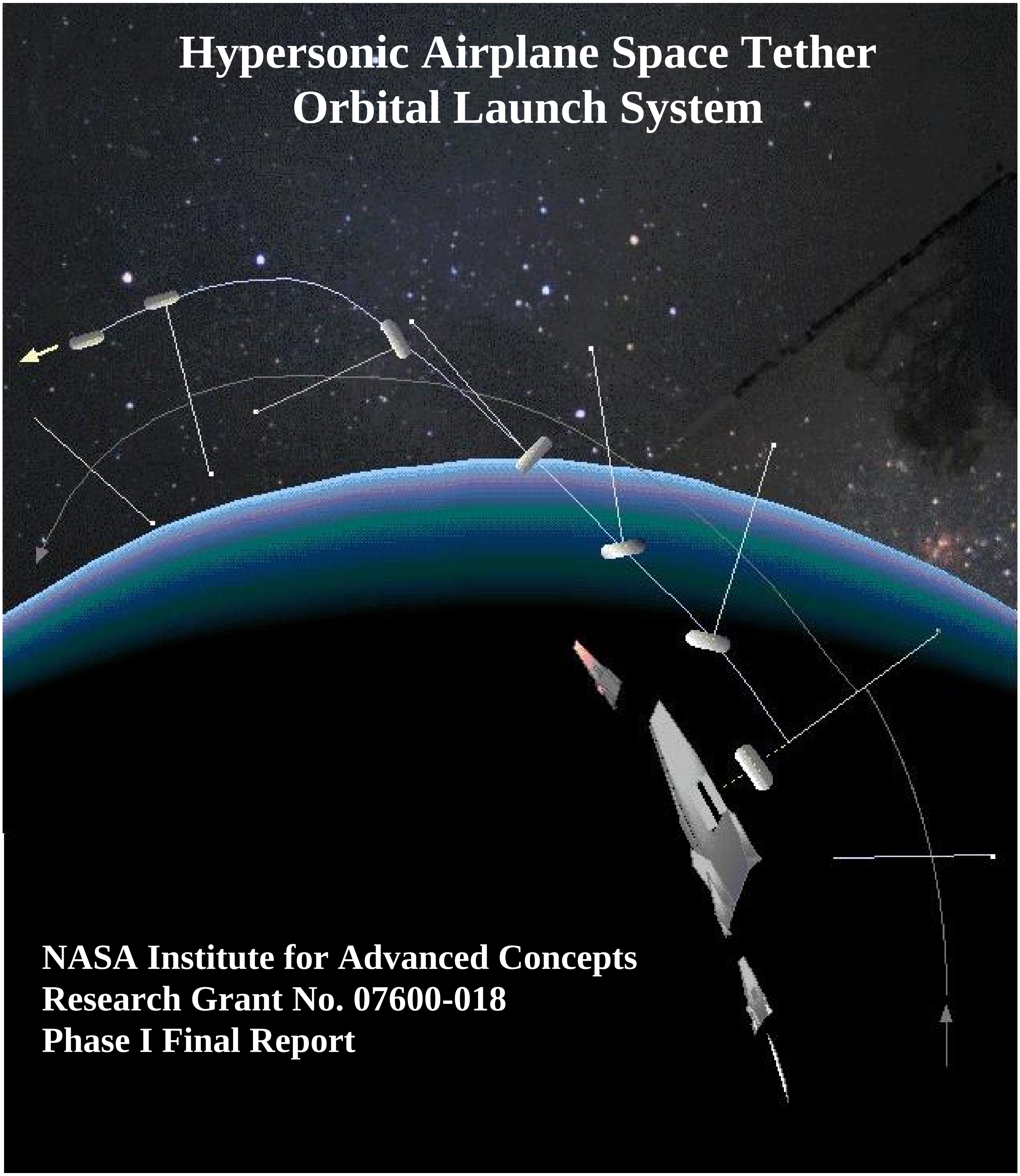
BOEING-STL 2000P0001



Hypersonic Airplane Space Tether Orbital Launch System

NASA Institute for Advanced Concepts
Research Grant No. 07600-018
Phase I Final Report

BOEING

BOEING-STL 2000P0001
07 January 2000

Hypersonic Airplane Space Tether Orbital Launch System

NASA Institute for Advanced Concepts University Space Research Association Research Grant No. 07600-018

Phase 1 Final Report

Principal Investigator: Thomas J. Bogar, Boeing/MDC Phantom Works
St. Louis, MO

Co-Investigators: Michal E. Bangham, Boeing/MDC Huntsville
Robert L. Forward, Tethers Unlimited, Inc.
Mark J. Lewis, University of Maryland

Contributors: Robert P. Hoyt, Tethers Unlimited, Inc.
Donald Johnson, Boeing/MDC-Phantom Works, St. Louis
Joseph Stemler, Boeing/MDC-Phantom Works, St. Louis
Benjamin Donahue, Boeing/MDC, Huntsville
Laura Beth Fleming, Boeing/MDC, Huntsville
Brian J. Tillotson, Boeing S&CS, Seattle
Daniel Stuart Bowman, University of Maryland, College Park

Copies may be obtained from the NIAC Web Site: <http://www.niac.usra.edu/bogar>
or by writing Boeing/MDC-Phantom Works, P.O. Box 516, Mail Code S106-7250,
St. Louis, MO 63166

BOEING

TABLE OF CONTENTS

Page

TABLE OF CONTENTS ii

LIST OF APPENDICES iii

INTRODUCTION 1

TECHNICAL SUMMARY OF SELECTED BASELINE HASTOL DESIGN 2

HYPERSONIC AIRPLANE 5

SPACE TETHER 9

- Rotovator™ 10
- LIFTether 15
- CardioRotovator™ 17
- Tillotson Two-Tier Tether 19
- HyperSkyhook 19
- HARGSTOL 20
- Rendezvous Simulations 21
- Space Tether Issues 24
- Relevance of Past, Present and Planned Tether Flight Experiments 28

TETHER GRAPPLE AND PAYLOAD ACCOMMODATION SYSTEM 32

- Design Requirements 33
- Configuration Options 35
- Architecture Control and Payload Transfer 46
- Grapple and Payload Transfer Issues 49
- Further Study/Recommendations 51

CANDIDATE PHASE II TASKS 52

- Mission Opportunities 52
- System Requirements Definition 52
- Conceptual Design 52
- System Analysis 53
- Technology Development Planning 53

CONCLUSIONS 54

REFERENCES 55

LIST OF APPENDICES

Page

APPENDIX 1 - Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System: Initial Study Results A1-1

APPENDIX 2 - Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System: Interim Study Results A2-1

APPENDIX 3 - Design and Simulation of Tether Facilities for the Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Architecture A3-1

APPENDIX 4 - Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System - NIAC Fellows Meeting A4-1

APPENDIX 5 - Modular Space Tether Design and Construction A5-1

INTRODUCTION

The Boeing Company - Phantom Works has led a team in a Phase I study which has shown the technical feasibility of a completely new concept for moving payloads and passengers from the surface of the Earth into low Earth orbit at low cost and low acceleration levels without the use of rockets as the main source of propulsion. The team includes the Boeing Company, Tethers Unlimited, Inc. (TUI), and the University of Maryland (UMd). The concept, named the Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Architecture, is shown schematically in Figure 1.

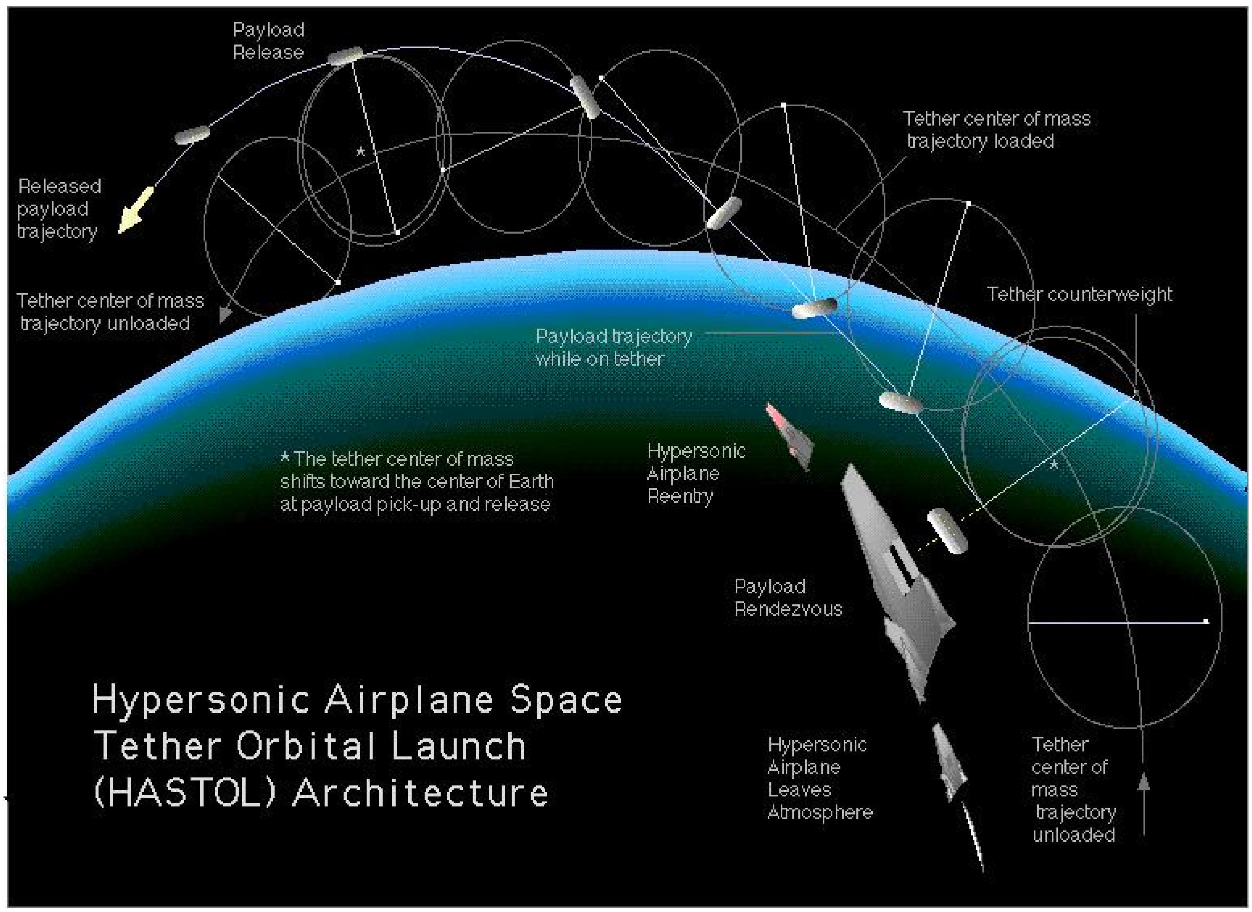


Figure 1. HASTOL System Architecture

The HASTOL architecture contains three major components: a hypersonic airplane, which will transport the payload as high and as fast as possible using air-breathing propulsion; an orbiting space tether, the tip of which will be lowered down and slowed down by some means so as to meet up with the hypersonic airplane; and a grappling system, part of which is at the tip of the tether and part of which is on the payload, that will take control of the payload and, with the lift supplied by the space tether, carry the payload on into orbit, then toss it to into its desired final trajectory. Each component will be discussed in more detail in the remainder of this report. The objective of the study is to examine the feasibility of such a system and optimize the combined system of airplane, tether, and grapple in order to maximize the overall performance in terms of payload mass and delivery rate, while minimizing the life cycle cost. As we shall show later, our Phase I study effort has determined that there are a number of technically feasible ways to implement the HASTOL architecture using existing design concepts and existing materials. The Phase II study effort can now concentrate on choosing the best implementation and optimizing it for minimum life cycle cost.

TECHNICAL SUMMARY OF SELECTED BASELINE HASTOL DESIGN

In the Phase I study effort we identified a number of different combinations of hypersonic airplane and space tethers that can result in a Hypersonic Airplane Space Tether Orbital Launch architecture that can bridge the present gap in altitude and speed between atmospheric flight and space flight. The best concept found to date is the simplest one, and is illustrated schematically in Figure 1. In this section we will give a brief summary of the baseline HASTOL concept that emerged from the Phase I study. Following the summary will be more detailed discussions of the individual systems in the HASTOL architecture, with even more detail available in the appendices. Three of the five appendices consist of two papers[1,2] already presented at professional society meetings and the presentation given at NIAC Fellows Review Meeting in Atlanta. The other two appendices will be submitted as papers[3] for some future professional society meetings.

For the hypersonic airplane portion of the baseline HASTOL system we use an existing Boeing design[4] for the DF-9, a dual-fuel airbreathing vehicle that has benefited from over a million dollars in NASA/LaRC and Boeing funding during prior study efforts. The Boeing DF-9 hypersonic airplane is similar to the X-43 research vehicle in shape and uses engines similar to those that will be tested in the X-43 in the Summer of 2000. The DF-9 has a 9 m (30 ft) long by 3 m (10 ft) diameter upward-opening central payload bay that can handle payloads up to 14 Mg (14 metric tons or 30,000 lb). It uses JP-fueled air-breathing turbo-ramjets up to Mach 4.5, and slush-hydrogen and air/oxygen ram/scram engines above Mach 4.5. With a full fuel load at takeoff, the hypersonic airplane masses 270 Mg (590,000 lb) or a little less than 20 times the 14 Mg payload mass, and can deliver the payload to 100 km (330 kft) altitude at an apogee speed with respect to the surface of the Earth of 3.6 km/s (12 kft/s) or approximately Mach 12. If we assume an eastward equatorial launch at the equator, the speed of the airplane with respect to inertial space is 4.1 km/s -- halfway to space.

The airplane is met as it approaches apogee by the lower end of an orbiting spinning space tether facility consisting of a massive tether control station, a heavy 600-km-long tapered tether, and a homing grapple assembly at the tether tip. The tether facility center-of-mass (CM) is 90 km from the tether control station and 510 km from the grapple tip. The tether facility CM is in a slightly elliptical orbit with an apogee altitude of 700 km, and a perigee altitude of 610 km. The facility is rotating around the CM such that the tip speed of the grapple end of the tether is 3.5 km/s. The orbital period is about 98 minutes while the rotation period is about 16 minutes. At perigee, the orbital speed of the facility CM is 7.6 km/s eastward. The phase of the tether rotation will be adjusted so that at perigee the tether is directly below the tether control station with the grapple tip of the rotating tether moving at a speed of 3.5 km/s westward. This will produce a net speed of the grapple tip with respect to inertial space of 4.1 km/s eastward, matching the apogee speed of the hypersonic airplane. The homing grapple, letting out tether from its onboard reel, meets with the airplane and connects to the payload in the open bay. The tether rotation then lifts the payload into space at a mild 2.3 g's acceleration.

Depending upon the needs of the payload, the tether adjusts its orbit eccentricity and energy, and its rotation rate, by using electrodynamic tether propulsion and tether length pumping, which require solar energy, but no propellant, then releases the payload into the desired final orbit or transfer trajectory. After each payload pickup and toss, the tether facility restores its original orbital and rotation state over a number of days until it is ready to pick up another payload. Alternatively, incoming payloads can supply the energy and angular momentum given to outgoing payloads. The total cycle time between payload pickups depends upon the final payload trajectory desired and the power available from the solar panel array on the tether control station.

The tether is predominantly made of high-tensile-strength (4.0 GPa) low specific density (0.97) highly-oriented-polyethylene AlliedSignal Spectra™ 2000 polymer used commercially to make ship hawsers and fishing line. Braided into the Spectra™ lines will be aluminum wire for use by the electrodynamic tether propulsion system. The outer 20 km of tether, near the grapple tip, will warm from a nominal 40 C to about 80 C during its pass through the upper atmosphere at 100 km altitude. This portion of the tether will be made of Zylon™ PBO polymer with a tensile strength of 5.8 GPa and a specific density of 1.56, which is almost as strong per unit density as Spectra™ 2000, and maintains most of its strength up to 300 C. Assuming a safety factor of 2.0 in the tether design, a payload mass of 14 Mg, and a tip speed requirement of 3.5 km/s, the required taper in the tether is 3-to-1, ranging from an equivalent cross-sectional diameter of 3.2 cm near the facility CM to 1.2 cm at the grapple. The total mass of the tether is a little more than 90 times the payload mass or about 1300 Mg. As stronger fibers become available in the future, the tether mass will drop significantly. To insure a high probability (0.999+) of survival over many decades despite strikes from space debris, the tether will be designed to use the TUI-patent-pending interconnected multiline open net Hoytether™ structure.

After the pickup of the payload at perigee, the apogee altitude of the tether facility CM will drop. The amount of altitude drop depends upon the mass of the tether facility. If the tether rotation rate is controlled so that the tether is pointing away from the nadir at the apogee point, then a considerable drop in altitude can be tolerated. To be conservative, we have assumed a worst case situation where after payload catch, control is lost over the tether rotation rate, so that it can be pointing straight down at apogee. To keep the grapple tip (and payload) out of the atmosphere, the tether control station must mass 110 times the payload mass. Thus, the total mass of the space tether facility will be a little more than 200 times the payload mass or about 3000 Mg. One of the objectives of the follow-on Phase II study will be to find ways to lower this mass ratio without jeopardizing safety.

In summary, we have identified a baseline HASTOL architecture that works. In Phase II we will optimize it.

HYPERSONIC AIRPLANE

The technology for the hypersonic airplane portion of the HASTOL system is being developed by Boeing and others elsewhere and is not part of the HASTOL effort. However, vehicle performance, flight trajectory requirements, and operational aspects peculiar to tether rendezvous and payload transfer in support of development and optimization of the HASTOL system are, and form a major portion of the hypersonic airplane portion of the HASTOL team effort. The hypersonic vehicle portion of the HASTOL effort started with an existing design for the DF-9, a multi-role hypersonic aerospaceplane shown in Figure 2. The DF-9 was developed by Boeing for NASA Langley Research Center, to perform both long-range hypersonic cruise missions and space launch missions. The vehicle is designed to operate from existing runways and incorporates a low-speed propulsion system based on JP fueled, Air (core-enhanced) Turbo Ramjets (AceTRs) for operations up to Mach 4.5 (46 kft/s or 1.4 km/s). Above Mach 4.5 a slush-hydrogen-fueled ram/scram system powers the vehicle.

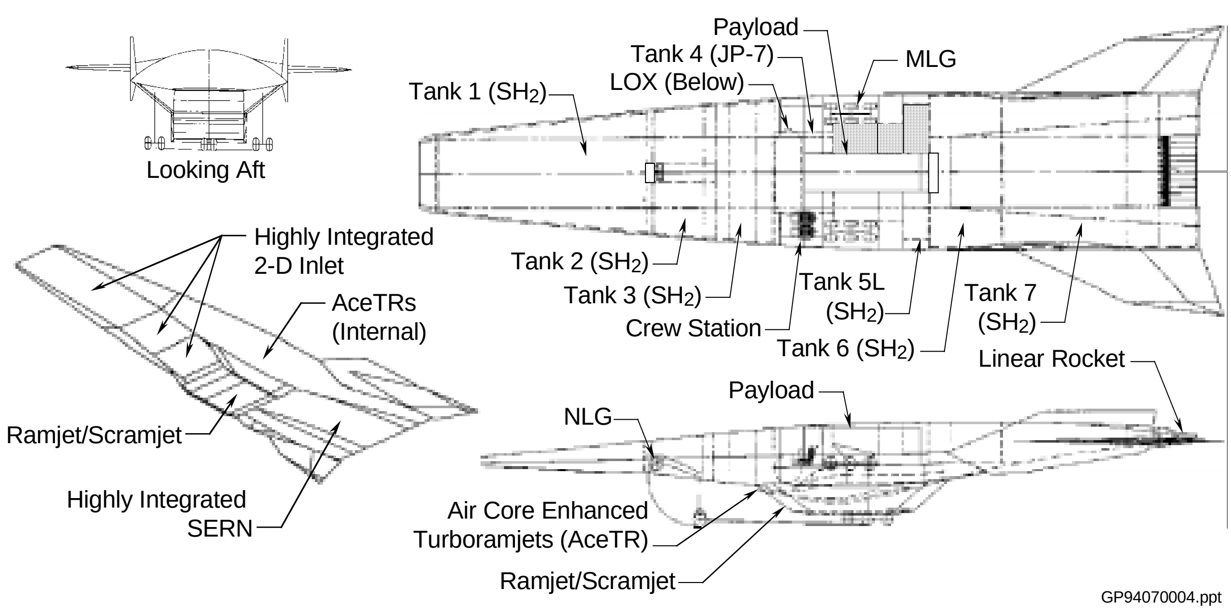


Figure 2. Boeing-NASA/LaRC DF-9 Dual-Fuel Aerospaceplane

While the design is optimized for long range cruise at Mach 10 (10 kft/s or 3.2 km/s) at 40 km altitude, the vehicle can also perform “pop-up”-type launches of satellites, as shown in Figure 3, and incorporates a 3 m (10 ft) diameter, 9 m (30 ft) long upward-opening payload bay for that purpose. The current design is capable of carrying a 14 Mg (14 metric tons or 30,000 lb.) payload to altitudes as high as 100 km (330 kft) at speeds as high as 3.6 km/s (12 ft/s or Mach 12) with respect to the atmosphere of the rotating Earth. If we assume an eastward equatorial launch at the equator, the speed of the airplane with respect to inertial space would be approximately 4.1 km/s.

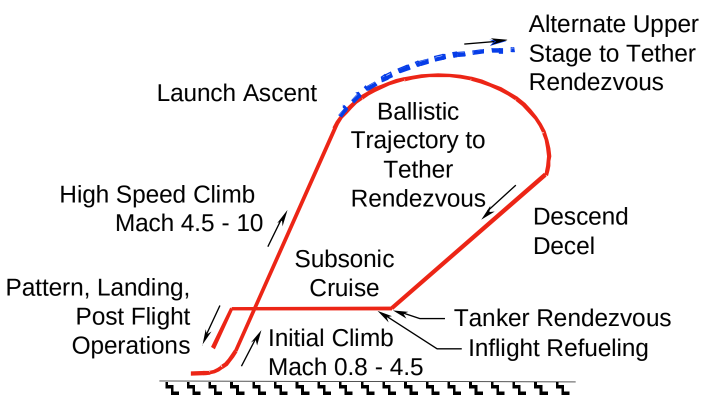


Figure 3. Vehicle Pop-Up to Tether Rendezvous

During the future efforts of this continuing study, the existing DF-9 hypersonic airplane design will be modified, as required, to perform HASTOL type missions and the modifications incorporated into its performance simulation model. The results of the hypersonic vehicle trade study will be incorporated in the overall HASTOL system assessment. Two principal variant types are candidates for further consideration. In the first, the aircraft will rendezvous with the grapple at altitude. This variant will be modified, as required, for each applicable HASTOL concept and its rendezvous geometry. In order to optimize operations in these HASTOL modes it will be useful to resize the existing auxiliary rocket engines and their propellant volumes for increased altitude and velocity. An enhanced reaction control system with six-axis capability (including limited trajectory control) will also be required in lieu of the current 3-axis (attitude only) system.

An alternate variant will have the hypersonic airplane carry the payload to an intermediate altitude and speed. From there a small rocket upper stage would carry the payload to the rendezvous with the grapple. This approach will require fewer modifications to the hypersonic airplane design, but will have less payload capability at a particular size due to the mass required by the rocket upper stage. Both variants will then be used to evaluate the concept through several trade studies and optimized with the tether and grapple studies.

The vehicle performance for the DF-9 hypersonic vehicle was modeled using the three-degree-of-freedom model (3DOF) in Holist[5]. Holist is a vehicle performance and sizing tool developed with partial support from NASA/LaRC. The driving force behind Holist is the need to model the important discipline interdependencies that are critical to the performance of hypersonic vehicles. Holist has been used in the Boeing hypersonics group to analyze the DF-9 Dual Fuel Mach 10 cruiser, Standoff Fast Reaction Missile (SFRW) concepts, and VTHL and HTHL Rocket Based Combined Cycle (RBCC) vehicle concepts for space access studies.

The 3DOF performance model in Holist was used to model the hypersonic airplane's flight from takeoff through apogee and to the end of the turn back toward the launch site. The 3DOF model is the most rigorous mission model available in Holist. Output from the model provides the user with detailed information about the vehicle weight, flight condition, position, aerodynamic state, and propulsion state. The 3DOF model is used when details of maneuvering flight are required. The analysis runs in seconds or minutes depending on the number of phases and the integration step size used. For the HASTOL study, various combinations of pull-up Mach number, rocket shutdown altitude, and rocket thrust were used to calculate multiple apogee altitude and velocity conditions, corresponding to various payload transfer points to the spinning tether. Figure 4 shows the "achievable" apogees in the velocity/altitude space in solid blue dots in the lower and right portions of the diagram, while the unachievable points are the open red circles in the upper and left portions of the diagram.

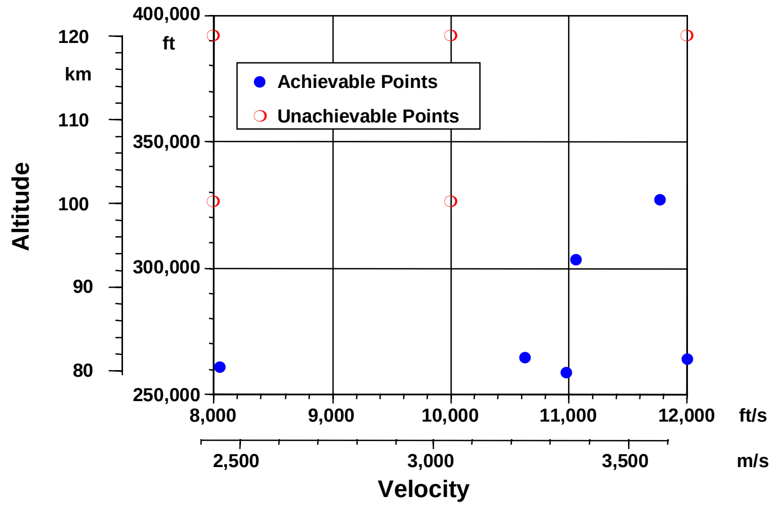


Figure 4. Matrix of Analyzed Payload Transfer Points

Analysis of these unachievable apogees with the Holist 3DOF model showed that the vehicle was unable to pull out during its re-entry mission phase without exceeding its structural limits. A comparison of the normal load factor and dynamic pressure time histories for an achievable and an unachievable apogee (the lower right and upper left cases shown in Figure 4) are shown in Figures 5 and 6, respectively. The combination of these two figures shows that if the airplane is flown from one of its unachievable apogees at its maximum design load factor of 2.5 g's, it is unable to pull-out of the dive after apogee before exceeding its maximum dynamic pressure limit of 2000 psf.

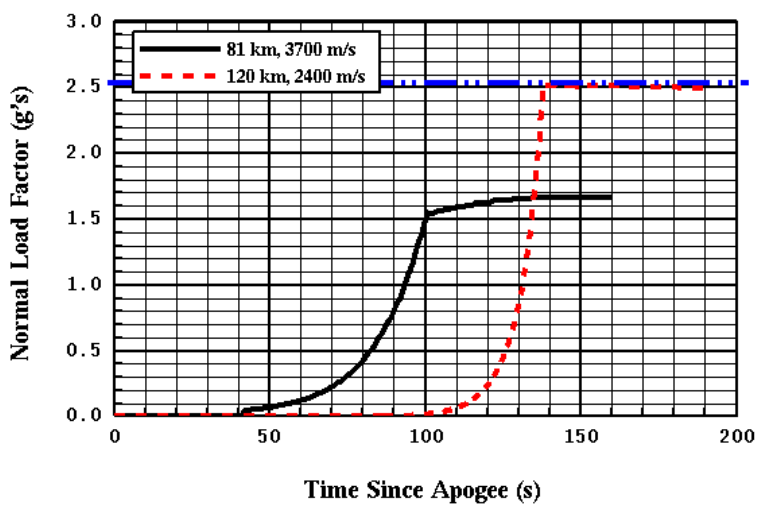


Figure 5. Normal Load Factor Along Descent Trajectory

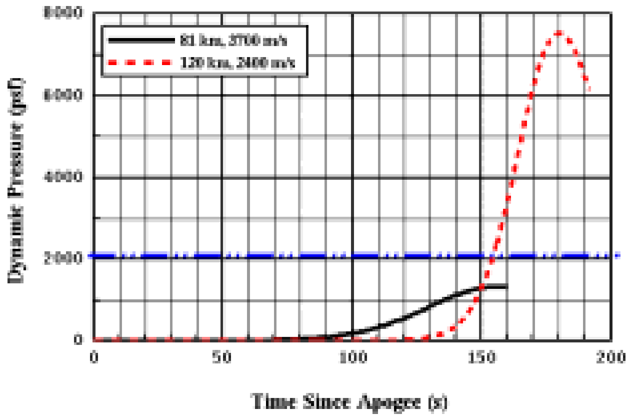


Figure 6. Dynamic Pressure Along Descent Trajectory

The situation is the same for all the apogees identified as unachievable in Figure 4. Changes to the structural or aerodynamic design of the DF-9 would be necessary to expand the envelope of achievable apogees. However, our Phase I study determined that changes to the design of the DF-9 hypersonic airplane were *not* necessary since the 100 km, 3.6 km/s apogee case was determined to be sufficient for the HASTOL architecture. The existing design will do.

SPACE TETHER

The space tether component of the HASTOL architecture is required to reach down from its orbital altitude hundreds of kilometers above the atmosphere, to place the grapple end of its tether at an altitude in the upper atmosphere that the hypersonic airplane can reach in order that a payload transfer can take place. The end of the tether must also be slowed down, by one means or another, from typical orbital speeds to a speed the hypersonic airplane can attain at that altitude. The six different space tether facility concepts initially considered during the Phase I contract effort were the: Rotovator™, LIFTether, CardioRotovator™, Tillotson Two-Tier Tether, HyperSkyhook and HARGSTOL. We found that nearly all of the concepts would work, and in the Phase I effort we analyzed two of them in some detail, the Rotovator™ and the LIFTether. The simplest concept is the Rotovator™, and it has been baselined for the Phase II effort. However, all of the concepts will be revisited in the Phase II effort.

Although in a typical space tether facility the mass of the tether will usually be less than the mass of the tether control station, we do not want to ignore the tether mass entirely. So, for each of the concepts, we estimated the mass of the tether alone, using the data we have for the tensile strength and density of high strength materials that are presently available in commercial quantities. If the mass of the tether alone started to exceed 200 times the mass of the payload, then that was an indication the particular scenario being considered was not engineeringly feasible using presently available materials, although the application might become feasible in the near future as better materials become available with higher tensile strengths at higher operational temperatures.

As we shall see, presently available commercial materials will suffice to make the HASTOL tethers needed. The primary message we want to leave with the Reader is:

> "We don't need *magic* materials like 'Buckminster-Fuller-carbon-nanotubes' to make the space tether facility for a HASTOL system. Existing materials will do."

Rotovator™

The standard method of attaining a low tether tip velocity at low altitude is to use a long rapidly spinning orbiting tether, or Rotovator™, in a nearly circular orbit. The Rotovator™ concept was invented in 1967 by Artsutanov and reinvented by Moravec in 1977, who did the first thorough analysis[6] of it. Since the Rotovator™ must reach down from orbital altitudes into the upper atmosphere to match speeds with the hypersonic airplane, the length of the tether and the orbital altitude are necessarily interrelated, with the orbital altitude of the tether center-of-mass (CM) being the length of the tether from the CM to the tip plus a nominal 100 km for the thickness of the atmosphere. The longer the tether, the higher the orbital altitude and the slower the velocity of the tether facility CM.

The mass of a rapidly spinning tether in free space is determined primarily by the tip speed of the tether. Equation (1) in Appendix 1 shows specifically that the mass ratio of a spinning tether grows exponentially with the *square* of the tether tip speed. The mass ratio of a long spinning tether near the Earth will depend not only on the tip velocity of the tether, but also the gravity gradient force which, in turn, depends upon the orbital altitude above the Earth and the length of the tether.[7-12] This will be true for most of the tether systems being considered for the HASTOL architecture. There is no simple analytical equation that takes both the tether rotation forces and gravity gradient forces into account, and the tether mass ratio needs to be numerically integrated for each case.

We found, in general, that Rotovators™ that were very short had a lower orbital altitude and therefore higher orbital velocity, so they needed a higher tip velocity to match speeds with a hypersonic airplane moving at a given hypersonic velocity. Thus, their mass ratio increased exponentially as the square of the tip velocity. We also found that Rotovators™ that were very long were orbiting more slowly, and thus needed less tip velocity, but because the gravity gradient forces on the tether increased with tether length, the mass ratio increased because of the increased gravity gradient force. We were able to find an intermediate-length Rotovator™ design that works. It is discussed in detail in Appendix 3 and summarized below. This design has been selected as the baseline space tether for the Phase II study.

The baseline Rotovator™ space tether facility shown in Figure 7 is composed of a tether control station (containing power supplies, tether reel, command and control, and ballast mass) , a 600 km long tapered tether, and a grapple assembly at the end of the tether. The tether facility is placed in a slightly elliptical orbit (e=0.0062) with a CM apogee altitude of 700 km, a perigee altitude of 610 km, and a perigee velocity of a little over 7.6 km/s. The orbit was chosen to be elliptical and payload capture was performed at perigee in order to reduce the amount of total facility mass needed to keep the facility and tether above the atmosphere after the facility captures a payload. The tether is set into rotation with a tip velocity of a little over 3.5 km/s. The center of mass of the tether facility is located about 90 km from the tether control station, so when the facility is at perigee altitude of 610 km, the tether control station is at an altitude of 700 km and the tether tip is at an altitude of 100 km, moving at a velocity of approximately 7.6 km/s - 3.5 km/s = 4.1 km/s relative to the inertial reference frame, thus matching the speed of the hypersonic airplane. The atmospheric drag on the tether at 100 km altitude was calculated and found to be negligible.

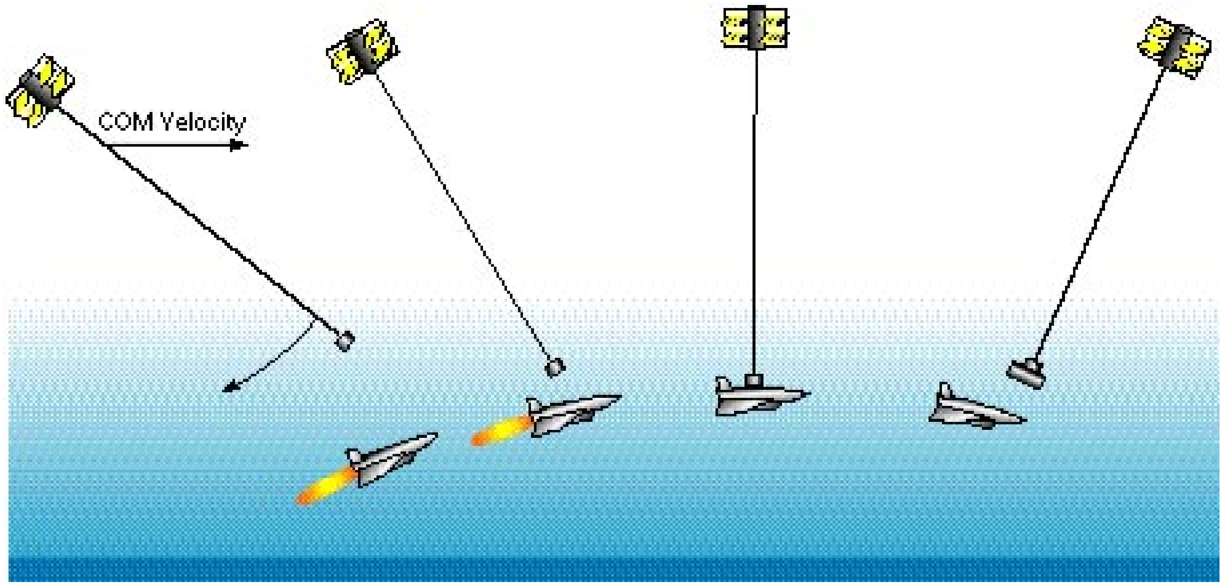


Figure 7. Rendezvous of a Rotovator™ and a Hypersonic Airplane

Tether Diameter: The required effective diameter for the Rotovator™ tether was calculated assuming it would be constructed of a material such as Spectra™ 2000, with a tensile strength of 4.0 GPa and a density of 970 kg/m^3. Although in the final implementation the tether would likely be a multiline Hoytether™ structure to provide tether survivability, in these simulations the tether was modeled as being a single-line structure, tapered to minimize the tether mass. The required tether taper is illustrated in Figure 8 and shows that the required tether taper varies by a factor of roughly 3 from an equivalent tether diameter of about 3.6 cm (1.5 in.) at the tether CM to about 1.2 cm (0.5 in.) at the tether tip. Along most of the tether, the safety factor was chosen to be 2.0. At the tether tip, however, the safety factor is increased in order to provide extra safety margin to handle transient loads due to payload capture. Because the portion of tether closer to the tether control station has a much larger cross section, the transient loads created at the tether tip due to payload capture become insignificant further up the tether, and thus the safety factor of 2 should be adequate. The total tether mass was calculated to be 1360 Mg, or approximately 90 times the payload mass. The station mass was calculated to be 1650 Mg, or approximately 110 times the payload mass. The total tether facility mass came to 3010 Mg, or just over 200 times the payload mass. Recent additional simulations since those in Appendix 3 have already found Rotovator™ designs with total facility mass ratios of 160 times the payload mass, and we expect the required facility mass to drop even further as the Rotovator™ designs are optimized in the Phase II effort.

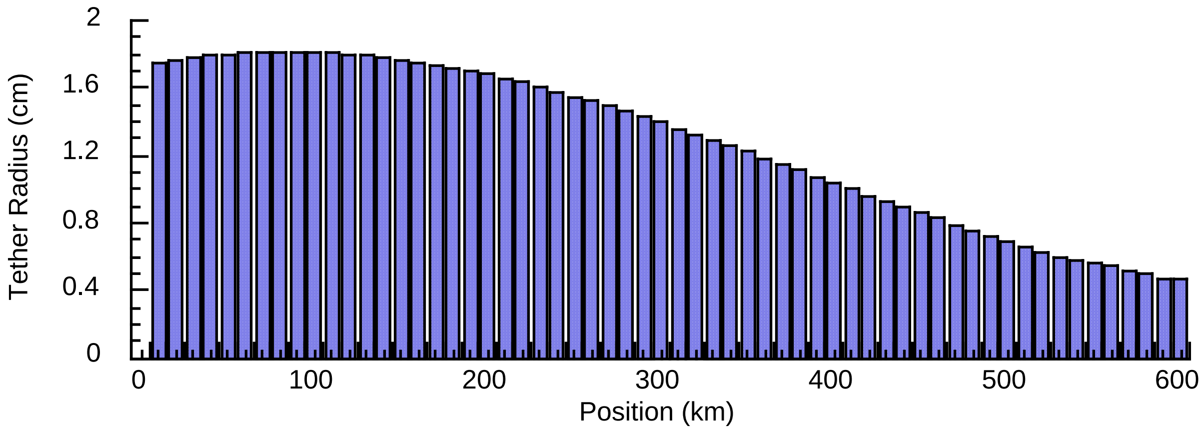


Figure 8. Radius of a Stepwise Tapered Spectra™ 2000 Tether
(15 Mg payload, 600 km long Rotovator™, tip velocity of 3.4 km/s)

Tether Heating: In addition to calculating the tether orbit and dynamics, our simulation program also calculated the atmospheric drag and the tether temperature. The first scenario studied was a rendezvous between the all-Spectra™ 2000 Rotovator™ and a hypersonic airplane at an apogee altitude of 100 km and a velocity of 4 km/s. Figure 9 shows the altitude of the tether tip during the rendezvous period, while Figure 10 shows the temperature of the bottom portion of the tether during the same time period. During the roughly 100 s the tether tip spends within the upper atmosphere (altitude <130 km), the tether temperature increases only about 40°C from a nominal 40°C to a maximum of 80°C. This temperature rise might be problematic for Spectra™ 2000, which loses strength rapidly with temperature. However, there exist several commercially-available materials, such as PBO (sold by Tyobo of Japan under the name Zylon™), that have strength-to-weight characteristics almost as good as Spectra™ 2000 and have significantly better temperature tolerance. PBO is also approximately 1.7 times as dense as Spectra™, so a PBO tether would have a smaller diameter, and thus experience smaller drag and heating. Consequently, we conclude that the heat loading at 100 km is low enough that a tether constructed of currently-available high-strength polymers (perhaps with some form of AO-resistant coating) can accomplish the HASTOL mission.

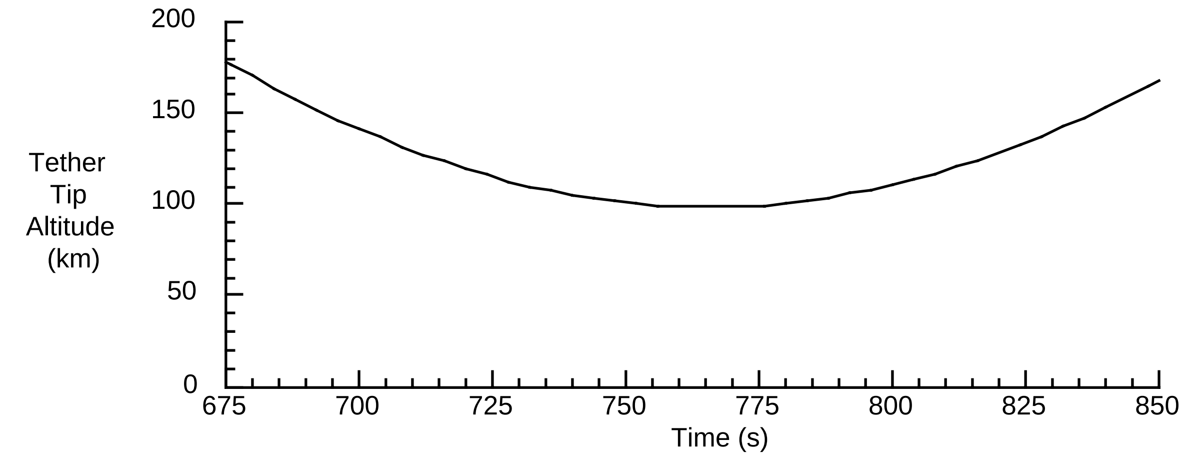


Figure 9. Altitude of the Rotovator™ Tether Tip

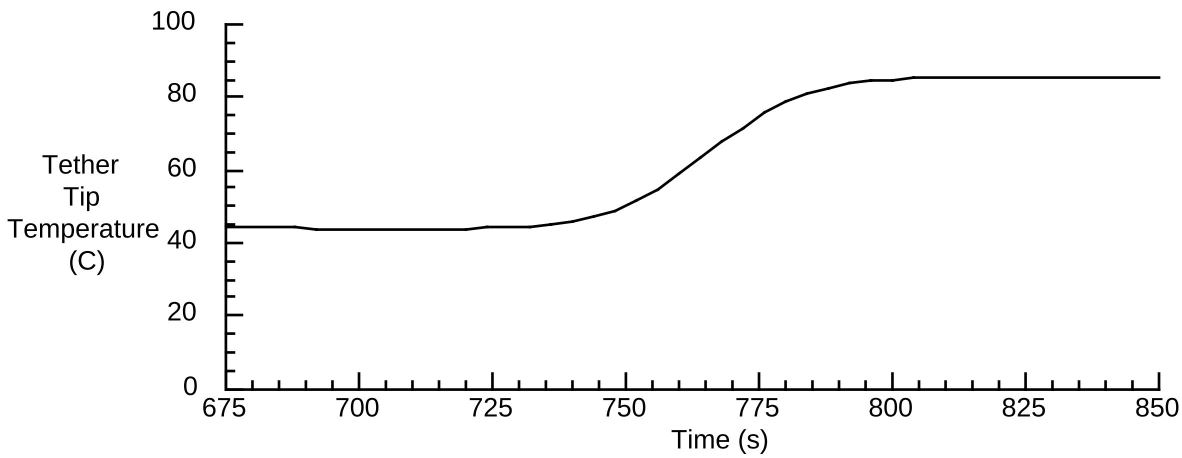


Figure 10. Temperature of the Rotovator™ Tether Tip

An important point to make about our Phase I study results so far, is that a simple orbiting spinning Rotovator™ space tether facility built using existing space tether materials can be used to pick up a payload from an existing design for a hypersonic airplane that is capable of taking a payload to an altitude of 100 km (330 kft) altitude while moving at 3.6 km/s (12 kft/s or Mach 12) with respect to the atmosphere, or 4.1 km/s with respect to inertial space.

Thus, the HASTOL system combination of a Boeing DF-9 hypersonic airplane and a Tethers Unlimited, Inc. Rotovator™ space tether, is capable of taking payloads from the surface of the Earth, putting them into space, and bringing payloads back. The other HASTOL concepts we will discuss later may prove to be better after further analysis in Phase II, but this concept has acceptable performance.

LIFTether

The second concept[1,13] for the space tether facility portion of a HASTOL system would use two separate methods of operating the tether, one method for getting the grapple/payload at the end of the tether down into the atmosphere, and another method for getting the grapple back up into orbit again. There are a number of variants for both the down and up options.

The simplest technique is illustrated in Figure 11. The tether length and tip speed of a rotating tether are selected so that, without letting out any tether, the grapple hits the denser portions of the upper atmosphere at about 80 km altitude, sufficiently ahead of the tether control station to allow time for drag deceleration of the grapple down to a velocity that matches the speed of the hypersonic airplane before the tether control station passes overhead. Since the decrease in velocity of the grapple does not involve using the strength of the tether, the mass of the tether is not affected by the amount of velocity decrease needed. If the relative positions of the grapple and tether control station are properly timed, the tether control station can be made to be directly overhead the hypersonic airplane at the time of the payload transfer to (or from) the grapple, while the distance between the two can be made to be equal to the total unreeled length of tether. As shown in Figure 11, with the tether control station directly overhead, the tether will smoothly "lift" and accelerate a payload (or empty grapple) into orbit without requiring any reeling in or out of the tether.

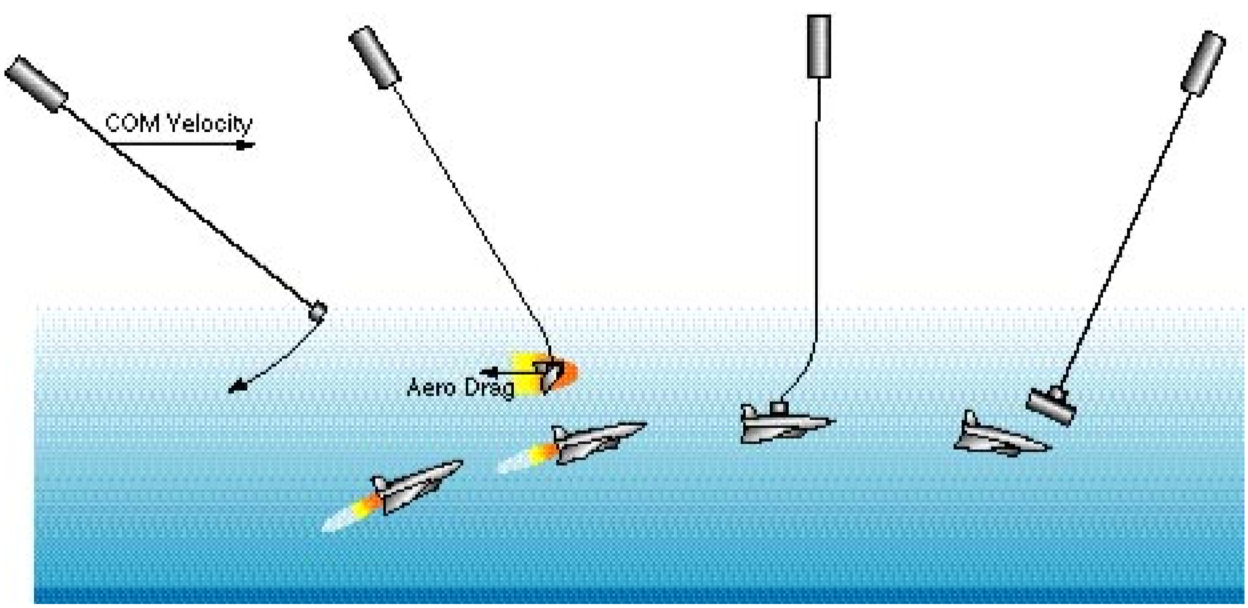


Figure 11. The LIFTether Concept

Although the payload and the section of tether nearest the payload are moving at 3.5 km/s relative to the facility's center of mass, the bulk of the tether is rotating more slowly. Consequently, once the tether pulls taught, the tether is again rotating at a lower tip velocity of approximately 3.1 km/s. This allows us to size the bulk of the tether for a 3.1 km/s tip velocity rather than 3.4 km/s, which reduces the mass of the tether considerably. The tether tip, however, must be designed with a higher safety factor to withstand the capture transients, and furthermore the tether material must be chosen to survive the heating due to the aerodynamic drag at the lower pickup altitude of 80 km.

A detailed simulation was carried out of a LIFTether design composed of a 600 km long Spectra™ 2000 tether picking up a payload from a hypersonic airplane that reaches apogee at 80-km altitude with a velocity of 4.1 km/s (relative to the inertial reference frame). The tether taper and facility mass were identical to the Rotovator tether design, and the orbital velocity of the tether facility's center of mass was approximately 7.5 km/s. The simulation was initiated with the tether initially oriented parallel to its orbital velocity, rotating so that its tip velocity was approximately 3.0 km/s relative to its center of mass. As the tether dropped towards the local vertical, its tip velocity increased to approximately 3.2 km/s due to gravity gradient forces. As the grapple vehicle entered the upper atmosphere, it extended retractable aerobraking panels to increase its cross-sectional area to 16 m^2. The aerodynamic force on the grapple increased the velocity of the tip an additional 0.3 km/s, giving it a total velocity of approximately 3.5 km/s relative to the center of mass. Because the tether tip is rotating backwards relative to the center of mass, this gave it a total velocity in the inertial frame of 4 km/s.

The temperature of the LIFTether tip as a function of time was calculated to increase from a nominal 40°C to a maximum of 1000°C toward the end of its pass through the atmosphere and is illustrated in Figure 15 of Appendix 3. Since Spectra™ 2000 melts at approximately 180°C, Spectra™ clearly would not survive this maneuver. Even PBO/Zylon™, which can operate at temperatures over 600°C, would not suffice. Consequently, for tether-airplane rendezvous at such low altitudes, the tether tip must be constructed of a high strength material with higher temperature tolerance and higher heat capacity such as Titanium-coated Silicon Carbide Textron™ fiber. Textron™ fiber maintains 65% of its strength at temperatures as high as 1200°C and so is suitable for this application even at these high temperatures.

Figure 12 shows the tether taper for a LIFTether designed to lift a 15-Mg payload into orbit. The bulk of the tether would be made of a high-strength polymer such as Spectra™ 2000 or Zylon™, but the bottom 20 km of tether would be constructed of Ti-coated SiC Textron™ fiber. The total tether mass is 530 Mg, or approximately 35 times the payload mass. The Station mass is 1650 Mg, or 110 times the payload mass. The entire tether facility mass is 2180 Mg, or 145 times the payload mass.

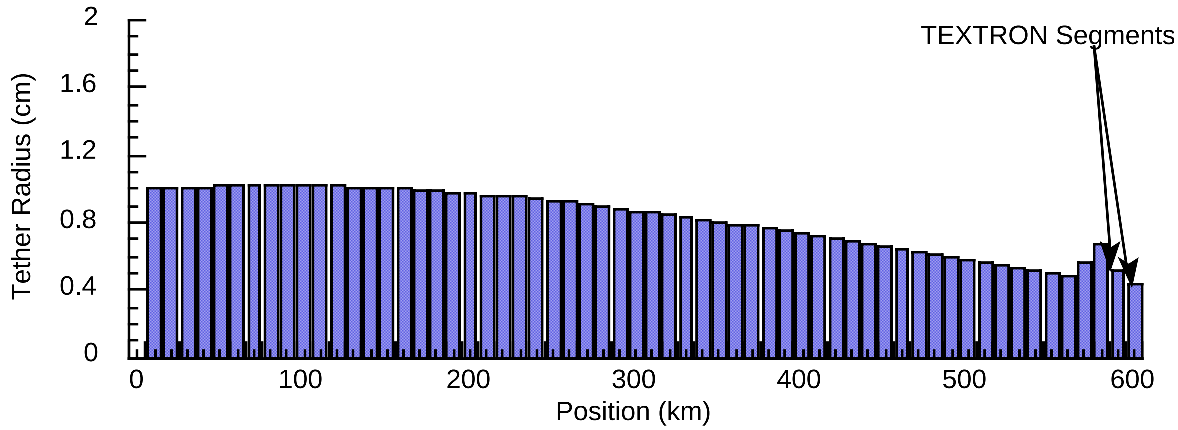


Figure 12. Tether Taper for a LIFTether with a 20 km Tip of Ti Coated Textron SiC

Since the LIFTether has a lower total mass than the Rotovator™ and can operate at a lower altitude, which makes the requirements on the hypersonic airplane less severe, in our Phase II effort we will continue to evaluate materials with high tensile strength at high temperatures so the LIFTether concept can continue to be considered in a search for an optimal HASTOL architecture. However, the higher tether temperatures, the uncertainty introduced by aerodynamic drag, and the drag and heating on the payload, have led us to choose the simpler Rotovator™ as our baseline design for the Phase II study.

CardioRotovator™

The CardioRotovator™ concept[13] consists of a tether control station in an elliptical orbit, with a single long tapered tether. The tether rotation rate is chosen to be exactly twice the orbital period. The phase of the rotation is chosen such that when the tether control station is at perigee, or closest to the Earth, the tether is pointing straight up, as is shown in Figure 13. Then, when tether control station is at apogee, or furthest from the Earth, the tether is pointing straight down at the Earth, reaching deep into the atmosphere for the payload pickup. As can be seen in

Figure 13, at intermediate points, the tether is pointing away from the Earth and does not penetrate below the tether control station altitude except near the touchdown point below the apogee point. The trajectory of the tip of the tether is approximately heart-shaped, which lead to the name of "CardioRotovator™" for the system concept. This concept has the advantage that, because the rendezvous between the tether tip occurs when the tether facility is at its apogee (and moving at its slowest speed relative to the Earth), the rotation velocity of the tether would be approximately 0.4-0.5 km/s slower than the tip velocity of an equivalent rotating tether in circular orbit. Due to the dependence of the mass ratio of the tether on the exponential of the *square* of its tip velocity, this could significantly reduce the required tether mass.

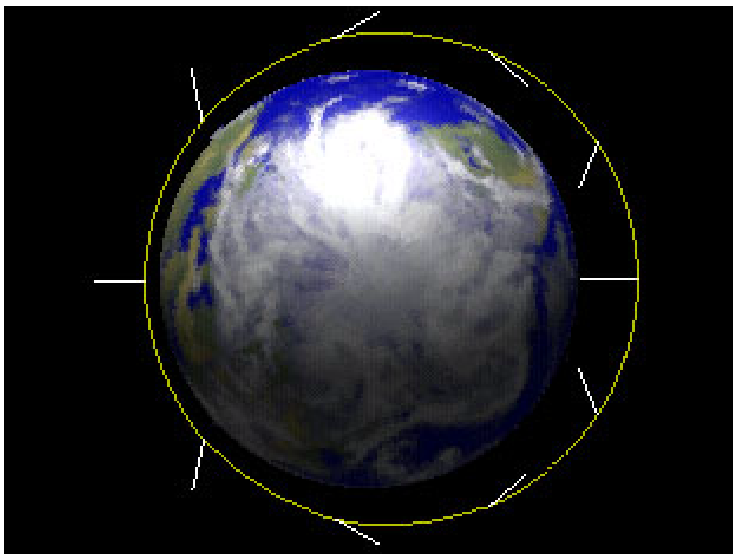


Figure 13. The CardioRotovator™ Concept

However, analysis showed that this concept has several problems that likely render it impractical. First, the payload pickup occurs when the tether is at apogee. Unless the tether drops a return payload at the same time as it picks up the outbound payload, this will result in a drop in the perigee altitude of the tether facility. The mathematics of the orbital mechanics are such that the tether facility would require a total mass on the order of 1000-2000 times the payload mass in order to keep the tether facility from entering the atmosphere after a payload capture. Second, this approach would require that the tether rotation be very carefully controlled so that the tether is always above the facility at perigee. When the tether catches a payload, conservation of angular momentum will result in its angular velocity remaining constant, but its orbital period will change due to its exchange of momentum with the payload. Consequently, the tether facility would have to perform significant tether reeling maneuvers to maintain the proper synchronization between the tether rotation and its orbit. While this may be technically feasible, any failure would result in the tether impacting the atmosphere, causing loss of the tether system. For these reasons, we concluded that the CardioRotovator™ concept is less favorable than the simpler Rotovator™ and LIFTether concepts.

Tillotson Two-Tier Tether

The Tillotson Two-Tier Tether (TTTT or T4)[14] illustrated in Figure 14, consists of a long, large, tapered "first stage" spinning tether, at the end of which is a smaller "second stage" spinning tether. The T4 is essentially a two-stage Rotovator™. The use of two tiers or two "stages" in the design of a spinning tether decreases the overall ratio of the tether launch system mass to payload mass, in a manner similar to the benefits of the lower mass ratio obtained when using a two-stage rocket in a rocket launch system. The T4 approach to the design of the Rotovator™ for a HASTOL system is much more complicated in design and dynamics than a simple one stage Rotovator™. The plan is to baseline the one-stage Rotovator™ for the study, but to carry out analyses of the T4 system in parallel. If the mass of the one-stage tether grows to where its mass begins to cast doubt on the engineering or financial feasibility of the HASTOL concept, then we always have the two-stage T4 concept available in order to drastically cut the tether mass needed.

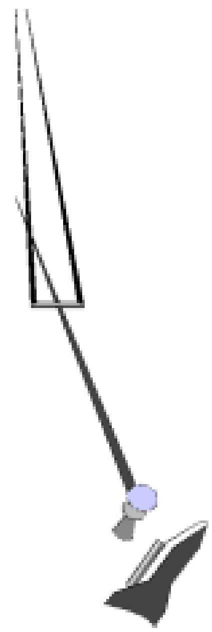


Figure 14. Tillotson Two-Tier Tether

HyperSkyhook

In 1995 Zubrin proposed[15] the "Hypersonic Skyhook" as a solution to the mismatch between the attainable atmospheric speeds of a hypersonic airplane and the orbital speeds of space tethers. Since the orbital speed of the space tether decreases with increasing altitude of the tether system center-of-mass, he proposed the use of very long non-spinning tethers or "skyhooks" reaching down from very high altitudes (thousands of kilometers). His analysis showed that because a hanging tether must be tapered to support its lower end in the gravitational field of the Earth, achieving a HyperSkyhook tether tip rendezvous with a 5.0 km/s (16 kft/s or Mach 16) airplane would require a HyperSkyhook tether mass of 25 times the payload mass. Trying to lower the tether tip speed to 4.0 km/s (13 kft/s or Mach 13) would require a HyperSkyhook tether mass greater than 200 times the payload mass. In general, the non-spinning tether HyperSkyhook concept does not look competitive with the spinning tether concepts. We will, however, revisit this concept in our Phase II studies.

HARGSTOL

The final method of accomplishing the HASTOL concept is to compromise, and allow the partial use of a rocket upper stage or a rocket-powered grapple to complete the payload transfer between the hypersonic airplane and the grapple assembly at the end of the space tether. Thus, instead of the HASTOL system, we will have the HA**RG**STOL or Hypersonic Airplane, **Rocket Grapple**, Space Tether Orbit Launch system. This concept has a number of possible variations. The normal method would be to have the rocket augmented grapple on the tip of the tether. The tether system would slow the tip down as much as possible using one of the tether tip slowing techniques, and the airplane would fly as fast and high as possible, and the rocket system on the grapple would make up any speed difference. The grapple would need to be refueled periodically. This could be done at each payload pickup, or there could be periodic pickups of propellant tanks, with the empty tanks added to the tether control station ballast.

A variation on this concept would be to have the major part of the tether mass be a permanent part of the space tether system, but the “tip” of the tether and the rocket grapple would be carried by the hypersonic airplane. At some time interval before the rendezvous time, the grapple would be separated from the airplane, pulling out the tether, which would be made of material capable of coping with the hypersonic heating and stress. The rocket grapple would then climb in altitude and speed to meet up with the lower end of the space tether out in space away from the atmosphere, while the airplane stays in the atmosphere at an optimum cruise altitude. The grapple grabs the end of the tether, the payload is pulled free from the airplane, and lifted into space by the tether.

The ultimate rocket grapple concept would have the rocket take the grapple from the hypersonic airplane all the way to the tether control station, pulling out tether from the payload. Since for normal ΔV requirements the tether mass would be much larger than the payload mass, it is obvious that a better technique would be to meet the downgoing tether from the tether control station "halfway". Finding the optimum ratio for the length of the airplane tether versus the space tether would be part of the overall system optimization. This concept, with the rocket grapple coming from the airplane without carrying the payload, would only be usable for taking payloads into orbit.

The most important feature of all the possible HARGSTOL systems is that we are confident we can make them work, no matter how poor the ultimate performance of the hypersonic airplane and the space tether. All it requires is that the rocket grapple be loaded with enough propellant to close the velocity gap. Since the mass ratio of the propellant to grapple-plus-payload is exponential in the grapple ΔV, and the rocket ΔV is low because of the ΔV contributions of both the airplane and tether, the propellant required should be low.

Rendezvous Simulations

In any rotating tether transport system, one of the most challenging tasks will be to enable the rendezvous between the payload and the tether tip. For the tether to successfully capture the payload, the payload and tether grapple vehicle must come together at nearly the same place in space and time with nearly the same velocity. Because the payload is in free fall, and the tether is rotating, the payload and grapple vehicle will experience a relative acceleration equal to $a = V_t^2/L$, where V_t is the velocity of the tether tip relative to the tether facility's center of mass, and L is the distance from the tether tip to the center of mass. In the HASTOL tether designs described above, V_t is approximately 3.5 km/s, and L is approximately 500 km, so this acceleration is about 2.5 g's. If neither grapple nor payload perform any maneuvering, the two will coincide only instantaneously, providing a minimal rendezvous window.

Fortunately, it is possible to extend this rendezvous window to five seconds or more by using tether deployment from the grapple vehicle. In this approach, the grapple vehicle will contain a tether deployer and a tether brake. Prior to the rendezvous, the grapple vehicle will wind up some of the tether into the deployer. As the tether nears the bottom of its swing, the payload will use its guidance and thrusters to adjust its trajectory so that it will meet up with the grapple vehicle. When the payload and grapple vehicle reach their closest approach to each other, the grapple vehicle immediately releases the brake on the tether deployer and allows the tether to deploy at as low a tension as possible. This will put the grapple vehicle into an almost-free-fall trajectory which will match the free-fall trajectory of the payload, as illustrated in Figure 15. The payload can then maneuver to close the gap and secure itself to the grapple vehicle. The length of the rendezvous window will therefore be determined by the incremental length ΔL of tether stored in the deployer, with the maximum window equal to $\Delta t = \sqrt{(2\Delta L / a)}$.

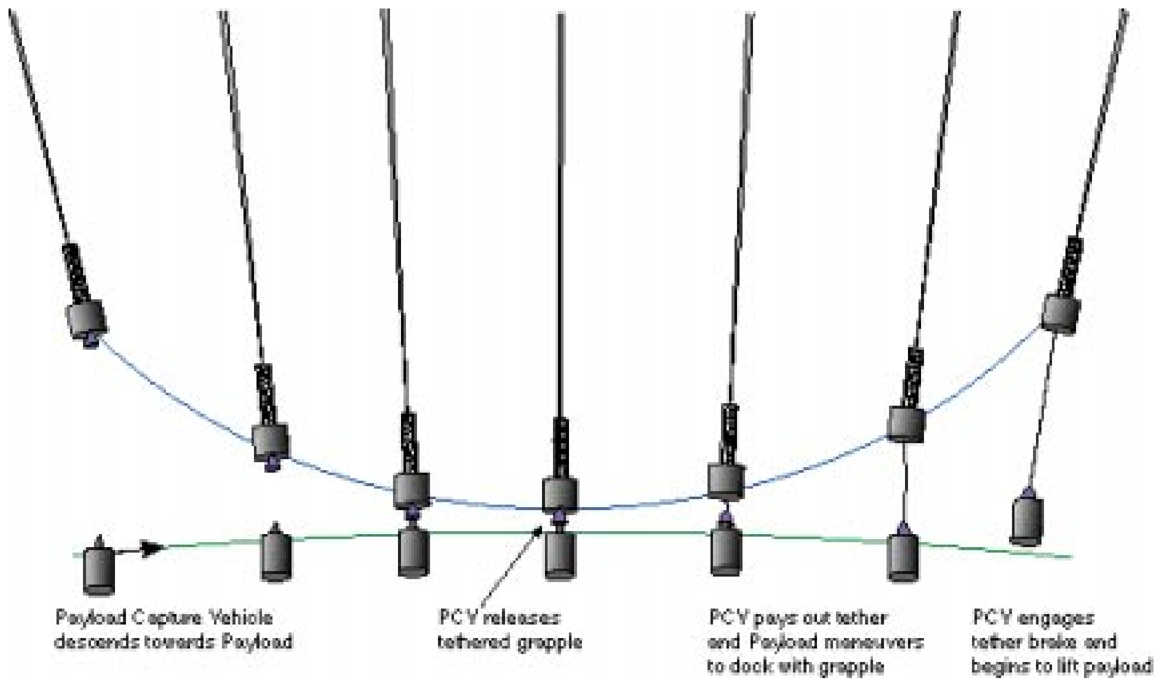


Figure 15. Schematic of Tethered-Grapple Method for Increasing Docking Window

We have simulated this maneuver for a HASTOL Rotovator™ architecture in which the Spectra™ 2000 tether illustrated in Figure 8 picks a payload up from a 100 km, 4 km/s apogee. In this simulation, the payload was launched into a trajectory that would meet up with the tether tip. Once they came into close proximity, the grapple vehicle released the tether brake and allowed tether to pay out at very low tension for five seconds. At that point, the grapple vehicle captured the payload and halted the tether deployment. Figure 16 shows the relative separation between the payload and tether tip in the x and y directions. This plot shows that the tether deployment maneuver extends the rendezvous window to about 5 seconds. The length of tether deployed in this time was 486 m.

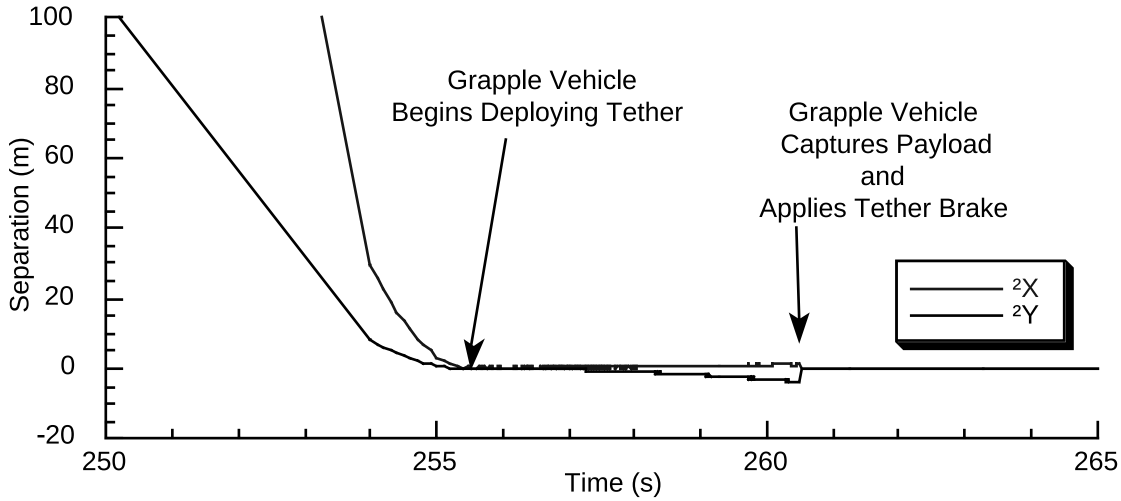


Figure 16. Relative Separation of Grapple Vehicle and Payload, with a Tether Deployment Maneuver to Extend Rendezvous Window

Figure 17 shows the tether load level at the grapple vehicle. During the tether deployment, the tension is essentially zero. When the grapple vehicle stops deploying tether, however, it experiences a relatively strong transient tension spike up to about 70% of capacity, followed by a longer period transient that peaks at about 80%. These higher tension transients result from the fact that the deployment maneuver allows the payload and grapple to accelerate away from the tether facility for several seconds, and thus the tether must apply a larger force to them to accelerate them into the tether rotation once the deployment is halted. This simulation result indicates that the portion of the tether near the tether tip should be designed with a higher safety factor to provide more margin for these tension transients.

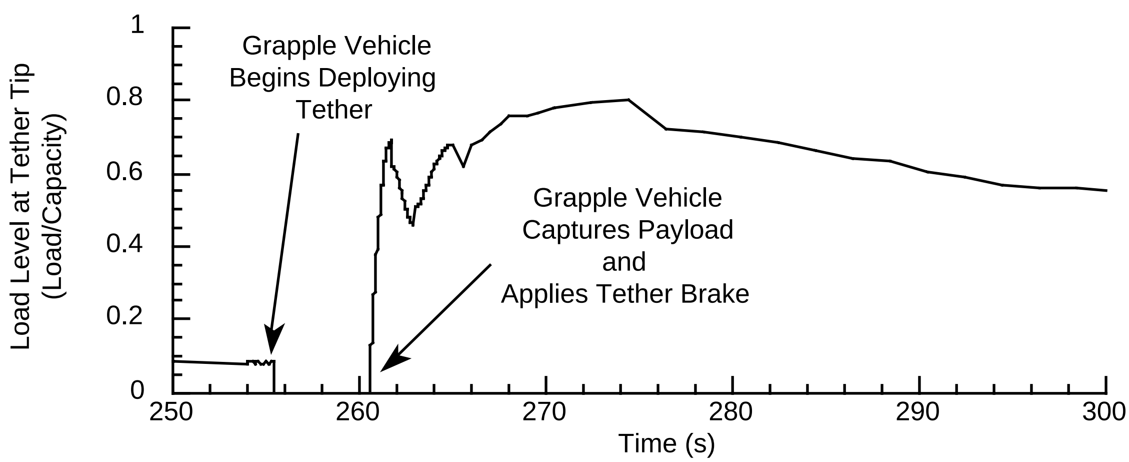


Figure 17. Load Level on Bottom Segment of Tether, with a Tether Deployment Maneuver to Extend Rendezvous Window

Space Tether Issues

The Space Tether portion of the HASTOL system has a number of issues that must be dealt with other than the method of operation, including surviving damage by meteorites and space debris, avoiding collisions with large spacecraft, fabricating the facility in space, and controlling the tether orbit, spin and dynamics.

Tether Survivability: For a tether transport system to be economically advantageous, it must be capable of handling frequent traffic for many years despite degradation due to impacts by meteorites and space debris. Yet, the tether mass must be minimized to reduce the cost of fabricating and launching the tethers. These two requirements present conflicting demands upon the tether design that make conventional single-line tethers impractical for the HASTOL application. For a single-line tether to achieve a high probability of survival for many years, it must be very thick and massive. Fortunately, a low mass survivable tether design exists, called the Hoytether™, which can balance the requirements of low weight and long life[16].

As shown in Figure 18, the Hoytether is an open net structure where the primary load bearing lines are interlinked by redundant secondary lines. The secondary lines are designed to be initially slack, so that the structure will not collapse under load. If a primary line breaks, however, the secondary lines become engaged and take up the load. Note in Figure 18, that four secondary line segments replace each cut primary line segment, so that their cross-sectional area need only be 0.25 of the primary line area to carry the same load. Typically, however, the secondary lines are chosen to have a cross-sectional area of 0.4 to 0.5 of the primary line area, so as to better cope with multiple primary and secondary line cuts in the same region of the tether. This redundant linkage enables the Hoytether™ structure to redistribute loads around primary segments that fail due to meteorite strikes or material failure. Consequently, the Hoytether structure can be loaded at high stress levels, yet achieve a high margin of safety. This is discussed in detail in Appendix 2.

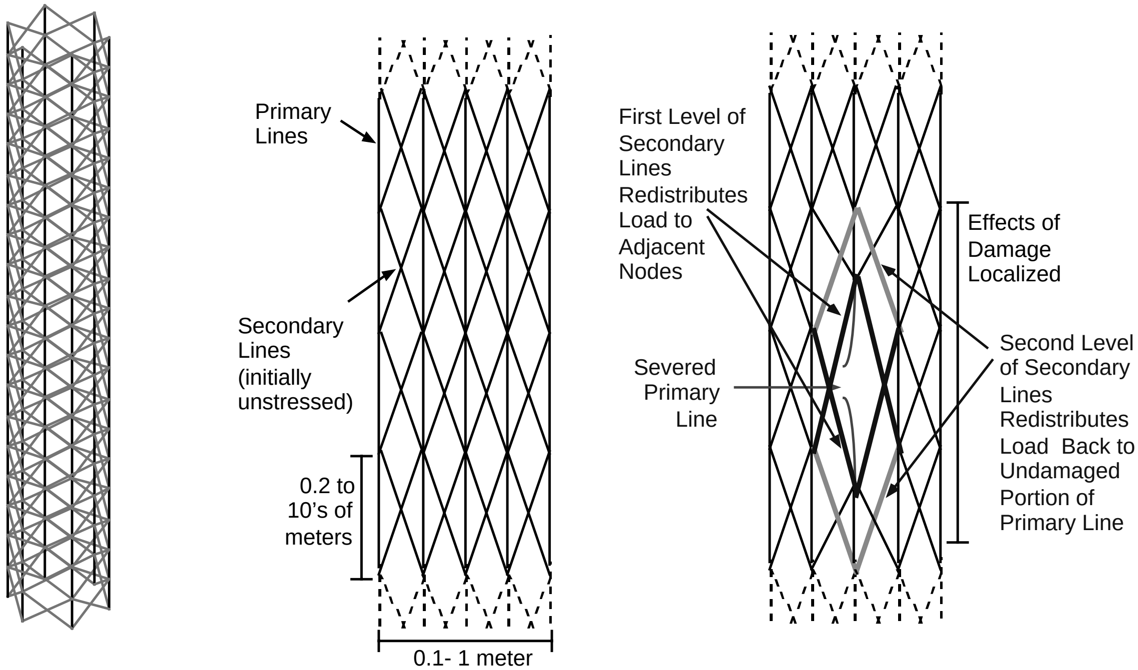


Figure 18. The Hoytether™ Design and Its Response to a Cut Line

Collision Avoidance: There are many objects in space, ranging from micrometeorites to operational spacecraft with 10-meter-long solar array panels. As shown in the previous section, we can design interconnected multiple strand open net Hoytether™ structures that can reliably (>99.9%) survive in space for decades despite impacts by objects up to 30 cm (1 ft) or so in size. Objects larger than 30 cm are all known and tracked by the U.S. Space Command. There are about 6000 such objects in low and medium Earth orbit, of which an estimated 600 will be operational spacecraft in the 2005 time frame. For an atmospheric tether application, we have estimated that, if no traffic control measures are instituted, a 20 km long tether in an orbit grazing the upper atmosphere has a 4% chance of striking one of the 6000 large objects during a one year mission, and an 0.4% chance of striking one of the 600 operational spacecraft. Longer tethers will have proportionately larger probabilities. It will therefore be incumbent on the HASTOL operators to maintain contact with the U.S. Space Command and keep an accurate inventory of the known large objects. They then need to control the tether facility CM orbital altitude and phase, the tether rotation rate and phase, and the tether libration and vibration amplitudes and phases, to insure that the tether facility components do not penetrate a volume of "protected space" around these large orbiting objects. The requirements that need to be put upon the Command and Control system to meet this need will be determined during the Phase II effort.

Modular Space Tether Design and Construction: The space tether facility portion of the HASTOL system will need to supply half or more of the energy and angular momentum needed to put the payload into orbit. In order to keep the payload from dragging the space tether facility down into the atmosphere after pickup, the facility *must* mass significantly more than the payload. A minimum space tether facility mass would be 30 times the payload mass, while a robust system would be 50 to 200 times the payload mass. Because the full-up space tether facility will *necessarily* be massive, it cannot easily be launched in one piece. We therefore will design it in a modular fashion so that it can be launched in many separate modules. The types of basic modules have yet to be fixed, but probably would consist of a single large command and control module, a grapple module, and a large number of power modules, winch modules, and tether modules. Further discussion of the modular design can be found in Appendix 5. The details of the modular design of the space tether facility will be carried further in the Phase II effort. The following summary of Appendix 5 should therefore be considered as merely one example of what the modules would look like and how they would be interconnected into a space tether facility.

The modules would be cylinders between one and two meters in diameter and height. A small 1 m (3-ft) module would mass about 1 Mg and be 1/15th of the nominal payload mass of 15 Mg, while the largest 2-m (6-ft) module would mass about 6-8 Mg and be half the mass of the nominal payload mass. The modules will be designed so that only a few modules are needed to assemble a minimal but functional initial space tether facility consisting of the large command and control module, a few power modules, a few winch modules, a number of tether modules, and a grapple module

The command and control module would probably be put into place first by a heavy lift rocket. Studies may show that it is more cost effective to put the other modules into orbit by rocket, but if the hypersonic airplane is available, we can start using the initial pieces of the HASTOL system to begin to assemble itself. The power modules, winch modules, grapple modules, and especially the tether modules, can be flown to Mach 12 (3.6 km/s) at 100 km altitude, then boosted on into orbit by a rocket upper stage to a rendezvous with the command and control module. There, they would be automatically assembled (with the aid of remote control guidance), into a minimal, but functional, initial space tether facility. Assuming the modules mass 1 Mg, the initial facility need only mass 50 Mg before it becomes capable of handling one module at a time at the full design tether tip speed of 3.4 km/s. Once the facility is capable of rotating at the full design tip speed, this capability then eliminates the need for using upper stage rockets to boost the modules from the hypersonic airplane up to the space tether facility, and the initial HASTOL architecture has been "born". This "infant" HASTOL now has the ability to "grow" by "feeding itself" additional modules brought up by the hypersonic airplane. (The analogy of "feeding itself" is an apt one, in that Oldson and Carroll[9] have shown that it is possible for a rotating tether system to "toss" a payload from its grapple at the end of the tether into a trajectory that ends up an orbit later with the payload coming to a gentle "dock" with the tether control station - just like tossing a peanut into your mouth.)

Once functional, that same initial HASTOL architecture can also make money by using its hypersonic airplane to deliver 1 Mg communication satellites and deep space probes to the space tether facility, which in turn delivers them to higher orbit or Earth escape. The HASTOL architecture will thus be "in business" and "producing income" from almost its first day of operations. After doubling its size with 50 more "bites" of power, winch, and tether modules, it will be able to handle 2 Mg payloads, "grow" itself even faster, and make even more money by handling larger and larger payloads.

The use of modular design in the tether portion of the space tether facility eliminates any concern about the manufacturability and packaging of a 600 km long tether. Since the continuous tether lengths required are only 20 km in length, they can each be fabricated in about a month or so using standard braiding machine speeds. As a result, any desired tether delivery schedule can be met by simply using more braiding machines in parallel.

Control of Tether Orbit, Spin and Dynamics: In order for the HASTOL system to achieve low operational costs, the system must have means for maintaining and controlling the orbit, spin and dynamics of the tether system that do not consume large amounts of propellant. The most important capability is for rapidly restoring the tether facility's orbit after it has boosted a payload into orbit. In addition, the tether facility must have the capability to counteract perturbations to its orbit and spin due to Earth oblateness, aerodynamic drag, and other phenomena in order to maximize the frequency of opportunities for rendezvous with a launch vehicle. Fortunately, several tether techniques can provide the capabilities needed without requiring propellant expenditure.

The primary technique to control the tether orbit and spin will be to use propellantless electrodynamic tether propulsion. Woven into the polymer tether nearest the tether control station will be an aluminum wire conductor to be used by the High-strength Electrodynamic Force Tether (HEFT) propulsion system[10] built into the tether. Electrical power from the solar panel array will be used to pump electric current through the conducting portions of the tether. The current flowing along the length of the tether pushes against the Earth's magnetic field. The reaction force can be used to reboost the orbit of the tether facility after it boosts a payload. This technique uses the mass of the Earth, coupled through its magnetic field, as a reaction mass, and thus requires no propellant. This technique can also be used to increase or decrease the rotation rate of the tether system, prevent elliptical orbit precession, change the orbit ellipticity, energy, angular momentum, and even inclination (slowly), as well as damp any librations or vibrations in the tether.

The secondary technique for controlling the orbit and spin of the tether facility is to use tether reeling maneuvers[18-21]. By using electrically powered winches to reel a tether in and out during proper portions of its orbit or rotation, the tether system can "do work" against the Earth's gravitational potential, adding or subtracting energy from the tether's orbit and/or rotation. The spin rate of the tether can be increased by reeling the tether in slightly when it is near vertical (and the gravity gradient forces are high), and letting the tether back out when it is near horizontal (and the gravity gradient forces are low). Alternatively, the eccentricity or argument of perigee of a tether's orbit can be changed by reeling the tether in and out during its orbit. Again, this method requires no propellant expenditure.

Lastly, once sufficient traffic to and from orbit has been established, the tether facility can be used to de-boost returning payloads and, in doing so, can regain the orbital momentum and energy that it loses when it boosts a payload.

Relevance of Past, Present and Planned Tether Flight Experiments

HASTOL is still a paper concept, but there does exist a significant amount of experimental flight data on tethers that are relevant to the success of a HASTOL program, and more is coming.

There have been 17 tether flight experiments to date[7], including one tether experiment still functioning in space after 3.5 years. The two most publicized experiments have been the Tethered Satellite System (TSS) experiments flown off the Shuttle Orbiter[7,22], which involved a 1.6-m-diameter Italian satellite deployed upward from the Orbiter on the end of a 20-km long, 2.5-mm diameter conducting copper wire tether strengthened with a Kevlar™ core and insulated with a Teflon™ sheath and a Nomex™ jacket. The TSS-1 experiment in July 1992 was aborted when the tether reel jammed. The TSS-1R reflight experiment in Feb 1996 was successful in deploying the Italian satellite smoothly upward to almost the full length of the tether. The motion of the 19.5-km length of conducting tether being dragged through the magnetic field of the Earth produced the expected nearly 3500 V potential difference between the ends of the tether. Periodically, the plasma contactors on the Italian satellite and the Orbiter were activated, allowing electrons in the space plasma to flow into the conducting surface of the Italian satellite at the positive end of the tether, down through the conductive wire in the tether, and out through the plasma contactors on the Orbiter back into the space plasma. The current through the tether was limited by the control electronics to 0.5 A. This measurement demonstrated one of the objectives of the experiment – that a 20-km long conducting tether could be used to convert Orbiter kinetic energy into at least 1.75 kW of electrical power. The plasma contactors were turned off, and the tether reeling was continued. With the current through the tether turned off, and with no voltage drop along the tether, the voltage on the portion of the conductor still remaining on the reel inside the Orbiter bay increased past 3500 V. Although the insulation had been designed to withstand more than 10,000 V, for some reason the insulation failed, and a small spark jumped through the insulation to the metal reel, which was at Orbiter “ground” potential. With the plasma contactors off, there should have been little current flow. But the bare conducting surface of the Italian satellite turned out to be a excellent electron collector, 2-3 times better than predicted by the existing Parker-Murphy Theory. The Orbiter, with its ever-present "cloud" of gas emitted from its large surface area of materials with high outgassing properties and its attitude control jets, also turned out to be an excellent negative electron emitter and positive ion collector. The resulting uncontrolled current flow through the spark jumped to 1.1 A, and the spark grew into a 3.85 kW arc that melted the copper and burned through Kevlar™, Teflon™ and Nomex™, causing the tether to part. The TSS-1R experiment was called a "failure", but the very method of failure showed that a large area of bare conductor alone, is sufficient to collect electrons from space, with no plasma contactor needed, and that a properly designed electrodynamic tether would be 2-3 times more effective in space than theory had previously predicted. In the HASTOL architecture, a major component of the space tether portion of the system is the conducting wire braided into the Spectra™ strength portion of the tether to form the TUI-patent-pending High-Strength Electrodynamic Force Tether (HEFT). Current from a solar power array pumped through the conducting tether will push against the magnetic field of the Earth, producing propulsive forces to restore the tether orbit and spin between payload lifts – without the use of propellant. We know the HEFT concept will work in the HASTOL architecture because of the TSS-1R data.

From 1993 to 1996, a number of smaller tether flight experiments[7] were carried out by NASA/MSFC and NASA/JSC using Small Expendable-tether Deployment System (SEDS) tether systems built by Joseph Carroll of Tether Applications in San Diego (a consultant to both TUI and Boeing). The Plasma Motor Generator (PMG) experiment in June 1993 deployed a 500-m long #18 American Wire Gauge (1.0 mm) Teflon™ insulated copper wire tether. The electronic packages in the PMG experiment included plasma contactors at both ends of the tether and a battery power supply to produce current flow in both directions along the tether, thus demonstrating operation of the electrodynamic tether in both the power production and propellantless propulsion mode. These experimental results are again of relevance to the HEFT tether in the HASTOL Architecture.

Two other SEDS flight experiments[7,23] each deployed a 20-km-long 0.75-mm-diameter nonconducting polymer tether with a 26 kg payload at the end. The SEDS-1 experiment in March 1993 demonstrated that rapid tether deployment using springs to push off the payload, and simple control laws to activate a brake to control the tether deployment rate would result in the tether being fully deployed with little shock and little residual dynamical motion, without the requirement for human intervention. This experiment is relevant to HASTOL since it showed that the tether dynamics computer simulation models that had been developed by Carroll and others would adequately predict actual tether dynamics performance in space. This tether was deliberately cut at a designated time in its orbit to demonstrate the accurate deorbit of the payload to a predetermined reentry point on the Earth. The follow-on SEDS-2 experiment in March 1994 left the tether hanging in space to determine its lifetime. It was cut in 5 days by a meteoroid or orbital debris (M/OD) impactor. This experiment showed the necessity for using open net interconnected multistrand structures for space tethers, such as the Hoytether™ design to be used on the HASTOL tethers, instead of the single compact braided line used in the SEDS-1 and -2 experiments.

The Naval Research Lab Tether Physics and Survivability (TiPS) experiment[7,24] launched in June 1996 on an NRO technology demonstration flight used another SEDS-type deployer with a thicker braided polymer tether 4 km long. To increase the survival lifetime, the polymer strands of the tether were spread out into a 2.5-mm-diameter open net by braiding the polymer strands around a "fluffed-out" yarn core. This tether connects two spacecraft in an orbit at 1000 km altitude, and they are still there as of this date. The open net structure has allowed the tether to survive cuts by space debris for over 3.5 years. The high strength polymer used in the TiPS tether is Spectra™ 2000, the same material that will be used in the HASTOL tether. The fact that the polymer material has survived exposure to the ultraviolet and charged particle radiation and the vacuum of space for over 3.5 years is encouraging, in that it indicates that Spectra™ 2000 is an acceptable candidate material for a first generation HASTOL system. The stress level on the tether is low, however, so no estimate can yet be made of any strength degradation of the Spectra™ 2000 by the space environment.

In 1997, NASA/MSFC funded an International Space Station (ISS) Electrodynamic Tether Reboost study[25]. The study team included both Boeing and TUI. The 7-km-long electrodynamic tether was designed to be made of aluminum wire braided with Spectra™ 2000 into a 10-mm-wide, 0.6-mm-thick tape massing about 100 kg. The 5 km portion near the ISS would be insulated, while the outer 2 km would be bare to collect electrons from the space plasma. The tether would be hung down below the ISS with a 200 kg ballast mass at the end. About 6 kW of off-peak power obtained from the 80 kW solar panel farm on the ISS would pump about 4 A of current through the tether. The current in the tether would push against the magnetic field of the Earth to provide a propellantless reboost thrust of about 0.5 N average, which is sufficient to completely overcome the estimated average air drag on the ISS. This would reduce, or even completely eliminate, the need for periodically hauling reboost propellant to the ISS with Russian Progress rockets, potentially saving billions of dollars. Although this study has not turned into a planned experiment as yet, the effort put into the study by MSFC, Boeing, TUI and others on the design of the tether, power converter circuits, tether deployment mechanism, and tether dynamics software, has already been relevant to the design of the High-Strength Electrodynamic Force Tether (HEFT) in the TUI patent application, and will be relevant to the HEFT portion of the HASTOL architecture.

The planned NASA/MSFC ProSEDS (Propulsive SEDS) tether experiment[7,26] is scheduled for launch in August 2000. This experiment will deploy a 5-km-long conductive tether in an attempt to repeat the PMG and TSS-1R experiments in a more precise and controlled fashion, with more detailed data collection. Both the deployment and the operation of this tether system will produce operational flight data that will be relevant to the design of the electrodynamic tether in the HASTOL architecture.

TETHER GRAPPLE AND PAYLOAD ACCOMMODATION SYSTEM

The actual payload transfer between the hypersonic vehicle and the tether systems is accomplished by a combination of a tether grapple and payload accommodation system. This is based on previous studies conducted for NASA. The system designer trades off the allocation of capture functions between the payload accommodation system, which is an expendable device used for each payload and the grapple assembly, which remains in orbit and is difficult to re-supply.

The approach to this subtask was to begin by defining the basic design requirements and constraints of the mission. Trade studies were then used to define what elements would perform what functions. Several design concepts were used to test our ideas against the required functions. This was repeated several times building on what was learned in each cycle. Since this study is at the architecture level, trades were also conducted between other elements of the architecture such as the hypersonic aircraft, the tether control station, and the tether itself. The products of the NASA-funded study of a LEO to GEO tether transportation study were used extensively herein as were the lessons learned.

Design Requirements

In order for successful rendezvous, docking, and transfer of the payload to occur, some basic functions must be performed by one or more of the HASTOL system architecture elements, which include the grapple assembly and payload accommodation system. The following basic functions have been identified and the design process considered all of them:

1. Establishing and updating a known absolute location for rendezvous, capture, and transfer
2. Establishing and updating the relative position between the payload and the grapple assembly
3. Recognizing the defined rendezvous point
4. Closing the gap to the rendezvous point
5. Payload/grapple docking
6. Payload separation from the hypersonic vehicle
7. Retention of the payload on the grapple during transfer

The results of earlier studies indicated that there is a high degree of cooperation required between the payload accommodation system and the grapple assembly. In this case, the hypersonic aircraft must also become an element of the capture and must be integrated into the capture event. In this approach the payload accommodation system provides the mechanisms to facilitate the capture and provides a common interface to the grapple assembly. Earlier studies indicated that any expendables such as propellants should be a part of the payload accommodation system or the hypersonic aircraft to avoid re-supplying the grapple assembly. This is a significant life cycle cost issue and will be treated in subsequent studies.

A general capture scenario was laid out in order to formulate grapple assembly design drivers and requirements, and to establish a configuration trade space. The payload capture scenario is defined by the following parameters:

- Capture at an altitude of 80-100 km
- Payload maximum weight of 14 Mg (15 English tons)
- Capture when the hypersonic airplane is traveling at Mach 10-12

- Tether tip temperature of 45°-85°C
- Very low dynamic pressure environment
- Relative acceleration of mated payload/grapple assembly after capture of <2.5 g's

Several grapple design requirements and drivers resulted from the definition of these parameters. The atmosphere is not very dense at 80-100 km altitude. The grapple assembly will therefore not need to be streamlined to any great extent, although it may have to withstand significant heating for its short duration in the atmosphere. The amount of heating will depend upon the exact rendezvous altitude and speed and the effective cross-sections of the grapple assembly and Payload accommodation system. Further analysis should show a clearer picture of the effects of thermal cycling due to multiple atmospheric passages. It will also aid in future material specifications.

The tethered grapple assembly motion at the point of capture must be in plane with the payload. Control of either the grapple assembly or the payload (payload itself or the hypersonic aircraft) must be possible to ensure a successful docking. Structural loading of the grapple assembly must be taken into account for rendezvous as well as for capture impact and transfer of the 14-Mg (14 metric tons or 30,000 lb.) payload. No damage must be allowed to occur to the payload.

A conservative assumption is that there will only be one capture attempt possible per mission. As a result, maximizing the capture opportunity window is a design objective. This assumption has also resulted in a requirement for the capture to be as automated as possible; a Go/No-Go decision initiated prior to the actual capture by ground control (or pilot, should there be one) will be included in the design. It is assumed that abort modes will be defined prior to each HASTOL mission for the specific client, though efforts are on-going to identify abort modes that can be built into the system - for instance, establishing the bounds of an "attempt-to-transfer window," and a "payload out-of-bounds" window.

Other grapple design issues deal with the "no damage" to client payload policy and communications issues. The payload's safety during transfer must be ensured, which means either the payload must not tumble during transfer, or it must be protected so limited tumbling can be accounted for at no consequence. The potential of communication loss at each phase of the payload transfer scenario must also be considered.

Configuration Options

The general functions listed above were allocated among the hypersonic vehicle, payload, and grapple assembly to define a system configuration trade space to drive out the implications each configuration would have on the grapple assembly and payload accommodation system design and HASTOL system architecture as a whole. Seven configurations resulted from the functional allocations between the hypersonic vehicle, payload accommodation system, and grapple assembly, focusing on methods in which to remove the payload from the hypersonic vehicle:

- Configuration 1 – Mechanical Arm on Hypersonic Vehicle
- Configuration 2 – Mechanical Arm on Grapple Assembly
- Configuration 3 – Atmospheric Vents Lift Payload out of Cargo Bay
- Configuration 4 – Payload Powers Itself Out of Cargo Bay
- Configuration 5 – Payload Ejected, Cradle/Clam Shell Mechanism captures Free-falling Payload
- Configuration 6 – Electromagnet on Grapple Assembly Removes Payload
- Configuration 7 – Electromagnet on Payload Pulls it from Bay to Grapple Assembly

Configuration 3, with atmospheric vents being used to lift the payload out of the cargo bay, was discarded based on the altitude range of 80 – 100 km of the HASTOL scenario for this study. At those altitudes there is not sufficient atmosphere for atmospheric vents to be used for this purpose (though the concept may become a viable candidate for other payload transfer concepts). Each configuration definition has been placed in its own configuration table. A subsystem definition table follows each configuration table. The “causes” in the configuration table result in the “effects” summarized in the subsystem table that follows. Every configuration assumes that the hypersonic vehicle is the only HASTOL element with the required absolute positional knowledge and that an electrodynamic tether is being used.

Table 1. Configuration 1, Mechanical Arm on Hypersonic Vehicle

NOTE: Hypersonic Plane is only element with absolute positional knowledge

	Relative Positional Knowledge	*Δ V Knowledge*	*Finer Maneuverability and Control*	*Removes P/L from Plane*	*Mechanism (passive or active) location*	*Comments*
Hypersonic Plane		X	X	X		Arm on plane does all the maneuvering
Payload					X	Passive
End Mass/Grapple Assembly	X	X			X	Active; End Mass/Grapple Assembly must carry on-board avionics for positonal and velocity knowledge relative to plane, including systems for updating and processing this information
Tether						
Tether Central Facility (TCF)						

Table 2. Configuration 1, Implied Subsystems

Required On-board systems	*Attitude, Vel. & Δ V Determ. Sys*	*Communications*	*Power Generation*	*Power Storage*	*RCS System*	*Tether Reel*	*Comments*
Hypersonic Plane	X	X			X		
Payload							Passive Docking Ring
End Mass/Grapple Assembly	X			X			LIDAR, batteries, Active Docking Ring
Tether			X				Electrodynamic tether
Tether Central Facility (TCF)						X	

The idea central to Configuration 1 (Figure 19) is a mechanical arm on the hypersonic vehicle that performs all of the necessary maneuvering to lift and orient the payload so it can be captured by the grapple assembly. The payload has a passive docking mechanism (a docking ring, perhaps) attached as a “payload adapter” that will be discarded after the payload is transferred into its destination orbit. The grapple assembly has the active docking mechanism, which will require a power system (storage and distribution) that will store power generated by the electrodynamic tether between missions. The grapple assembly does not have an on-board reaction control system (RCS), but does have a passive guidance system element (beacon or

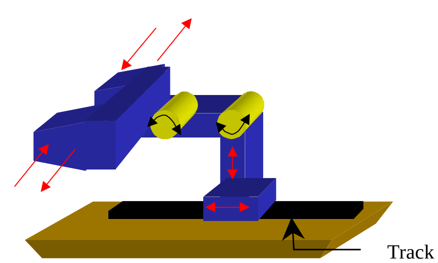


Figure 19. Conceptual Mechanical Arm on Hypersonic Vehicle

optical cube) that interfaces with a guidance system on the hypersonic vehicle and arm. The grapple assembly is moved entirely by the tether reel on the tether central facility (TCF). The only communications system in this first configuration is the hypersonic vehicle's communication system.

Pros:

- Reusable arm
- Arm maintenance would be a ground operation between missions instead of an on-orbit operation or an operation that involved tether central facility downtime
- Lower cost from disposing of a passive docking ring as opposed to disposing of an active docking mechanism with each mission
- Hypersonic aircraft knows performance of both "sides" of system to transfer payload
- Grapple assembly communicating some type of data to plane; boilerplate for future completely automated transfers and abort procedures
- Arm can grab payload and possibly orient it as well as lift it from cargo bay for transfer to grapple assembly
- Hypersonic aircraft RCS use could extend capture window

Cons:

- Grapple assembly batteries required to power avionics as well as active capture mechanism
- Hypersonic aircraft RCS may not extend capture window sufficiently
- Arm adds packaging/deployment complexity to aircraft design; additional weight and additional power requirements
- Questionable ability to perform "fine maneuvering" at scenario speeds
- Possibility of tether tip motion precessing so that it is not only out of plane with the hypersonic vehicle/payload, but is also out of the reach of the mechanical arm. Further mission analysis required to establish high probability bounds for the test case that would be used in the arm design.

Table 3. Configuration 2, Mechanical Arm on Grapple Assembly

NOTE: Hypersonic Plane is only element with absolute positional knowledge

	Relative Positional Knowledge	*ΔV Knowledge*	*Finer Maneuverability and Control*	*Removes P/L from Plane*	*Docking Mechanism (passive or active) location*	*Comments*
Hypersonic Plane						
Payload					X	passive docking
End Mass/Grapple Assembly	X	X	X	X	X	Robotic Arm mechanism; active docking
Tether						
Tether Central Facility (TCF)						

Table 4. Configuration 2, Implied Subsystems

Required On-board systems	*Attitude, Vel. & ΔV Determ. Sys*	*Communications*	*Power Generation*	*Power Storage*	*RCS System*	*Tether Reel*	*Comments*
Hypersonic Plane	X	X					comm ground-link and with Grapple Assembly
Payload							
End Mass/Grapple Assembly	X	X		X	X	X	comm gound-link and with Hypersonic Plane, RCS refueling adds ops complexity, tether reel adds weight
Tether			X				
Tether Central Facility (TCF)							

Configuration 2 (Figure 20) places the mechanical arm and all maneuvering responsibility on the grapple assembly. This requires the grapple assembly to have on-board active guidance and RCS systems, as it must seek the payload and manipulate the arm to capture it. In addition to an on-orbit power storage and distribution system, the grapple assembly also makes use of it's own tether deployment system. A portion of the tether extending from the TCF is still an electrodynamic tether which generates the power which is stored in the grapple assembly's power storage system, but the grapple assembly deploys the power/arm/RCS/active guidance package along its own tether line. The hypersonic vehicle now carries the passive guidance element of the capture system (beacon or optical cube or other). The payload still has the disposable, passive, docking element. The hypersonic vehicle may still need a means for orienting the payload so that a generic payload adapter can be used for all payload clients, some of which may take up the entire cargo bay and must be oriented "end up" in order to be captured.

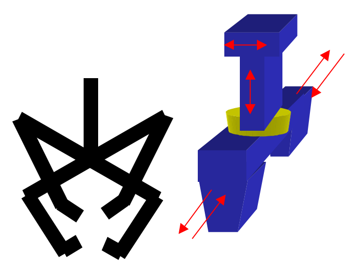


Figure 20. Conceptual Mechanical Arm on Grapple Assembly

Pros:

- Passive docking ring on payload has ease of manufacturing potential
- Disposable passive docking ring on payload as opposed to more expensive, active docking mechanism being thrown away with each mission
- Fewer additional constraints imposed on hypersonic vehicle design
- Additional tether reel on grapple assembly instead of only single Tether Central Facility (TCF) may result in quicker grapple responses to tether reeling
- Capture window opportunity increased
- Impact loads on main TCF tether (at capture) reduced

Cons:

- RCS on grapple assembly must be replenished; on-orbit maintenance
- Mechanism complexity is high
- Additional tether reel adds complexity to operations and system dynamics

Table 5. Configuration 4, Payload Powers Itself out of Cargo Bay

NOTE: Hypersonic Plane is only element with absolute positional knowledge

	Relative Positional Knowledge	*Δ V Knowledge*	*Finer Maneuverability and Control*	*Removes P/L from Plane*	*Docking Mechanism (passive or active) location*	*Comments*
Hypersonic Plane						supplies guide beam to optical cube that's on the Grapple Assembly, Payload follows beam for successful capture
Payload			X	X	X	Atmospheric vents on P/L lift it out of cargo bay; active docking using "radial clamp" idea Ben drew for NIAC paper
End Mass/Grapple Assembly	X	X			X	passive docking mech with optical cube target; passive docking ring
Tether						
Tether Central Facility (TCF)						

Table 6. Configuration 4, Implied Subsystems

Required On-board systems	*Position, Vel. & Δ V Determ. Sys*	*Communications*	*Power Generation*	*Power Storage*	*RCS System*	*Tether Reel*	*Comments*
Hypersonic Plane	X	X					
Payload	X	X		X	X		Disposable P/L adapter; adds capture wt and adds recurring cost
End Mass/Grapple Assembly							
Tether							
Tether Central Facility (TCF)						X	

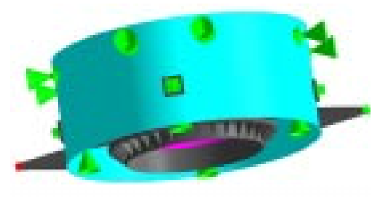


Figure 21. Concept for Payload Adapter to Power Payload Out of Cargo Bay

In Configuration 4 (Figure 21), the payload powers itself out of the cargo bay either by using an upperstage or a large RCS system built into a payload adapter. Here is another instance where the hypersonic vehicle will probably need a means to orient the payload for release built into the cargo bay, or it must have a payload ejection system. The payload adapter also has an active docking mechanism and power storage and distribution system to power avionics and RCS and docking elements. The guidance system in this configuration is really a proposed design solution; the use of a guide beam from the hypersonic vehicle, which targets the grapple assembly. The payload adapter's guidance system commands the RCS to follow the beam path to the grapple assembly. The grapple assembly has the passive docking element and any elements on the receiving end of the guidance beam system that are required.

Pros:

- Payload can maneuver itself and meet grapple assembly for capture
- No fine path adjustments imposed on the hypersonic vehicle
- Active docking mechanism on payload adapter reduces consumables on board the grapple assembly, which increases ease of maintenance of the grapple.
- Loads on tether may not be as bad at capture due to cooperative payload
- Guidance system with military heritage

Cons:

- Payload adapter imposes load carrying capability on client payload
- Payload adapter reduces size/weight of clients that can use the HASTOL system
- Use of upper stage on payload also reduces size/weight of clients that can use HASTOL

Table 7. Configuration 5, Payload Ejected, Cradle/Clam Shell Mechanism captures Free-falling Payload

NOTE: Hypersonic Plane is only element with absolute positional knowledge

	Relative Positional Knowledge	*Δ V Knowledge*	*Finer Maneuverability and Control*	*Removes P/L from Plane*	*Docking Mechanism (passive or active) location*	*Comments*
Hypersonic Plane			X	X		Ejects P/L
Payload	X					Ejection from plane may require disposable encapulation for protection (dynamic pressure); optical cube on P/L
End Mass/Grapple Assembly	X				X	Rel.position to P/L known and updated; structural "net" or clamshell capture mechanism
Tether						
Tether Central Facility (TCF)						

Table 8. Configuration 5, Implied Subsystems

Required On-board systems	*Relative Positional, Vel. & Δ V*	*Communications*	*Power Generation*	*Power Storage*	*RCS System*	*Tether Reel*	*Comments*
Hypersonic Plane							
Payload	X						optical cube
End Mass/Grapple Assembly	X	X		X			for on-board sensors and communication to let operators know if/when P/L is acquired, and for net/clamshell open and closing, for powering avionics for use of optical cube on P/L to establish and update relative position info.
Tether			X				
Tether Central Facility (TCF)						X	

Configuration 5 (Figure 22) has the payload being removed from the cargo bay in a simple manner; it's ejected from the bay and is left in free-fall. The payload is enclosed in a protective capsule which has a passive guidance element (beacon, other) on-board. The capsule would act like a launch vehicle's payload fairing, falling open and away, discarded after the payload is released. The grapple assembly has a simple capture mechanism; either a cradle/launch tube arm or a bulldozer-like clamshell that opens and closes to capture/release the payload.

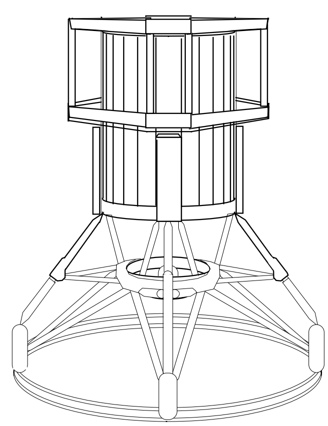


Figure 22. Concept for Passive Docking Mechanism on Tether Tip

Pros:

- Payload protected during transfer; clients happy
- Simple grapple assembly concept without consumables (except long-term battery replacement)
- Simple mechanisms with higher reliabilities could be used
- Free-falling payload increases capture opportunity window

Cons:

- Grapple assembly does not have "smarts" to capture free-falling payload; may require too much precision from system for reliable, repeatable payload transfers
- May not be able to ensure grapple/payload in plane with each other at capture instant unless RCS added to grapple assembly (adds consumables)
- Capsule must be designed to withstand impact loads of capture without imparting them to the P/L
- Won't allow for tether twisting unless RCS added with consumables or ingenious cradle/launch tube design can be developed

Table 9. Configuration 6, Electromagnet on Grapple Assembly Removes Payload

	Relative Positional Knowledge	*Δ V Knowledge*	*Finer Maneuverability and Control*	*Removes P/L from Plane*	*Docking Mechanism (passive or active) location*	*Comments*
Hypersonic Plane	X	X	X			must provide beam to optical cube on End Mass to have relative positional knowledge
Payload					X	dumb ferrous lump to attract End Mass electromagnet, needs to be disposable
End Mass/Grapple Assembly	X			X	X	Provides optical cube for plane to know relative position; Active electromagnet
Tether						
Tether Central Facility (TCF)						

Table 10. Configuration 6, Implied Subsystems

Required On-board systems	*Position, Vel. & ∆V Determ. Sys*	*Communications*	*Power Generation*	*Power Storage*	*RCS System*	*Tether Reel*	*Comments*
Hypersonic Plane	X	X		X			Avionics and beam for rel. position; communicate whether or not P/L has left the cargo bay
Payload							
End Mass/Grapple Assembly	X	X					An optical cube for relative position knowledge; sensors and comm to know if/when capture successful
Tether							
Tether Central Facility (TCF)							

Configuration 6 (Figure 23) provides an option that attempts to reduce the number of moving parts used in the capture mechanism design. An electromagnet, within the grapple assembly, lifts the payload out of the cargo bay and holds it during transfer. Simply removing the current from the electromagnet allows the payload to be smoothly released. This requires the grapple assembly to have capacitors with quick discharge capability. The payload needs a dumb, ferrous adapter with magnetic isolation barriers to protect its avionics from the concentrated magnetic field. A simplified analysis using the following equations was performed to check the feasibility of this concept:

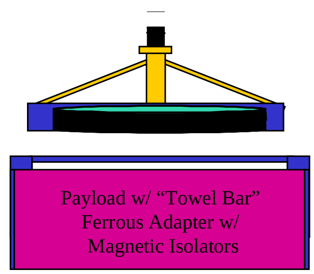


Figure 23. Electromagnetic Capture Concept

$$B = \sqrt{\frac{F(72{,}134{,}000)}{A(10^8)}}$$

F = load to be held, not lifted (lb.) = max. payload weight

B = flux density (Mx/in^2)

A = area of holding surface (in^2)

1 Wb = 10^8 Mx

$$I = \frac{BL_s}{\mu N}$$

B = magnetic field of a solenoid (Tesla, T)

N = number of turns of wire

I = current (Amps)

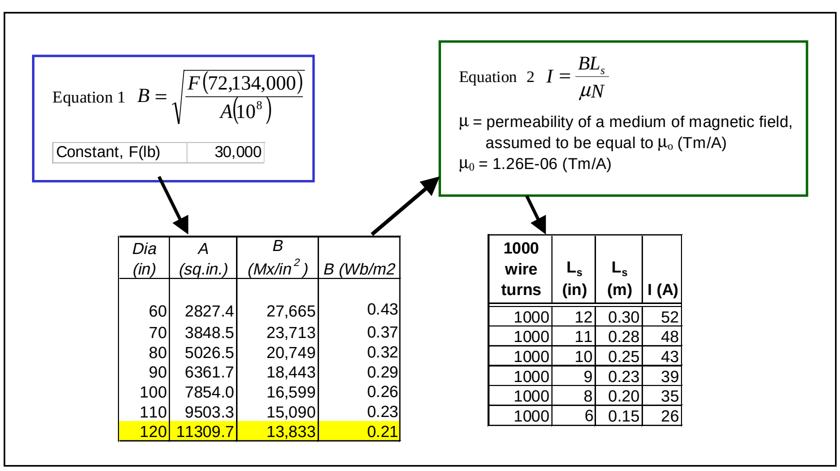
L_s = length of solenoid (m)

μ = permeability of a medium of magnetic field, assumed to be equal to μ_o (Tm/A)

μ_0 = 1.26E-06 (Tm/A)

1 T = 1 Wb/m^2

The holding force, F, was assumed to be a constant (30,000 lb., the maximum payload weight). The area was assumed to be circular, with the diameter varying from 60" to 120" in 10" increments. The magnetic field, B, was calculated over this varying area, and resulted in fields of strengths ranging from 0.4 to 0.2 Telsa. Three values of B were used as constants to calculate three sample sets of current values. Within a single sample set with constant B, the number of wire turns was held constant at values 500, 750, and 1000 to result in three data series per constant B (L_s handled as a variable ranging from 6"-12"). Figure 24 follows as an example of how these calculations were performed. Figure 25 shows the graphical results of the 0.2 Telsa magnetic field data set. Table 11 summarizes the calculation results for the three data sets.



Dia (in)	A (sq.in.)	B (Mx/in^2)	B (Wb/m2
60	2827.4	27,665	0.43
70	3848.5	23,713	0.37
80	5026.5	20,749	0.32
90	6361.7	18,443	0.29
100	7854.0	16,599	0.26
110	9503.3	15,090	0.23
120	11309.7	13,833	0.21

1000 wire turns	L_s (in)	L_s (m)	I (A)
1000	12	0.30	52
1000	11	0.28	48
1000	10	0.25	43
1000	9	0.23	39
1000	8	0.20	35
1000	6	0.15	26

Figure 24. Example of Estimated Current Calculations for B Held Constant

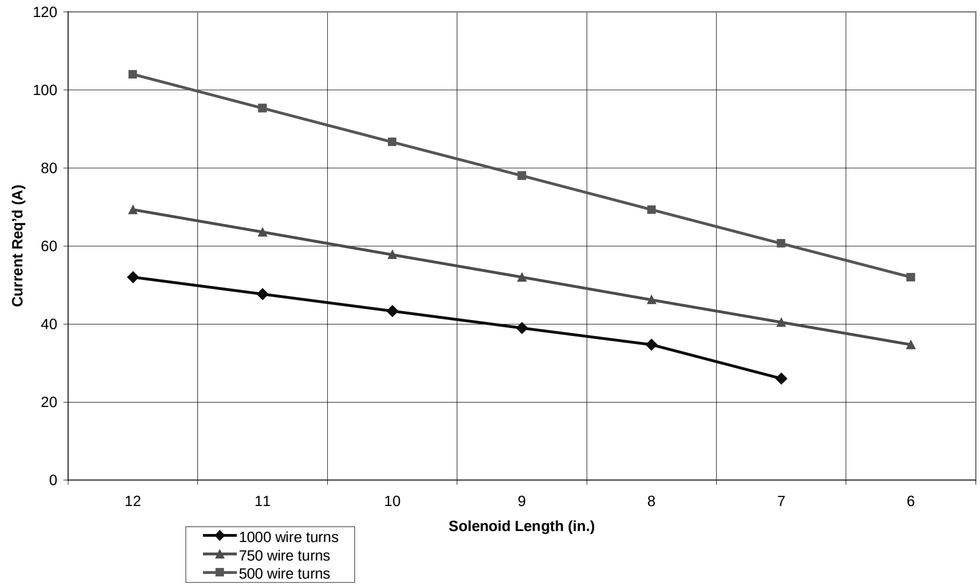


Figure 25. Current as a Function of Solenoid Length and Number of Wire Turns for B = 0.2 T

Table 11. Summary of Electromagnet Concept Feasibility Calculations

B (Tesla)	Number of Wire Turns (N)	Solenoid Length (in.)	Solenoid Diameter (in.)	Current Req'd (A)
0.4				
	500	12	60	208
	750	12	60	139
	1000	12	60	104
0.3				
	500	12	90	139
	750	12	90	92
	1000	12	90	69
0.2				
	500	12	120	104
	750	12	120	69
	1000	12	120	52

Pros:

- Easy way to align payload and grapple assembly.; soft dock
- Simple
- Makes use of electrodynamic tether; charge batteries or capacitors that will deliver a steady current during capture/softdock, or could deliver high current quickly to pick up payload from cargo bay just in time for docking mechanism to hard dock for transfer

Cons:

- Have to provide isolation barrier between any hypersonic vehicle avionics and Grapple electromagnet
- Must isolate payload avionics from grapple electromagnet
- Increases “dumb” or wasted mass on payload (electromagnet barriers) and/or hypersonic aircraft

The data shows that sizing an electromagnetic system just to hold a maximum-weight payload could require very high constant current values, but depending on physical limitations of wire turns along a cylindrical length, some more feasible constant currents will suffice. The amount of constant current required to size this system to perform work and actually pull this weight out of the cargo bay depends on the distance over which one wishes this work to be performed. It is expected at this early stage, that the current values required would be quite high for any amount of work other than holding to be performed.

Another version of this configuration (Configuration 7) is to put the electromagnet on the P/L. The Pros and Cons and subsystem requirements are the same, but the electromagnet would need to be on a payload adapter that would be disposed of (with each mission). The hypersonic vehicle avionics near the cargo bay would potentially need even more shielding, depending on how long before the expected capture the magnet was “hot.”

Architecture Control and Payload Transfer

The payload transfer must be approached as a system control problem due to the fact that several elements must be controlled to successfully complete the payload transfer. The system must be closely choreographed to maximize the payload transfer time and capture envelope. While having to control multiple elements appears to add complexity to the system, it actually adds robustness in that there are several elements that can be adjusted to complete a payload transfer and the entire burden of adjusting the system is not allocated to the hypersonic aircraft. The motions of all HASTOL elements are predictable with mathematical algorithms over the range of time required to complete a payload transfer. As the time scales increase beyond several orbits the ability to precisely extrapolate position data becomes much more difficult. The accuracy of the predicted motion will improve as experience is gained from future flights and demonstrations of tethers in orbit. Controlling the system motions will become easier in the future due new instrumentation now being developed to provide high precision position and motion data with inertial measurement units, differential GPS and optical tracking systems like the LIDAR and LADAR systems now under development.

As described earlier, the payload transfer will occur when the hypersonic aircraft enters a ballistic trajectory with an apogee near 90 km or higher. The hypersonic aircraft will use onboard instrumentation and data relayed from the tether central station and tether grapple assembly to accurately predict where in space and time the actual physical transfer will take place. The tether central station will make all required adjustments before the aircraft takes off and will provide position and status of both the tether central station, the state and condition of the tether, and the tether grapple assembly. The aircraft will launch and accelerate to rendezvous with the tether grapple assembly. At the end of the air breathing cycle the aircraft will ignite the on board rockets to propel the vehicle to the rendezvous point. Prior to entering into the ballistic rocket mode the aircraft will make the required adjustments based on differential GPS data, LIDAR/LADAR, or automated optical tracking devices (optical reflectors mounted on the grapple) to pin point the current grapple position and velocity data. The LIDAR/LADAR devices are used to both track the grapple and to measure and map the atmospheric density at or near the rendezvous point.

The earlier the corrections can be made to control the entire system the lower the thrust and fuel consumed. In this case, the system refers to the tether central station, tether grapple assembly and the hypersonic aircraft. To set up the transfer, the tether central station and grapple assembly will enter a fine control mode where the systems are configured to ensure very predictable motion of the grapple during the approach to the rendezvous point. This is practical due to the mass/inertia of the grapple assembly, centrifugal forces from the motion of the tether and the very low density of the atmosphere at these altitudes. The variation due to solar cycles and fluctuations in the geomagnetic field are less radical at these altitudes so prediction of the density is easier. The grapple may be equipped with thrusters to adjust the velocity in cases where density variations might cause a change in the predicted motion of the grapple. This would be used only in the case of higher than normal densities since this imposes a re-supply requirement on the grapple. As long as the LIDAR systems can measure the atmospheric density in the region of interest we will be able to predict the motion so corrections at the grapple should not be required. As the rendezvous point becomes lower in the atmosphere this becomes a more complex problem. It should be noted that much of the atmospheric absorption data and development of algorithms is being done for the Air Borne Laser where atmospheric absorption is a critical problem to controlling the propagation of the laser to its intended target. The aircraft will have the state data related to it through communications links and will compute the optimum approach corridor. Once the approach corridor is determined, the aircraft will accelerate into the corridor and will make any significant corrections at the beginning of the flight where there is significant aerodynamics for control of the vehicle. On-board thrusters will be used during the ballistic phase to make the minor corrections and maintain the attitude of the vehicle during the approach phase.

In our point of departure design we will open the payload doors of the aircraft and will track the grapple as it approaches from behind the aircraft. At or near the apogee of the aircraft the payload will be raised out of the bay and captured by the grapple. This motion of the grapple and tether at this point will be very predictable due in part to the mass of the system and the lack of any significant dynamic pressure from the atmosphere at these altitudes. The current concept is to have strong electromagnets mounted on the payload accommodation package to pull the payload into the capture envelope of the grapple to allow the actual mechanical capture. The time frame that the payload and grapple are in near contact is short which allows quick very strong pulsed electromagnets to complete the transfer. This approach works well for scenarios where the physical capture envelope is on the order of meters. Several other payload transfer techniques are described in the Phase 1 report which could also complete the transfer process for larger capture envelopes. This one was selected as our point of departure because of the short time frame, small capture envelope expected, the predictability of the electromagnets and the simplicity of the system.

Grapple and Payload Transfer Issues

The rendezvous, docking, and transfer of the payload to and from the hypersonic vehicle to the tethered grapple assembly will occur at around 330 kft (100 km) altitude in the presently planned HASTOL scenario. The atmosphere is not very dense at that altitude. There will be significant heating, but not much dynamic pressure despite the high velocities involved. The grapple assembly will therefore not have to be “streamlined” to any great extent, although it will have to withstand significant heating. The amount of heating will depend upon the exact rendezvous altitude and speed, and the “height” of the upper atmosphere at the time of the rendezvous.

A preliminary conceptual CAD drawing of a possible grapple assembly for the tether is shown in Figure 22. It features a circular attach ring at the bottom, which will mate with grapple hooks on the payload. The attach ring is connected to the rest of the end mass via a six-degree-of-freedom multiple-shock-absorber-strut suspension cradle. In the suspension cradle, all of the members are designed to compress as necessary, should the payload and grapple mechanism contact at some non-zero speed or some slightly non-tangential angle. The struts in the suspension cradle will also provide shock-absorber type damping of the resulting movement of the attach ring relative to the heavier end mass cylindrical structure at the top, which contains a tether winch, batteries, the RCS and its propellant, and command, control and guidance electronics.

The ring and the suspension leg elements would be made of materials and designed to withstand heating from the hypersonic molecular flow at the rendezvous altitude. This eliminates any need for an aerodynamic cone or shroud, which would increase the aerodynamic drag on the assembly compared to the mostly empty strut structure presented to the hydrodynamic molecular flow. The “ends up” cylindrical shape of the upper portion of the grapple assembly is already aerodynamically stable. Adding a cone to it would not help appreciably.

As a result of the relatively high rendezvous altitude of 100 km (330 kft), adding aerodynamic surfaces on the grapple assembly will not be effective in maneuvering the grapple toward a rendezvous with the hypersonic aircraft. The cylindrical portion of the grapple assembly will have a tether winch which will allow it to "leave" its normal position at the end of the tether by letting out tether. The centrifugal acceleration from the rotation of the tether will cause the grapple assembly to "fly" in toward the payload in the hypersonic vehicle before the tether itself arrives overhead. The grapple assembly will have attitude control rockets for fine control, but to minimize the problem of refueling of the grapple assembly, it will be up to the attitude control system on the hypersonic aircraft to remove most of the position and velocity errors during the rendezvous process.

The current concept is to fly the decelerating grapple assembly in so that it approaches the hypersonic airplane from behind. The attach ring would attach to the payload and pull the payload up to the grapple. The hypersonic vehicle would then return to ground and the grapple assembly, with payload, would continue its orbit to the correct location at which to release the payload at the correct velocity to achieve the intended higher orbit.

After the grapple assembly exits the atmosphere, the time spent in space will be used to cool, condition and recharge the batteries in the grapple assembly for the next aeropass. When the grapple assembly will not be used to capture or deploy a payload for long periods of time, the tether will be shortened by either the grapple tether winch, or one of the other winches along the tether, to raise the minimum altitude of the tether tip and keep the grapple assembly above most of the atmosphere.

The grapple assembly requires several internal functions to be successful for this kind of mission, which make it similar to grapple assembly concepts developed earlier for exo-atmospheric transfer of payloads. The grapple is attached to the end of a tether but some control, independent of the tether, will still be required. A means for controlling motion in and out of plane is necessary, as well as a mechanism to eliminate or control aerodynamic forces on the grapple assembly during aeropass phases.

The hypersonic grapple would not use externally mounted solar panel arrays during the aeropass due to the high aerodynamic forces and heating rates during this phase. Two initial options have been identified: a deployable/storable photovoltaic array or an electrically conductive tether. Each would generate the required power, the latter while moving through the earth's magnetic field, and would store excess energy in batteries for use during the aeropass phase.

In order to allow a reliable rendezvous, the grapple assembly must maintain location and attitude information and communicate with the hypersonic airplane. This can be done accurately with a differential GPS similar to those systems being developed for landing commercial aircraft. The approach velocities are too high to rely on human pilots on the ground so the system will require autonomous rendezvous and capture (AR&C) capabilities. AR&C technologies, such as advanced sensors for the final approach and rendezvous, are continuing to evolve, and are maturing based on Russian, NASA, and more recently, DARPA investments.

Further Study/Recommendations

No one design solution can be offered at this early phase of development; however, several of the configuration options have shown that some more investigation needs to be made into quantifying the impacts of functional allocations within the HASTOL system architecture. Any of these could be designed to make a working HASTOL system; the questions that must be answered are, "Which one has the best reliability for the lowest operating cost," and "Which one is more easily adapted to take advantages of technology advances?"

Configurations 1, 4, 5, and 6 represent the diverse span of functional allocations within the HASTOL architecture. Configuration 1, with the mechanical arm on the hypersonic vehicle, is a more traditional configuration that builds on a rich, past experience with Space Shuttle missions and ISS design, testing, and cost data. A revolutionary, new means of payload delivery to space should look at this traditional option (as a gauge, as well as a design solution) along with some other options that are more unconventional. Configuration 4 is the only option that requires the payload to remove itself from the cargo bay. It introduces a different type of consumable to the HASTOL system, the payload adapter, which may or may not be cost effective as well as performance effective. Configuration 5, with the payload being ejected from the cargo bay, has a simple, grapple assembly operation concept; it does need more investigation into timing, repeatability, and capture impact loading on the tether tip. Configuration 6, with the electromagnetic grapple, should be investigated as a soft docking design solution. A less powerful electromagnet could be used to soft dock the grapple to the payload before a hard dock, using any of the above hard dock suggestions, captured the payload. Though a mechanical arm on the orbiting grapple assembly is viewed as unnecessarily complex, the tether-based solution to increasing the capture window should be investigated for any type of grapple assembly that is used. The operational dynamics are a little more complex with this solution, but it has a great chance of increasing the capture opportunity window, especially when teamed with other design solutions aiming at that same end.

CANDIDATE PHASE II TASKS

In the process of demonstrating the technical feasibility of the HASTOL concept during Phase I, several areas were identified which would benefit from further investigation in Phase II. These include not only refinement of the HASTOL concept from a technical standpoint, but also development of the business aspects of the system. Areas identified as being worthy of further study are described below.

Mission Opportunities

The spectrum of mission opportunities which can be satisfied with the HASTOL system needs to be established, along with the mission requirements which support those opportunities. This may be accomplished by direct dialog with the potential user community, including NASA, the Department of Defense, and the commercial space industry.

System Requirements Definition

Based on the overall mission requirements generated above, a set of system requirements for each of the major HASTOL systems should be developed. These requirements should address such issues as payload characteristics, traffic rate, guidance and control requirements, g-force limitations, acquisition and life-cycle costs, and system interface requirements. This will assure that the system conceptual design will address the basic requirements, as defined by the potential customers.

Conceptual Design

Taking the concept developed in Phase I as a point of departure, the HASTOL concept should be refined through a more detailed design and analysis of each of the major systems. Studies should be to sufficient depth that it is clearly demonstrated that each system satisfies its stated requirements. This can be accomplished through more detailed design of selected systems, trade studies, modeling and simulation, and cost analyses.

System Analysis

There is a need to quantitatively assess the system concepts evolved through the follow-on concept refinement study and, ideally, provide feedback to the trade studies. In addition, it will be necessary to identify high risk areas (technical, cost, program) to indicate where technology development areas need to be focused. Such areas may include the following:

- Rendezvous and payload capture
- Abort modes
- Tether dynamics and structural integrity
- Electrodynamic thrust control
- Collision avoidance
- Tether survivability
- High-temperature tensile materials
- Tether fabrication
- Development cost uncertainties

Technology Development Planning

Defining a realistic technology development plan is key to gaining the confidence of a customer that we are ready to move on to Phase III in the HASTOL system development. A roadmap needs to be constructed which takes all major components of the system to a TRL of 7 or higher. This should address all of the concerns identified by potential customers. It should include basic technology development, component design and materials selection, and technical and cost trades. It should show early flight demonstration and qualification test plans, with ground and flight testing.

CONCLUSIONS

The fundamental conclusion of the Phase I HASTOL study effort is that the concept is technically feasible. We have evaluated a number of alternate system configurations that will allow hypersonic air-breathing vehicle technologies to be combined with orbiting, spinning space tether technologies to provide a method of moving payloads from the surface of the Earth into Earth orbit. For more than one HASTOL architecture concept, we have developed a design solution using existing, or near-term technologies. We expect that a number of the other HASTOL architecture concepts will prove similarly technically feasible when subjected to detailed design studies. The systems are completely reusable and have the potential of drastically reducing the cost of Earth-to-orbit space access. In particular, we have:

- Developed top-level system requirements
- Conducted top-level trades to define a basic design approach
- Selected a specific hypersonic aircraft concept
- Defined an achievable aircraft apogee altitude / velocity envelope
- Selected the Rotovator™ tether concept as our baseline tether system
- Determined that the tether tip can withstand the aerodynamic and thermal loads as it dips into the atmosphere using existing technology materials
- Validated overlap of the hypersonic aircraft operating envelope with achievable conditions for the tether tip for payload transfer
- Identified a simplified grapple concept

No show-stoppers have been uncovered. Hence, all elements of the concept are in place for further development and refinement of the concept.

REFERENCES

1. Robert L. Forward, Thomas J. Bogar, Michal E. Bangham, and Mark J. Lewis, “Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System: Initial Study Results,” IAF-99-S.6.05, presented at the 50th International Astronautical Congress, Amsterdam, The Netherlands, 4-8 October 1999.

2. Thomas J. Bogar, Michal E. Bangham, Robert L. Forward and Mark J. Lewis, “Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System: Interim Study Results,” AIAA-99-4802, presented at the 9th International Space Planes and Hypersonic Systems and Technologies Conference, Norfolk, VA, 1-5 November 1999.

3. Robert P. Hoyt, “Design and Simulation of Tether Facilities for the Hypersonic Airplane Space Tether Orbital Launch (HASTOL) Architecture,” submitted to the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, 17-19 July 2000.

4. L. F. Scuderi and J. L. Hunt, “Mach 10 Dual-Role Vehicle Concept,” Space Technology and Applications International Forum, Albuquerque, NM, 1-4 February 1999.

5. J.N. Stemler, D.H. Petley, and J.G. Martin, “Concept and Future State of the Vehicle Synthesis System ‘Holist’,” AIAA Paper 98-4742, 7th AIAA/USAF/NASA/ISSMD Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 1998.

6. Hans Moravec, “A Non-Synchronous Orbital Skyhook,” Journal of the Astronautical Sciences, Vol. 25, No. 4, pp. 307-322, 1977.

7. M.L. Cosmo and E.C. Lorenzini, *Tethers In Space Handbook - Third Edition*, prepared for NASA/MSFC by Smithsonian Astrophysical Observatory, Cambridge, MA, December 1997.

8. J. Carroll, “Preliminary Design for a 1 km/s Tether Transport Facility,” *NASA OAST Third Annual Advanced Propulsion Workshop*, JPL, Pasadena, CA, 30-31 Jan 1992.

9. J. Oldson and J.A. Carroll, "Potential Launch Cost Savings of a Tether Transport Facility," AIAA paper 95-2895, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 1995.

10. Robert P. Hoyt and Chauncey Uphoff, "Cislunar Tether Transport System," Paper AIAA-99-2690, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, 20-24 June 1999.

11. Robert L. Forward and Gerry D. Nordley, "Mars-Earth Rapid Interplanetary Tether Transport (MERITT) System: I. Initial Feasibility Analysis," Paper AIAA-99-2151, 35th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, 20-24 June 1999.

12. M. E. Bangham, E. Lorenzini, and L. Vestal, "Tether Transportation System Study," NASA/TP-1998-206959, NASA Marshall Space Flight Center, Huntsville, AL, March 1998.

13. Robert L. Forward and Robert P. Hoyt, "Hypersonic Airplane Space Tether Orbital Launch System," U.S. Provisional Patent Application 60/146852, filed 3 August 1999.

14. Brian Tillotson, "Tether as Upper Stage for Launch to Orbit," AIAA-89-1585-CP, 3rd International Conference on Tethers in Space, May 17-19, 1989.

15. Robert Zubrin, "The Hypersonic Skyhook," Journal of the British Interplanetary Society, Vol. 48, No. 3, pp. 123-128, March 1995.

16. Robert P. Hoyt and Robert L. Forward, "Failsafe Multiline Hoytether Lifetimes," Paper AIAA-95-2890, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA, 10-12 July 1995.

17. Robert L. Forward and Robert P. Hoyt, *Failure Resistant Multiline Tether*, U.S. International Patent Application PCT/US97/05840, filed 22 April 1997.

18. M. Martinez-Sanchez and S.A. Gavit, "Orbital Modifications Using Forced Tether Length Variations." Journal of Guidance, Control and Dynamics, Vol. 10, pp. 233-241, May-June 1987.

19. G. Landis, "Reactionless Orbital Propulsion Using Tether Deployment," Acta Astronautica, Vol. 26, No. 5, pp. 307-312 (1992); paper IAF-90-254.

20. Robert P. Hoyt, "Maintenance of Rotating Tether Orbits Using Tether Reeling," Appendix F in *Cislunar Tether Transport System*, Tethers Unlimited, Inc. Final Report on NIAC Phase I Contract 07600-011, 1999.

21. Robert P. Hoyt, "Cislunar System Dynamics Verification Through Simulation," Appendix C in *Cislunar Tether Transport System*, Tethers Unlimited, Inc. Final Report on NIAC Phase I Contract 07600-011, 1999.

22. N.H. Stone, et al., "A Review of Scientific and Technological Results from the TSS-1R Mission," pp. 1-12 in J.K. Harrison, Compiler, NASA/MSFC, *Tether Technology Interchange Meeting*, Huntsville, AL, 9-10 September 1997, NASA-CP-1998-206900, January 1998.

23. Joseph A. Carroll, "SEDS Deployer Design and Flight Performance," AIAA Paper 93-4764, AIAA Space Programs and Technologies Conference and Exhibit, Huntsville, Al, 21-23 September 1993.

24. Jim Barnds, et al., "TiPS: Results of a Tethered Satellite System," pp. 13-30 in J.K. Harrison, Compiler, NASA/MSFC, *Tether Technology Interchange Meeting*, Huntsville, AL, 9-10 September 1997, NASA-CP-1998-206900, January 1998.

25. I.E. Vas, T.J. Kelley, and E. Scarl, "Application of an Electrodynamic Tether System to Reboost the *International Space Station*," pp. 305-334 in J.K. Harrison, Compiler, NASA/MSFC, *Tether Technology Interchange Meeting*, Huntsville, AL, 9-10 September 1997, NASA-CP-1998-206900, January 1998.

26. Les Johnson and Judy Ballance, "Propulsive Small Expendable Deployer System (ProSEDS) Space Demonstration," pp. 103-108, J.K. Harrison, Compiler, NASA/MSFC, *Tether Technology Interchange Meeting*, Huntsville, AL, 9-10 September 1997, NASA-CP-1998-206900, January 1998.

APPENDIX 1
HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) SYSTEM: INITIAL STUDY RESULTS

IAF PAPER NO. 99-S.6.05

IAF-99-S.6.05

HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) SYSTEM:

INITIAL STUDY RESULTS

Dr. Robert L. Forward, Vice President & Chief Scientist [Presenter]
Tethers Unlimited, Inc. 8114 Pebble Court, Clinton, WA 98236 USA

Dr. Thomas J. Bogar, Senior Principal Engineer, Hypersonic Design and Applications,
Boeing/MDC Phantom Works, P.O. Box 516, St. Louis, MO 63166 USA

Michal E. Bangham, Senior Manager Advanced Engineering, Advanced Programs,
Boeing/MDC, P.O. Box 240002, Huntsville, AL 35824 USA

Dr. Mark J. Lewis, Associate Professor and Director of Center for Hypersonic Education and
Research, Aerospace Engineering Dept., University of Maryland, College Park, MD 20742 USA

ABSTRACT

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is a novel architecture for an Earth-to-orbit launch system consisting of: a completely reusable airbreathing subsonic-to-hypersonic dual-fuel airplane which transports the payload from the ground to some intermediate point in the upper atmosphere; an orbiting space tether system which picks up the payload from the intermediate point and takes it on into orbit; and a grapple system for transferring the payload from the hypersonic airplane to the lower end of the space tether. The system is revolutionary in that it minimizes, and perhaps even eliminates, the use of rockets for Earth-to-orbit launch of satellite payloads and even passengers, while limiting the design requirements for the reusable airbreathing hypersonic launch vehicle to less than 4650 m/s (Mach 15) and perhaps as low as 3100 m/s (Mach 10). There are four different options for the design of the space tether portion of the HASTOL system, all of which will work, although some design options promise better performance. The tethers can be built today using presently available commercial fibers. As better materials with higher strength at higher temperatures become available in the future, the performance and safety margin of the tethers can be improved significantly. The space tethers required are long, typically 400 to 1600 kilometers in length, while the total mass of the space tether portion of the HASTOL system is typically 20-50 times

the payloads being handled. Most of that mass ratio requirement is driven by the fact that the tether system, including the Tether Central Station, must mass considerably more than the payload it is handling, so that, upon pickup of the payload by the tether, the payload will not pull the space tether system out of orbit.

INTRODUCTION

Boeing, Tethers Unlimited, Inc. (TUI), and the University of Maryland, have formed a team to investigate the feasibility of a completely new concept for moving payloads and passengers from the surface of the Earth into low Earth orbit at low cost, low risk, and low acceleration levels. Our joint study effort has just come under contract funding, and this paper should be considered a preliminary report, rather than a finished piece of work. (You will be able to tell that from the lack of equations and the poor quality of the graphics.)

HASTOL Architecture

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system contains three major components: a hypersonic airplane, which will transport the payload as high and as fast as possible using air-breathing propulsion; an orbiting space tether, the lower tip of which will be slowed down by one means or another, so as to meet up with the hypersonic airplane; and a grapple vehicle at the tip of the space tether that will take control of the payload, and with the lift supplied by the space tether, carry the payload on into orbit. It would be desirable that the HASTOL system operate in both directions, allowing for return of payloads from orbit to the Earth's surface. This is not a firm requirement, however, for a launch-only HASTOL system would be useful in itself, since returning from orbit is much easier than launching into orbit. The objective of our ongoing study is to optimize the combined system of airplane, tether, and grapple in order to maximize the overall system performance in terms of payload mass and delivery rate, while minimizing the life cycle cost.

Background

Let us first give some scale to the problem of launching a payload into space. In order to fly an airbreathing vehicle directly into orbit requires an airplane capable of reaching horizontal speeds of 7800 m/s (Mach 25) at 150 km altitude (orbital radius of 6528 km). Designs exist for hypersonic airplanes capable of 3100 m/s (Mach 10), and concepts exist for faster planes of 3875 m/s (Mach 12.5) and higher, but the difficulty of making and operating the hypersonic airplane rises rapidly with increasing Mach number. There is another scale to the problem of putting things into orbit. Since space is 100 km up, most people think that to get into space only involves 100 to 200 km worth of travel. What they fail to realize is that every rocket launched into orbit to date has had to travel thousands of kilometers down range to attain the necessary 7800 m/s orbital speed. Since the distance D that must be traveled at constant acceleration a to reach a final velocity V is $D=V^2/2a$, to reach an orbital velocity of 7800 m/s at an acceleration of one gee (a=9.8 m/s), requires covering a distance of 3100 km. At three gees acceleration, the distance is 1035 km. Similar scaling laws apply to space tethers. If a rotating space tether is to produce a change in velocity of a third of orbital speed, or 2600 m/s, then the tether length L for a one gee acceleration at the tether tip needs to be of order $L=V^2/a$=690 km. As will be illustrated in the following section on HASTOL Space Tether Concepts, there are many designs for space tether systems which can lower a payload grapple vehicle into the upper atmosphere at grapple speeds with respect to the Earth’s atmosphere ranging from 4650 m/s (Mach 5) to 3100 m/s (Mach 10) and lower, but the difficulty of operating the space tether rises rapidly with decreasing grapple speed. We are quite sure that the bridge between air and space can be crossed by using the right combination of hypersonic airplane and orbiting space tether. Finding that optimum combination is the objective of the ongoing study.

HASTOL SPACE TETHER CONCEPTS

There are many ways of designing the orbiting space tether component of the HASTOL system. The five different space tether system concepts initially studied were the: HyperSkyhook, Rotovator, CardioRotovator, CASTether/LIFTether, and HARGSTOL. In our initial analyses of each concept, we assumed that the tether system would have a Tether Central Station (TCS) that was many times more massive that the tether or the payloads being handled. This was assumed so that the center-of-mass (CM) of the tether system was at the TCS. In reality, the TCS will be only 5 to 20 times heavier than the payloads, and the CM of the tether system will not be exactly at the TCS. These minor corrections can be taken into account later. Although the tether mass will usually be less than the TCS mass, we do not want to ignore the tether mass entirely. So, for each of the following concepts we have estimated the mass of the tether alone, using the data we have for the tensile strength and density of high strength materials that are presently available in commercial quantities. If the mass of the tether starts to exceed 100 times the mass of the payload, then that is an indication the particular scenario being considered is not engineeringly feasible using presently available materials, although it might become feasible in the near future as newer or better materials become available with higher tensile strengths at higher operational temperatures. As we shall see later, presently available commercial materials will suffice to make the HASTOL concept work. Just a modest improvement over present-day materials in the ratio of the tensile strength to the density by a factor of two will lower the tether masses to where they are no longer a significant factor in the commercial feasibility of the concept. The primary message we want to leave with the Reader is: "We don't need *magic* materials like 'Buckminster-Fuller-carbon-nanotubes' to make the HASTOL space tether. Present-day materials will do."

HyperSkyhook

In 1995 Zubrin proposed[1] the "Hypersonic Skyhook" as a solution to the mismatch between the attainable atmospheric speeds of a hypersonic airplane and the orbital speeds of space tethers. Since the orbital speed of the space tether decreases with increasing altitude of the tether system center-of-mass, he proposed the use of very long non-spinning tethers or "skyhooks" reaching down from very high altitudes. His analysis showed that because a hanging tether must be tapered to support its lower end in the gravitational field of the Earth, achieving a HyperSkyhook tether tip rendezvous with a 5000 m/s (Mach 16) airplane would require a HyperSkyhook tether mass of 25 times the payload mass. Trying to lower the tether tip speed to 4000 m/s (Mach 13) would require a HyperSkyhook tether mass greater than 200 times the payload mass. Unless a major breakthrough occurs in high strength tether materials, such as the commercial development of carbon nanotube fibers, it does not seem possible to push the non-rotating tether HyperSkyhook concept down to speeds of 3100 m/s (Mach 10).

Rotovator™

The standard method of attaining a low tether tip velocity is to use a rapidly spinning tether, or Rotovator™. The Rotovator concept was invented in 1967 by Artsutanov and reinvented by Moravec in 1977, who did the first thorough analysis[2] of it. Since the Rotovator must reach down from orbital altitudes into the upper atmosphere to match speeds with the hypersonic airplane, the length of the tether and the orbital altitude are necessarily interrelated, with the orbital altitude of the tether center-of-mass (CM) being the length of the tether plus a nominal 100 km for the thickness of the atmosphere. The longer the tether, the higher the orbital altitude and the slower the velocity of the tether system CM.

Rotovator™ Tether Mass: The mass of a rapidly spinning tether in free space is determined primarily by the tip speed of the tether, not the tether length or the tether tip acceleration. The basic equation for the ratio of the mass M_T of one arm of a spinning tether to the mass M_P of the payload plus grapple on the end of the tether arm, was derived by Moravec in 1978 in an unpublished paper, based on a previously published paper[2], and is:

$$\frac{M_T}{M_P} = \sqrt{\pi}\left(\frac{V_T}{V_C}\right) \exp\left[\left(\frac{V_T}{V_C}\right)^2\right] \operatorname{erf}\left(\frac{V_T}{V_C}\right) \qquad (1)$$

Where the error function

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}}\left[z - \frac{z^3}{1!\times 3} + \frac{z^5}{2!\times 5} - ...\right] \qquad (2)$$

varies from erf(0)=0 to erf(>3)=1.0, while erf(1)=0.843, V_T is the tether tip speed, and $V_C=(2U/Fd)^{1/2}$ is the maximum tip speed of an untapered tether, where U is the ultimate tensile strength of the tether material, d is its density, and F>1 is an engineering safety factor derating the “ultimate” tensile strength to a safer “practical” tensile strength. Equation (1) shows specifically that the mass ratio of a spinning tether is a function of the ratio of the tether tip speed to the characteristic velocity (V_T/V_C) only, and to first order does not depend on the tether tip acceleration or the length of the tether. The exponential growth in the mass ratio with the *square* of the velocity ratio seen in Eq. (1) means that attempting to achieve tip velocities significantly higher than the characteristic velocity of the material rapidly leads to unfeasible mass ratios. Equation (1), however, is for spinning tethers in deep space, and does not include gravity gradient forces, which can be significant for long tethers that are operating close to the Earth.

The mass ratio of a long tether near the Earth will depend not only on the tip velocity of the tether, but also the length of the tether and the gravitational acceleration on the tip of the tether. This will be true for most of the tether systems being considered for the HASTOL architecture. There is no simple analytical equation that takes these gravity gradient forces into account, and the mass ratio needs to be numerically integrated for each case. Thus, we have used a numerical integration program to generate a table of tether mass ratios for Rotovator tethers of various lengths L, rotating at various tip speeds V_T, with the center of mass of the tether at the orbital radius R_O=6378 km+100 km+L, and moving at a circular orbit velocity of $V_O=(GM_E/R_O)^{1/2}$, where $M_E=5.98\text{x}10^{24}$ kg is the mass of the Earth, and the gravitational constant $G=6.67\text{x}10^{-11}$ kg–m/s^3. The lower end of the orbiting, spinning tether then reaches down into the atmosphere to match speeds with a hypersonic airplane moving at a hypersonic velocity $V_H=V_O–V_T–470$ m/s, where 470 m/s is the velocity through inertial space of the atmosphere at 80 km altitude at the equator of the rotating Earth.

We found that rotating tethers that were very short had a lower orbital altitude and therefore higher orbital velocity, so they needed a higher tip velocity to match speeds with a hypersonic airplane moving at a given hypersonic velocity. Thus, their mass ratio increased exponentially as the square of the velocity because of Eq. (1). We also found that tethers that were very long were orbiting more slowly, and thus needed less tip velocity, but because the gravity gradient forces on the tether increased with tether length, the mass ratio increased because of the increased gravity force.

After a lengthy search through the parameter space, we found that there was a broad minimum in the mass ratio that occurred when the tether length and the tether tip velocity were such that the centrifugal acceleration at the tether tip was approximately 16 m/s (1.6 gees). The results are summarized in Table 1. For the calculation of the mass ratio, we used data available for Spectra™ 2000, a polymer made by AlliedSignal with an ultimate tensile strength of 4.0 GPa, a specific density of 0.97, and a derated (safety factor of F=2) characteristic velocity of 2030 m/s. This material, along with others, is discussed in more detail later in the paper.

In Table 1, the column labeled '2x' is for a future material (Spectra™ X000?) that has twice the tensile strength of presently available Spectra™ 2000, while the column '10x' is a "placecard" for some far future material (derated carbon nanotubes?) that has ten times the ratio of tensile strength to density of the presently available Spectra™ 2000 fiber.

From looking at Table 1, we can see that the use of present-day Spectra™ in a HASTOL system will enable the Rotovator system to work down to about 3875 m/s (Mach 12.5) without the tether becoming too heavy. Column '2x' indicates that it only takes a small improvement in tether materials for the Rotovator concept to work down to 3100 m/s (Mach 10). Column '10x' indicates that carbon nanotubes would be "overkill" as far as the Rotovator concept is concerned. We don't need carbon nanotubes to make a HASTOL system, as we will need to retain some amount of mass in the tether in order to keep the tether system itself from being pulled out of orbit by the payload!

Table 1 - Minimum Mass Ratio Rotovator Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra™	2x	10x
400	6878	7614	2494	4650	15.0	10.4	2.4	0.37
500	6978	7559	2749	4340	14.0	16.7	4.2	0.56
600	7078	7506	3006	4030	13.0	27.1	5.9	0.65
700	7178	7453	3263	3720	12.0	44.0	8.2	0.73
800	7278	7402	3522	3410	11.0	71.8	11.6	0.90
900	7378	7352	3782	3100	10.0	117.6	16.3	1.07

CardioRotovator

The CardioRotovator concept consists of a Tether Central Station in an elliptical orbit, with a single long tapered tether. The tether rotation rate is chosen to be exactly twice the orbital period, with the phase of the rotation such that when the Tether Central Station is at perigee, or closest to the Earth, the tether is pointing straight up, while, when Tether Central Station is at apogee, or furthest from the Earth, the tether is pointing straight down at the Earth, reaching deep into the atmosphere.

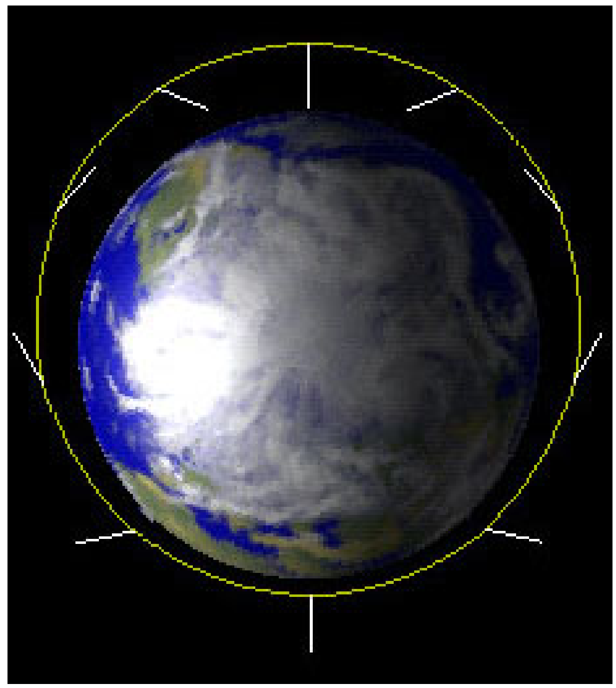


Fig. 1 - CardioRotovator Concept

As can be seen in Figure 1, at intermediate points, the tether is pointing away from the Earth and does not penetrate below the Tether Central Station altitude except near the touchdown point below the apogee point. The trajectory of the tip of the tether is approximately heart-shaped, which lead to the name of "CardioRotovator" for the system concept.. Unlike the circular orbit Rotovator system, the tether length and tip velocity of a CardioRotovator cannot be chosen independently. Once a particular apogee radius R_A is chosen, that determines the length of the tether, since $L=R_A-(6378\text{ km}+100\text{ km})$. Then, once a particular perigee radius R_P is chosen, that, along with the apogee radius, fixes the orbital period P to be:

$$P=\sqrt{\pi}\left\{\frac{(R_A+R_P)^3}{2\mathrm{GM_E}}\right\} \qquad (3)$$

The rotational period p of the spinning tether itself is then also determined, since the design of the CardioRotovator requires that $p=P/2$. This rotational period, together with the tether length L, then determines the tether tip speed as $V_T=2pL/p=\pi L/P$.

In Table 2, we have tabulated some relevant examples of the CardioRotovator system parameters, assuming that in all cases the perigee altitude of the Tether Central Station is 500 km, which is just outside the International Space Station nominal altitude of 400 km. With these assumptions, the CardioRotovator tether tip acceleration levels were found to between 0.43 and 0.66 gees, acceleration levels easily accommodated by human passengers.

From comparing Table 1 for the Rotovator systems and Table 2 for the CardioRotovator systems, it is seen that the CardioRotovator gives somewhat better results than the Rotovator. In general, however, the length of the CardioRotovator tether is much longer than the length of the Rotovator tether, which leads to greater concern about collisions of the tether with other objects in space. This concern is partially compensated by the fact that the CardioRotovator tether spends most of its time at high altitudes where there is less traffic.

Table 2 - CardioRotovator Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Tip Accel.	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	a	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s^2)	(m/s)	Mach	Spectra	2x	10x
1000	7478	7147	2076	0.43	4601	14.8	10.8	3.1	0.39
1200	7678	7004	2440	0.50	4094	13.2	22.2	5.2	0.55
1400	7878	6868	2789	0.56	3608	11.6	44.7	8.4	0.75
1600	8078	6737	3124	0.61	3143	10.1	87.8	13.4	0.97
1800	8278	6611	3445	0.66	2695	8.7	168.5	21.0	1.24

CASTether/LIFTether

The fourth concept for the space tether portion of a HASTOL system uses two separate methods of operating the tether, one method for getting the grapple/payload at the end of the tether down into the atmosphere, and another method for getting the grapple back up into orbit again. There are a number of variants for both the down and up options. We have yet to calculate the tether masses needed for this option.

<u>CASTether:</u> The Cast Ahead Supersonic Tether or CASTether concept was originally invented decades ago by Guiseppe Colombo as a method of using a tether to “cast” a penetrator sampling device onto an airless body like the Moon or Mercury from a spacecraft in low orbit around the planetoid, then pulling the sample up out of the penetrator by the tether as the

spacecraft orbited past overhead. The concept was analyzed by Chauncey Uphoff and Jerome Wright, then of JPL[4].

The CASTether technique can be implemented around Earth in many ways. The technique invented by Colombo involved letting the grapple and payload, on the end of the tether, drift ahead of the spacecraft in their common orbit, then having the spacecraft rapidly "reel in" the tether, decreasing the orbital speed of the grapple/payload, and causing it to fall into an elliptical orbit that intercepted the atmosphere. An alternate technique would be to set the tether in rotation, then, at the proper instant in its rotation, release the brake on the tether winch and let more tether reel out, "casting" the grapple forward and downward in the same manner as casting a fly with a fishing rod.

An even simpler technique, which is illustrated in Fig. 2, is to select a tether length and tip speed of a rotating tether so that, without letting out any tether, the grapple hits the upper atmosphere sufficiently ahead of the Tether Central Station to allow time for drag deceleration of the grapple down to match the speed of the hypersonic airplane before the TCS passes overhead. Since the decrease in velocity does not involve using the strength of the tether, the mass of the tether is not affected by the amount of velocity decrease needed.

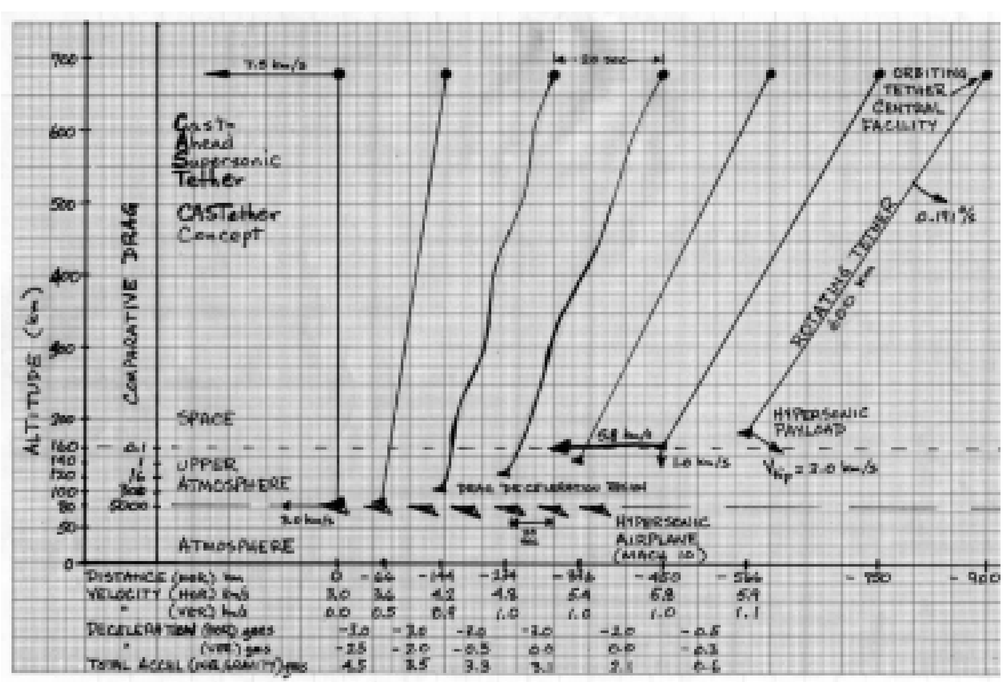


Fig. 2 - Cast Ahead Supersonic Tether (CASTether) Concept

LIFTether: To complement the CASTether concept, we will use the Lift Into Freefall Tether or LIFTether concept for increasing the velocity of the grapple from hypersonic speeds up to orbital speeds. The LIFTether concept was implicit in the original Colombo idea for obtaining surface samples from small airless planetoids. It wasn't until recently that it was recognized how powerful the technique could be for use near a large gravitating body like Earth. If, during the CASTether procedure, the relative positions of the grapple and Tether Central Station are properly timed, the TCS can be made to be directly overhead the hypersonic airplane at the time of the payload transfer to (or from) the grapple, while the distance between the two can be made to be exactly equal to the total unreeled length of tether. As shown in Figure 3, with the TCS directly overhead, the tether will smoothly "lift" and accelerate a payload (or empty grapple) into orbit without requiring any reeling in or out of the tether. Although in Figure 3 the TCS is moving at orbital speeds while the hypersonic airplane is moving some 4500 m/s slower, if a long enough tether (L>600 km) is used, the "lift" of the tether on the payload is found to be relatively benign in terms of maximum acceleration on the payload. The maximum acceleration

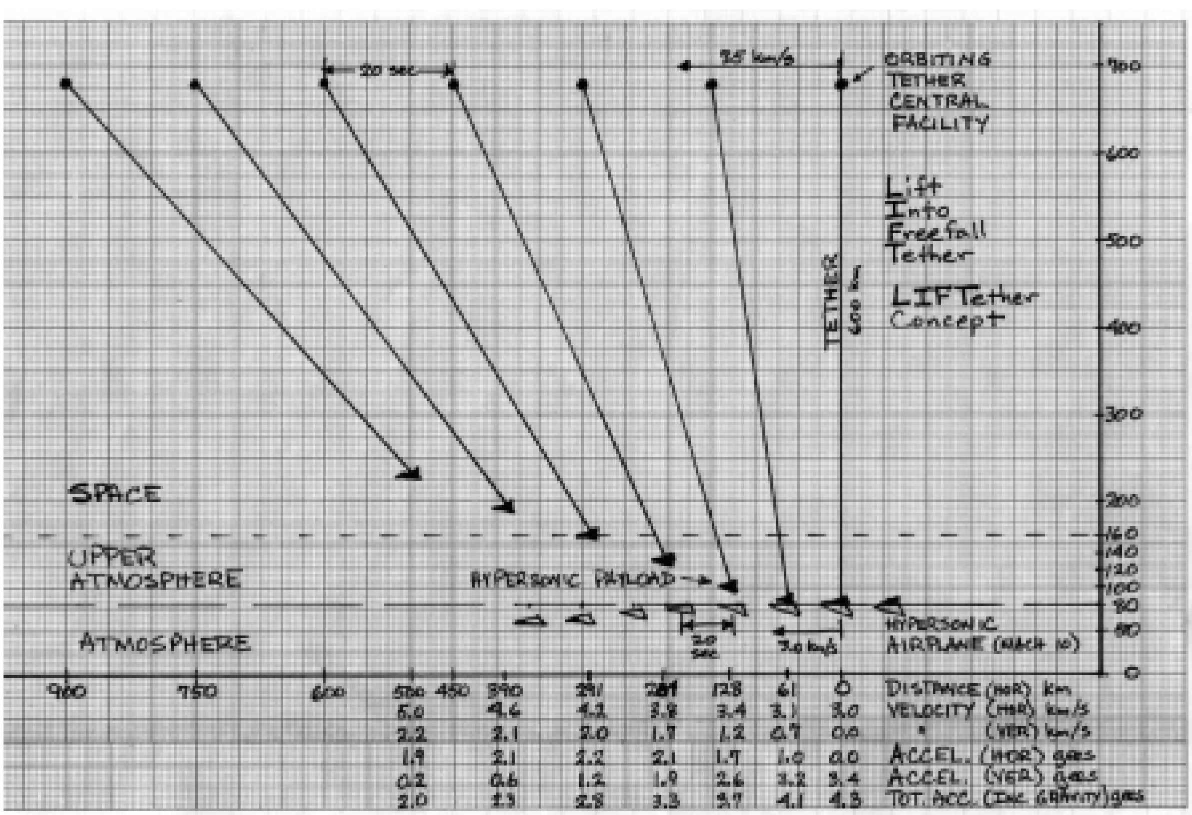


Fig. 3 - Lift Into Freefall Tether (LIFTether) Concept

on the payload occurs at the beginning of the lift, and is equal to $a = \Delta V^2/L$, where ΔV is the velocity difference between the TCS and the hypersonic airplane, and L is the length of the tether. For a tether length of L=600 km, and a velocity difference of ΔV=4500 m/s between the orbiting TCS and the hypersonic airplane, the total acceleration is only 4.3 gees, consisting of the lift acceleration of 3.4 gees, plus 0.85 gees from the Earth gravity as seen in the moving frame of the 3000 m/s hypersonic aircraft flying a curved trajectory. Even this acceleration level would be smoothed out to a lower value by the elastic response of the tether. Moreover, the stress level on a LIFTether is many times less than the stress level on a rotating tether with a tether tip speed equal to the differential speed ΔV at the start of the "lift", since the tether is not rotating at 4500 m/s. It is rotating at half that speed about its own center of mass (not the TCS CM), and the "end mass" at its rotating tip is only the outer portions of the tether material, not the payload.

HARGSTOL

The fifth method of accomplishing the HASTOL concept is to compromise, and allow the partial use of rockets. Thus instead of the HASTOL system, we will have the HARGSTOL or Hypersonic Airplane, Rocket Grapple, Space Tether Orbit Launch system. Instead of requiring the hypersonic airplane and the space tether to close the entire velocity gap between the airplane and the tether tip, we use rockets on the grapple at the end of the tether to contribute to the ΔV requirement. This concept has a number of possible variations. The normal method would be to have the rocket augmented grapple on the tip of the tether. The tether system would slow the tip down as much as possible using one of the tether tip slowing techniques, and the airplane would fly as fast and high as possible, and the rocket system on the grapple would make up any speed difference. The grapple would need to be refueled periodically. This could be done at each payload pickup, or there could be periodic pickups of propellant tanks, with the empty tanks added to the Tether Central Station ballast.

A variation on this concept would be to have the major part of the tether mass be a permanent part of the space tether system, but the "tip" of the tether and the rocket grapple would be carried by the hypersonic airplane. Some time before the rendezvous time, the grapple would be separated from the airplane, pulling out the tether, which would be made of material capable of coping with the hypersonic heating and stress. The rocket grapple would then climb in altitude and speed to meet up with the lower end of the space tether out in space away from the atmosphere, while the airplane stays in the atmosphere at an optimum cruise altitude. The grapple grabs the end of the tether, the payload is pulled free from the airplane, and is pulled into space by the tether.

The ultimate rocket grapple concept would have the rocket take the grapple from the hypersonic airplane all the way to the Central Station, pulling out tether from the payload. Since for normal ΔV requirements the tether mass would be much larger than the payload mass, it is obvious that a better technique would be to meet the downgoing tether from the Tether Central Station "halfway". Finding the optimum ratio for the length of the airplane tether versus the space tether would be part of the overall system optimization. This concept, with the rocket grapple coming from the airplane without carrying the payload, would only be usable for taking payloads into orbit. For two-way systems, it would be necessary to have the rocket grapple on the end of the space tether, and have the rockets on the grapple capable of accelerating both the grapple and the payload.

The most important feature of all the possible HARGSTOL systems is that we KNOW we can make them work, no matter how poor the ultimate performance of the hypersonic airplane and the space tether. All it requires is that the rocket grapple be loaded with enough propellant to close the velocity gap. Since the mass ratio of the propellant to grapple-plus-payload is exponential in the grapple ΔV, and the rocket ΔV is low because of the ΔV contributions of both the airplane and tether, the propellant required should be low.

SPACE TETHER ISSUES

The space tether portion of the HASTOL system has a number of issues that must be dealt with other than the method of operation, including surviving damage by meteorites and space debris, operating at hypersonic speeds in the upper atmosphere, avoiding collisions with other spacecraft, and safe and reliable operation at low system mass.

Tether Survivability

For a tether transport system to be economically advantageous, it must be capable of handling frequent traffic for many years despite degradation due to impacts by meteorites and space debris. Yet, the tether mass must be minimized to reduce the cost of fabricating and launching the tethers. These two requirements present conflicting demands upon the tether design that make conventional single-line tethers impractical for the HASTOL application. For a single-line tether to achieve a high probability of survival for many years, it must be very thick and massive. Fortunately, a low mass survivable tether design exists, called the Hoytether™, which can balance the requirements of low weight and long life[5]. As shown in Fig. 4, the Hoytether is an open net structure where the primary load bearing lines are interlinked by redundant secondary lines. The secondary lines are designed to be initially slack, so that the structure will not collapse under load. If a primary line breaks, however, the secondary lines become engaged and take up the load. Note in Fig. 4, that four secondary line segments replace each cut primary line segment, so that their cross-sectional area need only be 0.25 of the primary line area to carry the same load. Typically, however, the secondary lines are chosen to have a cross-sectional area of 0.4 to 0.5 of the primary line area, so as to better cope with multiple primary and secondary line cuts in the

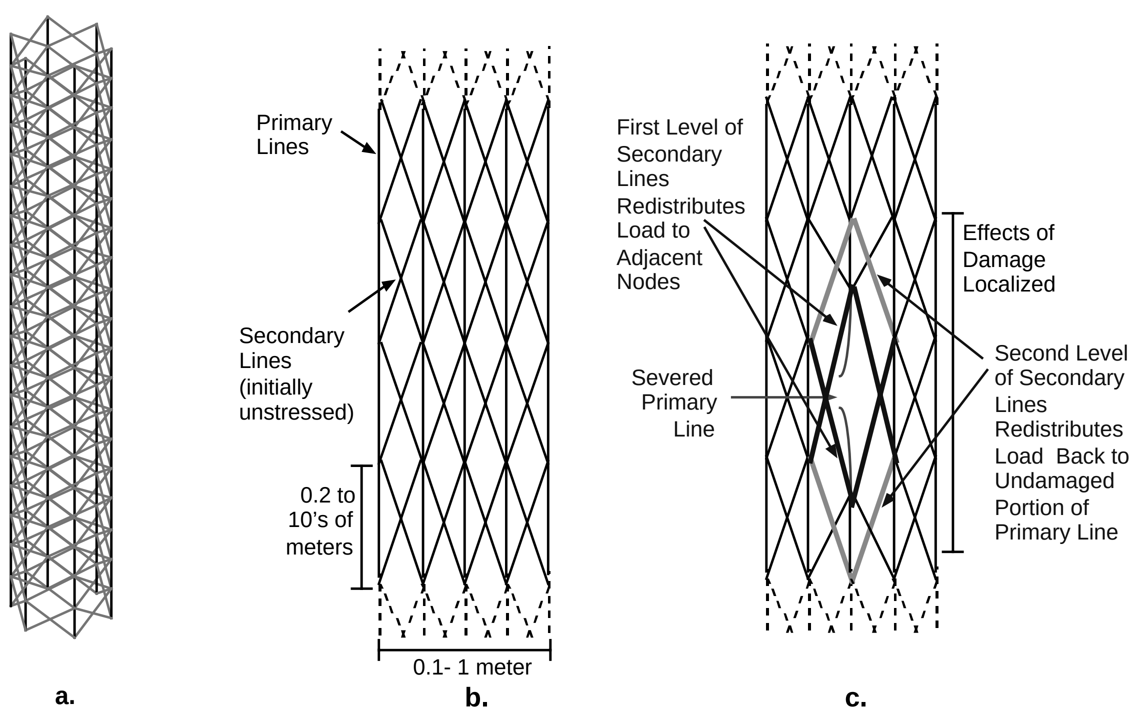


Fig. 4 - The Hoytether™ design and its response to a cut line

same region of the tether. This redundant linkage enables the Hoytether™ structure to redistribute loads around primary segments that fail due to meteorite strikes or material failure. Consequently, the Hoytether structure can be loaded at high stress levels, yet achieve a high margin of safety.

Tether System Collision Avoidance

There are many objects in space, ranging from micrometeorites to operational spacecraft with 10-meter-long solar array panels. We can design interconnected multiple strand open net Hoytether™ structures that can reliably (>99.9%) survive in space for decades despite impacts by objects up to 30 cm (1 foot) or so in size. Objects larger than one meter will impact all the strands at one time, cutting the tether. These large objects could include operational spacecraft, and they will also be damaged by the impact. Objects larger than 30 cm are all known and tracked by the U.S. Space Command. There are about 6000 such objects in low and medium Earth orbit, of which an estimated 600 will be operational spacecraft in the 2005 time frame. For an atmospheric tether application, we have estimated that, if no traffic control measures are instituted, a 20 km long tether in an orbit grazing the upper atmosphere has a 4% chance of being cut by one of the 6000 large objects during a one year mission, and an 0.4% chance of striking one of the 600 operational spacecraft. Longer tethers will have proportionately larger probabilities. It will therefore be incumbent on the HASTOL system operators to maintain contact with the U.S. Space Command and keep an accurate inventory of the known large objects. They then need to control the tether system CM orbital altitude and phase, the tether rotation rate and phase, and the tether libration and vibration amplitudes and phases, to insure that the tether system components do not penetrate a volume of “protected space” around these orbiting objects.

Tether Safety Factor and System Reliability

When a tension member such as a tether is developed, it is normally designed to operate at a load level somewhat lower than the maximum it could support without breaking. This derating provides margin of error in case of imperfections in the material or the construction. Typically, a single line tether is designed to carry a maximum load that is 50% of its breaking limit. This tether would thus have a "design safety factor" of F=1/0.50=2.0. For the Hoytether, we define the safety factor as the ratio of the maximum load capacity *of both primary and secondary lines* to the design strees load S_P of the *primary lines alone*.

$$F=[1+(N_S A_S)/(N_P A_P)]/S_P \qquad (4)$$

where N_P and N_S are the number of primary lines and secondary lines, and A_P and A_S are their respective cross-sectional areas. For a typical tubular Hoytether™ there are twice as many secondary lines as primary lines so $N_S=2N_P$ and Eq. (4) reduces to $F=[1+2A_S/A_P]/S_P$. For the case where the secondary line area is half the primary line area or As=0.5Ap and the stress on the primary lines is 67% of the ultimate tensile strength of the material or $S_P=0.67$, then the Hoytether™ safety factor would be: $F=[1+2(0.5)]/0.67=3$. This definition of the Hoytether™ safety factor provides the same measure of the strength-to-weight ratio of the Hoytether structure as it does for a single-line tether. However, this definition of the safety factor does not accurately represent the margin of safety for the Hoytether. Because the Hoytether has redundant links that can reroute stress around parts of the tether that have failed, it is possible to load the Hoytether at a large fraction of the capacity of the primary lines (i.e.- small "line safety factor") and still have a large margin of safety against parting. To study the optimization of the Hoytether structure for high-load applications, we performed a series of simulations of variations of the structure using our "SpaceNet" tether simulation program. The SpaceNet program uses a combination of finite-element methods with a structural relaxation scheme to calculate the effects of damage to complex 3-D net structures such as the Hoytether. The results of our analyses indicate that the design of an optimal Hoytether depends upon how much of its mission duration will be spent under high load. Consequently, there are two classes of Hoytether™ designs, one for tethers that are always under high load, and one for tethers that are heavily loaded for brief periods only.

<u>Continuous High Load Tether:</u> If the tether will be under high load for most of its mission, then it should be designed with secondary lines slack at the expected load level. This will enable the tether lines to remain spread apart at all times, minimizing the chances of a single impactor cutting several lines. For this case, SpaceNet simulations showed that a near-optimal tether design would be a cylindrical Hoytether with a large number of primary lines (~20) stressed at 75% of their maximum load and with initially-slack secondary lines that each have a cross-sectional area 0.4 times that of a primary line. Simulations showed that splitting the tether up into a large number of primary lines prevented the stress energy released by a cut of one of the

primary lines from overloading neighboring primary lines before the secondary lines could become taut enough to take up the released stress and pass it around the cut primary line segment to the uncut primary line segments above and below the cut segment. From Eq. (4), such a tether will have a design safety factor of 2.4. However, the redundant nature of the structure will make the Hoytether far more reliable than a single line tether with the same safety factor. Simulations with the SpaceNet program have shown that this tether design can withstand multiple cuts on a single level. In fact, even if all of the primary lines on one level are cut (one at a time), the secondary lines will support the load.

Intermittent High Load Tether: The HASTOL Space Tether facility, however, would likely be loaded at high levels for only a few hours at a time. Therefore, it is possible to reduce the tether weight by designing it to have slack secondary lines at the load level experienced during its long “off-duty” periods, but to have the secondary lines bear a significant portion of the load during a brief high-stress operation such as a payload catch-and-throw operation. During the high-stress period, the loading of the secondary lines will cause the structure to collapse to a cylindrical tube. Once a payload is released and the stress is reduced, however, the tether lines will spread back apart. If this high-load period is brief, it will only slightly increase the chances of tether failure due to impact by a large object. Simulations indicate that a 20-primary line Hoytether with the secondary line areas 1/4 of the primary lines can be safely loaded to 85% of the primary line capacity during peak stress operations. The design safety factor of this tether from Eq. (4) is F=1.75. In this paper we will use a slightly more conservative safety factor of F=2.

Space Tether Materials

The space tether used in the HASTOL system will consist of a long strength member made of a high strength, low density polymer, with a “hypersonic” tip made of a high strength at high temperature, atomic-oxygen resistant material. Woven into the initial 10 km of the polymer tether will be an aluminum wire conductor to be used by the Hoyt Electrodynamic Force Tether (HEFT) propulsion system[3] built into the tether and used by the TCS to control the tether sustem orbit and rotation parameters.

High Strength Main Member The two candidate polymers for the high tensile strength main portion of the tether, Spectra™ and Zylon™, are both stronger per pound than either steel or Kevlar™ polymer fiber. Their "characteristic velocity", defined as the maximum tip speed of an untapered tether, is: $V_C=(2U/d)$^1/2, where U is the ultimate tensile strength of the material and d is its density. Spectra 2000™ has a U=4.0 GPa, d=970kg/m^3 and V_C=2872 m/s, while Zylon™ has a U=5.8 GPa, d=1560 kg/m^3 and V_C=2727 m/s. Both of these materials are commercially available in tonnage quantities with reasonable prices and delivery times. These polymer materials are sensitive to attack by atomic oxygen (AO), however, so the portions that get near the atmosphere would probably be coated with a proprietary AO-resistant resin coating available from Aeroplas.

Hypersonic Tip: The material for the hypersonic tip will not only have to withstand attack by atomic oxygen, but maintain a moderately high strength at high temperatures. We have estimated that the tether temperature due to air drag heating will range from room temperature (300K or 27C) for a tether speed through the air of 3 km/s at 120 km altitude, up to as high as 2100K (1830C) for a relative speed of 5 km/s at 80 km altitude. The candidate materials and their ultimate tensile strength GPa (gigapascals) as a function of temperature are summarized in the Table 3. (For reference, 1 GPa = 10^9 N/m^2 = 145,000 psi). To allow a relative comparison of the suitability of the various different tether materials for use in various rotating tether systems, we also included in Table 3 the density d and the room temperature "characteristic velocity" $V_C=(2U/d)^{1/2}$ of the material, which is the maximum attainable tip speed of an untapered rotating tether made solely of that material. For reference, the melting points of some of the materials in Table 3 are: Al–660C, Ti–1660C, Ni–1453C, W–3410C, Al_2O_3–2015C, SiC–2700C, and SiO_2–1610C.

Table 3 - Tether Material Tensile Strength (GPa) vs. Temperature

Material	V_C (km/s)	Density d (g/cc)	20 C	300 C	600 C	800 C	1000 C	1200 C
Spectra 2000	2.87	0.97	4.0	-	-	-	-	-
Quartz Glass (SiO_2)	1.81	2.20	3.6	3.6	3.6	3.6	3.6	?
S-glass	1.94	2.50	4.7	?	?	?	?	?
Carbon	2.77	1.80	6.9	?	?	?	?	?
Carbon/Ni-coated	2.12	2.68	6.0	?	?	?	?	?
Tyranno (SiTiCO)	1.66	2.55	3.5	3.5	3.5	3.5	3.5	3.5
Textron β-SiC	2.19	2.93	7.0	6.6	6.0	5.6	5.2	4.5
0.72 β-SiC/Ti-coated	1.72	3.37	5.0	4.8	4.3	4.0	3.7	3.2
Altex (Al_2O_3/SiO_2)	1.21	3.30	2.4	2.4	2.4	2.4	2.4	1.5
Nextel (α-Al_2O_3)	1.30	3.88	3.3	?	?	?	?	?
0.65 Nextel/Al-coated	0.97	3.40	1.6	1.4	?	?	?	?
Tungsten Wire	0.55	19.35	2.9	2.9	2.9	2.9	2.9	2.9

HYPERSONIC AIRPLANE ISSUES

The technology for the hypersonic airplane itself is being developed by Boeing and others elsewhere and is not part of the HASTOL effort. However, vehicle performance, flight trajectory requirements, and operational aspects peculiar to tether rendezvous and payload transfer in support of development and optimization of the HASTOL system are, and form a major portion of the hypersonic airplane portion of the HASTOL team effort. The hypersonic vehicle portion of the HASTOL effort will start with an existing design for a multi-role, hypersonic aircraft developed by Boeing for NASA LaRC, which can perform both cruise and space launch missions (See Fig. 5). The vehicle is designed to operate from existing runways and incorporates a low-speed propulsion system based on JP fueled, Air-core-enhanced Turbo Ramjets (AceTRs) for operations up to Mach 4.5. Above Mach 4.5 a slush-hydrogen-fueled ram/scram system powers the vehicle. While the design is optimized for long range cruise at Mach 10, the vehicle can also perform “pop-up”-type launches of satellites, and incorporates a ten-foot diameter, thirty-foot long payload bay for that purpose.

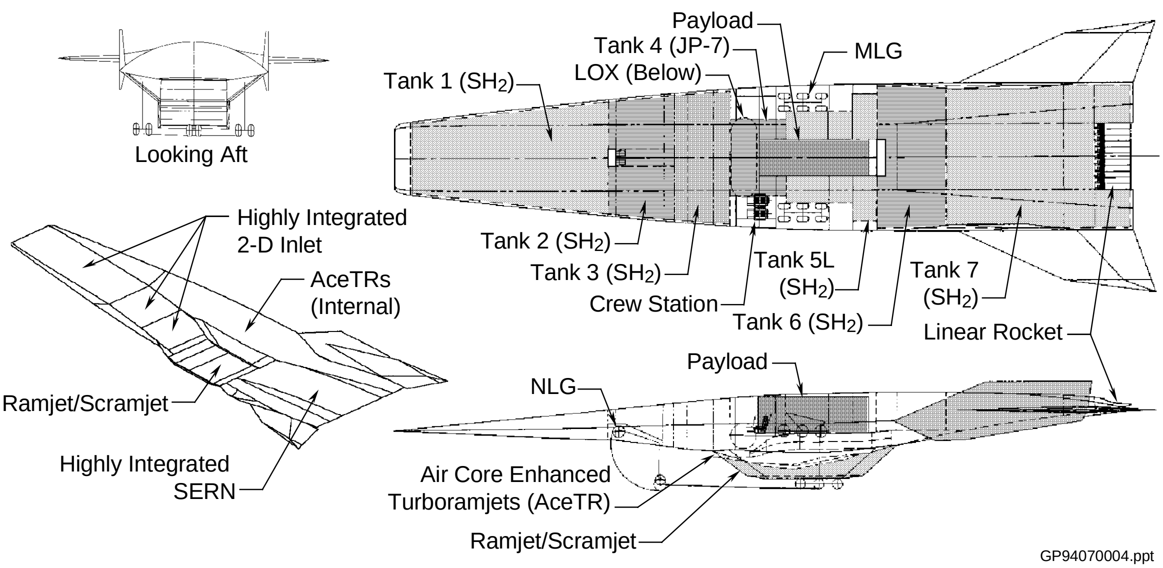


Fig. 5 - Mach 10 Dual-Fuel Airbreathing Aerospaceplane

An initial assessment of the HASTOL concept for this vehicle indicates that at the probable 80 km rendezvous altitude, the dynamic pressure and therefore the combustor pressure will be too low for continuous cruise operation using current air-breathing hypersonic engine concepts. However, the 80 km rendezvous altitude is readily attainable using a “pop-up” maneuver as shown in Fig. 6. This maneuver allows the safe staging of minimally streamlined, satellite/upper stage combinations at conditions where the velocity provided by the hypersonic aircraft could be maximized and the performance of the upper stage optimized. The current design shown in Fig. 5 is capable of carrying a 13,600 kg (30,000 lb.) combination upper stage and payload to speeds of approximately 3,400 m/sec (11,120 ft/s or Mach 11) at altitudes as high as 85 km (280,000 ft).

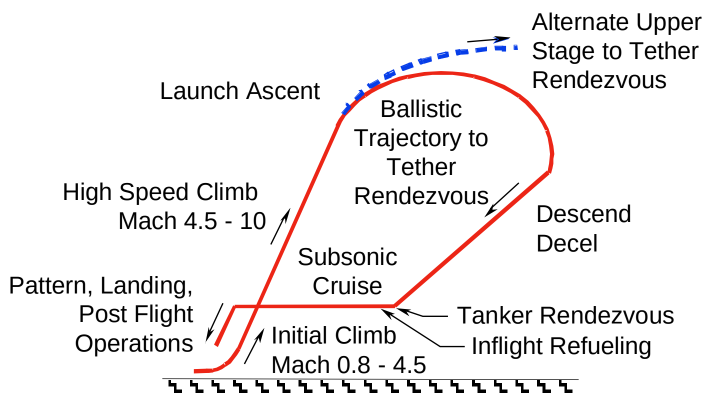


Fig. 6 - Vehicle Pop-Up To Tether Rendezvous

During the future efforts of this continuing study, the existing hypersonic airplane design will be modified, as required, to perform HASTOL type missions and the modifications incorporated into its performance simulation model. The results of the hypersonic vehicle trade study will be incorporated in the overall HASTOL system assessment. Two principal variant types will be assessed. In the first, the aircraft will rendezvous with the grapple. This variant will be modified, as required, for each applicable HASTOL concept and its rendezvous geometry. In order to operate in these HASTOL modes it will be necessary to resize the existing auxiliary rocket engines and their propellant volumes for increased altitude and velocity. An enhanced reaction control system with six-axis capability (including limited trajectory control) will also be required in lieu of the current 3-axis (attitude only) system.

The second variant, the HARGSTOL concept, will have the hypersonic airplane carry the payload to an intermediate condition. From there a small rocket upper stage will carry the payload to the rendezvous with the grapple. This approach will require fewer system modifications, but will have less payload capability at a particular size due to the mass required by the rocket upper stage. Both variants will then be used to evaluate the concept through several trade studies and optimized with the tether and grapple studies.

GRAPPLE AND PAYLOAD TRANSFER ISSUES

The rendezvous and capture/transfer of the payload from the hypersonic vehicle to the tethered grapple assembly will occur at around 80 km altitude, or near the perigee of the tether trajectory. While the atmosphere is not very dense at that altitude, there will be significant dynamic pressure due to the high velocities involved. The high dynamic pressure will allow the use of aerodynamic control surfaces, which will minimize or eliminate refueling requirements for the grapple vehicle. The current concept is to fly the decelerating grapple vehicle in so that it approaches the hypersonic airplane from behind. A mechanism would be deployed from the grapple vehicle that would attach to the payload and pull the payload up to the grapple. The hypersonic vehicle would then return to ground and the grapple vehicle, with payload, would continue its orbit to the correct location at which to release the payload at the correct velocity to achieve the intended higher orbit. After the grapple vehicle exits the atmosphere, the time spent in space will be used to cool and condition the grapple vehicle for the next aeropass. For periods when the grapple will not be used to capture/deploy a payload, the tether will be shortened to raise the lower altitude of the grapple and keep the grapple vehicle above most of the atmosphere.

The grapple vehicle requires several internal functions to be successful for this kind of mission, which make it similar to grapple assembly concepts developed earlier for exo-atmospheric transfer of payloads[6]. The grapple is attached to the end of a tether but some control, independent of the tether, will still be required. A means for controlling motion in and out of plane is necessary, as well as a mechanism to eliminate or control aerodynamic forces on the grapple assembly during aeropass phases. Previous space grapple vehicles used storable propellants and thrusters to maintain this control, but the high dynamic pressure should allow a pure aerodynamic control concept that would eliminate propellant requirements. This eliminates the refueling requirements and allows additional payload transfers for a selected configuration.

The hypersonic grapple would not use externally mounted solar panel arrays during the aeropass due to the high aerodynamic forces and heating rates during this phase. Two initial options have been identified: a deployable/storable photovoltaic array or an electrically conductive tether. Each would generate the required power, the latter while moving through the earth's magnetic field, and would store excess energy in batteries for use during the aeropass phase.

In order to allow a reliable rendezvous, the grapple vehicle must maintain location and attitude information and communicate with the hypersonic airplane. This can be done accurately with a differential GPS similar to those systems being developed for landing commercial aircraft. The approach velocities are too high to rely on human pilots on the ground so the system will require autonomous rendezvous and capture (AR&C) capabilities. AR&C technologies, such as advanced sensors for the final approach and rendezvous, are continuing to evolve, and are maturing based on Russian and NASA investments.

CONCLUSIONS

We have described a number of alternate system configurations that will allow hypersonic air-breathing airplane technologies to be combined with orbiting space tether technologies to produce a method of moving payloads from the surface of the Earth into Earth orbit *without* the use of rockets, and without subjecting the payloads and passengers to high accelerations or high risk. The resultant Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is completely reusable and has the potential to drastically cut the cost of Earth-to-orbit space access.

ACKNOWLEDGEMENTS

This work was supported by a contract with the NASA Institute for Advanced Concepts (NIAC), Dr. Robert Cassanova, Director. The authors also acknowledge technical contributions from their fellow co-workers, Dr. Robert P. Hoyt of Tethers Unlimited, Inc., Donald B. Johnson of Boeing/MDC Phantom Works, and student Daniel Stuart Bowman of the University of Maryland.

REFERENCES

1. Robert Zubrin, “The Hypersonic Skyhook,” Journal of the British Interplanetary Society, Vol. 48, No. 3, pp. 123-128, March 1995.
2. Hans Moravec, “A Non-Synchronous Orbital Skyhook,” Journal of the Astronautical Sciences, Vol. 25, No. 4, pp. 307-322, 1977.
3. Robert P. Hoyt and Chauncey Uphoff, “Cislunar Tether Transport System,” Paper AIAA-99-2690, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, 20-24 June 1999.

4. Chauncey W. Uphoff, pages 69 and 72-75 in JPL Publication 80-26, *Discussion Meeting on Gossamer Spacecraft (Ultralight Spacecraft): Final Report*, edited by Roy G. Brereton (Jet Propulsion Laboratory, Pasadena, CA, 15 May 1980).

5. Robert P. Hoyt and Robert L. Forward, “Failsafe Multiline Hoytether Lifetimes,” Paper AIAA-95-2890, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA, 10-12 July 1995.

6. M. E. Bangham, E. Lorenzini, and L. Vestal, “Tether Transportation System Study,” NASA/TP-1998-206959, NASA Marshall Space Flight Center, Huntsville, AL, March 1998.

APPENDIX 2
HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) SYSTEM:
INTERIM STUDY RESULTS

AIAA PAPER NO. 99-4802

AIAA-99-4802

HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) SYSTEM: INTERIM STUDY RESULTS

Dr. Thomas J. Bogar [Presenter], Senior Principal Engineer, Hypersonic Design and Applications, Boeing/MDC Phantom Works, P.O. Box 516, St. Louis, MO 63166 USA

Michal E. Bangham, Senior Manager Advanced Engineering, Advanced Programs, Boeing/MDC, P.O. Box 240002, Huntsville, AL 35824 USA

Dr. Robert L. Forward, Vice President & Chief Scientist
Tethers Unlimited, Inc. 8114 Pebble Court, Clinton, WA 98236 USA

Dr. Mark J. Lewis, Associate Professor and Director of Center for Hypersonic Education and Research, Aerospace Engineering Dept., University of Maryland, College Park, MD 20742 USA

ABSTRACT

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is a novel architecture for an Earth-to-orbit launch system consisting of: a completely reusable airbreathing subsonic-to-hypersonic dual-fuel airplane which transports the payload from the ground to some intermediate point in the upper atmosphere; an orbiting spinning space tether system which picks up the payload from the intermediate point and takes it on into orbit; and a grapple assembly for transferring the payload from the hypersonic airplane to the lower end of the space tether. The system is revolutionary in that it minimizes, and perhaps even eliminates, the use of rockets for Earth-to-orbit launch of satellite payloads and even passengers. For the hypersonic airplane portion of the HASTOL system we use an existing Boeing design for the DF-9, a dual-fuel airbreathing launcher that has benefited from over a million dollars in NASA/LaRC and Boeing funding during prior study efforts. The DF-9 has a 9 m (30 ft) long by 3 m (10 ft) diameter upward-opening central payload bay that can handle payloads up to 14 Mg (14 metric tons or 30,000 lb). With a full fuel load at takeoff, the hypersonic airplane masses approximately 20 times the payload mass, and can deliver the payload to 100 km (330 kft) altitude at an apogee speed of 3.6 km/s (12 kft/s) or approximately Mach 12. For the space tether portion of the

HASTOL system, there are a number of design options, all of which will work, although some options promise better performance. The tethers can be built today using presently available commercial fibers. The tethers are long, typically 400 to 1600 km (1300 to 5300 kft) in length. The total mass of the space tether plus the Tether Central Station typically will be 30-200 times the payloads being handled. Most of that mass ratio requirement is driven by the fact that the tether system must mass considerably more than the payload it is handling, so that, upon pickup of the payload by the tether, the payload will not pull the space tether system down into the atmosphere. Thus, the advent in the future of better tether materials with higher strength at higher temperatures will not be used to lower the tether system mass significantly, but instead will be used to increase the tether safety margins, lifetime, and system performance, by allowing payload pickup at lower altitudes and lower speeds, thus decreasing the performance requirements on the hypersonic airplane portion of the system.

INTRODUCTION

The Boeing Company, Tethers Unlimited, Inc. (TUI), and the University of Maryland, have teamed to study the feasibility of a completely new concept for moving payloads and passengers from the surface of the Earth into low Earth orbit at low cost and low acceleration levels without the use of rockets as the main source of propulsion. Our joint study effort, funded by a $75,000 Phase I grant from the NASA Institute for Advanced Concepts, is halfway through its 6-month term. This paper builds upon work reported in a previous paper[1], and should be considered an interim report of the study results to date, rather than a finished piece of work.

HASTOL Architecture

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system contains three major components: a hypersonic airplane, which will transport the payload as high and as fast as possible using air-breathing propulsion; an orbiting spinning space tether, the lower tip of which will be lowered down and slowed down by one means or another, so as to meet up with the hypersonic airplane; and a grapple assembly at the tip of the space tether that will take control of

---

the payload, and with the lift supplied by the space tether, carry the payload on into orbit. There, after the space tether has used propellantless propulsion to change its orbit and rotation, the payload will be tossed into its desired final trajectory. It would be desirable that the HASTOL system function in both directions, allowing for return of payloads from orbit to the Earth's surface. This is not a firm requirement, however, for a launch-only HASTOL system would be useful in itself, since returning from orbit is much easier than launching into orbit. The objective of our ongoing study is to optimize the combined system of airplane, tether, and grapple in order to maximize the overall system performance in terms of payload mass and delivery rate, while minimizing the life cycle cost.

Background

Let us first give some scale to the problem of launching a payload into space. In order to fly an airbreathing vehicle directly into orbit requires an airplane capable of reaching horizontal speeds of 7.8 km/s (26 kft/s or approximately Mach 25) at 150 km (490 kft) altitude or an orbital radius of 6530 km (21,400 kft). Designs exist for hypersonic airplanes capable of level flight at 3.1 km/s (10 kft/s or approximately Mach 10), and concepts exist for faster planes of Mach 12.5 and higher, but the difficulty of making and operating the hypersonic airplane rises rapidly with increasing Mach number.

There is another scale to the problem of putting things into orbit. Since space starts at about 100 km up, most people think that to get into space only involves 100 to 200 km worth of travel. What they fail to realize is that every rocket launched into orbit to date has had to travel thousands of kilometers down range to attain the necessary 7.8 km/s orbital speed. Since the distance D that must be traveled at constant acceleration a to reach a final velocity V is $D=V^2/2a$, to reach an orbital velocity of 7.8 km/s at an acceleration of one gee (a=9.8 m/s), requires covering a distance of 3100 km. Similar scaling laws apply to space tethers. If a spinning space tether is to produce a change in velocity of a third of orbital speed, or 2.6 km/s, then the tether length L for a one gee acceleration at the tether tip needs to be of order $L=V^2/a$=690 km. As will be illustrated in the following section on HASTOL Space Tether Concepts, there are many designs for space tether systems which can lower a payload grapple assembly into the upper atmosphere at grapple speeds with respect to the Earth's atmosphere ranging from 4.65 km/s (15 kft/s or Mach 15) to 3.1 km/s (10 kft/s or Mach 10) and lower, but the difficulty of operating the space tether rises rapidly with decreasing grapple speed. We are quite sure that the bridge between air and space can be crossed by using the right combination of hypersonic airplane and orbiting space tether. Finding that optimum combination is the objective of our study.

HYPERSONIC AIRPLANE

The technology for the hypersonic airplane portion of the HASTOL system is being developed by Boeing and others elsewhere and is not part of the HASTOL effort. However, vehicle performance, flight trajectory requirements, and operational aspects peculiar to tether rendezvous and payload transfer in support of development and optimization of the HASTOL system are, and form a major portion of the hypersonic airplane portion of the HASTOL team effort. The hypersonic vehicle portion of the HASTOL effort will start with an existing design[2] for the DF-9 (See Fig. 1), a multi-role, hypersonic aircraft developed by Boeing for NASA LaRC. The DF-9 can perform both cruise and space launch missions. The vehicle is designed to operate from existing runways and incorporates a low-speed propulsion system based on JP fueled, Air-core-enhanced Turbo Ramjets (AceTRs) for operations up to Mach 4.5. Above Mach 4.5 a slush-hydrogen-fueled ram/scram system powers the vehicle. While the design is optimized for long range cruise at Mach 10, the vehicle can also perform "pop-up"-type launches of satellites, and incorporates a 3 m (10-ft) diameter, 9 m (30 ft) long payload bay for that purpose.

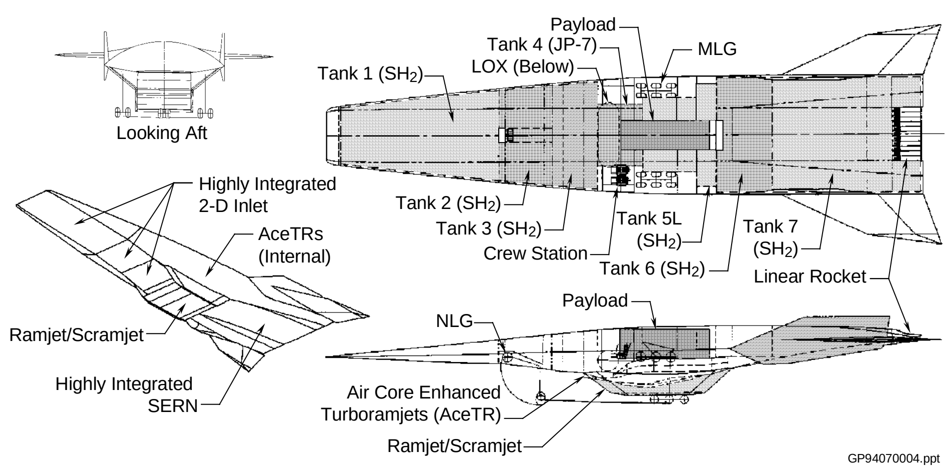


Fig. 1 - DF-9 Dual-Fuel Aerospaceplane

The vehicle design does incorporate a linear rocket to provide thrust at altitudes where the airbreathing systems are ineffective. One important objective of the study will be to identify HASTOL scenarios where the rocket is not needed.

Our initial assessment of the application of this particular vehicle design for accomplishing the HASTOL concept indicates that at the probable 80 to 100 km rendezvous altitude, the dynamic pressure and therefore the combustor pressure will be too low for continuous cruise operation using current air-breathing hypersonic engine concepts. However, a 100 km (330 kft) rendezvous altitude was found to be readily attainable using a “pop-up” maneuver as shown in Fig. 2. This maneuver would allow the safe staging of minimally streamlined payloads, or payload/upper-stage combinations, at conditions where the velocity provided by the hypersonic aircraft could be maximized and the performance of the upper stage optimized. The current design shown in Fig. 1 is capable of carrying a 30,000 lb. (14 Mg or 14 metric ton) combination upper stage and payload to speeds of approximately 3.6 km/s (12 ft/s or Mach 12) at altitudes as high as 100 km (330 kft).

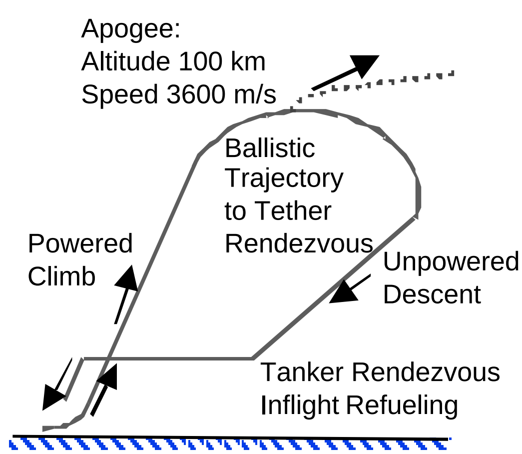


Fig. 2 - Vehicle Pop-Up To Tether Rendezvous

During the future efforts of this continuing study, the existing hypersonic airplane design will be modified, as required, to perform HASTOL type missions and the modifications incorporated into its performance simulation model. The results of the hypersonic vehicle trade study will be incorporated in the overall HASTOL system assessment. Two principal variant types will be assessed. In the first, the aircraft will rendezvous with the grapple assembly. This variant will be modified, as required, for each applicable HASTOL concept and its rendezvous geometry. In order to operate in these HASTOL modes it will be necessary to resize the existing auxiliary rocket engines and their propellant volumes for increased altitude and velocity. An enhanced reaction control system with 6-axis capability (including limited trajectory control) will also be required in lieu of the current 3-axis (attitude only) system.

A different variant that will also be studied, will have the hypersonic airplane carry the payload to an intermediate condition. From there a small rocket upper stage will carry the payload to the rendezvous with the grapple. This approach will require fewer system modifications, but will have less payload capability at a particular size due to the mass required by the rocket upper stage. Both variants will then be used to evaluate the concept through several trade studies and optimized with the tether and grapple studies.

HASTOL SPACE TETHER CONCEPTS

There are many ways of designing the orbiting spinning space tether component of the HASTOL system. The six different space tether system concepts initially studied were the: HyperSkyhook, Rotovator, CardioRotovator, CASTether/LIFTether, Tillotson Two-Tier Tether, and HARGSTOL. In our initial analyses of each concept, we assumed that the tether system would have a Tether Central Station (TCS) that was many times more massive that the tether or the payloads being handled. This was assumed so that the center-of-mass (CM) of the tether system was at the TCS. In reality, the TCS will have a finite mass, and the CM of the tether system will not be exactly at the TCS. These corrections will be taken into account in later, more detailed, tether system design studies.

Although the tether mass will usually be less than the TCS mass, we do not want to ignore the tether mass entirely. So, for each of the following concepts we have estimated the mass of the tether alone, using the data we have for the tensile strength and density of high strength materials that are presently available in commercial quantities. If the mass of the tether starts to exceed 200 times the mass of the payload, then that is an indication the particular scenario being considered is not engineeringly feasible using presently available materials, although the application might become feasible in the near future as better materials become available with higher tensile strengths at higher operational temperatures.

As we shall see later, presently available commercial materials will suffice to make the HASTOL concept work. Just a modest improvement by a factor of two over present-day materials in the ratio of the tensile strength to the density will lower the ratio of the tether mass to the payload mass to the point to where they are no longer a significant factor in the commercial feasibility of the concept. The primary message we want to leave with the Reader is: “We don't need *magic* materials like ‘Buckminster-Fuller-carbon-nanotubes’ to make the space tether for a HASTOL system. Present-day materials will do.”

HyperSkyhook

In 1995 Zubrin proposed[3] the “Hypersonic Skyhook” as a solution to the mismatch between the attainable atmospheric speeds of a hypersonic airplane and the orbital speeds of space tethers. Since the orbital speed of the space tether decreases with increasing altitude of the tether system center-of-mass, he proposed the use of very long non-spinning tethers or “skyhooks” reaching down from very high altitudes. His analysis showed that because a hanging tether must be tapered to support its lower end in the gravitational field of the Earth, achieving a HyperSkyhook tether tip rendezvous with a 5.0 km/s (16 kft/s or Mach 16) airplane would require a HyperSkyhook tether mass of 25 times the payload mass. Trying to lower the tether tip speed to 4.0 km/s (13 kft/s or Mach 13) would require a HyperSkyhook tether mass greater than 200 times the payload mass. Unless a major breakthrough occurs in high strength tether materials, such as the commercial development of carbon nanotube fibers, it does not seem possible to push the non-spinning tether HyperSkyhook concept down to speeds of 3.1 km/s (10 kft/s or Mach 10).

Rotovator™

The standard method of attaining a low tether tip velocity is to use a rapidly spinning tether, or Rotovator™. The Rotovator concept was invented in 1967 by Artsutanov and reinvented by Moravec in 1977, who did the first thorough analysis[4] of it. Since the Rotovator must reach down from orbital altitudes into the upper atmosphere to match speeds with the hypersonic airplane, the length of the tether and the orbital altitude are necessarily interrelated, with the orbital altitude of the tether center-of-mass (CM) being the length of the tether plus a nominal 100 km for the thickness of the atmosphere. The longer the tether, the higher the orbital altitude and the slower the velocity of the tether system CM.

Rotovator™ Tether Mass: The mass of a rapidly spinning tether in free space is determined primarily by the tip speed of the tether, not the tether length or the tether tip acceleration. The basic equation for the ratio of the mass M_T of one arm of a spinning tether to the mass M_P of the payload plus grapple on the end of the tether arm, was derived by Moravec in 1978 in an unpublished paper, based on a previously published paper[4], and is:

$$\frac{M_T}{M_P} = \sqrt{\pi}\left(\frac{V_T}{V_C}\right)\ \exp\left[\left(\frac{V_T}{V_C}\right)^2\right]\text{erf}\left(\frac{V_T}{V_C}\right) \qquad (1)$$

Where the error function

$$\text{erf}(z) = \frac{2}{\sqrt{\pi}}\left[z - \frac{z^3}{1!\times 3} + \frac{z^5}{2!\times 5} - \ldots\right] \qquad (2)$$

varies from erf(0)=0 to erf(>3)=1.0, while erf(1)=0.843, V_T is the tether tip speed, and $V_C=(2U/Fd)^{1/2}$ is the maximum tip speed of an untapered tether, where U is the ultimate tensile strength of the tether material, d is its density, and $F>1$ is an engineering safety factor derating the “ultimate” tensile strength to a safer “practical” tensile strength. Equation (1) shows specifically that the mass ratio of a spinning tether is a function of the ratio of the tether tip speed to the characteristic velocity (V_T/V_C) only, and to first order does not depend on the tether tip acceleration or the length of the tether. The exponential growth in the mass ratio with the *square* of the velocity ratio seen in Eq. (1) means that attempting to achieve tip velocities significantly higher than the characteristic velocity of the material rapidly leads to unfeasible mass ratios. Equation (1), however, is for spinning tethers in deep space, and does not include gravity gradient forces, which can be significant for long tethers that are operating close to the Earth.

The mass ratio of a long tether near the Earth will depend not only on the tip velocity of the tether, but also the length of the tether and the gravitational acceleration on the tip of the tether.[5-7] This will be true for most of the tether systems being considered for the HASTOL architecture. There is no simple analytical equation that takes these gravity gradient forces into account, and the mass ratio needs to be numerically integrated for each case. Thus, we have used a numerical integration program to generate a table of tether mass ratios for Rotovator tethers of various lengths L, spinning at various tip speeds V_T, with the center of mass of the tether at the orbital radius $R_O=R_E+h+L$, and moving at a circular orbit velocity of $V_O=(GM_E/R_O)^{1/2}$, where h=100 km is the nominal payload pickup altitude, R_E=6378 km is the radius and $M_E=5.98x10^{24}$ kg is the mass of the Earth, and the gravitational constant $G=6.67x10^{-11}$ $m^3/kg\text{-}s^2$. The lower end of the orbiting, spinning tether then reaches down into the atmosphere to match speeds with a hypersonic airplane moving at a hypersonic velocity $V_H=V_O-V_T-470$ m/s, where 470 m/s is the velocity through inertial space of the atmosphere at 100 km altitude at the equator of the rotating Earth.

We found that spinning tethers that were very short had a lower orbital altitude and therefore higher orbital velocity, so they needed a higher tip velocity to match speeds with a hypersonic airplane moving at a given hypersonic velocity. Thus, their mass ratio increased exponentially as the square of the velocity because of Eq. (1). We also found that tethers that were very long were orbiting more slowly, and thus needed less tip velocity, but because the gravity gradient forces on the tether increased with tether length, the mass ratio increased because of the increased gravity force. After a lengthy search through the parameter space, we found that there was a broad minimum in the mass ratio that occurred when the tether length and the tether tip velocity were such that the centrifugal acceleration at the tether tip was approximately 16 m/s^2 (52 ft/s^2 or 1.6 gees).

Idealized Rotovator™ Results: The results of our first cut analysis are summarized in Table 1. It should be emphasized that in generating Table 1 we have made two highly idealistic assumptions. First, we assumed that the Tether Central Station is much more massive than the tether. If this is not true, then the tether mass ratios given in Table 1 could rise by up to a factor of 2. The factor of 2 would be the case where there is no TCS at all, and the counterbalance to the tether arm is an equally massive arm stretching out in the opposite direction from the CM. Second, we assumed that we are dropping off a payload at the same time (or nearly the same time) as we are picking up a payload. This assumption produces the ideal result that the load on the tether does not change, the CM of the tether does not change, and the orbit of the CM of the total tether facility around the Earth does not change.

In prior studies of systems for picking up payloads from low Earth orbits and tossing them to the Moon[6] and Mars[7], we showed that practical spinning tether systems could be designed without using any of the above ideal assumptions, that were capable of carrying out those difficult payload pickup and toss tasks while massing less than 30 times the payloads being thrown. As we move further into our HASTOL studies, we will go through the same procedure of replacing these idealistic first cut tether system designs with progressively more realistic designs.

For the calculation of the tether to payload mass ratio, we used data available for Spectra™ 2000, a polymer made by AlliedSignal with an ultimate tensile strength of 4.0 GPa (580,000 psi), a specific density of 0.97, and a derated (safety factor of F=2) characteristic velocity of 2030 m/s (6660 ft/s). This material, along with others, is discussed in more detail later in the paper.

In Table 1, the column labeled ‘2x’ is for a future material (Spectra™ X000?) that has twice the tensile strength to density ratio of presently available Spectra™ 2000, while the column ‘10x’ is a “placecard” for some far future material (derated carbon nanotubes?) that has ten times the ratio of tensile strength to density of the presently available Spectra™ 2000 fiber.

From looking at Table 1, we can see that the use of present-day Spectra™ in a HASTOL system will enable the Rotovator system to work down to about 3.4 km/s (Mach 11) without the tether becoming too heavy. Column ‘2x’ indicates that it only takes a small improvement in tether materials for the Rotovator concept to work down to 3100 m/s (Mach 10). Column ‘10x’ indicates that carbon nanotubes would be “overkill” as far as the Rotovator concept is concerned. We don't need carbon nanotubes to make a HASTOL system, as we will need to retain some amount of mass in the tether in order to keep the tether system itself from being pulled out of orbit by the payload!

Table 1 - Minimum Mass Ratio Rotovator™ Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra™	2x	10x
400	6878	7614	2494	4650	15.0	10.4	2.4	0.37
500	6978	7559	2749	4340	14.0	16.7	4.2	0.56
600	7078	7506	3006	4030	13.0	27.1	5.9	0.65

Table 1 – (Continued) Minimum Mass Ratio Rotovator™ Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
700	7178	7453	3263	3720	12.0	44.0	8.2	0.73
800	7278	7402	3522	3410	11.0	71.8	11.6	0.90
900	7378	7352	3782	3100	10.0	117.6	16.3	1.07

<u>Realistic Rotovator™ Results:</u> We recently have generated some new results where we assumed a more realistic design for the Rotovator™ Facility and a more realistic operational scenario. In this analysis, we assumed a payload mass of 15 Mg (33,000 lb), grapple assembly mass of 0.5 Mg, tether length of 600 km, pickup altitude of 100 km (330 kft), and pickup velocity of 4.1 km/s (13 kft/s), which requires the hypersonic aircraft to fly at 3.6 km/s (12 kft/s or Mach 12) at the equator so that it can take advantage of the 470 m/s (1500 ft/s) rotation of the Earth. This more realistic operational scenario assumed that there would be *only* a pickup of the payload, without a compensating drop-off of a payload. This, in turn, required that the CM of the Rotovator Facility be in an initially elliptical orbit with an eccentricity of 0.0062, so that after pickup of the payload, the Rotovator Facility dropped into an orbit with a perigee such that the tip of the spinning tether did not hit the atmosphere.

The analysis is still in the process of being optimized, but with the assumption that we use Spectra™ 2000 material with a safety factor of 2, then the required mass of the tether alone was calculated to be approximately 91 times the payload mass (about double that in Table 1), while the mass of the Tether Central Facility needed to be 110 times the payload mass, for an overall Rotovator Facility mass ratio of 201. If a stronger material becomes available, that has twice the strength-to-density of Spectra™ 2000, then an optimized Rotovator Facility with a tether length of 600 km would operate in a slightly more elliptical orbit with an eccentricity of 0.0145. The mass of the tether alone would now be only 11 times the payload mass, while to avoid the payload from dragging the Rotovator Facility down into the atmosphere, the TCS mass would actually have to increase to 120 times the payload mass! The total Rotovator Facility mass would then be 131 times the payload mass. We expect that these total mass ratios will drop as we optimize the system.

Although these mass ratios are high, they are not impractical, considering that the Rotovator Facility can be used to "build itself" by starting out small, then picking up tether and power modules to build up the length, thickness, and taper of the tether, and picking up solar power modules to build up the power supply needed by the propellantless electrodynamic tether propulsion system[6] that maintains the Rotovator Facility orbital altitude and spin speed. Carroll has shown[5] that tether facilities are capable of pickup up a payload with the end of a tether, then "tossing" the payload into an orbit where the payload later can rendezvous and dock with the CM of the facility (somewhat like tossing a peanut into your mouth)!

The important point to make about our study results so far, is that an orbiting spinning space tether built using existing space tether materials, and using the simplest existing tether facility design, can be used to pick up a payload from an existing design for a hypersonic airplane that is capable of taking a payload to an altitude of 100 km (330 kft) altitude while moving at 3.6 km/s (12 kft/s or Mach 12). Thus, the HASTOL system combination of a Spectra™ 2000 Rotovator™ and a DF-9 Aeropaceplane is capable of taking payloads from the surface of the Earth and putting them into space. The other HASTOL concepts we will discuss later may prove to be better, but this concept will suffice.

CardioRotovator

The CardioRotovator concept consists of a Tether Central Station in an elliptical orbit, with a single long tapered tether. The tether rotation rate is chosen to be exactly twice the orbital period. The phase of the rotation is chosen such that when the Tether Central Station is at perigee, or closest to the Earth, the tether is pointing straight up, as is shown in Fig. 3. Then, when Tether Central Station is at apogee, or furthest from the Earth, the tether is pointing straight down at the Earth, reaching deep into the atmosphere for the payload pickup.

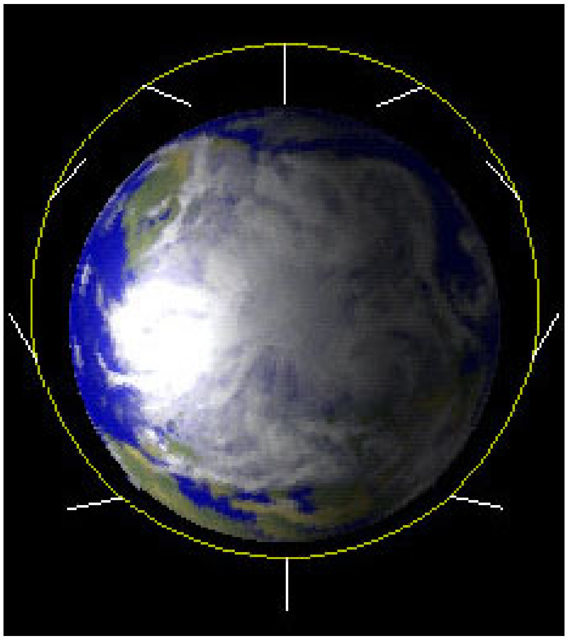


Fig. 3 - CardioRotovator Concept

As can be seen in Fig. 3, at intermediate points, the tether is pointing away from the Earth and does not penetrate below the Tether Central Station altitude except near the touchdown point below the apogee point. The trajectory of the tip of the tether is approximately heart-shaped, which lead to the name of "CardioRotovator" for the system concept. Unlike the circular orbit Rotovator system, the tether length and tip velocity of a CardioRotovator cannot be chosen independently. Once a particular apogee radius R_A is chosen, that determines the length of the tether, since $L=R_A-R_E+h$. Then, once a particular perigee radius R_P is chosen, that, along with the apogee radius, fixes the orbital period P to be:

$$P = \pi \left\{ \frac{(R_A + R_P)^3}{2GM_E} \right\}^{1/2} \qquad (3)$$

The rotational period p of the spinning tether itself is then also determined, since the design of the CardioRotovator requires that $p=P/2$. This rotational period, together with the tether length L, then determines the tether tip speed as $V_T=2\pi L/p=\pi L/P$.

In Table 2, we have tabulated some relevant examples of the CardioRotovator system parameters, assuming that in all cases the perigee altitude of the Tether Central Station is 500 km, which is just outside the International Space Station nominal altitude of 400 km. With these assumptions, the CardioRotovator tether tip acceleration levels were found to between 0.43 and 0.66 gees, acceleration levels easily accommodated by human passengers. Again, for Table 2, we have assumed an idealistic situation where the TCS has an infinite mass and that a payload pickup is compensated by a payload drop-off.

By comparing Table 1 for the Rotovator systems with Table 2 for the CardioRotovator systems, it is seen that the CardioRotovator gives somewhat better results than the Rotovator. In general, however, the length of the CardioRotovator tether is much longer than the length of the Rotovator tether, which leads to greater concern about collisions of the tether with other objects in space. This concern is partially compensated by the fact that the CardioRotovator tether spends most of its time at high altitudes where there is less traffic.

Table 2 - CardioRotovator Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Tip Accel.	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	a	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s^2)	(m/s)	Mach	Spectra	2x	10x
1000	7478	7147	2076	0.43	4601	14.8	10.8	3.1	0.39
1200	7678	7004	2440	0.50	4094	13.2	22.2	5.2	0.55
1400	7878	6868	2789	0.56	3608	11.6	44.7	8.4	0.75
1600	8078	6737	3124	0.61	3143	10.1	87.8	13.4	0.97
1800	8278	6611	3445	0.66	2695	8.7	168.5	21.0	1.24

Two-Stage Rotovator

The Tillotson Two-Tier Tether (TTTT or T4)[8] consists of a long, large, tapered "first stage" spinning tether, at the end of which is a smaller "second stage" spinning tether as shown in Fig. 4. The T4 is essentially a two-stage Rotovator. The use of two tiers or two "stages" in the design of a spinning tether decreases the overall ratio of the tether launch system mass to payload mass, in a manner similar to the benefits of the lower mass ratio obtained when using a two-stage rocket in a rocket launch system.

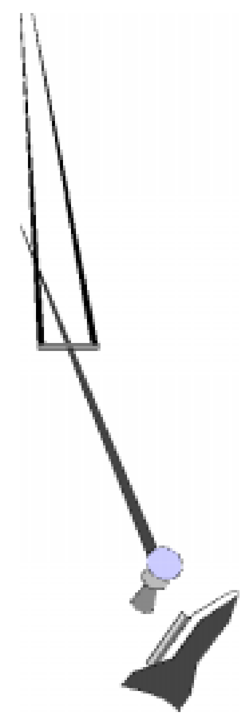


Fig. 4 - Tillotson Two-Tier Tether (T4) Concept

Since the ratio of the tether mass to the payload mass of a spinning tether increases as the exponential of the square of the tip velocity (see Eq. 1), large reductions in overall mass ratio can be obtained by dividing up the total tip velocity required into nearly equal amounts. In a typical HASTOL scenario where a tether tip velocity of 3.6 km/s (12 kft/s) is needed to meet, say, a Mach 11 hypersonic aircraft moving at 3.4 km/s (11 kft/s), the tether mass required might be 80 times the payload mass. If instead, the first stage tether rotates at a tip speed of 1.8 km/s (6 kft/s), while the second stage tether also rotates at a tip speed of 1.8 km/s, the combined velocities reach the 3.6 km/s needed for the pickup, but the combined mass of the two tethers could be as little as 21 times the mass of the payload.

In the T4 concept, there will be a Tether Central Station (TCS) (assumed to have infinite mass for this first cut analysis), around which will be spinning a one-arm first stage tether, with an effective radius of rotation around the TCS of R_1. At the end of the first stage tether will be a stiff pivot bearing supported at both ends by the split end of the first stage tether, as shown in Fig. 4. This pivot bearing will be the central support point for the spinning second-stage tether, which will have a radius of rotation R_2. The total length, when both tethers are aligned along the nadir, will be $L=R_1+R_2$. Since we want the pickup to take place at an altitude h=100 km (330 kft), this determines the orbital radius of the TCS to be $R_O=R_E+h+L$, where R_E is the radius of the Earth. The orbital velocity is then just $V_O=(GM_E/R_O)^{1/2}$, where G is the Newtonian gravitational constant and M_E is the mass of the Earth.

Dividing the total tip velocity V_T evenly between the two stages gives each stage a tip velocity of $V_T/2$. To distribute the mass of the second stage tether evenly about its center of rotation, the second stage tether must have two arms with equal mass on each side of the pivot bearing. The second stage tether mass is therefore twice as great as a single-arm tether with tip velocity $V_T/2$. The first stage tether is a single-arm tether which must support the mass of the payload plus the second stage tether. The total tether system mass is the sum of the first and second stage masses. The relative advantage of a T4 system compared to a single stage rotovator is expressed by Equation 4, where $M_1(V_T/V_C)$ is the mass ratio for a single stage single arm tether as shown in equation 1.

$$M_{2STAGE} = 2\left[M_1\left(\frac{V_T}{2V_C}\right)\right]^2 + 3M_1\left(\frac{V_T}{2V_C}\right) \qquad (4)$$

Equation 5 describes the total tether mass in more fundamental terms:

$$\frac{M_T}{M_P} = 2\pi\left(\frac{V_T}{2V_C}\right)^2 \exp\left[2\left(\frac{V_T}{2V_C}\right)^2\right]\left[\operatorname{erf}\left(\frac{V_T}{2V_C}\right)\right]^2 + 3\sqrt{\pi}\left(\frac{V_T}{2V_C}\right)\exp\left[\left(\frac{V_T}{2V_C}\right)^2\right]\operatorname{erf}\left(\frac{V_T}{2V_C}\right) \qquad (5)$$

In Table 3, we have tabulated some relevant examples of the T4 system parameters, assuming that in all cases the total tip speed is evenly divided between the two stages. Because the second stage tether has a shorter radius than a single-stage tether for equivalent total tip speed, the acceleration at the tip is higher than for a single stage system. For this analysis we assumed the ratio of stage 1 tether radius to stage 2 radius is 5:1. With that assumption, the cases described in Table 3 have a maximum acceleration of 2.9 gravities, which is less than the 3-g maximum acceleration experienced during a Space Shuttle launch. It is possible to change the ratio of stage lengths and tip velocities to adjust system mass, acceleration, and dynamics.

The T4 approach to the design of the Rotovator for a HASTOL system is much more complicated in design and dynamics than a simple one stage Rotovator. The plan is to baseline the one-stage Rotovator for the study, but to carry out analyses of the T4 system in parallel. If the mass of the one-stage tether grows to where its mass begins to cast doubt on the engineering or financial feasibility of the HASTOL concept, then we always have the T4 two-stage concept available in order to drastically cut the tether mass needed.

Table 3 - Tillotson Two-Tier Tether Parameters for HASTOL Application

1st Tier Tether Radius	2nd Tier Tether Radius	Total Tether Length	TCS Orbital Radius	TCS Orbital Velocity	Total Tip Velocity Needed	Hypersonic Airplane Velocity		Total Tether to Payload Mass Ratio	
R_1	R_2	L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P	
(km)	(km)	(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra	2x
333	67	400	6878	7614	2494	4650	15.0	4.83	1.65
417	83	500	6978	7559	2749	4340	14.0	6.91	2.18
500	100	600	7078	7506	3006	4030	13.0	9.91	2.85
583	117	700	7178	7453	3263	3720	12.0	14.2	3.71
667	133	800	7278	7402	3522	3410	11.0	20.6	4.81
750	150	900	7378	7352	3782	3100	10.0	29.9	6.23

CASTether/LIFTether

Another concept for the space tether portion of the HASTOL system uses two separate methods for operating the tether. The Cast Ahead Supersonic Tether or CASTether concept involves "casting" the tether ahead of the Tether Central Station and using aerodynamic drag to slow the tip of the tether down to hypersonic speeds. The Lift Into Freefall Tether concept involves arranging for the aerodynamically slowed tether to be vertical just as the TCS is passing overhead. The TCS will then initially "lift" the payload vertically upwards, then pull it along behind into orbit. The two concepts are illustrated in our previous publication.[1] We have yet to carry out an analysis of this concept, so we will not discuss it further here.

HARGSTOL

The final method of accomplishing the HASTOL concept is to compromise, and allow the partial use of a rocket upper stage or a rocket-powered grapple to complete the payload transfer between the hypersonic airplane and the grapple assembly at the end of the space tether. Thus, instead of the HASTOL system, we will have the HA**RG**STOL or Hypersonic Airplane, Rocket Grapple, Space Tether Orbit Launch system. This concept has a number of possible variations. The normal method would be to have the rocket augmented grapple on the tip of the tether. The tether system would slow the tip down as much as possible using one of the tether tip slowing techniques, and the airplane would fly as fast and high as possible, and the rocket system on the grapple would make up any speed difference. The grapple would need to be refueled periodically. This could be done at each payload pickup, or there could be periodic pickups of propellant tanks, with the empty tanks added to the Tether Central Station ballast.

A variation on this concept would be to have the major part of the tether mass be a permanent part of the space tether system, but the "tip" of the tether and the rocket grapple would be carried by the hypersonic airplane. At some time interval before the rendezvous time, the grapple would be separated from the airplane, pulling out the tether, which would be made of material capable of coping with the hypersonic heating and stress. The rocket grapple would then climb in altitude and speed to meet up with the lower end of the space tether out in space away from the atmosphere, while the airplane stays in the atmosphere at an optimum cruise altitude. The grapple grabs the end of the tether, the payload is pulled free from the airplane, and lifted into space by the tether.

The ultimate rocket grapple concept would have the rocket take the grapple from the hypersonic airplane all the way to the Tether Central Station, pulling out tether from the payload. Since for normal requirements the way to the Tether Central Station, pulling out tether from the payload. Since for normal ΔV requirements the tether mass would be much larger than the payload mass, it is obvious that a better technique would be to meet the downgoing tether from the Tether Central Station "halfway". Finding the optimum ratio for the length of the airplane tether versus the space tether would be part of the overall system optimization. This concept, with the rocket grapple coming from the airplane without carrying the payload, would only be usable for taking payloads into orbit. For two-way systems, it would be necessary to have the rocket grapple on the end of the space tether, and have the rockets on the grapple capable of accelerating both the grapple and the payload.

The most important feature of all the possible HARGSTOL systems is that we KNOW we can make them work, no matter how poor the ultimate performance of the hypersonic airplane and the space tether. All it requires is that the rocket grapple be loaded with enough propellant to close the velocity gap. Since the mass ratio of the propellant to grapple-plus-payload is exponential in the grapple ΔV, and the rocket ΔV is low because of the ΔV contributions of both the airplane and tether, the propellant required should be low.

SPACE TETHER ISSUES[6,9]

The space tether portion of the HASTOL system has a number of issues that must be dealt with other than the method of operation, including surviving damage by meteorites and space debris, operating at hypersonic speeds in the upper atmosphere, avoiding collisions with other spacecraft, and safe and reliable operation at low system mass.

Tether Survivability

For a tether transport system to be economically advantageous, it must be capable of handling frequent traffic for many years despite degradation due to impacts by meteorites and space debris. Yet, the tether mass must be minimized to reduce the cost of fabricating and launching the tethers. These two requirements present conflicting demands upon the tether design that make conventional single-line tethers impractical for the HASTOL application. For a single-line tether to achieve a high probability of survival for many years, it must be very thick and massive. Fortunately, a low mass survivable tether design exists, called the Hoytether™, which can balance the requirements of low weight and long life[9]. As shown in Fig. 5, the Hoytether is an open net structure where the primary load bearing lines are interlinked by redundant secondary lines. The secondary lines are designed to be initially slack, so that the structure will not collapse under load. If a primary line breaks, however, the secondary lines become engaged and take up the load. Note in Fig. 5, that four secondary line segments replace each cut primary line segment, so that their cross-sectional area need only be 0.25 of the primary line area to carry the same load. Typically, however, the secondary lines are chosen to have a cross-sectional area of 0.4 to 0.5 of the primary line area, so as to better cope with multiple primary and secondary line cuts in the same region of the tether. This redundant linkage enables the Hoytether™ structure to redistribute loads around primary segments that fail due to meteorite strikes or material failure. Consequently, the Hoytether structure can be loaded at high stress levels, yet achieve a high margin of safety.

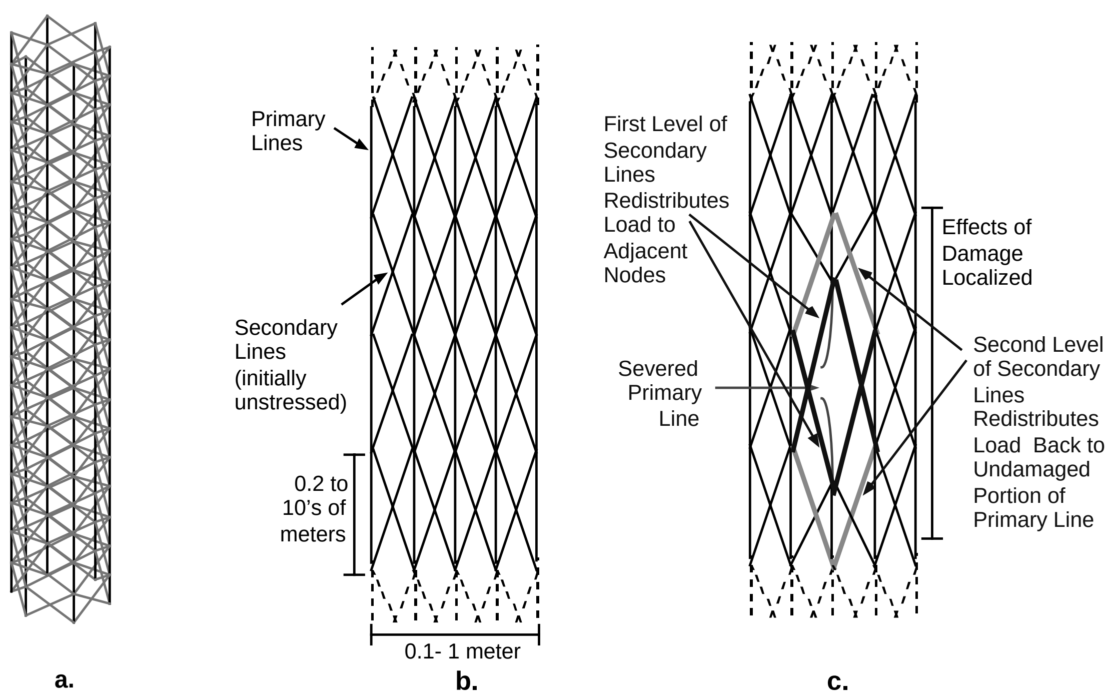


Fig. 5 - The Hoytether™ design and its response to a cut line

Tether System Collision Avoidance

There are many objects in space, ranging from micrometeorites to operational spacecraft with 10-meter-long solar array panels. We can design interconnected multiple strand open net Hoytether™ structures that can reliably (>99.9%) survive in space for decades despite impacts by objects up to 30 cm (1 ft) or so in size. Objects larger than one meter will impact all the strands at one time, cutting the tether. These large objects could include operational spacecraft, and they will also be damaged by the impact. Objects larger than 30 cm are all known and tracked by the U.S. Space Command. There are about 6000 such objects in low and medium Earth orbit, of which an estimated 600 will be operational spacecraft in the 2005 time frame. For an atmospheric tether application, we have estimated that, if no traffic control measures are instituted, a 20 km long tether in an orbit grazing the upper atmosphere has a 4% chance of being cut by one of the 6000 large objects during a one year mission, and an 0.4% chance of striking one of the 600 operational spacecraft. Longer tethers will have proportionately larger probabilities. It will therefore be incumbent on the HASTOL system operators to maintain contact with the U.S. Space Command and keep an accurate inventory of the known large objects. They then need to control the tether system CM orbital altitude and phase, the tether rotation rate and phase, and the tether libration and vibration amplitudes and phases, to insure that the tether system components do not penetrate a volume of "protected space" around these large orbiting objects.

Tether Safety Factor and System Reliability

When a tension member such as a tether is developed, it is normally designed to operate at a load level somewhat lower than the maximum it could support without breaking. This derating provides margin of error in case of imperfections in the material or the construction. Typically, a single line tether is designed to carry a maximum load that is 50% of its breaking limit. This tether would thus have a "design safety factor" of F=1/0.50=2.0. For the Hoytether[9], we define the safety factor as the ratio of the maximum load capacity *of both primary and secondary lines* to the design stress load S_P of the *primary lines alone*.

$$F=[1+(N_S A_S)/(N_P A_P)]/S_P \qquad (6)$$

where N_P and N_S are the number of primary lines and secondary lines, and A_P and A_S are their respective cross-sectional areas. For a typical tubular Hoytether™ there are twice as many secondary lines as primary lines so $N_S=2N_P$ and Eq. (6) reduces to $F=[1+2A_S/A_P]/S_P$. For the case where the secondary line area is half the primary line area or As=0.5Ap and the stress on the primary lines is 67% of the ultimate tensile strength of the material or S_P=0.67, then the Hoytether™ safety factor would be: F=[1+2(0.5)]/0.67=3. This definition of the Hoytether™ safety factor provides the same measure of the strength-to-weight ratio of the Hoytether structure as it does for a single-line tether. However, this definition of the safety factor does not accurately represent the margin of safety for the Hoytether. Because the Hoytether has redundant links that can reroute stress around parts of the tether that have failed, it is possible to load the Hoytether at a large fraction of the capacity of the primary lines (i.e.- small “line safety factor”) and still have a large margin of safety against parting.

To study the optimization of the Hoytether structure for high-load applications, we performed a series of simulations of variations of the structure using our “SpaceNet” tether simulation program[6]. The SpaceNet program uses a combination of finite-element methods with a structural relaxation scheme to calculate the effects of damage to complex 3-D net structures such as the Hoytether. The results of our analyses indicate that the design of an optimal Hoytether depends upon how much of its mission duration will be spent under high load. Consequently, there are two classes of Hoytether™ designs, one for tethers that are always under high load, and one for tethers that are heavily loaded for brief periods only.

Continuous High Load Tether: If the tether will be under high load for most of its mission, then it should be designed with secondary lines slack at the expected load level. This will enable the tether lines to remain spread apart at all times, minimizing the chances of a single impactor cutting several lines. For this case, SpaceNet simulations showed that a near-optimal tether design would be a cylindrical Hoytether with a large number of primary lines (~20) stressed at 75% of their maximum load and with initially-slack secondary lines that each have a cross-sectional area 0.4 times that of a primary line. Simulations showed that splitting the tether up into a large number of primary lines prevented the stress energy released by a cut of one of the primary lines from overloading neighboring primary lines before the secondary lines could become taut enough to take up the released stress and pass it around the cut primary line segment to the uncut primary line segments above and below the cut segment.. From Eq. (6), such a tether will have a design safety factor of 2.4. However, the redundant nature of the structure will make the Hoytether far more reliable than a single line tether with the same safety factor. Simulations with the SpaceNet program have shown that this tether design can withstand multiple cuts on a single level. In fact, even if all of the primary lines on one level are cut (one at a time), the secondary lines will support the load.

Intermittent High Load Tether: The HASTOL Space Tether facility, however, would likely be loaded at high levels for only a few hours at a time. Therefore, it is possible to reduce the tether weight by designing it to have slack secondary lines at the load level experienced during its long "off-duty" periods, but to have the secondary lines bear a significant portion of the load during a brief high-stress operation such as a payload catch-and-throw operation. During the high-stress period, the loading of the secondary lines will cause the structure to collapse to a cylindrical tube. Once a payload is released and the stress is reduced, however, the tether lines will spread back apart. If this high-load period is brief, it will only slightly increase the chances of tether failure due to impact by a large object. Simulations indicate that a 20-primary line Hoytether with the secondary line areas 1/4 of the primary lines can be safely loaded to 85% of the primary line capacity during peak stress operations. The design safety factor of this tether from Eq. (6) is F=1.75. In this paper we will use a more conservative safety factor of F=2.

Space Tether Materials

The space tether used in the HASTOL system will consist of a long strength member made of a high strength, low density polymer, with a "hypersonic" tip made of a high strength at high temperature, atomic-oxygen resistant material. Woven into the initial 10 km of the polymer tether nearest the Tether Central Station will be an aluminum wire conductor to be used by the Hoyt Electrodynamic Force Tether (HEFT) propulsion system[6] built into the tether and used by the TCS to control the tether system orbit and spin parameters.

High Strength Main Member: The two candidate polymers for the high tensile strength main portion of the tether, Spectra™ and Zylon™, are both stronger per pound than either steel or Kevlar™ polymer fiber. Their "characteristic velocity", defined as the maximum tip speed of an untapered tether, is: $V_C=(2U/d)^{1/2}$, where U is the ultimate tensile strength of the material and d is its density. Spectra™ 2000 has a U=4.0 GPa, d=970 kg/m^3 and V_C=2872 m/s, while Zylon™ has a U=5.8 GPa, d=1560 kg/m^3 and V_C=2727 m/s. Both of these materials are commercially available in tonnage quantities with reasonable prices and delivery times. These polymer materials are sensitive to attack by atomic oxygen (AO), however, so the portions that get near the atmosphere would probably be coated with a proprietary AO-resistant resin coating available from Aeroplas.

Hypersonic Tip: The material for the hypersonic tip will not only have to withstand attack by atomic oxygen, but maintain a moderately high strength at high temperatures. We have estimated that the tether temperature due to air drag heating will range from room temperature (300K or 27C) for a tether speed through the air of 3 km/s at 120 km altitude, up to as high as 2100K (1830C) for a relative speed of 5 km/s at 80 km altitude. The candidate materials and their ultimate tensile strength in GPa (gigapascals) as a function of temperature are summarized in the Table 4. (For reference, 1 GPa = 10^9 N/m^2 = 145,000 psi). To allow a relative comparison of the suitability of the various different tether materials for use in various spinning tether systems, we also included in Table 4 the density *d* and the room temperature "characteristic velocity" $V_C=(2U/d)^{1/2}$ of the material, which is the maximum attainable tip speed of an untapered spinning tether made solely of that material. For reference, the melting points of some of the materials in Table 3 are: Al–660C, Ti–1660C, Ni–1453C, W–3410C, Al_2O_3–2015C, SiC–2700C, and SiO_2–1610C.

Table 4 - Tether Material Tensile Strength (GPa) vs. Temperature

Material	V_C (km/s)	Density d (g/cc)	20 C	300 C	600 C	800 C	1000 C	1200 C
Spectra 2000	2.87	0.97	4.0	-	-	-	-	-
Zylon (PBO)	2.73	1.56	5.8	3.7	-	-	-	-
Quartz Glass (SiO_2)	1.81	2.20	3.6	3.6	3.6	3.6	3.6	?
S-glass	1.94	2.50	4.7	?	?	?	?	?
Carbon	2.77	1.80	6.9	?	?	?	?	?
Carbon/Ni-coated	2.12	2.68	6.0	?	?	?	?	?
Tyranno (SiTiCO)	1.66	2.55	3.5	3.5	3.5	3.5	3.5	3.5
Textron β-SiC	2.19	2.93	7.0	6.6	6.0	5.6	5.2	4.5
0.72 β-SiC/Ti-coated	1.72	3.37	5.0	4.8	4.3	4.0	3.7	3.2
Altex (Al_2O_3/SiO_2)	1.21	3.30	2.4	2.4	2.4	2.4	2.4	1.5
Nextel (α-Al_2O_3)	1.30	3.88	3.3	?	?	?	?	?
0.65 Nextel/Al-coated	0.97	3.40	1.6	1.4	?	?	?	?
Tungsten Wire	0.55	19.35	2.9	2.9	2.9	2.9	2.9	2.9

GRAPPLE AND PAYLOAD TRANSFER ISSUES[8]

In order for successful rendezvous, docking, and transfer of the payload to occur, some basic functions must be performed by one or more of the HASTOL system architecture elements, which include the grapple assembly. The following basic functions have been identified and the grapple assembly design process must consider all of them:

- Establishing a known absolute location for rendezvous, capture, and transfer and keeping it updated
- Establishing and updating relative position between the payload and the grapple assembly
- Recognizing the defined rendezvous point
- Closing the gap to the rendezvous point
- Payload/grapple docking
- Payload separation from the hypersonic vehicle
- Retention of payload on grapple during transfer

Several grapple design requirements, drivers, and concerns have resulted from or are associated with the identification of these functions. Rendezvous, docking, and payload transfer will occur at around 100 km (330 kft) altitude in the presently planned HASTOL scenario. The atmosphere is not very dense at that altitude. There will be significant heating, but not much dynamic pressure despite the high velocities involved. The grapple assembly will therefore not need to be streamlined to any great extent, although it will have to withstand significant heating for its short duration in the atmosphere. The amount of heating will depend upon the exact rendezvous altitude and speed, and the "height" of the upper atmosphere at the time of the rendezvous. Later analysis will also show a clearer picture of the effects of thermal cycling due to multiple atmospheric passages. It will also aid in future material specifications.

The tethered grapple assembly motion at the point of capture must be in-plane with the payload. Control of either the grapple assembly or the payload (payload itself or the hypersonic vehicle) must be possible to insure a successful docking. Structural loading of the grapple assembly must be taken into account for rendezvous as well as for capture impact and transfer of the 14 Mg (14 metric tons or 30,000 lb) payload. No damage should occur to the payload.

A conservative assumption is that there will only be one capture attempt possible per mission. As a result, maximizing the capture opportunity window is a grapple design objective. This assumption has also resulted in a requirement for the capture to be as automated as possible; a Go/No Go decision initiated prior to the actual capture by ground control or pilot, should there be one, will be included in the grapple assembly design. It is assumed that abort modes will be defined prior to each HASTOL mission for the specific client, though efforts are on-going to identify abort modes that can be built into the system, for instance, establishing the bounds of an “attempt-to-transfer window,” and a “payload out-of-bounds” window.

Other grapple design issues deal with the “no damage” to client payload policy and communications issues. The payload's safety during transfer must be insured, which means either the payload must not tumble during transfer, or it must be protected so limited tumbling can be accounted for at no consequence. The potential of communication loss at each phase of the payload transfer scenario must also be considered.

A preliminary conceptual CAD drawing of one possible grapple assembly option for the tether is shown in Fig. 6. It features a circular “attach ring” at the bottom, which will mate with grapple hooks on the payload. The attach ring is connected to the rest of the end mass via a six-degree-of-freedom, multiple-shock-absorber-strut suspension cradle. In the suspension cradle, all of the members are designed to compress as necessary, should the payload and grapple mechanism contact at some non-zero speed or some slightly non-tangential angle. The struts in the suspension cradle will also provide shock-absorber type damping of the resulting movement of the attach ring relative to the

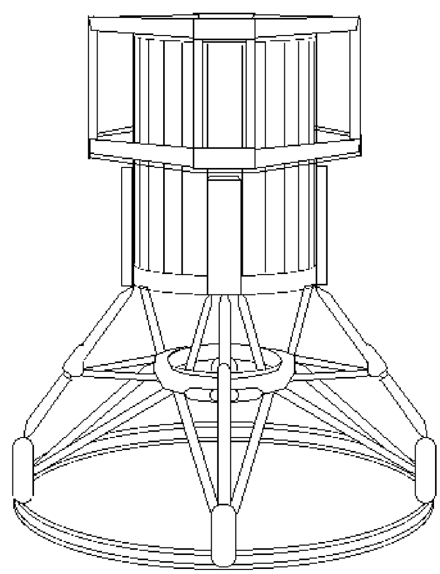


Fig. 6 - Grapple Assembly Concept Drawing

heavier end mass cylindrical structure at the top, which contains a tether winch, batteries, the reaction control system and its propellant, and the command, control and guidance electronics.

The ring and the suspension leg elements would be made of materials selected to withstand heating from the hypersonic molecular flow at the rendezvous altitude. This eliminates any need for an aerodynamic cone or shroud, which would increase the aerodynamic drag on the assembly compared to the mostly empty strut structure presented to the hydrodynamic molecular flow. The “ends up” cylinder of the upper portion of the grapple assembly is already aerodynamically stable. Adding a forward-facing conical aerodynamic “shield” to it would not help appreciably.

The grapple assembly requires several internal functions to be successful for this kind of mission, which make it similar to grapple assembly concepts developed earlier for exo-atmospheric transfer of payloads[10]. As a result of the relatively high rendezvous altitude of 100 km (330 kft), adding aerodynamic “lift” surfaces on the grapple assembly will not be effective in maneuvering the grapple toward a rendezvous with the hypersonic aircraft. The cylindrical portion of the grapple assembly will have a tether winch will allow the grapple assembly to “leave” its normal position at the end of the tether by letting out tether. The centrifugal force from the rotation of the tether can be used to “cast” the grapple assembly in toward the hypersonic vehicle before the Tether Central Station arrives overhead. The grapple assembly will have a reaction control system for fine control of its position, velocity, and orientation, but to minimize the problem of refueling of the grapple assembly, it will be up to the reaction control system on the hypersonic aircraft to remove most of the position and velocity errors during the rendezvous process.

The current concept is to fly the decelerating grapple vehicle in so that it approaches the hypersonic airplane from above and behind (this holds true for all grapple assembly designs considered). The attach ring would attach to the payload and pull the payload up to the grapple. The hypersonic vehicle would then return to ground and the grapple assembly, with payload, would be carried into space by the motion of the tether.

After the grapple assembly exits the atmosphere, the time spent in space will be used to cool and condition the grapple assembly, and recharge the batteries in preparation for the next aeropass. When the grapple assembly is not going to be used to capture or deploy a payload for long periods of time, the tether will be shortened by either the grapple tether winch, or one of the other winches along the tether, to raise the minimum altitude of the tether tip and keep the grapple assembly above most of the atmosphere.

The hypersonic grapple would not use externally mounted solar panel arrays during the aeropass due to the high aerodynamic forces and heating rates during this phase. Two options to supply electrical power to the grapple assembly have been identified: a deployable/storable photovoltaic array or an electrically conductive tether. Each would generate the required power, the latter while moving through the earth's magnetic field, and would store excess energy in the batteries for use during the aeropass phase.

In order to allow for a reliable rendezvous, the grapple vehicle must maintain location and attitude information and communicate with the hypersonic airplane. This can be done accurately with a differential GPS similar to those systems being developed for landing commercial aircraft. The approach velocities are too high to rely on human pilots on the ground so the system will require autonomous rendezvous and capture (AR&C) capabilities. AR&C technologies, such as advanced sensors for the final approach and rendezvous, are continuing to evolve, and are maturing based on Russian and NASA investments on docking technologies, and more recently, DARPA investments in the ASTRO refueling vehicle concept.

CONCLUSIONS

We have described a number of alternate system configurations that will allow hypersonic air-breathing airplane technologies to be combined with orbiting spinning space tether technologies to produce a method of moving payloads from the surface of the Earth into Earth orbit. The resultant Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is completely reusable and has the potential to drastically cut the cost of Earth-to-orbit space access. The system is revolutionary in that it minimizes, and perhaps even eliminates, the use of rockets for Earth-to-orbit launch of satellite payloads and even passengers.

ACKNOWLEDGEMENTS

This work was supported by a contract with the NASA Institute for Advanced Concepts (NIAC), Dr. Robert Cassanova, Director. The authors also acknowledge technical contributions from their fellow co-workers, Robert Hoyt of Tethers Unlimited, Inc.; Donald Johnson and Joseph Stemler of Boeing/MDC Phantom Works, St. Louis; Benjamin Donahue and Beth Fleming of Boeing/MDC, Huntsville; Brian Tillotson of Boeing S&CS, Seattle; and student Daniel Stuart Bowman of the University of Maryland.

REFERENCES

1. Robert L. Forward, Thomas J. Bogar, Michal E. Bangham, and Mark J. Lewis, “Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System: Initial Study Results,” IAF-99-S.6.05, presented at the 50th International Astronautical Congress, Amsterdam, The Netherlands, 4-8 October 1999.
2. L. F. Scuderi and J. L. Hunt, “Mach 10 Dual-Role Vehicle Concept,” Space Technology and Applications International Forum, Albuquerque, NM, 1-4 February 1999.
3. Robert Zubrin, “The Hypersonic Skyhook,” Journal of the British Interplanetary Society, Vol. 48, No. 3, pp. 123-128, March 1995.
4. Hans Moravec, “A Non-Synchronous Orbital Skyhook,” Journal of the Astronautical Sciences, Vol. 25, No. 4, pp. 307-322, 1977.
5. J. Carroll, “Preliminary Design for a 1 km/s Tether Transport Facility,” *NASA OAST Third Annual Advanced Propulsion Workshop*, JPL, Pasadena, CA, 30-31 Jan 1992.
6. Robert P. Hoyt and Chauncey Uphoff, “Cislunar Tether Transport System,” Paper AIAA-99-2690, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, 20-24 June 1999.
7. Robert L. Forward and Gerry D. Nordley, “Mars-Earth Rapid Interplanetary Tether Transport (MERITT) System: I. Initial Feasibility Analysis,” Paper AIAA-99-2151, 35th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, 20-24 June 1999.

8. Brian Tillotson, “Tether as Upper Stage for Launch to Orbit,” AIAA-89-1585-CP, 3rd International Conference on Tethers in Space, May 17-19, 1989.

9. Robert P. Hoyt and Robert L. Forward, “Failsafe Multiline Hoytether Lifetimes,” Paper AIAA-95-2890, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA, 10-12 July 1995.

10. M. E. Bangham, E. Lorenzini, and L. Vestal, “Tether Transportation System Study,” NASA/TP-1998-206959, NASA Marshall Space Flight Center, Huntsville, AL, March 1998.

APPENDIX 3
DESIGN AND SIMULATION OF TETHER FACILITIES FOR THE HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) ARCHITECTURE

(UNPUBLISHED)

DESIGN AND SIMULATION OF TETHER FACILITIES FOR THE HYPERSONIC-AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) ARCHITECTURE

Rob Hoyt
Tethers Unlimited, Inc.

ABSTRACT

In this paper, we develop and evaluate designs for several tether concepts for the HASTOL system, including a “Rotovator”, the “LIFTether” concept, and the “Cardiorotovator” concept. Using numerical simulations of these tether systems, we examine the effects of hypersonic aerodynamic drag and heating on the tethers as they dip into the upper atmosphere, and study the tether load dynamics that result from capture of the payload. We also investigate the use of tether deployment to extend the rendezvous “window”. We find that a LIFTether that dips down to 80 km altitude could, through proper use of aerodynamic drag and dynamical tether behavior, increase the ΔV capability of the tether relative to a simple Rotovator. However, of the three tether concepts, a Rotovator designed to pick payloads up from an altitude of 100 km is found to offer the least system complexity and minimize the mass of the tether facilty. In addition, we find that a simple tether deployment maneuver can extend the rendezvous window to facilitate capture of the payload by the tether.

Introduction

The HASTOL architecture seeks to reduce by an order of magnitude the recurring cost of transporting large payloads into Earth orbit by matching an air-breathing hypersonic airplane with an orbiting tether platform to minimize the amount of fuel needed to deliver the payload into orbit. In a HASTOL system, the hypersonic airplane would carry a payload up to an altitude of 80-100 km at a speed of Mach 10-13. At its apogee, the airplane would meet up with the tip of a long rotating tether that swings down from a massive facility in Earth orbit. The airplane would hand the payload off to a grapple vehicle at the tether tip, and the tether would pull the payload up into orbit.

The potential launch-cost savings of the HASTOL architecture would result from the large reduction in ΔV that must be provided by the launch vehicle, and from the ability to use airbreathing engines for most of the ΔV it imparts to the payload. A conventional launch vehicle would require a total ΔV of over 7.5 km/s to place a payload into LEO. In the HASTOL concept, however, the launch vehicle only needs to provide a ΔV of about 3.5 km/s (Mach 12) to the payload. If the hypersonic airplane takes off from near the equator, the Earth's rotation will add approximately 0.5 km/s to the velocity of the airplane. The remaining 3.5 km/s needed to deliver the payload into orbit is provided by the rotating tether. Due to the exponential behavior of the rocket equation, the reduction in launch vehicle ΔV from 7.5 to 3.5 km/s can result in a very large reduction in required propellant mass and launch vehicle size. This can result in a large reduction in recurring launch costs.

In this work we examine the design of the tether component of the HASTOL architecture. Several different concepts have been proposed for this tether, including a simple rotating tether in near-circular orbit, a "LIFTether", which uses aerobraking to achieve rendezvous with the payload, and a "CardioRotovator" in an elliptical orbit. We begin by describing the various tether system designs. We then use a numerical simulation to model the operation of the first two tethers in order to determine if the tethers can withstand the aerodynamic heating at the altitudes of interest, and to determine if the tethers can sustain the dynamic loads that result from payload capture. We will also use the simulation to determine if tether deployment maneuvers can extend the window for rendezvous between the tether tip and the payload.

Tether Facility Designs

Each of the following tethers were designed to handle the 15 Mg payload that can be launched by the Boeing DF-9 vehicle.

Rotovator

The first tether design studied was a simple rotating tether facility, also known as a "Rotovator," illustrated in Figure 1. The facility was composed of a central station (containing power supplies, tether reel, command and control, and ballast mass), a 600 km long tapered tether, and a grapple vehicle at the end of the tether. The tether facility was placed in a slightly elliptical orbit with a perigee altitude of 611 km and a perigee velocity of 7.55 km/s. This was a

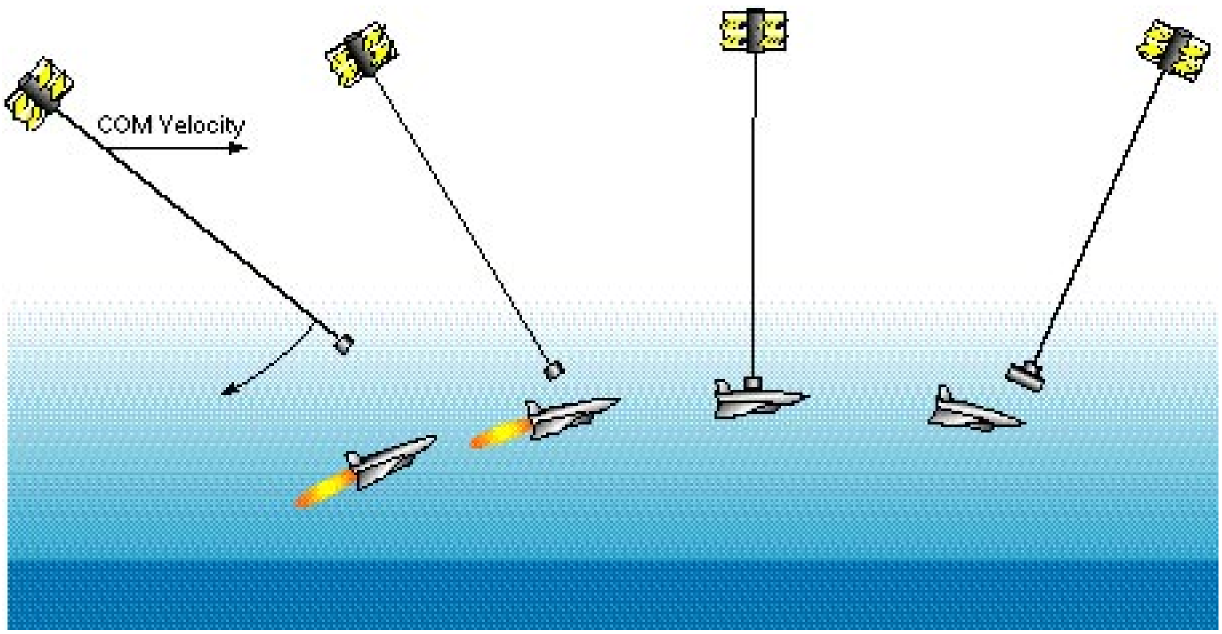


Figure 1. Rendezvous of a rotating tether ("Rotovator") and a hypersonic airplane.

slightly elliptical orbit, with an eccentricity of 0.0062. The orbit was chosen to be elliptical and payload capture was performed at perigee in order to reduce the amount of total facility mass needed to keep the facility and tether above the atmosphere after it captures a payload. The tether was set into rotation with a tip velocity of 3.4 km/s.

The tether sizing was calculated assuming it would be constructed of a material such as Spectra 2000, with a tenacity of 4.0 GPa and a density of 970 kg/m^3. Although in the final implementation the tether would likely be a multiline structure to provide tether survivability, in these simulations the tether was modeled as being a single-line structure, tapered to minimize the tether mass. The tether taper is illustrated in Figure 2. This tether was designed with a safety factor (computed for nominal static loads) that varied along the length of the tether as shown in Figure 3. Along most of the tether, the safety factor was chosen to be 2.0. At the tether tip, however, the safety factor is increased in order to provide extra safety margin to handle transient loads due to payload capture. Because the portion of tether closer to the central station has a much larger cross section, the transient loads due to payload capture are insignificant further up the tether, and thus the safety factor of 2 should be adequate. The total tether mass is 1358 Mg, or approximately 90 times the payload mass. The Station mass is 1650 Mg, or 110 times the payload mass. The total Tether Facility mass is 3009 Mg, or just over 200 times the payload mass. With these masses, the center of mass of the tether facility is located 89 km from the

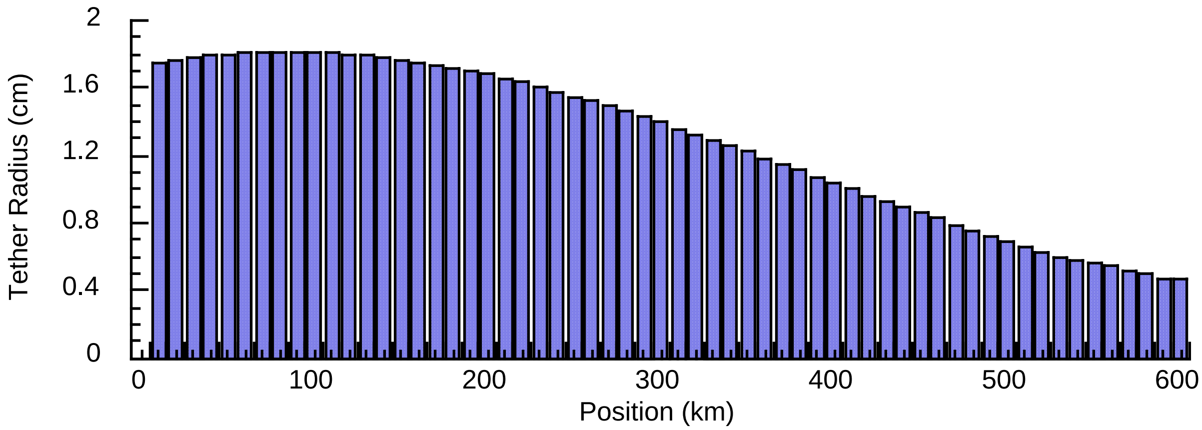


Figure 2. Radius of a stepwise tapered Spectra 2000 tether designed to support a 15 ton payload with a tip velocity of 3.42 km/s.

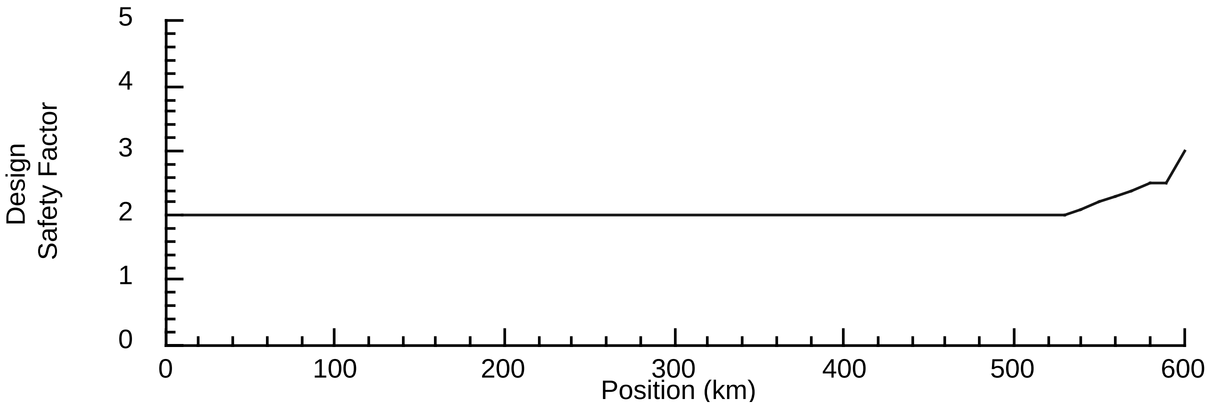


Figure 3. Design safety factor profile for the Spectra 2000 tether shown in Figure 2 (safety factor computed for nominal static loads). The safety factor is increased at the tether tip to provide protection against transient loads due to payload capture.

central station, so when the facility is at perigee, the station is at an altitude of 700 km and the tether tip is at an altitude of 100 km, moving at a velocity of approximately 4.1 km/s relative to the inertial frame.

LIFTether

The LIFTether concept seeks to reduce the required tether mass by decreasing the nominal tip velocity of the tether. In order to enable the tether to rendezvous with the payload, the velocity of the tether grapple vehicle and the section of tether nearest the tip is briefly increased just prior to rendezvous through utilization of aerobraking, as illustrated in Figure 4.

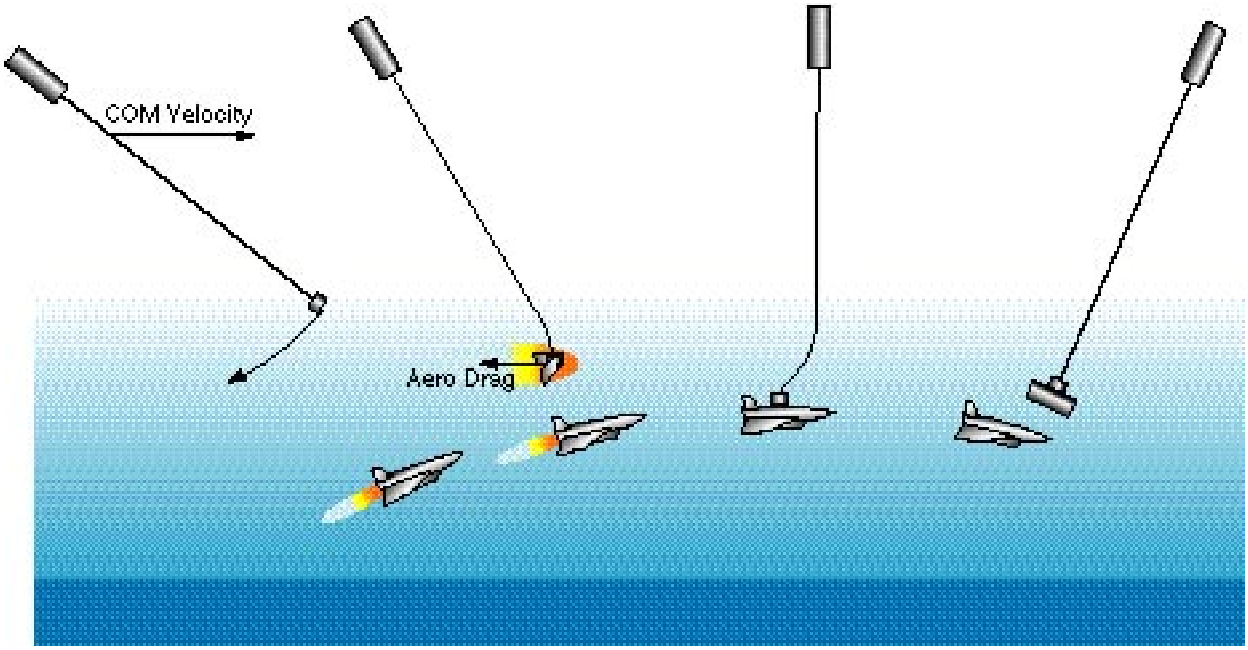


Figure 4. The LIFTether concept.

After the payload is captured, the tether pulls taught. Although the payload and the section of tether nearest the payload are moving at 3.5 km/s relative to the facility's center of mass, the bulk o the tether is rotating more slowly. Consequently, once the tether pulls taught, the tether is again rotating at a lower tip velocity of approximately 3.1 km/s. This enables us to design the bulk of the tether to be sized for a 3.1 km/s tip velocity, which reduces the mass of the tether considerably. The tether tip, however, must be designed with a higher safety factor to withstand the capture transients, and furthermore it must be designed to survive the loads and heating due to aerodynamic drag.

Figure 5 shows the tether taper for a design for a LIFTether. The bulk of the tether would be made of a high-strength polymer such as Spectra 2000 or PBO, but the bottom 20 km of tether would be constructed of Titanium-coated Silicon Carbide "TEXTRON" fiber, which has a density of 3090 kg/m^3 and a room-temperature tenacity of 4.7 GPa. The total tether mass is 526.4 Mg, or approximately 35 times the payload mass. The Station mass is 1650 Mg, or 110 times the payload mass. The total Tether Facility mass is 2177 Mg, or 145 times the payload mass.

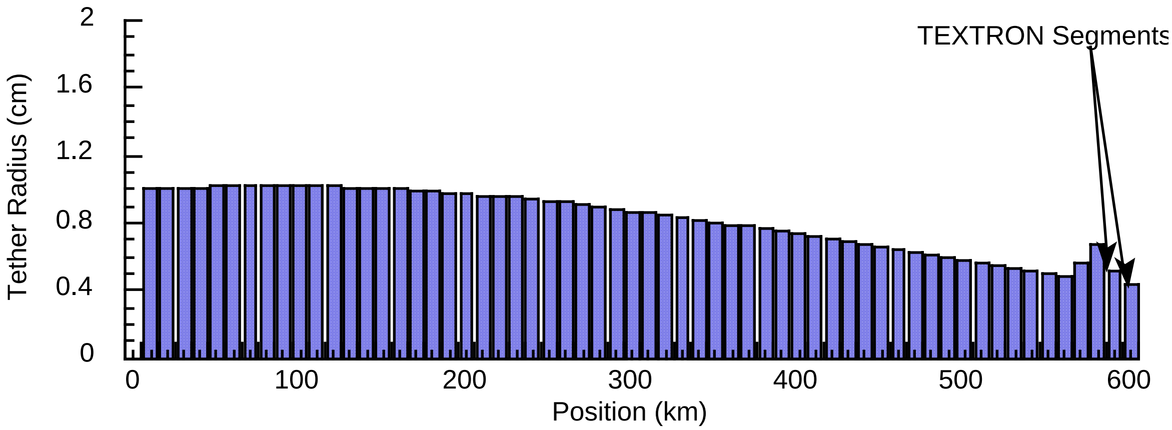


Figure 5. Stepwise tether taper for a LIFTether where the 20 km of tether nearest the grapple vehicle is made of Textron SiC coated with Ti.

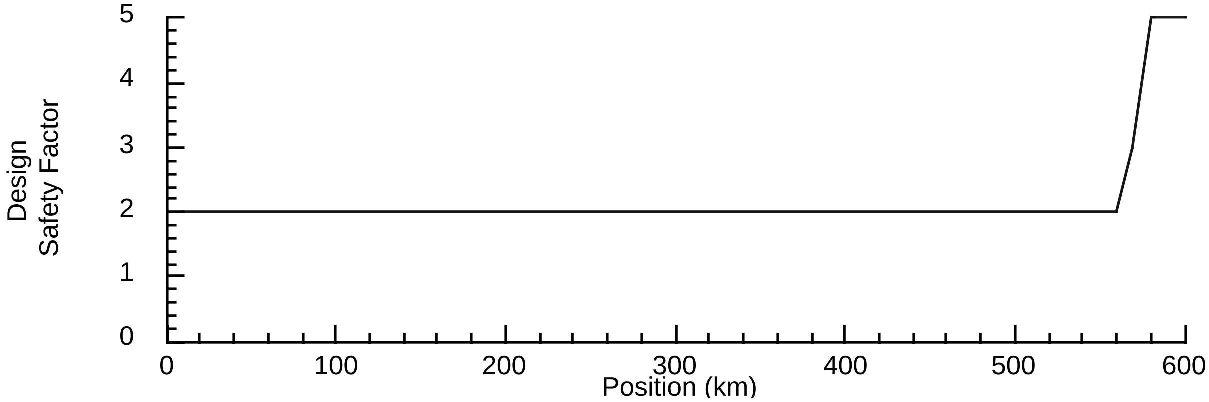


Figure 6. Design safety factor profile for the Spectra 2000 tether shown in Figure 5 (safety factor computed for nominal static loads). The safety factor is increased at the tether tip to provide protection against transient loads due to payload capture.

CardioRotovator

In the CardioRotovator concept proposed by Forward, a very long tether would be placed into an elliptical orbit, rotating twice per orbit (relative to the inertial frame), as shown in Figure 7. The rotation would be carefully controlled so that the tether would be oriented below the central facility when the tether is at apogee, and oriented above the facility when the tether is at perigee. This concept would

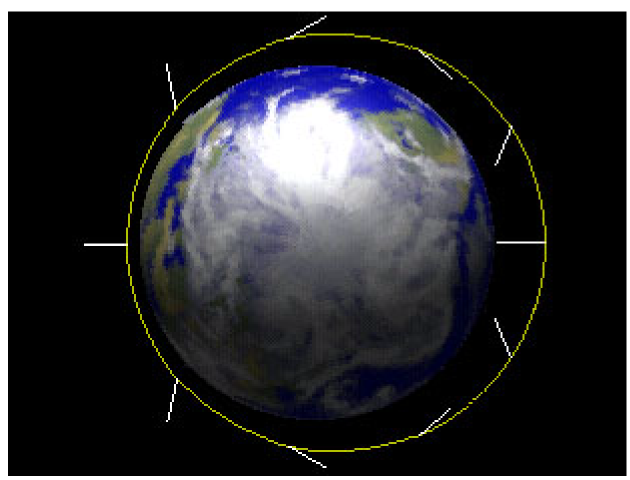


Figure 7. The Forward-CardioRotovator Concept.

have the advantage that, because the rendezvous between the tether tip would occur when the tether facility is at its apogee (and moving at its slowest speed relative to the Earth), the rotation velocity of the tether could be approximately 0.4-0.5 km/s slower than the tip velocity of an equivalent rotating tether in circular orbit. Due to the exponent-of-the-square dependence of the mass of a tapered tether on its tip velocity, this could significantly reduce the required tether mass.

However, this concept has several problems that likely render it impractical. First, the payload pickup occurs when the tether is at apogee. Unless the tether drops a return payload at the same time as it picks up the outbound payload, this will result in a drop in the perigee altitude of the tether facility. The mathematics of the orbital mechanics are such that the tether facility would require a total mass on the order of 1000-2000 times the payload mass in order to keep the tether facility from entering the atmosphere after a payload capture. Second, this approach would require that the tether rotation be very carefully controlled so that the tether is always above the facility at perigee. When the tether catches a payload, conservation of angular momentum will result in its angular velocity remaining constant, but its orbital period will change due to its exchange of momentum with the payload. Consequently, the tether facility would have to perform significant tether reeling maneuvers to maintain the proper synchronization between the tether rotation and its orbit. While this may be technically feasible, any failure would result in the tether impacting the atmosphere, causing loss of the tether system.

For these reasons, we conclude that the CardioRotovator concept is less favorable than the simpler Rotovator and LIFTether concepts, and it will not be analyzed further in this work.

Tether Facility Simulations

In order to examine and compare the feasibility of the Rotovator and LIFTether concepts for picking payloads up from a hypersonic airplane, we have used the TetherSim program to model these concepts during payload pickups from 100 and 80 km altitudes. The TetherSim program is a numerical simulation that includes models for orbital mechanics, tether dynamics, ionospheric density, geomagnetic fields, tether thermal behavior, and capture/release of payloads.[1] In order

---

[1] Hoyt, R.P., "Cislunar System Dynamics Verification Through Simulation", Appendix C in *Cislunar Tether Transport System*, Tethers Unlimited, Inc. final report on NIAC Phase I contract NIAC-07600-011.

to model the HASTOL concepts, the TetherSim code was extended to include models for atmospheric density, hypersonic aerodynamic drag on the tether, and aerodynamic heating of the tether. Figure 8 shows a screen capture of the TetherSim program simulating one of the HASTOL concepts.

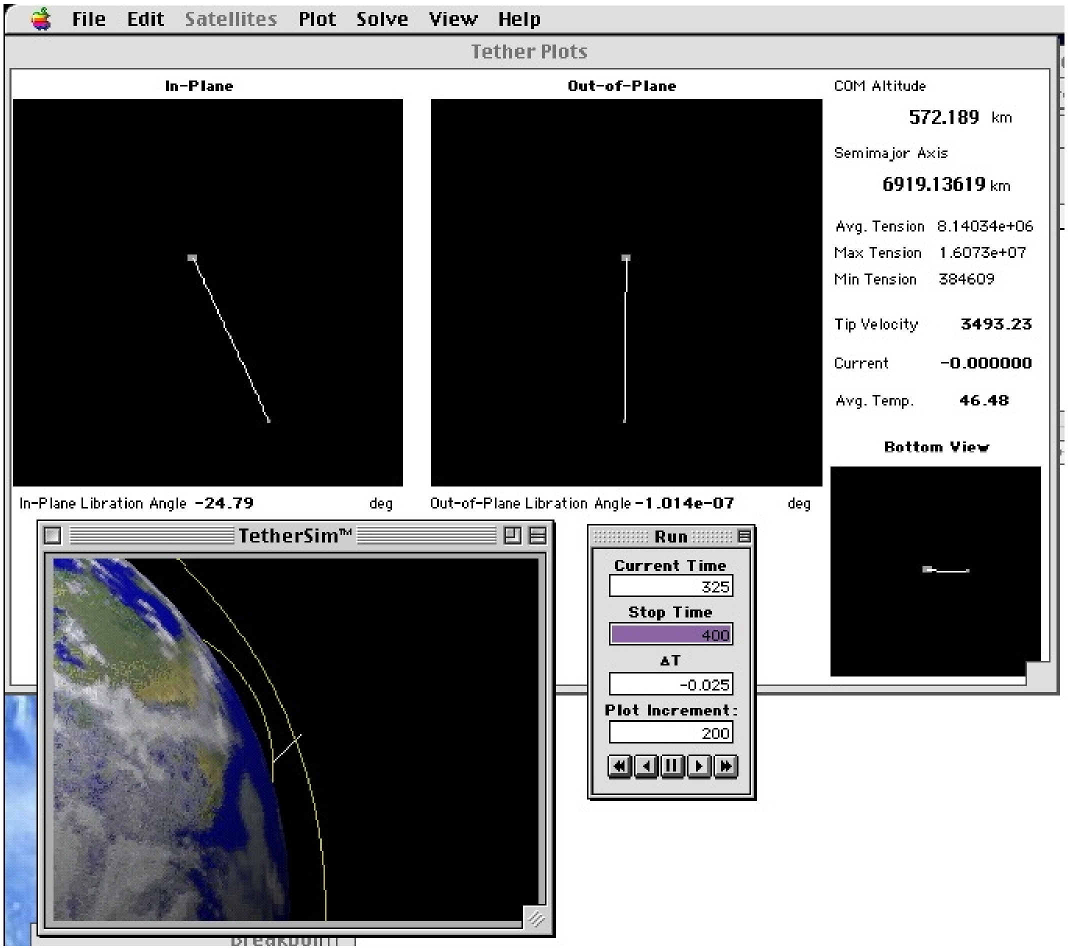


Figure 8. Screen capture of a TetherSim run.

Atmospheric Density Model

The model of the atmospheric density used was the NASA/GSFC MSISE 1990 model.[2] This model provides neutral densities and constituent densities across an altitude range of 0 to 1000 km. The model has the capability to calculate densities depending upon the date, time of day, and latitude and longitude data. In all of these simulations, we chose the date and time as mid-summer, and early morning, local time.

Hypersonic Drag and Heating Model

The drag and heat load on the tether was calculated using the MSISE atmospheric density model and a hypersonic model developed by Stuart Bowman and Mark Lewis at U. Maryland.[3] In calculating the drag and heating on the tether segments, the simulation assumed that the atmosphere is rotating with the Earth; this results in a relative velocity between the tether and the atmosphere that is approximately 0.5 km/s lower than would be calculated if one assumed that the atmosphere was motionless in the inertial frame.

Rotovator Simulation

The first scenario studied was a rendezvous between the all-Spectra 2000 Rotovator illustrated in Figure 2 and a hypersonic airplane at an apogee altitude of 100 km and a velocity of 4 km/s (Mach 13). Figure 9 shows the altitude of the tether tip during the rendezvous period. Figure 10 shows the velocity of the tether tip relative to the inertial frame and relative to the tether facility's center of mass. Figure 11 shows the temperature of the bottom portion of the tether. During the several-hundred seconds the tether tip spends within the upper atmosphere, the tether temperature increases only about 40°C. This temperature rise might be problematic for Spectra 2000, which loses strength rapidly with temperature. However, there exist several commercially-available materials, such as PBO (sold by Tyobo of Japan under the name ZYLON), that have strength-to-weight characteristics almost as good as Spectra 2000 and have significantly better temperature tolerance. PBO is also approximately 1.7 times as dense as Spectra, so a PBO tether would have a smaller diameter, and thus experience smaller drag and heating. Consequently, we conclude that the heat loading at 100 km is low enough that a tether could be constructed of currently-available high-strength polymers (with some form of AO-resistant coating) that could achieve this mission. Figure 12 shows the perigee altitude of the tether facility's center of mass before and after the payload pick-up. Because the payload is moving 3.5 km/s slower than the facility, the facility must transfer some of its orbital momentum and energy to the payload, and thus the facility's perigee drops by about 60 km. This perigee drop could be reduced by using a larger ballast mass on the central station.

---

[2] http://nssdc.gsfc.nasa.gov/space/model/atmos/msise.html. The GSFC web site provides FORTRAN code for this model. In this work, the code was translated into C++ for compatibility with the TetherSim code.

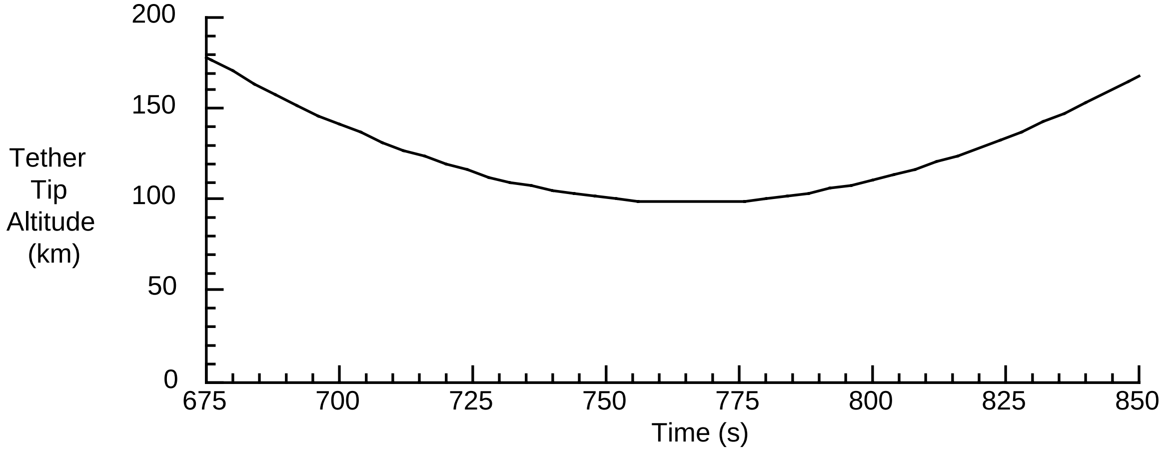


Figure 9. Altitude of the tether tip.

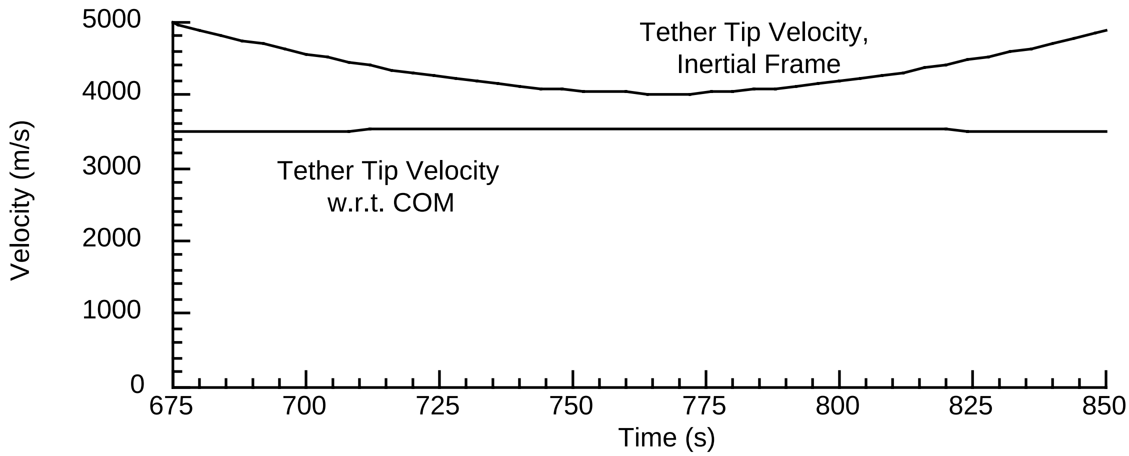


Figure 10. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass.

[3] Bowman, S. and Lewis, M.

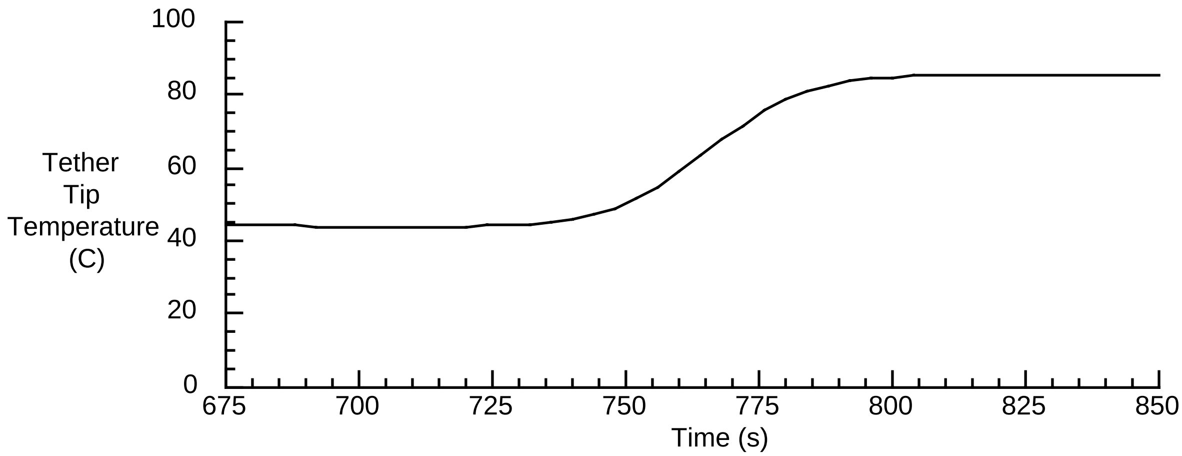


Figure 11. Temperature of the tether tip.

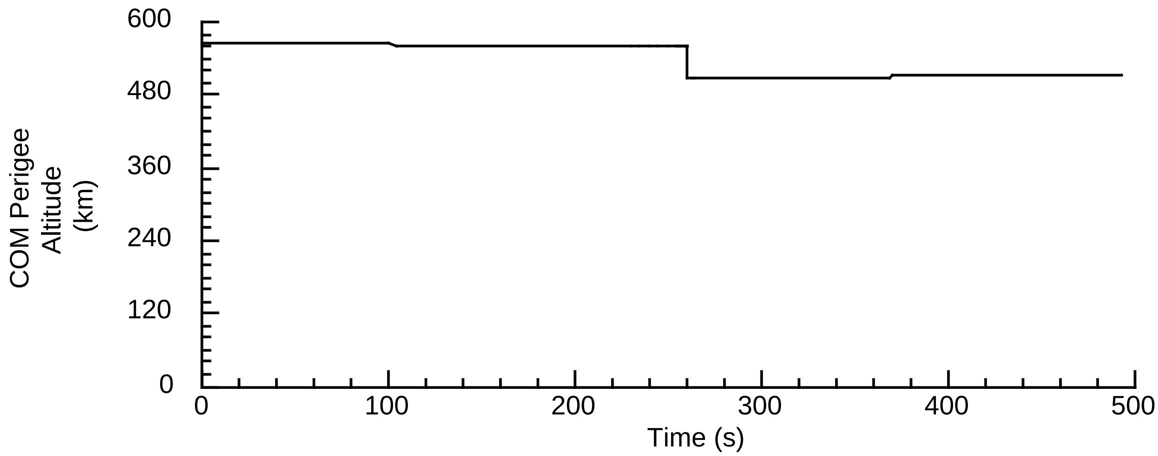


Figure 12. Perigee altitude of the tether facility.

LIFTether Simulations

Case A: All Polymer Tether

The next simulation was of of a LIFTether design composed of Spectra 2000 picking up a payload from a hypersonic airplane that reaches apogee at 80 km altitude with a velocity of 4.1 km/s (relative to an inertial frame). The tether taper and facility mass were identical to the Rotovator tether design, and the orbital velocity of the tether facility's center of mass was approximately 7.5 km/s. The simulation was initiated with the tether initially oriented parallel to its orbital velocity, rotating so that its tip velocity was approximately 3.0 km/s relative to its center of mass. Figure 13 shows the altitude of the tether tip during the rendezvous.

As the tether dropped towards the local vertical, its tip velocity increased to approximately 3.2 km/s due to gravity gradient forces. As the grapple vehicle entered the upper atmosphere, it extended retractable aerobraking panels to increase its cross-sectional area to 16 square meters. Figure 14 shows the velocity of the tether tip in the inertial frame and its velocity relative to the tether system's center of mass during the period when the grapple vehicle is below 130 km altitude. Examination of the trace of tether tip velocity with respect to the center of mass reveals that the aerobraking succeeded in increasing the tip velocity an additional 0.3 km/s, giving it a total velocity of approximately 3.5 km/s relative to the center of mass. Because the tether tip is rotating backwards relative to the center of mass, this gave it a total velocity in the inertial frame of 4 km/s.

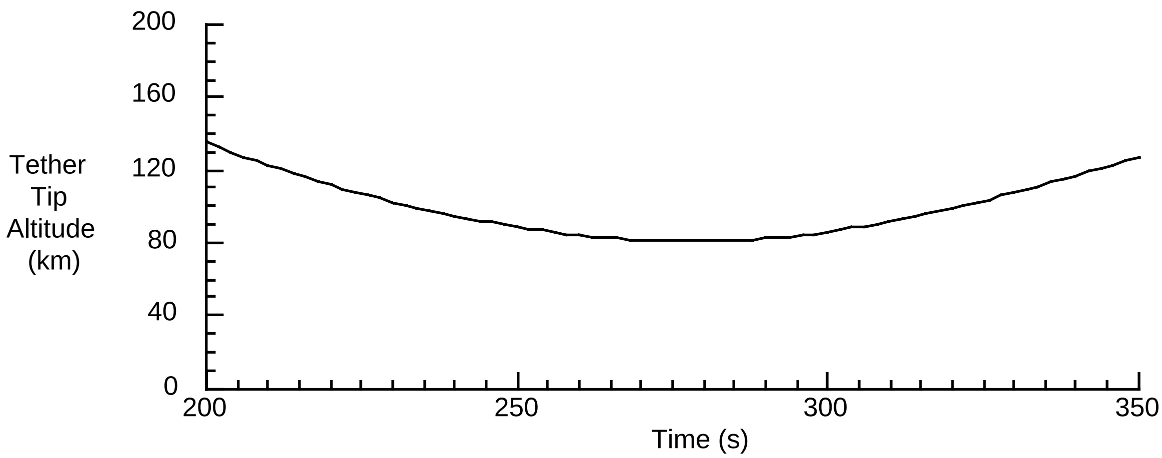


Figure 13. Altitude of the tether tip. High-strength polymer LIFTether reaching down to 80 km.

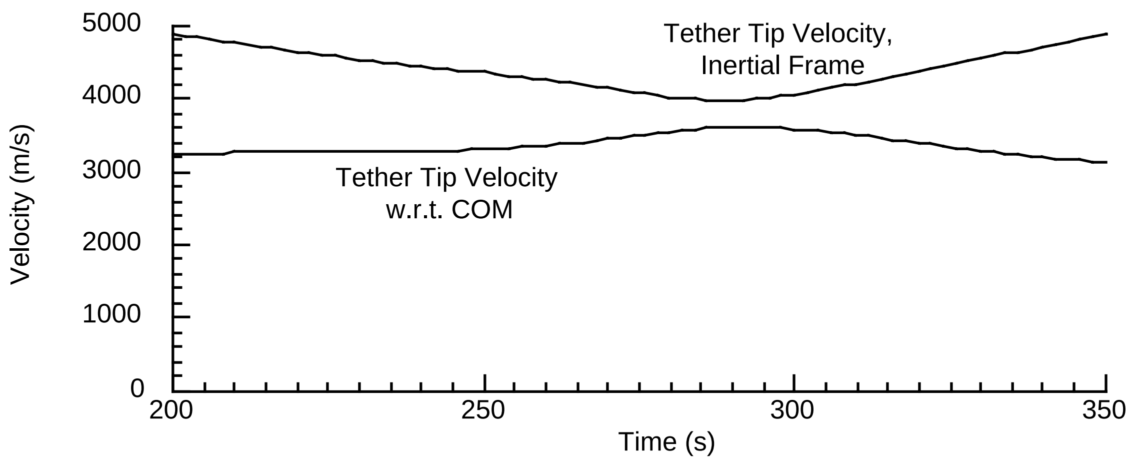


Figure 14. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass. High-strength polymer LIFTether reaching down to 80 km.

Figure 15 shows the temperature of the bottom section of tether during the rendezvous. At this low altitude, aerodynamic heating increases the tether's temperature by almost 1000 K. Since Spectra 2000 melts at approximately 180°C, Spectra clearly would not survive this maneuver. Even PBO/Zylon, which can operate at temperatures over 600°C, would not suffice. Consequently, for tether-airplane rendezvous at such low altitudes, the tether tip must be constructed of a high strength material with higher temperature tolerance and higher heat capacity.

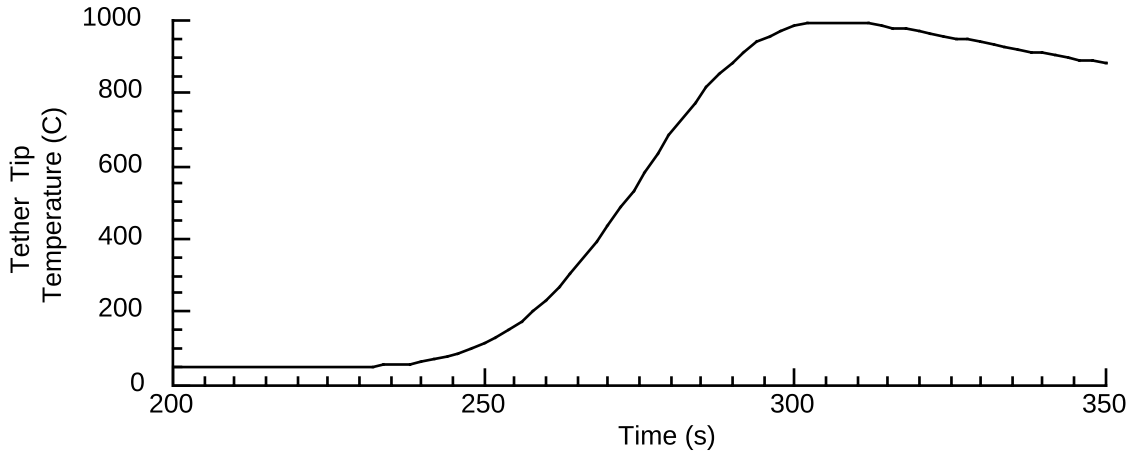


Figure 15. Temperature of the tether tip. High-strength polymer LIFTether reaching down to 80 km.

Case B: High-Temperature Composite Tether Tip

The rendezvous at 80 km was simulated again, this time using the LIFTether design with the bottom 20 km of tether constructed of high-temperature tolerant Titanium-coated TEXTRON SCS-6 Silicon Carbide fiber. Figure 16 shows the altitude of the tether tip during the rendezvous, and Figure 17 shows the velocity of the tether tip relative to the inertial frame and relative to the tether facility's center of mass. As in Case A, the trace of the tether tip velocity relative to the center of mass shows that the aerobraking increases the tether tip velocity. However, the ΔV achieved by the aerobraking is smaller than in Case A. This is because although the radius of the bottom portion of the LIFTether shown in Figure 5 is roughly the same as the bottom portion of the all-Spectra Rotovator shown in Figure 2, the TEXTRON material is over three times as dense as Spectra 2000, so the bottom 20 km of the LIFTether is 4 times as massive as the bottom 20 km of the all-Spectra tether. Consequently, the aerobraking force is less effective at decelerating the heavier TEXTRON tether segments.

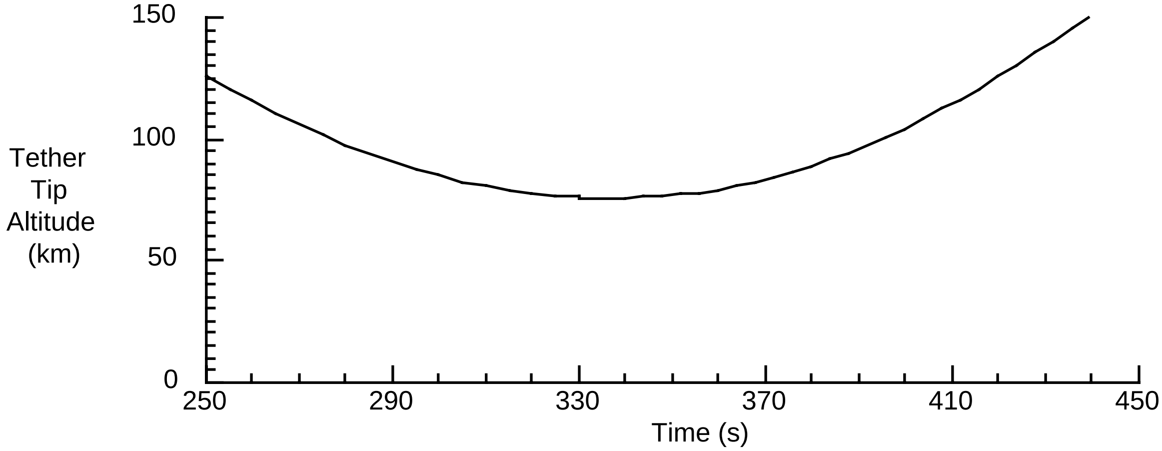


Figure 16. Altitude of the tether tip. CAST/LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

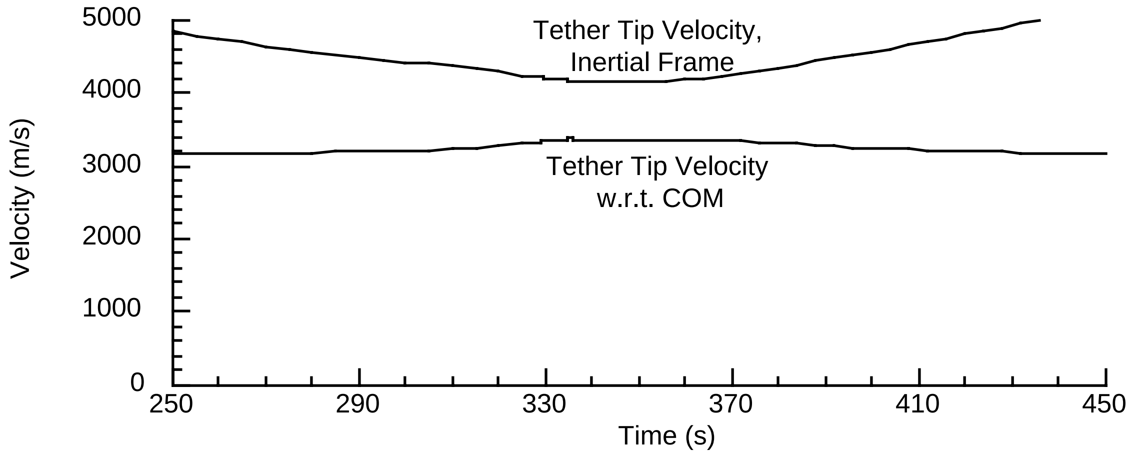


Figure 17. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

Figure 18 shows the increase in temperature of the TEXTRON tip of the LIFTether. Using this high-temperature composite, the temperature increase during the period the tether is in the upper atmosphere is only about 40°C. The large change relative to the all-Spectra tether is due to the larger mass and higher heat capacity of the TEXTRON material. This temperature rise is well within the capabilities of the TEXTRON material.

The load level on the section of tether nearest to the grapple vehicle is shown in Figure 19. Immediately after payload capture, the tether load level increases to approximately 0.4 (safety factor of 2.5), rises over half a minute to 0.5 (safety factor of 2.0), then slowly drops back down to 0.4. Thus even despite the tether dynamics resulting from sudden loading of the tether as the payload is captured, the tether remains above a safety factor of 2.0.

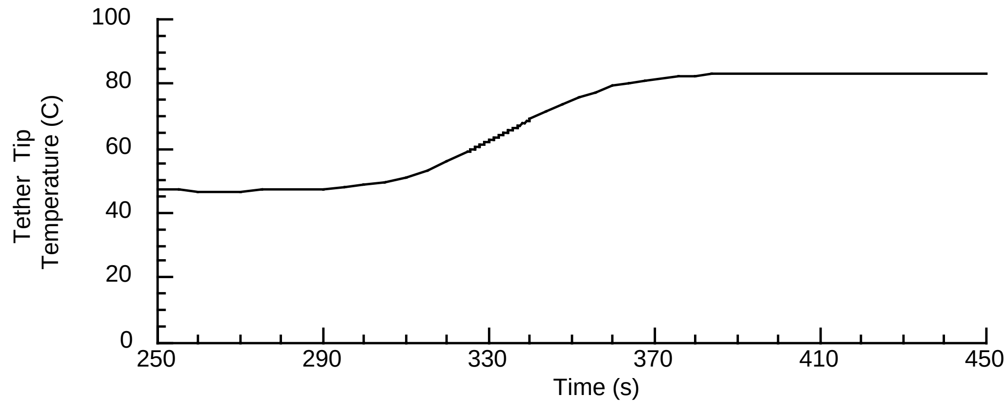


Figure 18. Temperature of the tether tip. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

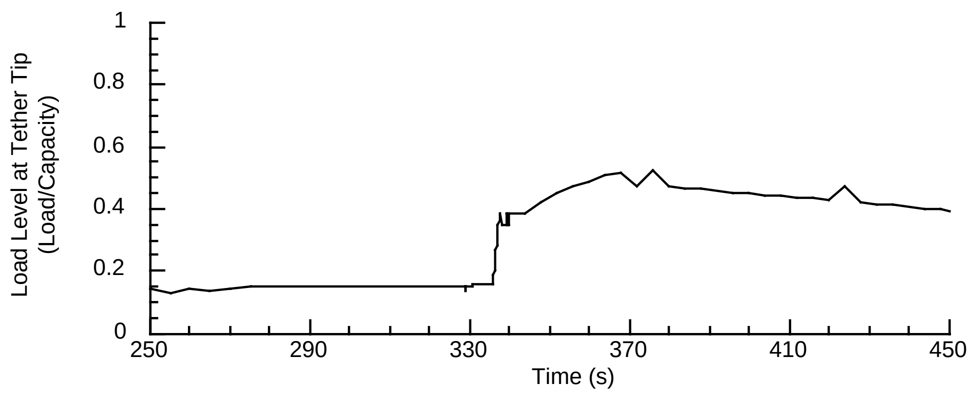


Figure 19. Load level at the tether tip before and after tether capture. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

Shows the perigee altitude of the tether facility's center of mass before and after the payload capture. Because the payload is moving approximately 3.5 km/s slower than the tether facility, when the tether captures the payload, the tether facility transfers some of its orbital momentum and energy to the payload. As a result, the tether facility's perigee drops from 616 km to 506 km. This large change in the orbit results from the fact that the LIFTether system modeled had a total mass of only 145 times the payload mass. To keep the tether from falling too deep into the atmosphere, this facility would either have to ensure that the tether is oriented above the facility when it is at perigee or reel in about 100 km of tether within half an orbit. As both of these requirements would likely be difficult to achieve, a better solution would be to increase the total mass of the tether facility so that its orbit is not so strongly perturbed by the payload capture. Thus, although the LIFTether concept can reduce the required tether mass, the total system mass would likely have to be equal to the mass of a Rotovator system due to purely orbital mechanics considerations.

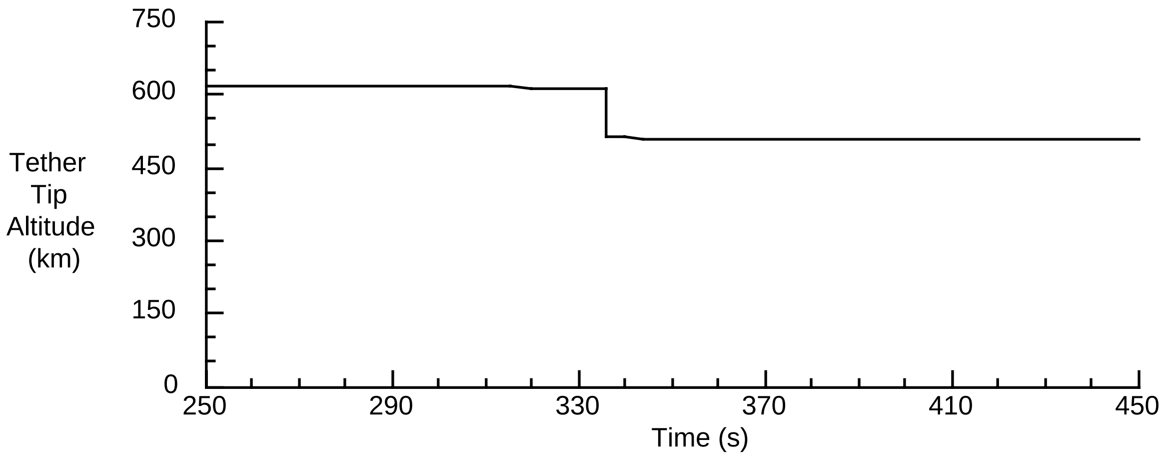


Figure 20. Perigee altitude of the tether facility's center of mass. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

Rendezvous Window

In any rotating tether transport system, one of the most challenging tasks will be to enable the rendezvous between the payload and the tether tip. For the tether to successfully capture the payload, the payload and tether grapple vehicle must meet with the same position and the same velocity. Because the payload is in free fall, and the tether is rotating, the payload and grapple vehicle will experience a relative acceleration equal to $= V_{tip}^2/L$, where V_{tip} is the velocity of the tether tip relative to the tether facility's venter of mass, and L is the distance from the tether tip to the center of mass. In the HASTOL tether designs described above, V_{tip} is approximately 3.5 km/s, and L is approximately 500 km, so this acceleration is about 2.5 gees. If neither grapple nor payload perform any maneuvering, the two will coincide only instantaneously, which is a rather small rendezvous window.

Fortunately, it may be possible to extend this rendezvous window to a period of several seconds or more by using tether deployment from the grapple vehicle. In this approach, the grapple vehicle will contain a tether deployer and a tether brake. Prior to the rendezvous, the grapple vehicle will wind up some of the tether into the deployer. As the tether nears the bottom of its swing, the payload will use its guidance and thrusters to adjust its trajectory so that it will meet up with the grapple vehicle. When the payload and grapple vehicle reach their closest approach to each other, the grapple vehicle immediately releases the brake on the tether deployer and allows the tether to deploy at as low a tension as possible. This will put the grapple vehicle into an almost-free fall trajectory which will match the trajectory of the payload, as illustrated in

Figure 21. The payload can then maneuver to close the gap and secure itself to the grapple vehicle. The length of the rendezvous window will therefore be determined by the amount of tether stored in the deployer, with the maximum window equal to $\Delta t = \sqrt{(2l/a)}$.

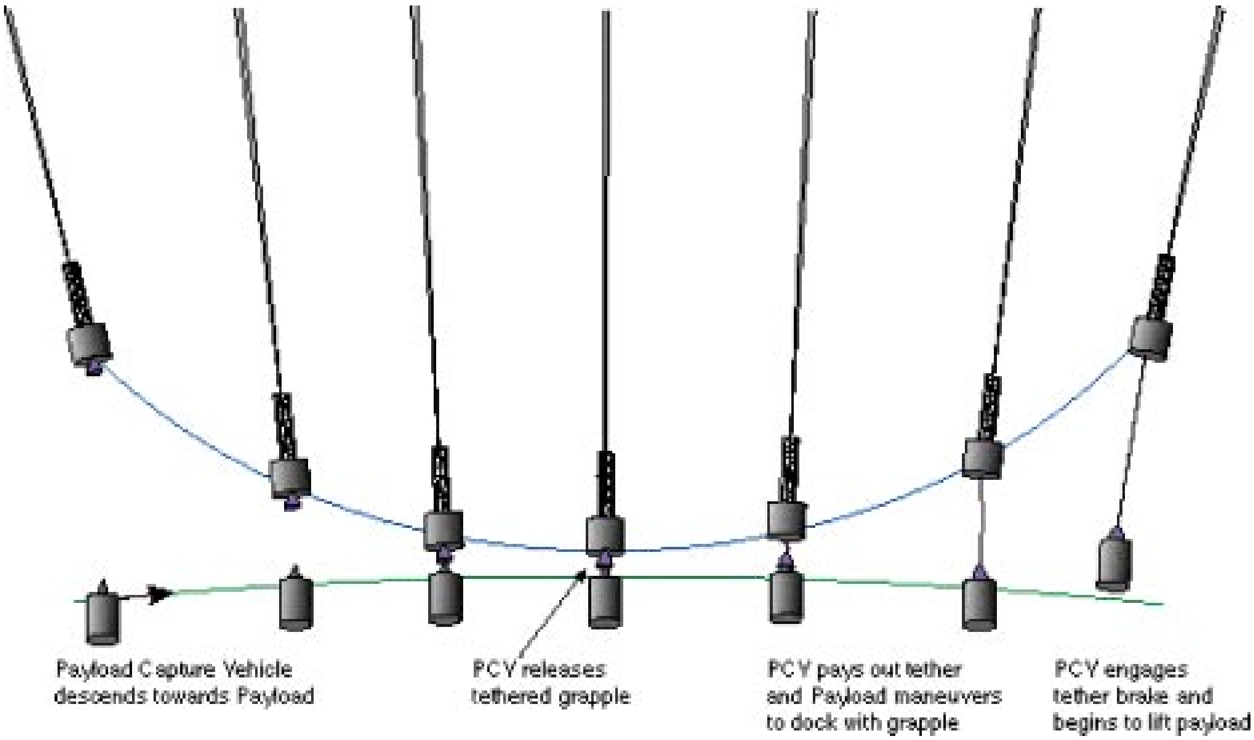


Figure 21. Schematic of tethered-grapple method for increasing docking window.

Using TetherSim, we have investigated this maneuver for a HASTOL system in which the Spectra-2000 tether illustrated in Figure 2 picks a payload up from a 100 km, 4 km/s apogee. In this simulation, the payload was launched into a trajectory that would meet up with the tether tip. Once they came into close proximity, the grapple vehicle released the tether brake and allowed tether to pay out at very low tension for five seconds. At that point, the grapple vehicle captured the payload and halted the tether deployment. Figure 22 shows the relative separation between the payload and tether tip in the x and y directions. This plot shows that the tether deployment maneuver extends the rendezvous window to several seconds. The length of tether deployed in this time was 486 meters. Figure 23 shows the tether load level at the grapple vehicle. During the tether deployment, the tension is essentially zero. When the grapple vehicle stops deploying tether, however, it experiences a relatively strong transient tension spike up to about 70% of

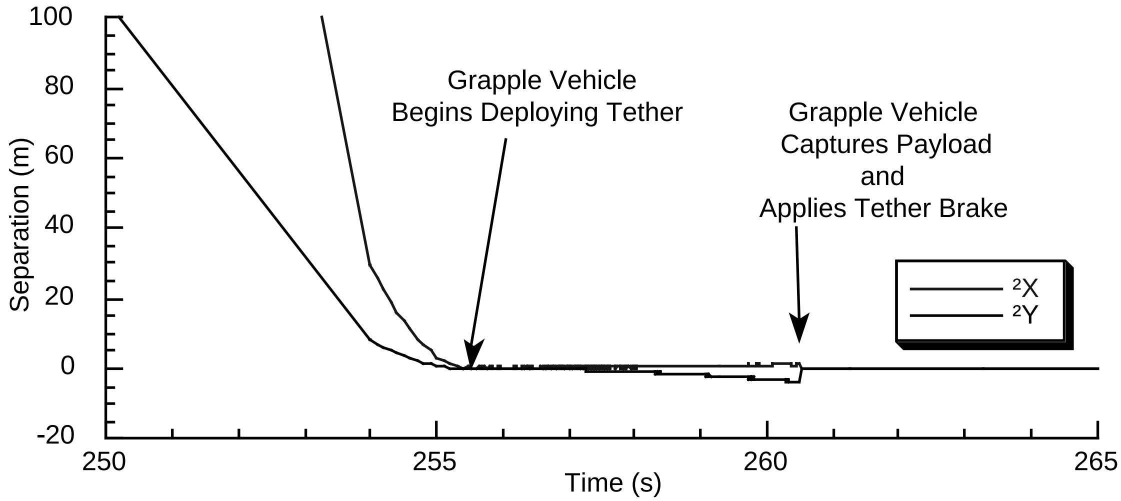


Figure 22. Relative separation of grapple vehicle and payload, with a tether deployment maneuver to extend rendezvous window.

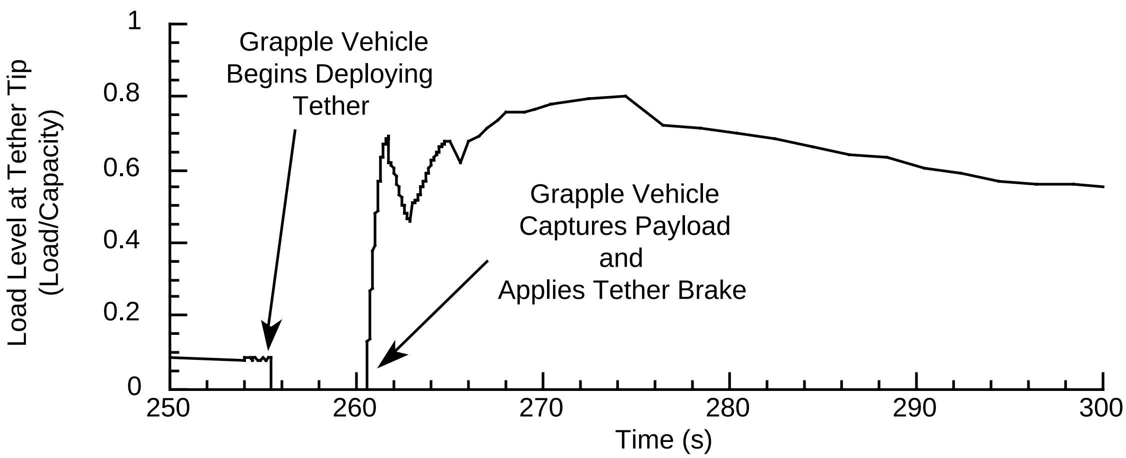


Figure 23. Load level on bottom segment of tether, with a tether deployment maneuver to extend rendezvous window.

capacity, followed by a longer period transient that peaks at about 80%. These higher tension transients result from the fact that the deployment maneuver allows the payload and grapple to accelerate away from the tether facility for several seconds, and thus the tether must apply a larger force to them to accelerate them into the tether rotation once the deployment is halted. This result indicates that the portion of the tether near the tether tip should be designed with an even higher safety factor to provide more margin for these tension transients.

CONCLUSIONS

We have developed analytical designs of three tether facility concepts for the HASTOL system. The CardioRotovator concept was eliminated due to the high facility masses required to keep it in orbit and the complexity of maintaining a proper synchronization between its rotation and orbit. A Rotovator tether facility designed to pick payloads up from a 100 km, 4 km/s apogee would require a total mass of approximately 200 times the payload mass, with the tether massing about 90 times the payload. Simulations of the Rotovator and a LIFTether designed to pick payloads up from a 80 km, 4.1 km/s apogee indicate that utilization of aerodynamic drag might enable a LIFTether design to reduce the amount of tether mass required relative to the Rotovator. However, the primary mass driver for the system is the amount of total facility mass needed to keep the station and tether from deorbiting after catching a payload. Thus, although a LIFTether could minimize the tether mass, it does not significantly reduce the total system mass. Moreover, since the density of the upper atmosphere varies significantly with solar conditions and other phenomena, accurately predicting and controlling a LIFTether would likely prove to be rather difficult. Consequently, we conclude that the most viable tether concept for the HASTOL system is a rotating tether designed to pick payloads up from as high an altitude as the hypersonic airplane can reach. In addition, we investigated the use of tether deployment to increase the window of opportunity for rendezvous between the payload and tether tip, and found that the rendezvous window can be extended to a period of several seconds or more, depending on the length of tether that can be deployed. This maneuver will, however, result in larger tension transients, and thus will require higher safety factors for the portions of tether nearest to the grapple vehicle.

APPENDIX 4
HYPERSONIC AIRPLANE SPACE TETHER ORBITAL LAUNCH (HASTOL) SYSTEM - NIAC FELLOWS MEETING

9 NOVEMBER 1999

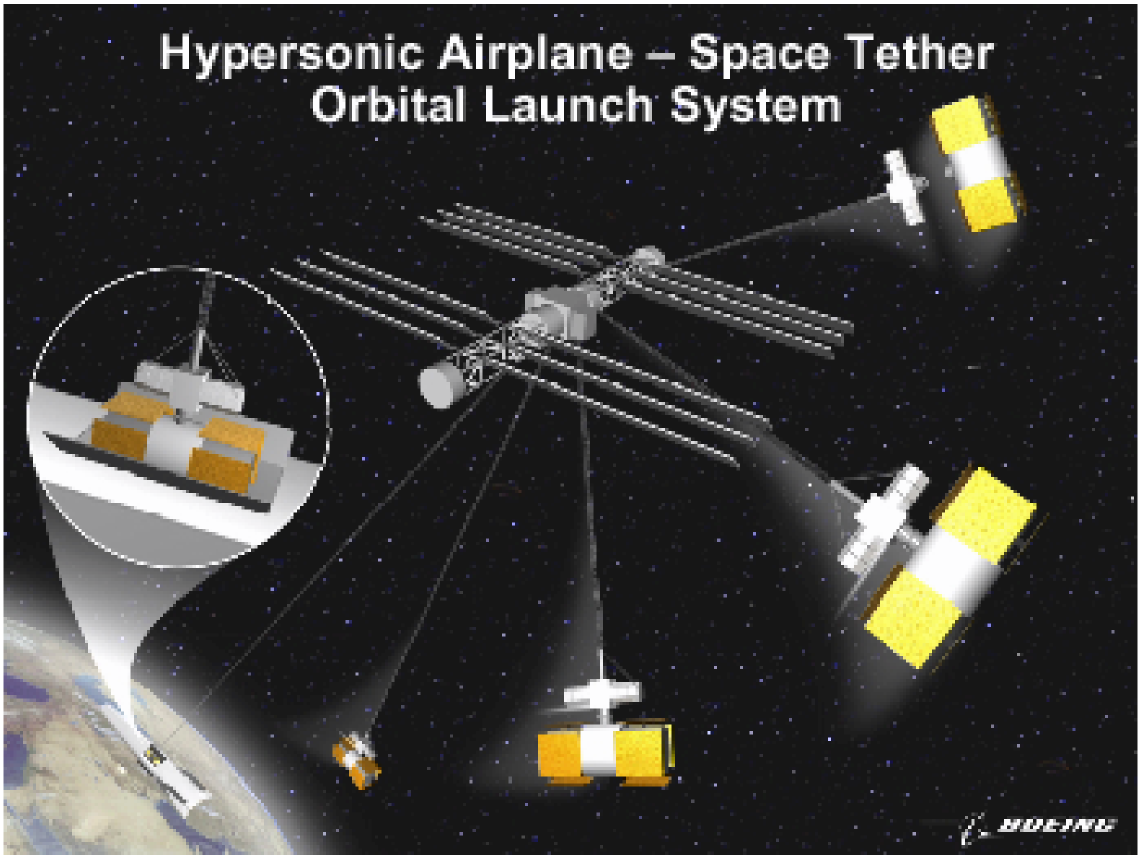
NIAC Fellows Meeting
Atlanta, GA
9 November 1999

Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System

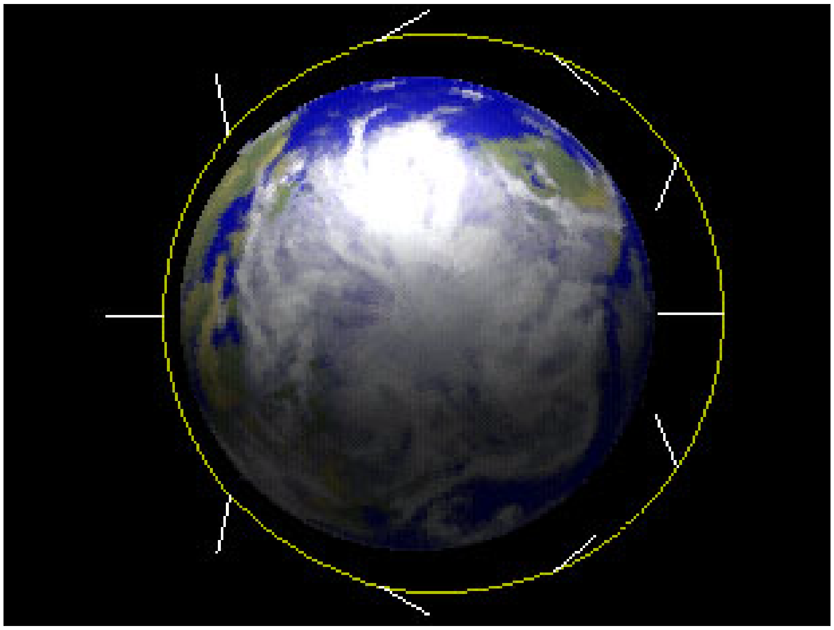
Thomas J. Bogar, Boeing - Phantom Works
Robert L. Forward, Tethers Unlimited, Inc.
Michal E. Bangham, Boeing - Huntsville
Mark J. Lewis, University of Maryland

Discussion Topics

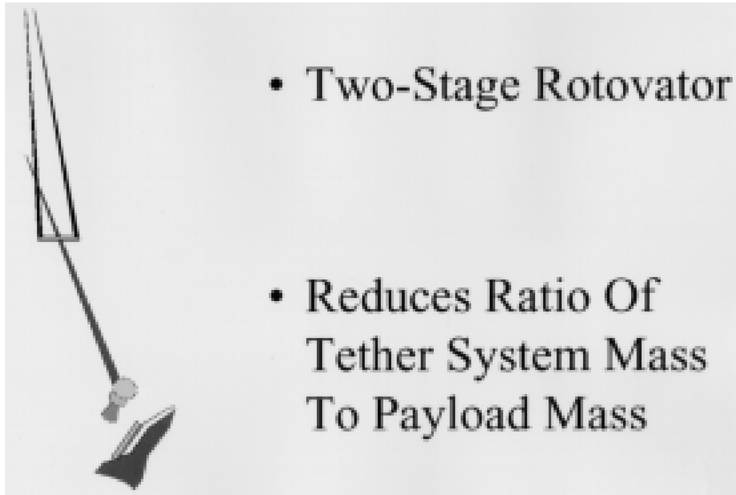
- **HASTOL Concept Overview**
- **Hypersonic Vehicle Description**
- **Trajectory Analysis Results**
- **Tether Design Considerations**



CardioRotovator Concept



Tillotson Two-Tier Tether (T4) Concept



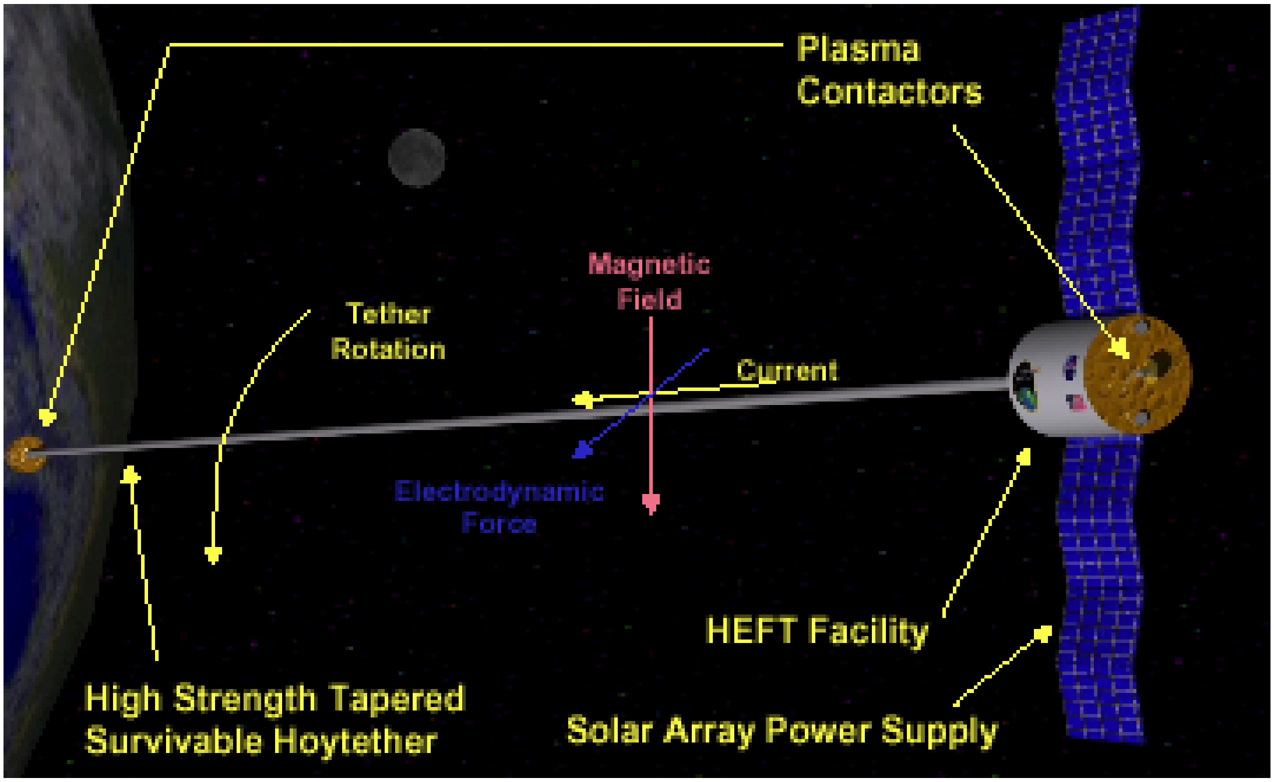
Rotovator Tether Mass Ratios

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra ™	2x	10x
400	6878	7614	2494	4650	15.0	10.4	2.4	0.37
500	6978	7559	2749	4340	14.0	16.7	4.2	0.56
600	7078	7506	3006	4030	13.0	27.1	5.9	0.65
700	7178	7453	3263	3720	12.0	44.0	8.2	0.73
800	7278	7402	3522	3410	11.0	71.8	11.6	0.90
900	7378	7352	3782	3100	10.0	117.6	16.3	1.07

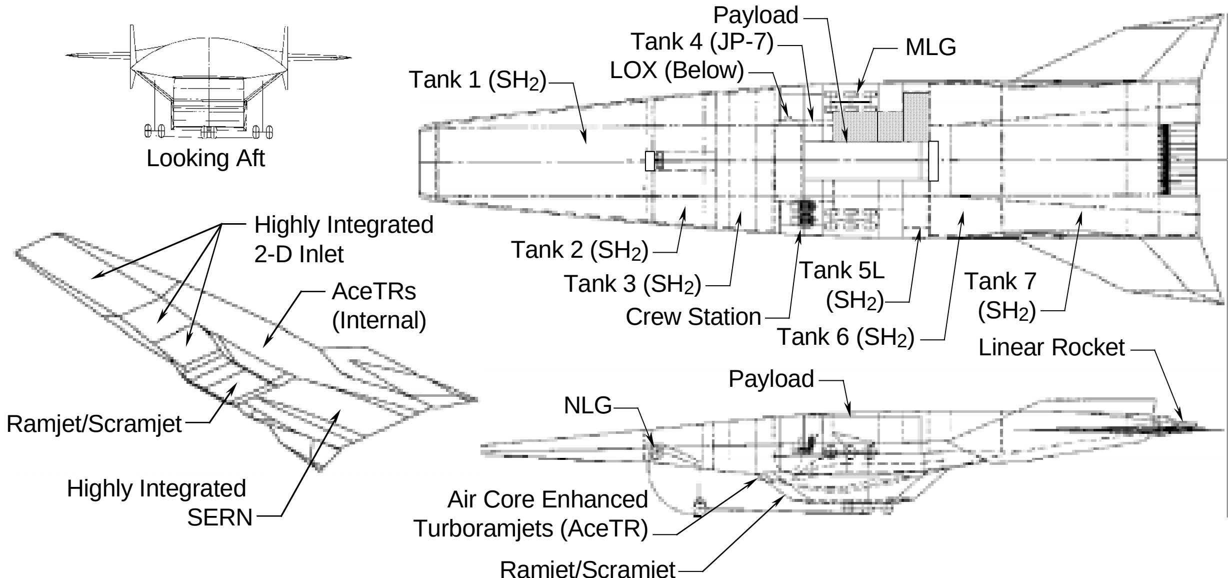
CardioRotovator Tether Mass Ratios

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Tip Accel.	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	a	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s^2)	(m/s)	Mach	Spectra	2x	10x
1000	7478	7147	2076	0.43	4601	14.8	10.8	3.1	0.39
1200	7678	7004	2440	0.50	4094	13.2	22.2	5.2	0.55
1400	7878	6868	2789	0.56	3608	11.6	44.7	8.4	0.75
1600	8078	6737	3124	0.61	3143	10.1	87.8	13.4	0.97
1800	8278	6611	3445	0.66	2695	8.7	168.5	21.0	1.24

High-strength Electrodynamic Force Tether (HEFT) Facility

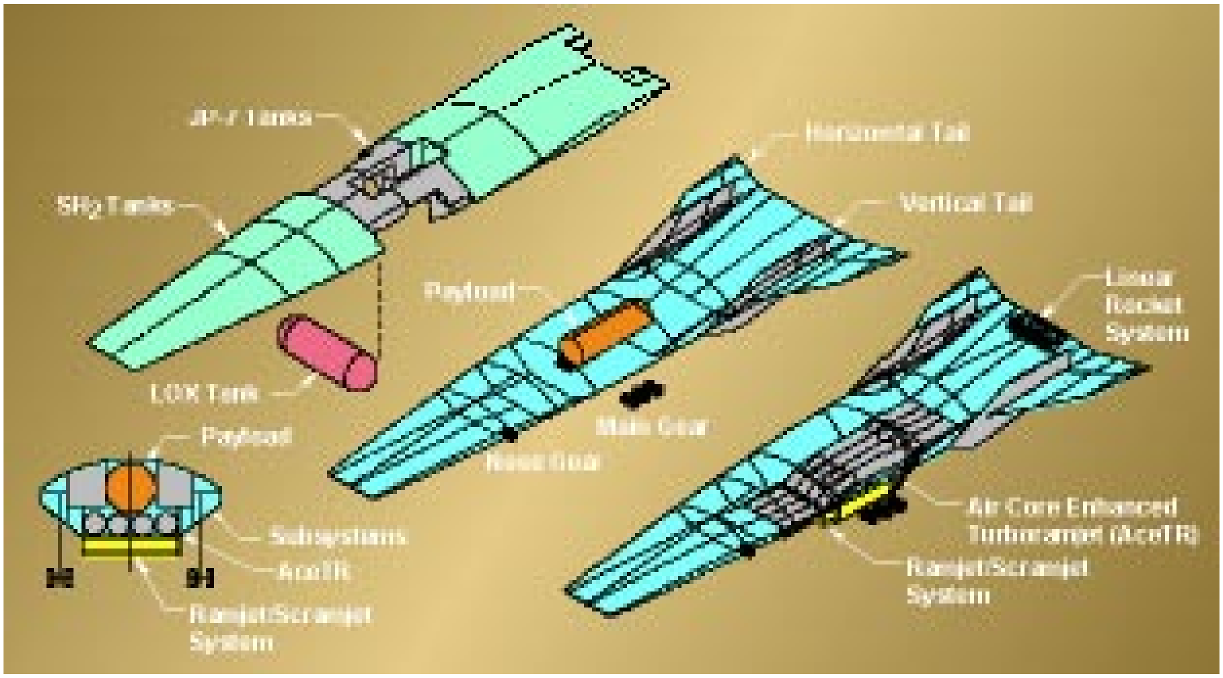


Dual-Fuel DF-9 Dual Role Vehicle

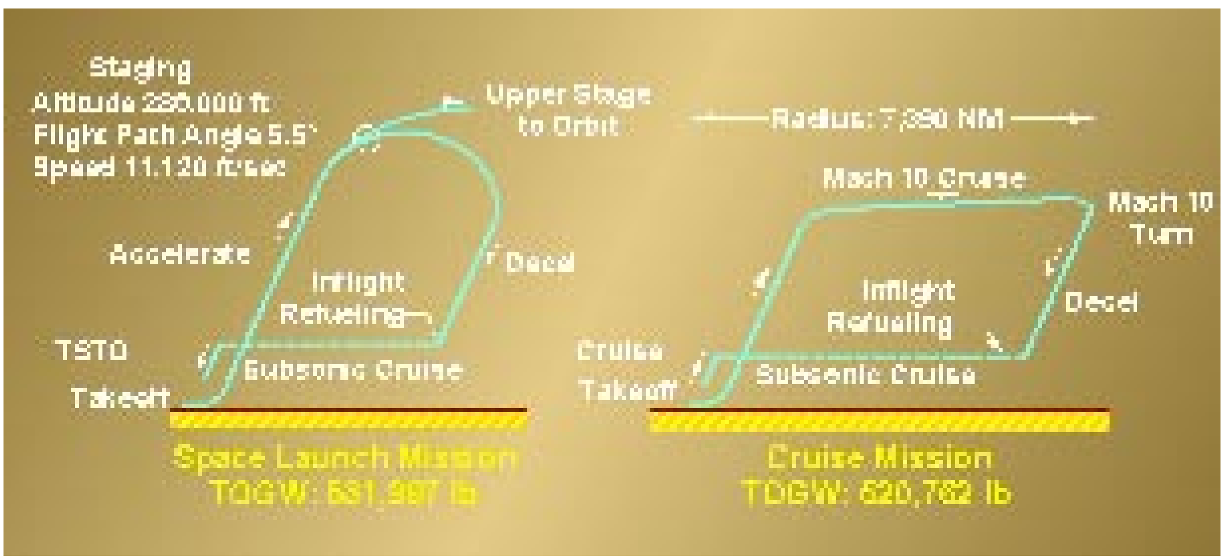


GP94070004.ppt

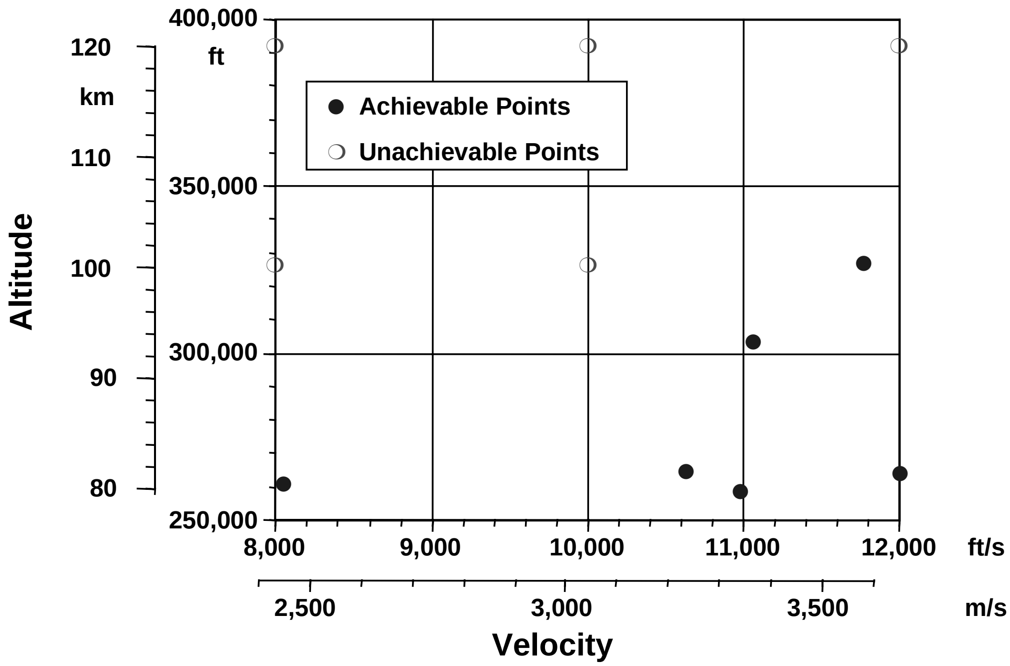
Dual-Fuel DF-9 Dual Role Vehicle



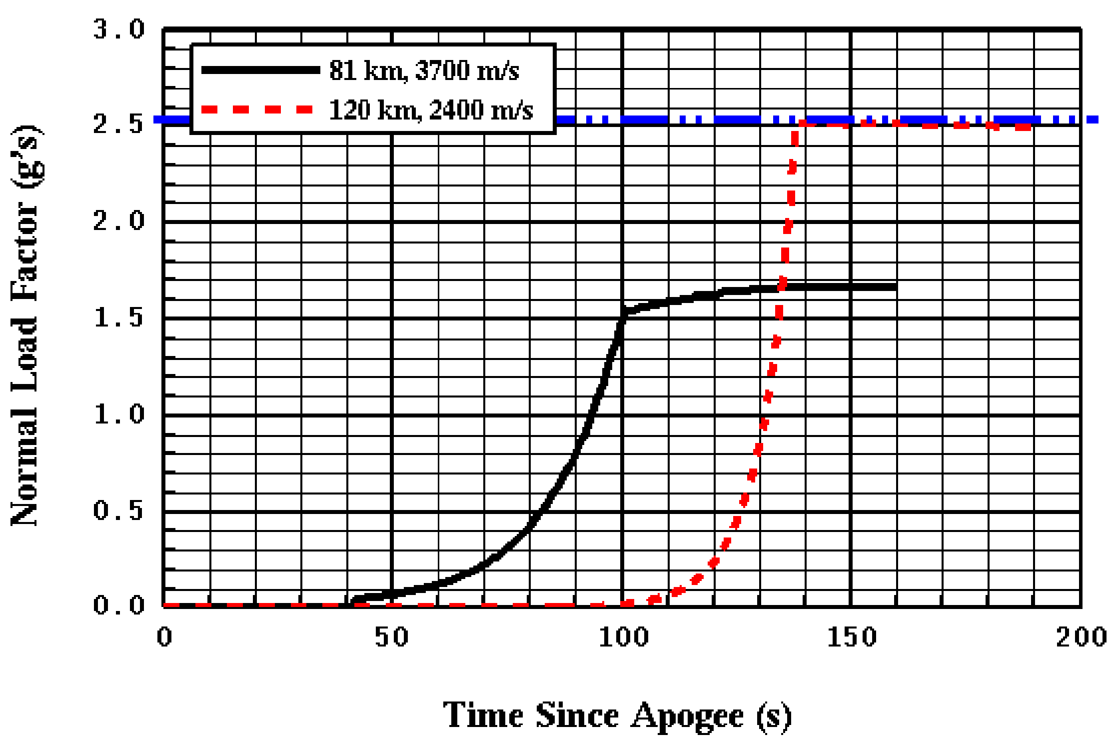
Dual-Fuel DF-9 Performance



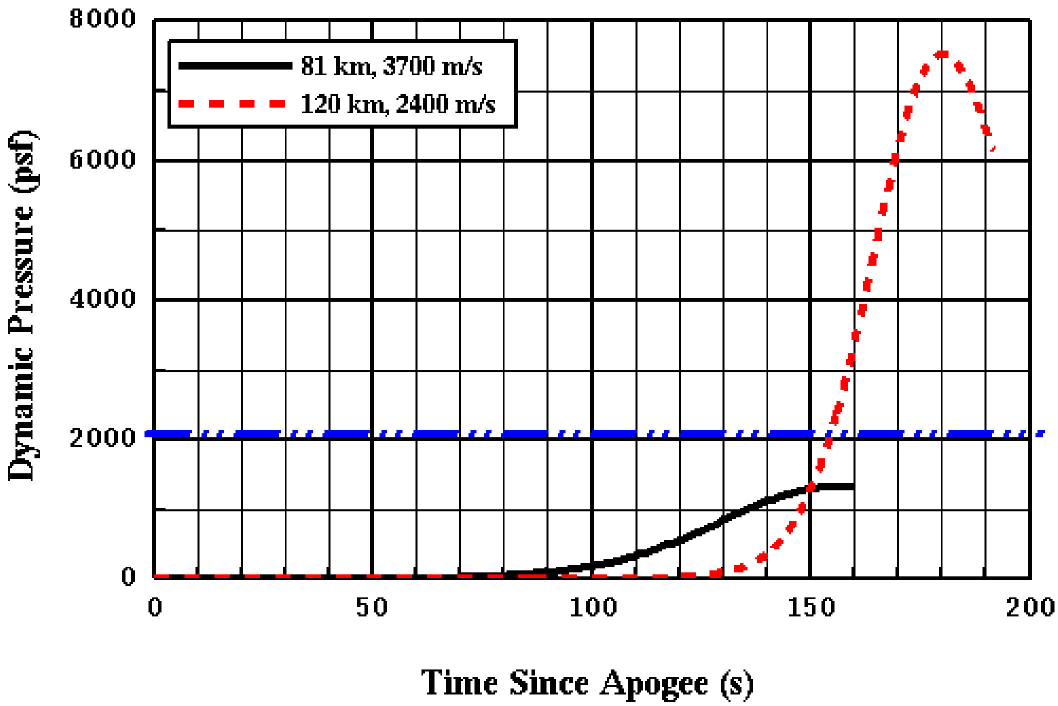
Matrix of Payload Transfer Points Analyzed



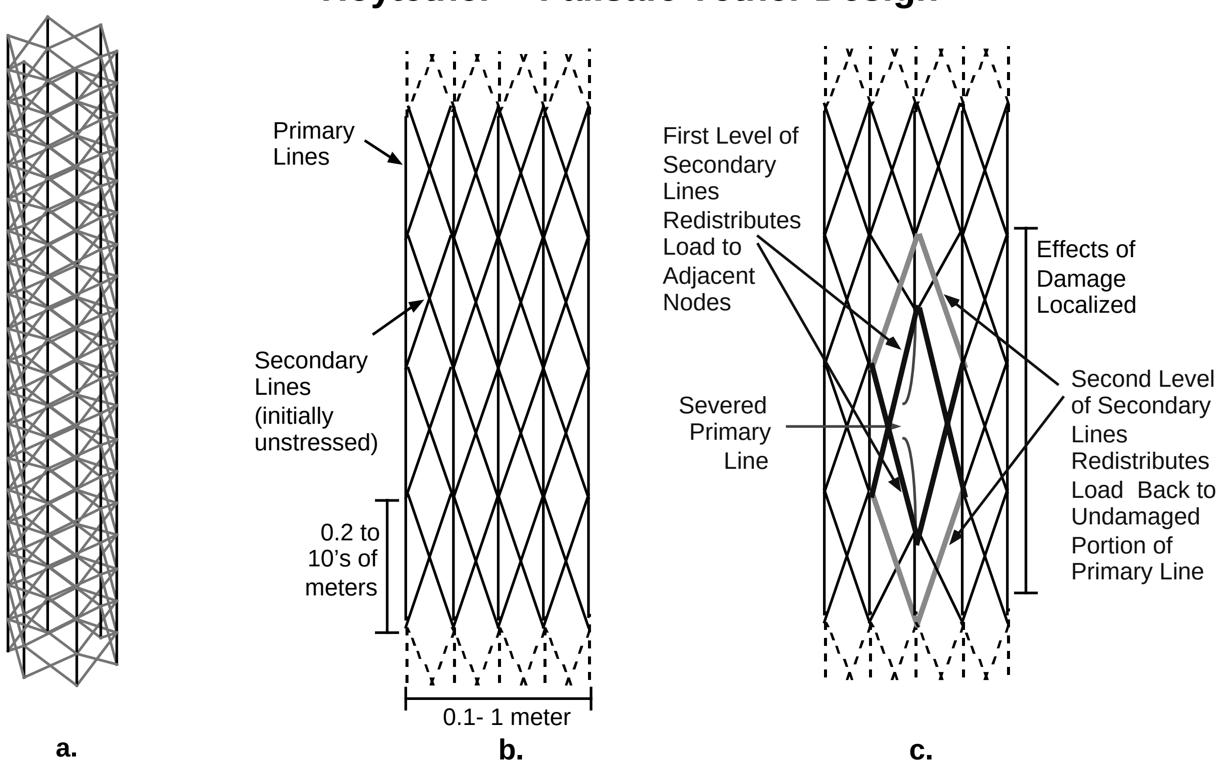
Normal Load Factor Along Descent Trajectory



Dynamic Pressure Along Descent Trajectory



Hoytether™ Failsafe Tether Design

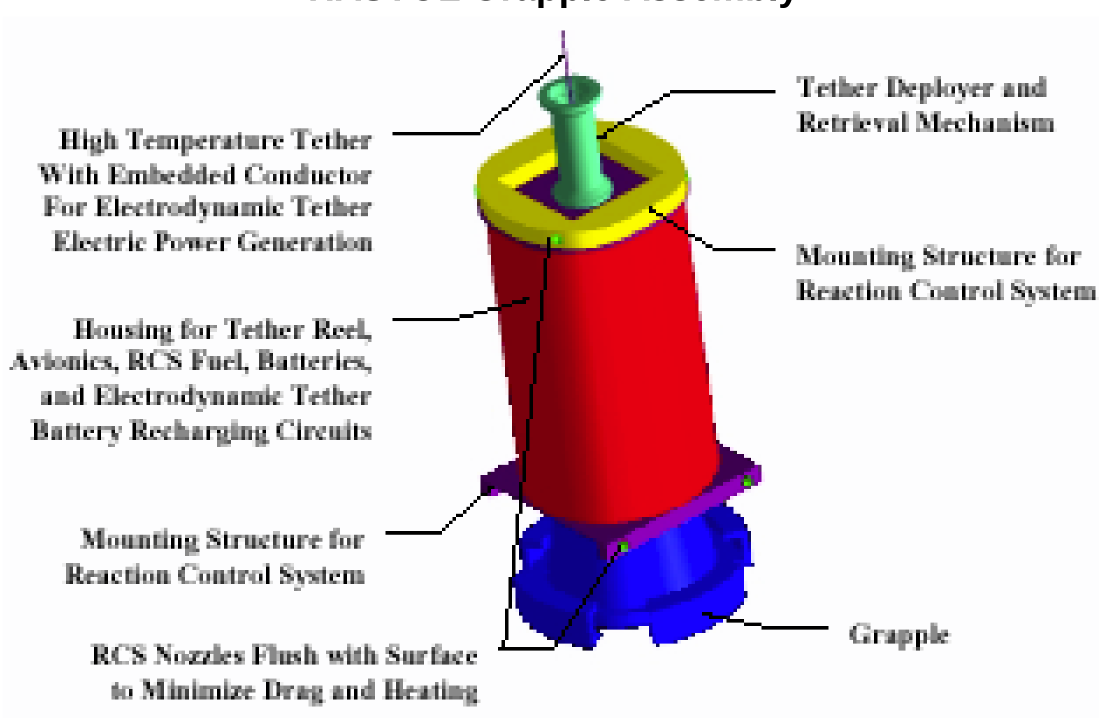


High Temperature Tether Materials

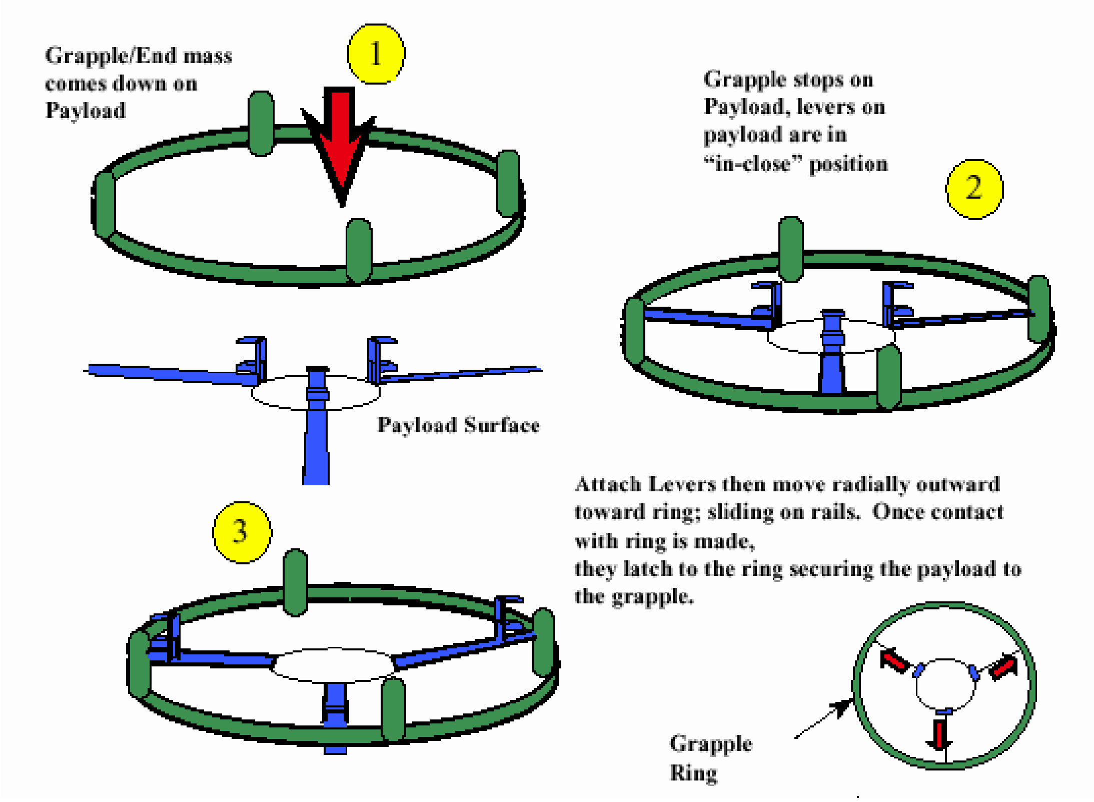
Tensile Strength (Gpa) vs. Temperature

Material	V_C (km/s)	Density d (g/cc)	20 C	300 C	600 C	800 C	1000 C	1200 C
Spectra 2000	2.87	0.97	4.0	-	-	-	-	-
Quartz Glass (SiO_2)	1.81	2.20	3.6	3.6	3.6	3.6	3.6	?
S-glass	1.94	2.50	4.7	?	?	?	?	?
Carbon	2.77	1.80	6.9	?	?	?	?	?
Carbon/Ni-coated	2.12	2.68	6.0	?	?	?	?	?
Tyranno (SiTiCO)	1.66	2.55	3.5	3.5	3.5	3.5	3.5	3.5
Textron □-SiC	2.19	2.93	7.0	6.6	6.0	5.6	5.2	4.5
0.72 □-SiC/Ti-coated	1.72	3.37	5.0	4.8	4.3	4.0	3.7	3.2
Altex (Al_2O_3/SiO_2)	1.21	3.30	2.4	2.4	2.4	2.4	2.4	1.5
Nextel (□-Al_2O_3)	1.30	3.88	3.3	?	?	?	?	?
0.65 Nextel/Al-coated	0.97	3.40	1.6	1.4	?	?	?	?
Tungsten Wire	0.55	19.35	2.9	2.9	2.9	2.9	2.9	2.9

HASTOL Grapple Assembly



Grapple to Payload Attachment Option



Conclusions

- **The HASTOL System provides a system to deliver payloads to space with minimal reliance on rocket propulsion**
- **Tether designs using existing materials can provide required strength at required thermal loads**
- **The Hoytether™ design provides a survivable tether concept for long duration operation**
- **Issues to be addressed in future work include Grapple design refinement and payload transfer logisitics**

APPENDIX 5
MODULAR SPACE TETHER DESIGN AND CONSTRUCTION

MODULAR SPACE TETHER DESIGN AND CONSTRUCTION

Robert L. Forward
Email: forward@tethers.com
Phone & Fax: +1-360-579-1340
Tethers Unlimited, Inc.
8114 Pebble Court, Clinton, WA 98236
<http://www.tethers.com>

The space tether facility portion of the HASTOL system will need to supply half or more of the energy and angular momentum needed to put the payload into orbit. In order to keep the payload from dragging the space tether facility down into the atmosphere after pickup, the facility *must* mass significantly more than the payload. A minimum facility mass would be 30 times the payload mass, while a robust system would mass 50 to 200 times the payload mass. Because the ultimate full-up space tether facility will *necessarily* be massive because we want it to handle payloads of 15 Mg or more and the laws of physics requires that it mass 30-200 times more than the payloads, it cannot easily be launched in one piece. We therefore will design it in a modular fashion so that it can be launched in many separate modules. The basic modules have yet to be fixed, but probably would consist of a single large command and control module, one or two grapple modules, depending upon whether the tether is single- or double-ended, and a large number of power modules, winch modules, and tether modules. The details of the modular design of the space tether facility, the design of the individual modules, and the method of assembling the separate modules to construct the first functional minimal space tether facility, and then "grow" it into the ultimate full-up space tether facility, will be carried further in the Phase II effort. The following description should therefore be considered as merely one "example" of what the modules would look like and how they would be interconnected into a space tether facility.

The modules would be cylinders between one and two meters in diameter and height. A small 1-m (3-ft) module would mass about 1 Mg and be 1/15th of the nominal payload mass of 15 Mg, while the largest 2-m (6-ft) module would mass about 6-8 Mg and be half the mass of the nominal payload mass. The modules will be designed so that only a few modules are needed to assemble a minimal but functional initial space tether facility consisting of the large command

and control module, a few power modules, a few winch modules, a number of tether modules, and a grapple module. These would form an initial space tether facility which would not only service customers and start bringing in a revenue stream, but would be used to haul up additional modules and add them to itself to increase its length, width, taper, power, and lift capability.

The command and control module would probably be put into place first by a heavy lift rocket. Studies may show that it is more cost effective to put the other modules into orbit by rocket, but if the hypersonic airplane is available, we can start using the initial pieces of the HASTOL system to begin to assemble itself. The power modules, winch modules, grapple modules, and especially the tether modules, can be flown to Mach 12 (3.7 km/s) at 100 km altitude, then boosted on into orbit by a rocket upper stage to a rendezvous with the command and control module. There, they would be automatically assembled (with the aid of remote control guidance), into a minimal, but functional, initial space tether facility. Assuming the modules mass 1 Mg, the initial facility need only mass 50 Mg before it becomes capable of handling one module at a time at the full design tether tip speed of 3.4 km/s. This now eliminates the need for using upper stage rockets to boost the modules from the hypersonic airplane up to the space tether facility, and the initial HASTOL architecture has been “born”. This “infant” HASTOL now has the ability to “grow” by “feeding itself” space tether facility additional modules brought up by the hypersonic airplane. (The analogy of “feeding itself” is an apt one, in that Oldson and Carroll[1] have shown that it is possible for a rotating tether system to “toss” a payload from its grapple into a trajectory that ends up an orbit later with the payload coming to a gentle “dock” with the tether control station, just like tossing a peanut into your mouth.)

Once functional, that same initial HASTOL architecture can also make money by using its hypersonic airplane to deliver 1 Mg communication satellites and deep space probes to the space tether facility, which in turn delivers them to higher orbit or Earth escape. The HASTOL architecture will thus be “in business” and “producing income” from almost its first day of operations. After doubling its size with 50 more “bites” of power, winch, and tether modules, it will be able to handle 2 Mg payloads, “grow” itself even faster, and make even more money by handling bigger and bigger payloads.

The tether control station would consist of the command and control module, power modules, and winch modules. The power modules would consist of unfolding solar power panels, standard power converters to supply power to the command and control module, and high power converters that supply electrical current to the winches that drive the tether length pumping propellantless propulsion system and the conducting portions of the tether that drive the electrodynamic tether propellantless propulsion system. A key aspect of the power module design would be to insure that the stacked power modules produced a cooperative array of solar power panels that could follow the Sun with minimal shading of one panel by another as the tether orbits and spins.

The tether portion would consist of a large number of identical tether modules. Each tether module would consist of a standardized deploy-only canister module about a meter in diameter and height with unfolding 50 cm spreader struts to spread out the tether, and unfolding 2 m triangular separator trusses with interconnection fittings to interconnect the module canisters into a “frame” many meters across. These separation frames would be spaced every 20 km along the tether, keeping the tether lines spread out from each other. Inside each canister would be would a 20-km-long, 24 primary line Hoytube™ type Hoytether™, which, after deployment, would be spread out by the spreader struts into a 1-m-diameter by 20 km long sparse net tube. Six or more Hoytether canisters would be interconnected by their built-in separator trusses into an open hexagonal array many meters across. In advanced versions, the arrangement of Hoytethers between the “frames” formed by the separator trusses each 20 km along the tether, will itself follow the failsafe Hoytether design philosophy, with some of the Hoytethers being straight “primary” lines that carry the load, while other Hoytethers are slack diagonal “secondary” backup lines.

Being modular in design, the tether can be beefed up in width and taper as needed by simply adding tether modules between the periodically-placed frames. The final full space tether structure would have the spacing between the outer Hoytethers be 20 m or more, in order to insure that the structure would survive even a strike by a full-sized spacecraft. Except by strikes by full-sized spacecraft, such a tether structure would never need repair during its 100-year operational lifetime, so there would be no need for “repair robots”.

In exploring the optimal means to assemble such a modular structure, we will investigate methods of coupling the tethers to the frames using the same grapple mechanism design as is used at the tip, with a semi-intelligent grapple at each end of the deploy-only canister containing the Hoytether, so additional tether modules could self-attach to the frames (with some remote control help from the ground), after having been hauled into rough position by a “crane” winch module running between frames.

Near the tip, the design would change from deploy-only tether modules to specialized winch modules, which would have, at one or both ends, a built-in winch box with 20 km of thick-line two primary Hoytapes or three primary Hoytubes that it can wind in and out rapidly. These rapid winching 2-3 primary line Hoytether designs would have failsafe lifetimes measured in years as compared to centuries for the 24 primary line Hoytethers, so as the winch winds the tether in, it would check the lines in the Hoytether, and if it notices weakness or breaks, it would signal ground control, and a new winch and grapple, with a new 20 km of Hoytether would come up, and replace the winch and grapple with the damaged line. There would be perhaps up to 12 winch layers, each capable of reeling in 20 km of tether at some speed of x meters per second. The whole system can then reel in at a rate of 12x m/s. The last grapple module, which would connect to and pick up the payload, would be a single large custom winch and grapple mechanism, with either a very thick single cable or perhaps a two-primary one-secondary thick-line half-Hoytape 20 km long. The line material would be chosen for strength at high temperature and the ability to withstand weakening by atomic oxygen. The grapple winch would also check the line(s) on its tether after each use and the whole grapple module would be replaced if any damage is found.

All the winches would have sufficient battery capacity to carry out a wind-in of the tether against the centrifugal load, but the winch drives should be motor-generators so that upon letting out the tether, most of the energy gained from lowering the load mass in the centrifugal force field of the spinning tether is converted into electricity and put back into the batteries. The makeup energy would come from an electrodynamic tether generator build into the non-windup portion of the tether.

The use of modular design in the tether portion of the space tether facility eliminates any concern about the manufacturability and packaging of a 600 km long tether. Since the continuous tether lengths required are only 20 km in length, they can each be fabricated in about a month or so using standard braiding machine speeds. As a result, any delivery time greater than a month can be met by simply using more braiding machines in parallel. A braided Hoytether has a unique structure, with typically 24 "primary" lines running along the length of the tether and 48 "secondary" lines spiraling around the tether, 24 clockwise and 24 counterclockwise. Each line is braided from 8 strands. The secondary lines are interconnected to the primary lines where they cross by interbraiding the primary line strands along with the secondary line strands for an interval, before taking the secondary lines out to cross over to the adjacent primary line. This interbraiding produces a slipless interconnection without using knots or producing high curvature in the strands that would cause stress buildup. This produces a line interconnection where the tensile strength of the strands in the connected region is close to that elsewhere on the strand. Standard braiding machines, which are essentially "Maypole" braiding machines, cannot produce the Hoytether structure, but a simple modification will allow an array of standard braiding machines to fabricate the structure. The Hoytether fabrication array would consist of a braiding machine for each primary and secondary line in the Hoytether, arranged in a circle, 24 "primary line" machines and 48 "secondary line" machines in pairs between each "primary line" machine. Each machine would have 8 bobbins, one for each strand. The standard braiding machines would be modified so that they can pass bobbins back and forth between adjacent braiding machines. The resulting array would have "primary line" machines that interbraided the same 8 bobbins most of the time, but periodically would trade bobbins with the four "secondary line" machines adjacent to it to form the braided interconnections. The "secondary line" machines would braid 8 bobbins for a while, until the interconnection region was reached, and after the interconnection was made, would end up with 8 different bobbins from the "secondary line" machine on the other side of the "primary line" machine, resulting in spiraling clockwise and counterclockwise secondary lines.

Although such an array of simple braiding machines has never been assembled, our fabrication vendor, Flemings Textiles Ltd of Kilmarnock, Scotland, thinks it would be a straightforward process to assemble one, given the funding to design the machine modifications and build the prototype. Flemings Textiles is a major textile fabricator that specializes in producing custom industrial fabrics rather than the lower-margin clothing and household goods fabrics. They, in turn, are owned by Scott & Fyfe, Ltd. of Tayport, Scotland, a much larger company which has the financial resources and production space to handle very large production jobs. One of their recent contracts was to produce Velcro™-backed custom carpeting for one of the Boeing airplanes. Since we see no particular need to be concerned about the feasibility of tether production, these foreign companies will not be involved in the Phase II effort.

1. J. Oldson and J.A. Carroll, "Potential Launch Cost Savings of a Tether Transport Facility", AIAA paper 95-2895, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 1995.