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DESIGN AND SIMULATION OF TETHER FACILITIES FOR THE HASTOL ARCHITECTURE

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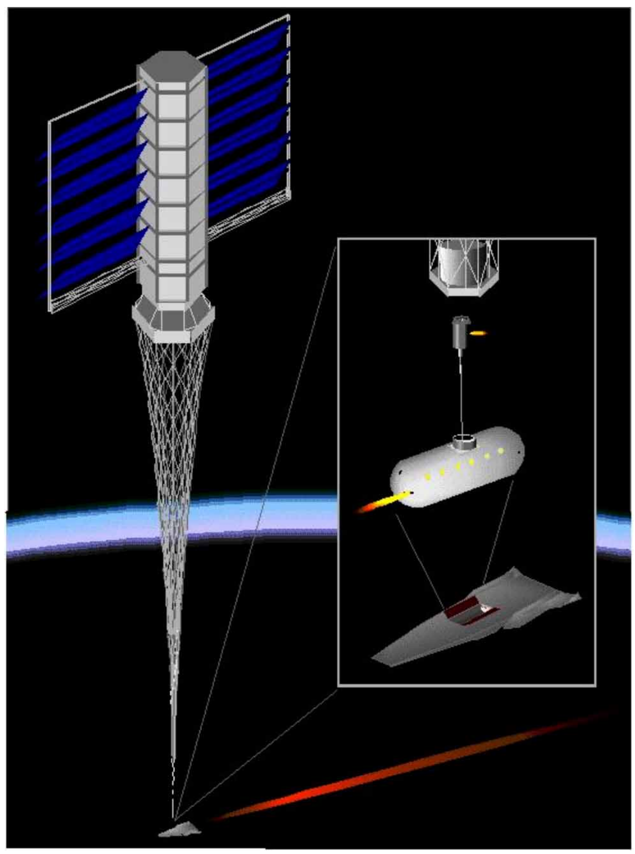

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DESIGN AND SIMULATION OF TETHER FACILITIES FOR THE HYPERSONIC-AIRPLANE SPACE-TETHER ORBITAL LAUNCH (HASTOL) ARCHITECTURE

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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 will carry a payload up to an altitude of 80-100 km at a speed of Mach 10-13. At its apogee, the airplane will rendezvous 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, as illustrated in Figure 1, and the tether would pull the payload up into orbit.

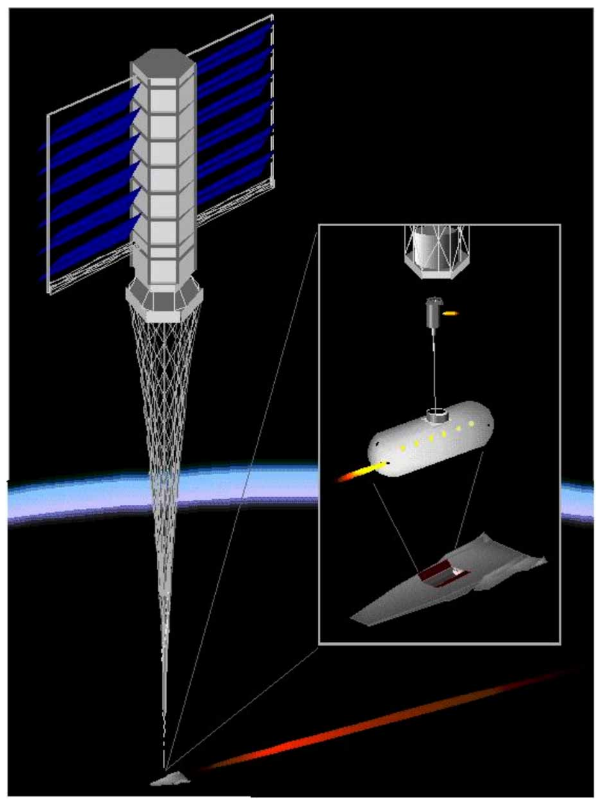

Figure 1. Illustration of the HASTOL concept.

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

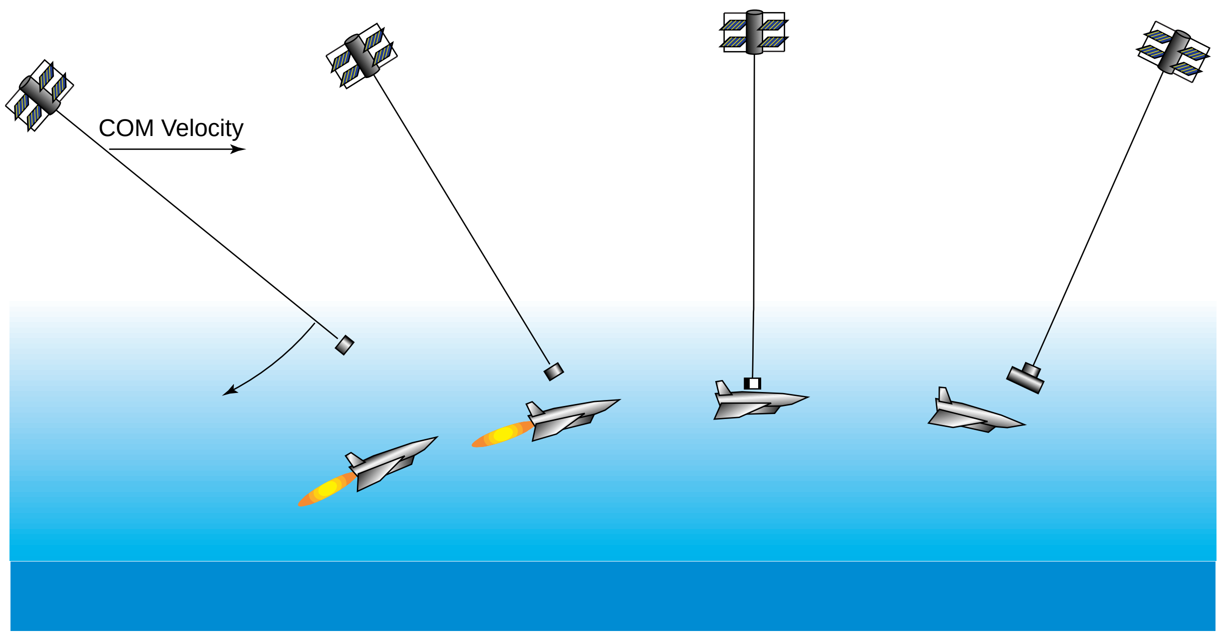

Figure 2. Rendezvous of a rotating tether ("Rotovator") and a hypersonic airplane.

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.[1]

Rotovator

The first tether design studied was a simple rotating tether facility, also known as a "Rotovator," illustrated in Figure 2. 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, a perigee velocity of 7.55 km/s, and 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 3.42 km/s.

The tether sizing 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 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 3. 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 4.

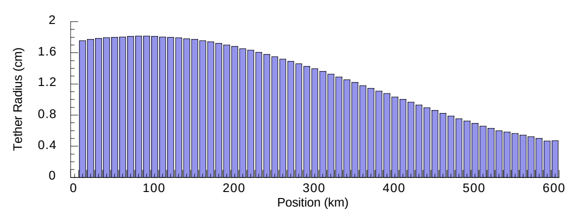

Figure 3. Radius of a stepwise tapered Spectra 2000 tether designed to support a 15 ton payload with a tip velocity of 3.42 km/s.

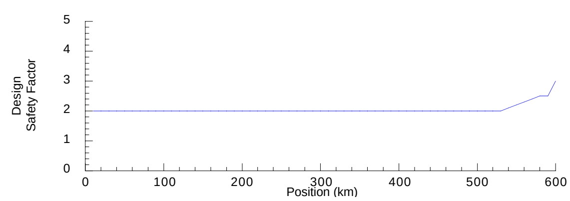

Figure 4. Design safety factor profile for the Spectra 2000 tether shown in Figure 3 (safety factor computed for nominal static loads). The safety factor is increased at the tether tip to provide protection against transient loads due to payload capture.

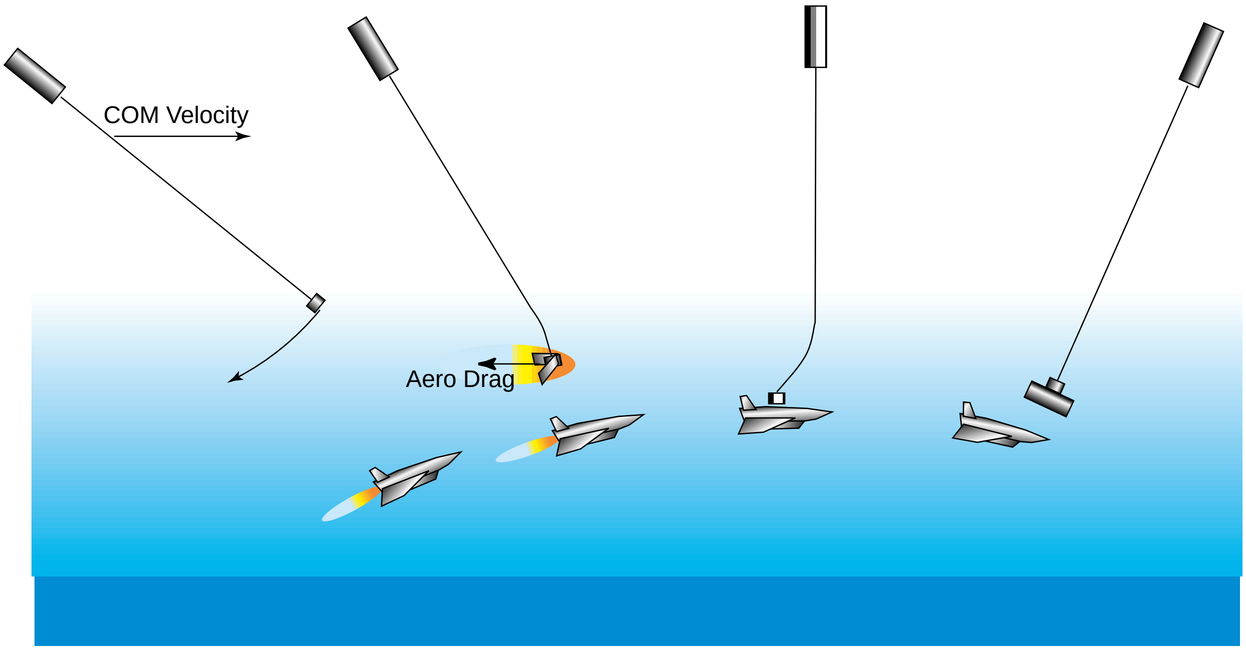

Figure 5. The LIFTether concept.

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 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.

<u>LIFTether</u>

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 5.

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.

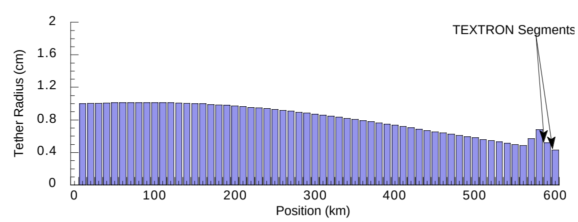

Figure 6. Stepwise tether taper for a LIFTether where the 20 km of tether nearest the grapple vehicle is made of Textron SiC coated with Ti.

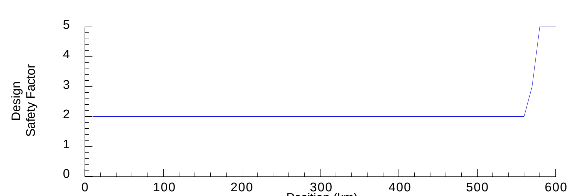

Figure 7. Design safety factor profile for the Spectra 2000 tether shown in Figure 6 (safety factor computed for nominal static loads). The safety factor is increased at the tether tip to provide protection against transient loads due to payload capture.

Figure 6 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.

CardioRotovator

In the CardioRotovator concept proposed by Forward,[2] a very long tether would be placed into an elliptical orbit, rotating twice per orbit (relative to the inertial frame) , as shown in Figure 8. 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 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.

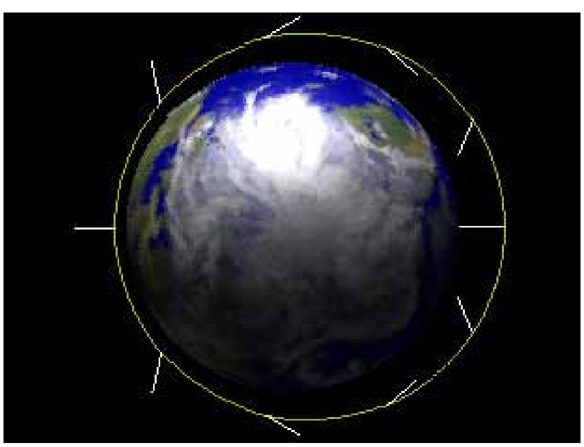

Figure 8. The Forward-CardioRotovator Concept.

For these reasons, we concluded that the CardioRotovator concept is less favorable than the simpler Rotovator and LIFTether concepts, and it was 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.[3] In order 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 9 shows a screen capture of the TetherSim™ program simulating one of the HASTOL concepts.

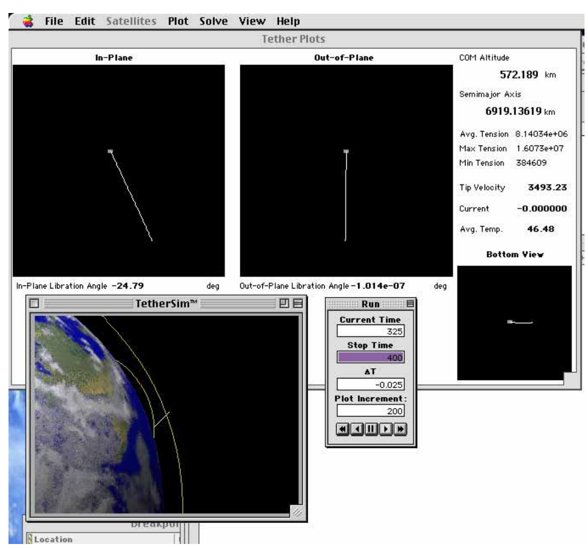

Figure 9. Screen capture of a TetherSim™ run.

Atmospheric Density Model:

The model of the atmospheric density used was the NASA/GSFC MSISE 1990 model.[4] 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.[5] 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 3 and a hypersonic airplane at an apogee altitude of 100 km and a velocity of 4.0 km/s relative to the inertial frame, or about Mach 12 with respect to the atmosphere. Figure 10 shows the altitude of the tether tip during the rendezvous period. Figure 11 shows the velocity of the tether tip relative to the inertial frame and relative to the tether facility's center of mass. Figure 12 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 would be problematic for Spectra 2000, which loses strength rapidly with temperature. However, there exist several commercially-available materials, such as 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 13 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 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.

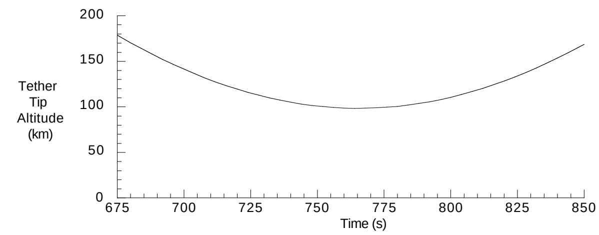

Figure 10. Altitude of the tether tip.

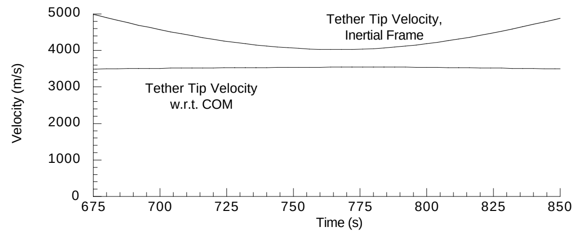

Figure 11. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass.

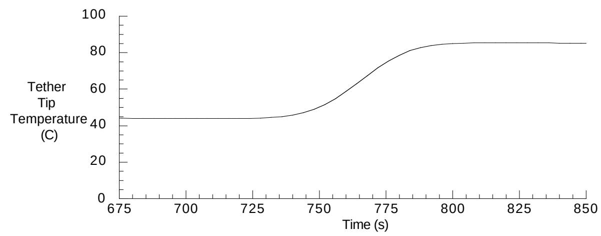

Figure 12. Temperature of the tether tip.

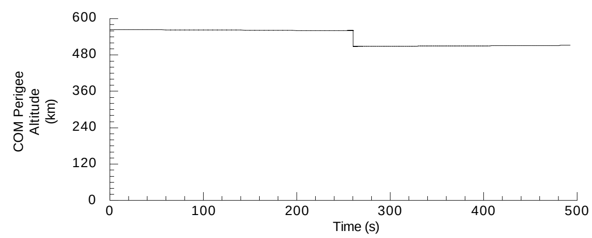

Figure 13. Perigee altitude of the tether facility.

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) or Mach 12 w.r.t. the atmosphere. 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 14 shows the altitude of the tether tip during the rendezvous.

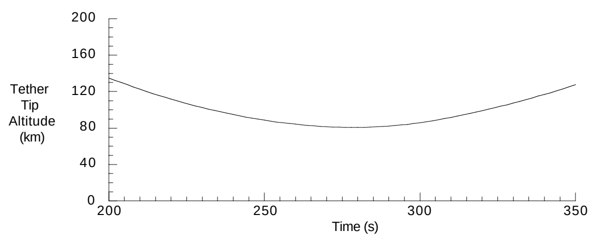

Figure 14. Altitude of the tether tip. High-strength polymer LIFTether reaching down to 80 km.

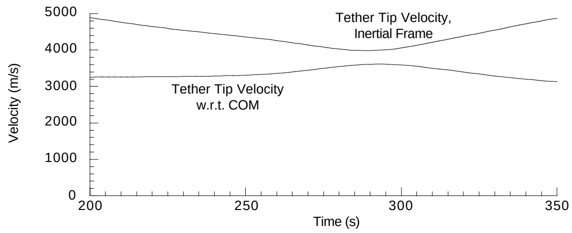

Figure 15. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass. High-strength polymer LIFTether reaching down to 80 km.

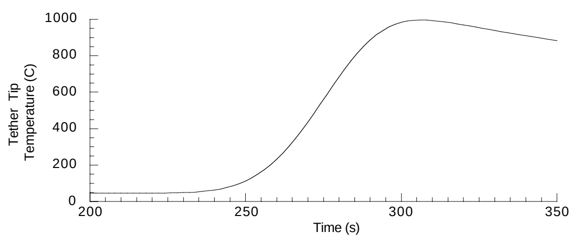

Figure 16. Temperature of the tether tip. High-strength polymer LIFTether reaching down to 80 km.

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 15 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 16 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

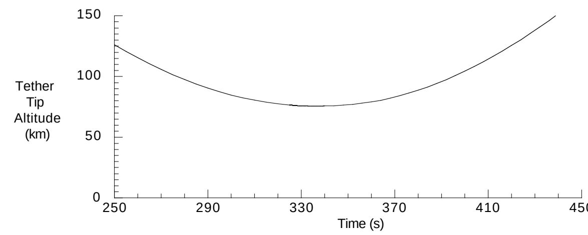

Figure 17. Altitude of the tether tip. CAST/LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

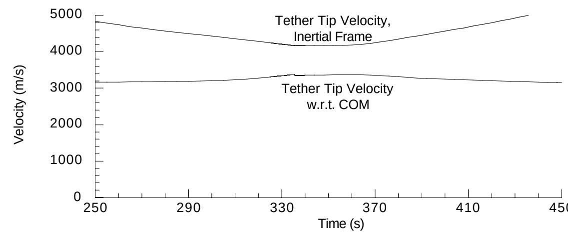

Figure 18. Velocity of the tether tip relative to an inertial frame and relative to the facility's center of mass. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

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.

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 17 shows the altitude of the tether tip during the rendezvous, and Figure 18 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 6 is roughly the same as the bottom portion of the all-Spectra Rotovator shown in Figure 3, 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 19 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 20. 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.

Shows the perigee altitude of the tether facility's center of mass before and after the payload capture.

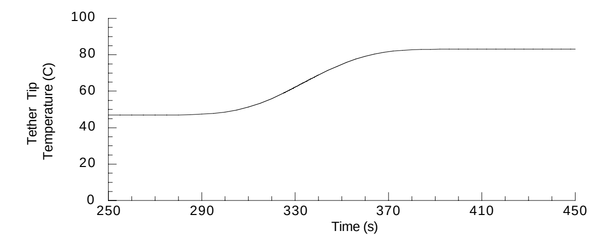

Figure 19. Temperature of the tether tip. LIFTether with tip made of Ti-coated _-Textron reaching down to 80 km.

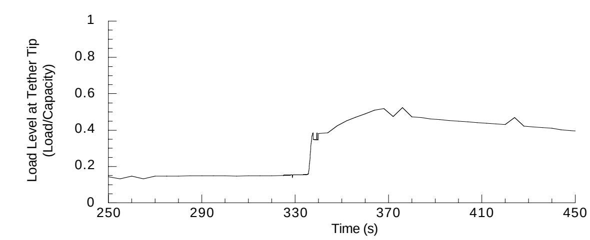

Figure 20. Load level at the tether tip before and after tether capture. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

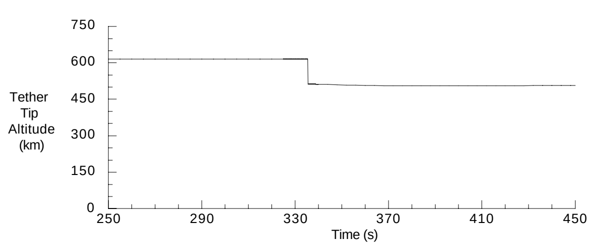

Figure 21. Perigee altitude of the tether facility's center of mass. LIFTether with tip made of Ti-coated β-Textron reaching down to 80 km.

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.

Rendezvous Window

In any momentum-exchange 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 24. The payload can then maneuver to close the

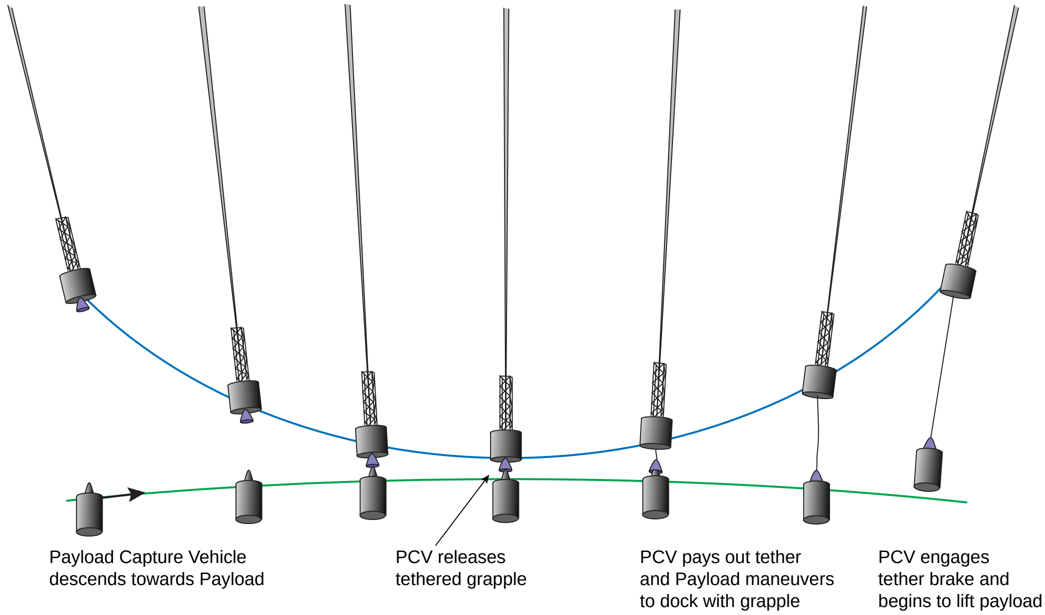

Figure 24. Schematic of tethered-grapple method for increasing docking window.

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 $\Delta t = \sqrt{(2l/a)}$.

Using TetherSim™, we have investigated this maneuver for a HASTOL system in which the Spectra-2000 tether illustrated in Figure 3 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

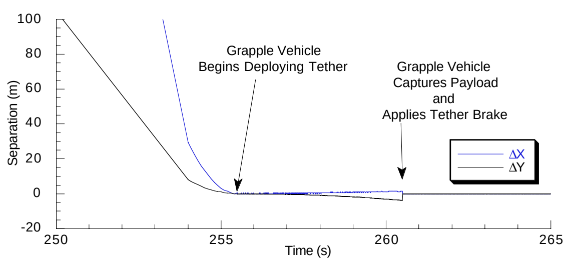

Figure 22. Relative separation of grapple vehicle and payload, with a tether deployment maneuver to extend rendezvous window.

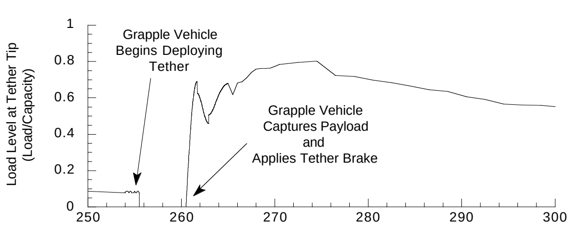

Figure 23. Load level on bottom segment of tether, with a tether deployment maneuver to extend rendezvous window.

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 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.

Acknowledgements

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