THE CISLUNAR TETHER TRANSPORT SYSTEM ARCHITECTURE

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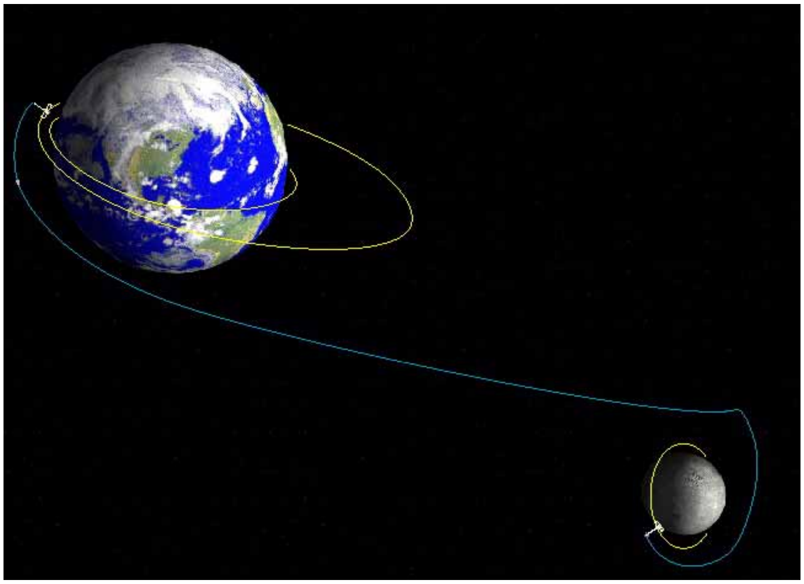

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Abstract

We describe a space systems architecture for repeatedly transporting payloads between low Earth orbit and the surface of the moon without significant use of propellant. This architecture consists of one rotating momentum-exchange tether in elliptical, equatorial Earth orbit and a second rotating momentum-exchange tether in a circular low lunar orbit. The Earth-orbit tether picks up a payload from a circular low Earth orbit and tosses it into a minimal-energy lunar transfer orbit. When the payload arrives at the Moon, the lunar tether catches it and deposits it on the surface of the Moon. Simultaneously, the lunar tether picks up a lunar payload to be sent down to the Earth orbit tether. By transporting equal masses to and from the Moon, the orbital energy and momentum of the system can be conserved, eliminating the need for transfer propellant. The Earth-orbit tether can also be used to send payloads to the Moon without return traffic if electrodynamic tether propulsion is used to restore its orbit in between payload boost operations. Using currently available high-strength tether materials, this system can be built with a total mass of less than 37 times the mass of the payloads it can transport. Using numerical simulations that incorporate the full three-dimensional orbital mechanics and tether dynamics, we have verified the feasibility of this system architecture and developed scenarios for transferring a payload from a low Earth orbit to the surface of the Moon that require less than 25 m/s of thrust for trajectory targeting corrections.

Introduction

Under funding from NASA's Institute for Advanced Concepts, Tethers Unlimited, Inc. has investigated the feasibility of using momentum-exchange tether techniques and electrodynamic tether propulsion to create a modular architecture for transporting payloads from low Earth orbit (LEO) to the surface of the Moon, and back, *with little or no propellant consumption*.[1,2] A "Cislunar Tether Transport System" would be composed of one rotating momentum exchange/electrodynamic reboost tether in elliptical, equatorial Earth orbit and a momentum-exchange rotating tether facility in a low circular polar lunar orbit. This architecture can repeatedly exchanging payloads between LEO and the surface of the Moon, with the only propellant requirements being for trajectory corrections and rendezvous maneuvering.

In 1991, Forward[3] showed that such a system is theoretically possible from an energetics standpoint. A later study by Hoyt and Forward[4] developed a first-order design for such a system. These previous studies, however, utilized a number of simplifying assumptions regarding orbital and tether mechanics in the Earth-Moon system, including assumptions of coplanar orbits, ideal gravitational potentials, and infinite facility ballast masses. In this paper, we summarize work done to develop an architecture for such a system that takes into account the full complexities of orbital mechanics in the Earth-Moon system. We then present a system concept for a Tether Boost Facility designed to boost 1000 kg payloads to the Moon.

The basic concept of the Cislunar Tether Transport System is to use a rotating tether in Earth orbit to pick payloads up from LEO orbits and toss them to the Moon, where a rotating tether in lunar orbit, called a "Lunavator™", could catch them and deliver them to the lunar surface. As the Lunavator™ delivers payloads to the Moon's surface, it can also pick up return payloads, such as water or aluminum processed from lunar resources, and send them down to LEO. By balancing the flow of mass to and from the Moon, the orbital momentum and energy of the system can be conserved, eliminating the need to expend large quantities of propellant to move the payloads back and forth. This system is illustrated in Figure 1.

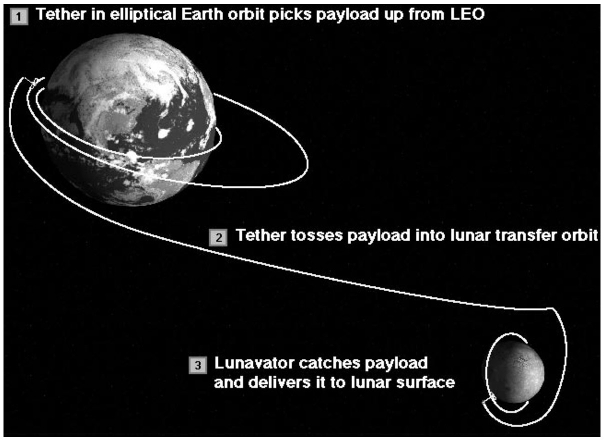

Figure 1. Conceptual illustration of the Cislunar Tether Transport System.

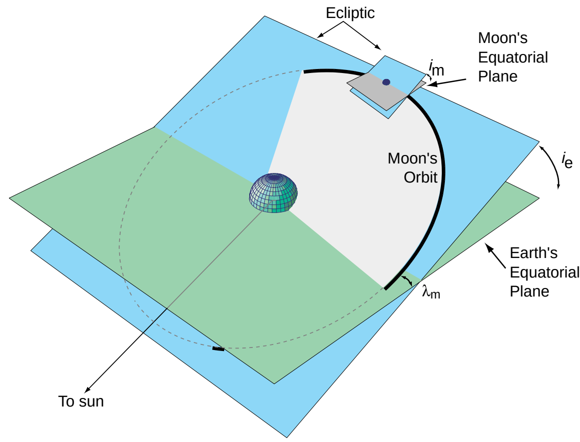

Figure 2. Schematic illustrating the geometry of the Earth-Moon system.

Orbital Mechanics of the Earth-Moon System

Orbital mechanics in cislunar space are made quite complex by the different and varying orientations of the ecliptic plane, the Earth's equatorial plane, the Moon's orbital plane, and the Moon's equatorial plane. Figure 2 attempts to illustrate these different planes. The inclination of the Earth's equatorial plane (the "obliquity of the ecliptic"), is approximately 23.45°, but varies due to tidal forces exerted by the Sun and Moon. The angle i_m between the Moon's equatorial plane and a plane through the Moon's center that is parallel to the ecliptic plane is constant, about 1.58°. The inclination of the Moon's orbit relative to the ecliptic plane is also constant, about λ_m = 5.15°.[5] The line of nodes of the Moon's orbit regresses slowly, revolving once every 18.6 years. As a result, the inclination of the Moon's orbit relative to the Earth's equator varies between 18.3-28.6 degrees. The Moon's orbit also has a slight eccentricity, approximately e_m = 0.0549.

Tether Orbits

After considering many different options, including the three-tether systems proposed previously and various combinations of elliptical and circular orbits, we have determined that the optimum configuration for the Cislunar Tether system is to utilize one tether in an elliptical, equatorial Earth orbit and one tether in a circular, polar lunar orbit, as illustrated in Figure 1. This two-tether system will require the lowest total system mass, minimize the system complexity and provide the most frequent transfer opportunities. The Earth-orbit tether will pick payloads up from equatorial low-LEO orbits and toss them towards one of the two points where the Moon crosses the Earth's equatorial plane. The toss is timed so that the payload reaches its apogee ahead of the Moon. The Moon approaches the payload from behind, and its gravity causes the payloads velocity to slow and then reverse, pulling it into a hyperbolic polar lunar trajectory. As the payload approaches the Moon, it will need to perform a small ΔV maneuver to set it up into the proper approach trajectory; the size of this maneuver will vary depending upon the inclination of the Moon's orbit plane and launch dispersions, but under most conditions it will only require about 25 m/s of ΔV.

In the following sections, we will first develop a design for a tether facility for boosting payloads from low-LEO orbits to lunar transfer orbits (LTO). We will then develop a design for a Lunavator™ capable of catching the payloads and delivering them to the surface of the Moon. We will then discuss the numerical simulations used to verify the feasibility of this system architecture.

Design for Incremental Development

This effort has sought to design the Cislunar Tether Transport System so that it can be developed and deployed in an incremental, modular fashion. The first components deployed will generate revenue by transporting materials to the Moon to facilitate lunar base development, and this revenue will be invested in the deployment of additional modules to increase the system capacity and eventually enable round trip transport between LEO and the lunar surface.

Although the system will realize its full potential when it is capable of transporting payloads both to and from the Moon, and thus can use the orbital energy of inbound payloads to boost outbound payloads, it is possible for the first component of the system, the Earth-orbit Tether Boost Facility, to repeatedly boost payloads into lunar transfer trajectories *without propellant expenditure or return traffic needed*. The key to achieving this is the combination of momentum-exchange tether techniques with electrodynamic tether propulsion.

HEFT Tether Boost Facility

This concept, the "High-strength Electro-dynamic Force Tether" (HEFT) Facility,[6] is illustrated in Figure 3. The HEFT Facility would include a central facility housing a power supply, ballast mass, plasma contactor, and tether deployer, which would extend a long, tapered, high-strength tether. A small grapple vehicle would reside at the tip of the tether to facilitate rendezvous and capture of the payloads. The tether would include a conducting core, and a second plasma contactor would be placed near the tether tip. By using the power supply to drive current along the tether, the HEFT Facility could generate electrodynamic forces on the tether. By properly varying the direction of the current as the tether rotates and orbits the Earth, the facility can use these electrodynamic forces to generate either a net torque on the system to change its rotation rate, or a net thrust on the system to boost its orbit. The HEFT Facility thus could repeatedly boost payloads from LEO to the Moon, and in between each payload boost operation it would use propellantless electro-dynamic propulsion to restore its orbital energy.

Design of a Tether Boost Facility for Lunar Transfer Injection

The first stage of the Cislunar Tether Transport System will be a Tether Boost Facility in elliptical, equatorial Earth orbit. The mission of this facility is to pick up a payload from low-Earth orbit and inject it into a near-minimum energy lunar transfer orbit. The desired lunar transfer trajectories have a C_3 of approximately $-1.9\ (km/s)^2$. A payload originating in a circular orbit at 350 km altitude has an initial velocity of 7.7 km/s and a C_3 of $-60\ (km/s)^2$. To impulsively inject the payload into the lunar transfer orbit would require a ΔV of approximately 3.1 km/s.

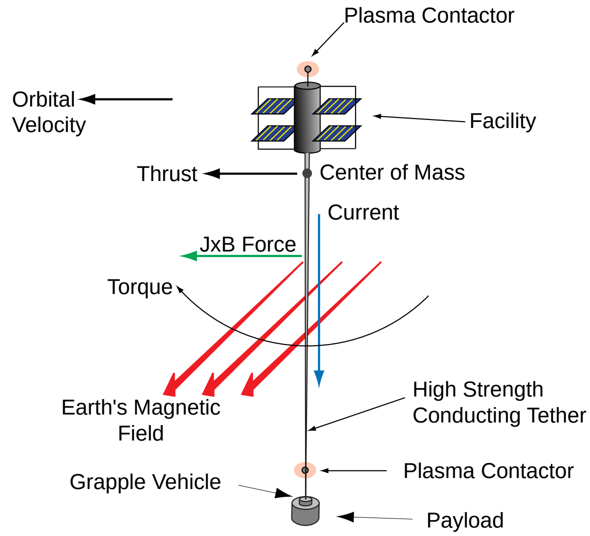

Figure 3. Schematic of the HEFT Facility design.

Orbital Design

In the Cislunar Tether Transport System, the transfer of payloads between a low-LEO and lunar transfer orbits is performed by a single rotating tether facility. This facility performs a catch and release maneuver to provide the payload with two boosts of approximately 1.5 km/s each. To enable the tether to perform two "separate" ΔV operations on the payload, the facility is placed into a highly elliptical orbit with its perigee in LEO. When the tether is near perigee, its center of mass is moving approximately 1.5 km/s faster than the payload in circular LEO. The tether rotation is arranged such that when the facility is at perigee, the tether is swinging vertically below the facility so that it can catch a payload moving more slowly than the facility. After it catches the payload, it holds the payload for half a rotation and then releases it at the top of the tether's rotation, injecting the payload into the high-energy transfer trajectory.

Table 1 shows the orbital design for the LEO⇒LTO Tether Boost Facility. To minimize the mass of the tether, it is tapered along its length to maintain a constant load level; Figure 4 illustrates this tapering.

Table 1. System Orbital Design for LEO⇒LTO Boost

System Masses		
Tether mass	8,274	kg
CS Active Mass	11,514	kg
CS Ballast Mass	3490	kg
Grapple mass	650	kg
Total Facility Mass	**23,928**	kg
Total Launch Mass	**20,438**	kg
Payload Mass	**1,000**	kg

Tether Characteristics		
Tether Length	100	km
Tether mass ratio	8.27	
Tether tip velocity at catch	1,555	m/s
Tether tip velocity at toss	1,493	m/s
Tether angular rate	0.01905	rad/s
Gravity at Control Station	0.80	g
Gravity at payload	2.90	g
Rendezvous acceleration	3.02	g

		Pre-Catch		Joined System	Post-Toss	
Positions & Velocities		**Payload**	**Tether**	**Post-catch**	**Tether**	**Payload**
perigee altitude	km	300	382	378	375	457
apogee altitude	km	300	11935	11018	10172	406515
perigee radius	km	6678	6760	6757	6753	6835
apogee radius	km	6678	18313	17397	16550	412893
perigee velocity	m/s	7726	9281	9219	9156	10712
apogee velocity	m/s	7726	3426	3580	3736	177
CM dist. From Station	m		18356	21632	18356	
CM dist. To Grapple	m		81644	78368	81644	
ΔV to Reboost	m/s				125	
Basic Orbital Parameters						
semi-major axis	km	6678	12537	12077	11652	209864
eccentricity		0.0	0.461	0.441	0.420	0.967
inclination	rad	0	0	0	0	0
semi-latus rectum	km	6678	9875	9733	9592	13447
sp. mech. energy	m2/s2	-2.98E+07	-1.59E+07	-1.65E+07	-1.71E+07	-9.50E+05
vis-viva energy	m2/s2	-5.97E+07	-3.18E+07	-3.30E+07	-3.42E+07	-1.90E+06
period	sec	5431	13970	13208	12517	956793
period	min	90.5	232.8	220.1	208.6	15946.5
station rotation period	sec		329.8	329.8	329.8	
rotation ratio			42.4	40.0	37.9	

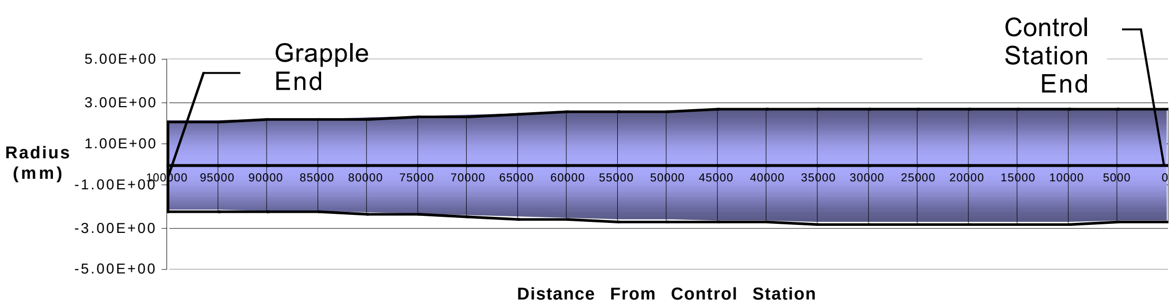

Figure 4. Taper of the tether cross-section (tether will actually be composed of multiple smaller lines).

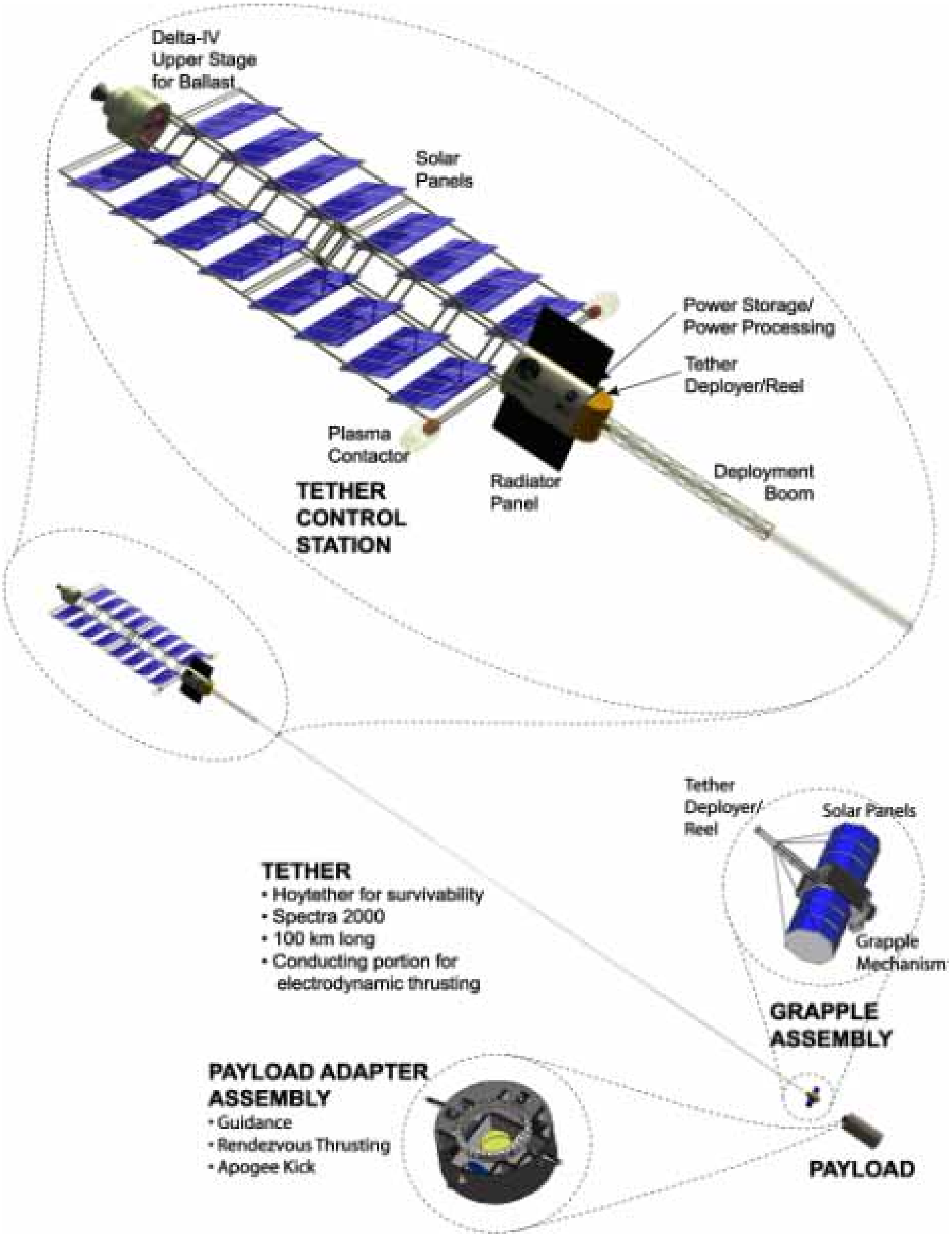

Figure 5. System Design for a Tether Boost Facility.

System Design

Figure 5 illustrates the system concept design for the Tether Boost Facility. The Tether Boost Facility is composed of a Control Station, a tapered high-strength tether, and a Grapple Assembly. In addition, a Payload Accommodation Assembly (PAA) will be attached to the payload to provide maneuvering and guidance for rendezvous. This PAA will initially be an expendable unit incurring recurring costs, but once round-trip traffic is established the PAA's could be re-fueled and reused for return payloads.

The tether facility is sized to be deployed with a single launch of a Delta-IV-H or comparable vehicle. Note that the system mass given in Table 1 is not the minimum possible system mass; a lighter system mass could be designed for a system optimized for boosting payloads to LTO. This system mass was chosen to utilize the full capability of the Delta-IV-H vehicle, and to optimize the system for boosting larger satellites to geostationary transfer orbits. As Figure 5 shows, the 3490 kg Delta upper stage will be retained for use as ballast mass. The control station includes an array of solar panels which swivel to track the sun as the tether facility rotates. In this design, we have chosen to place the control station at the end of the tether, rather than at the center of mass of the facility. This choice was made for several reasons: because it minimizes the dynamical complexity, because it requires only one tether deployer, and because the center of mass of the system shifts when the payload is captured and released.

Electrodynamic Reboost of the Tether Orbit

After boosting the payload, the tether facility will be left in a lower energy elliptical orbit. To restore the orbit, the tether system must increase the perigee velocity by 125 m/s, and increase the facility's orbital energy by 29 GJ. Because the tether is rotating, the direction of the current must be alternated as the tether rotates to produce a net thrust on the facility. Using a simulation of tether dynamics and electrodynamics, we have modeled reboost of a rotating tether system and found that the electrodynamic thrusting efficiency is approximately 33 μN/W, averaged over the perigee thrust period (shown in Figure 6). The tether facility will be able to collect solar power over approximately 80% of its orbital period. To reboost the orbit within 30 days, the facility will need a solar panel able to collect approximately 50 kW, and the tether facility will expend the collected energy at a rate of 200 kW during the perigee passes.

Dealing with Apsidal Precession

In order to deliver the payload to the Moon, the tether facility in equatorial Earth orbit must toss the payload out to a point near where the Moon will cross the Earth's equatorial plane. Thus the tether's perigee must be lined up on the opposite side of the Earth from that point. The oblateness of the Earth, however, will cause the line of apsides of the tether facility's elliptical orbit to precess. In the Cislunar Tether Transport System, we can deal with this issue in three ways.

First, we can use propellantless electrodynamic tether propulsion to change or oppose the oblateness-induced precession, either by raising/ lowering the orbit or by generating thrust perpendicular to the facility's velocity.

Second, we can utilize tether reeling maneuvers to counteract the apsidal precession.[7] By reeling the tether in and out a small percentage of its total length once per orbit, the tether facility can exchange angular momentum between its rotation and its orbit, resulting in precession or regression of the line of apsides. With proper phasing and amplitude, tether reeling can hold the tether's orbit fixed so that it can send payloads to the

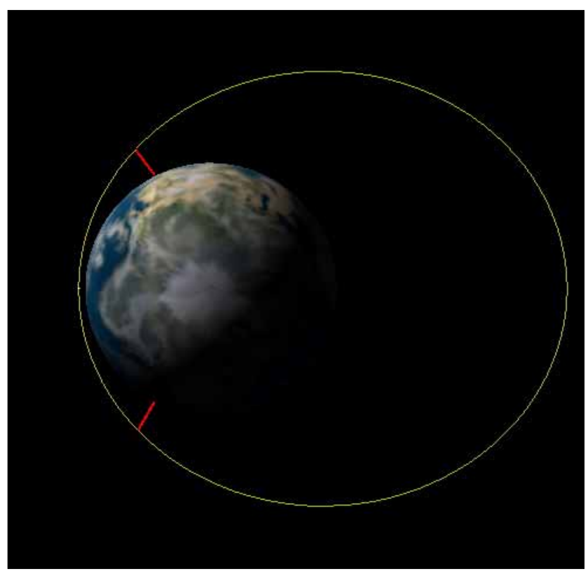

Figure 6. The HEFT Boost Facility's initial orbit. The red lines indicate the bounds of the perigee portion of the orbit where electrodynamic thrusting is effective.

Moon once per month.[8]

A third method is to choose the tether orbits such that their precession rates are nearly harmonic with the Moon's orbital rate, so that the line of apsides lines up with the Moon's nodes once every several months.

LEO⇒GTO Payload Transfer

The same Tether Boost Facility can, by changing its initial orbit and rotation rate, boost 2,500 kg payloads from a 308 km circular orbit to geostationary transfer orbit. To perform this LEO⇒GTO boost operation once per month, the system must have a 150 kW solar power array, and expend the collected energy at a rate of 450 kW during perigee passes. The Control Station shown in Figure 5 is sized with a 200 kW (beginning of life) solar array.

System Modularity

The Tether Boost Facility concept has been designed to enable it to be grown incrementally. After the initial facility, capable of tossing 1000 kg to LTO and 2,500 kg to GTO, has been deployed and tested, a second module of nearly identical hardware can be launched and combined in a parallel fashion with the first module, as illustrated in Figure 7. This will increase the system's capacity to 2,000 kg to LTO and 5,000 kg to GTO. The parallel construction will provide redundancy to the system, reducing the need for redundancy within each module. Cross-linking between the two parallel tethers could be added to increase their redundancy. Additional modules can be launched to increase the system capacity further.

Design of a Lunavator™ Compatible with Minimal-Energy Lunar Transfers

The second stage of the Cislunar Tether Transport System is a lunar-orbit tether facility that catches the payloads sent by the Earth-orbit tether and deposits them on the Moon with zero velocity relative to the surface.

Background: Moravec's Lunar Skyhook

In 1978, Moravec[9] proposed that it would be possible to construct a tether rotating around the Moon that would periodically touch down on the lunar surface. Moravec's "Lunar Skyhook" would have a massive central facility with two tether arms, each with a length equal to the facility's orbital altitude. It would rotate in the same direction as its orbit with a tether tip velocity equal to the orbital velocity of the tether's center-of-mass so that the tether tips would periodically touch down on the Moon with zero velocity relative to the surface (to visualize this, imagine the tether as a spoke on a giant bicycle wheel rolling around the Moon).

As it rotates and orbits around the Moon, the tether will capture payloads from Earth as they reach perilune and then set them down on the surface of the Moon. Once round-trip traffic is established, the tether could simultaneously pick up payloads to be returned to Earth, and later toss them down to LEO.

Lunavator™ Design

In order to minimize the ΔV requirements placed upon the Earth-orbit portion of the Cislunar Tether Transport System and thereby permit the use of a single Earth-orbit tether with a reasonable mass, we have developed a method for a single lunar-orbit tether to capture a payload from a minimal-energy lunar transfer orbit and deposit it on the tether surface with zero velocity relative to the surface.

Moon-Relative Energy of a Minimum-Energy LTO

A payload that starts out in LEO and is injected into an elliptical, equatorial Earth-orbit with an apogee that just reaches the Moon's orbital radius will have a C_3 relative to the Moon of approximately 0.72 km^2/s^2. For a lunar transfer trajectory with a closest-approach altitude of several hundred kilometers, the payload will have a velocity of approximately 2.3 km/s at perilune. As a result, it would be moving too slowly to rendezvous with the upper tip of

Figure 7. Tether Boost Facility with two modules, capable of tossing 2000 kg to LTO. (Tether length not to scale)

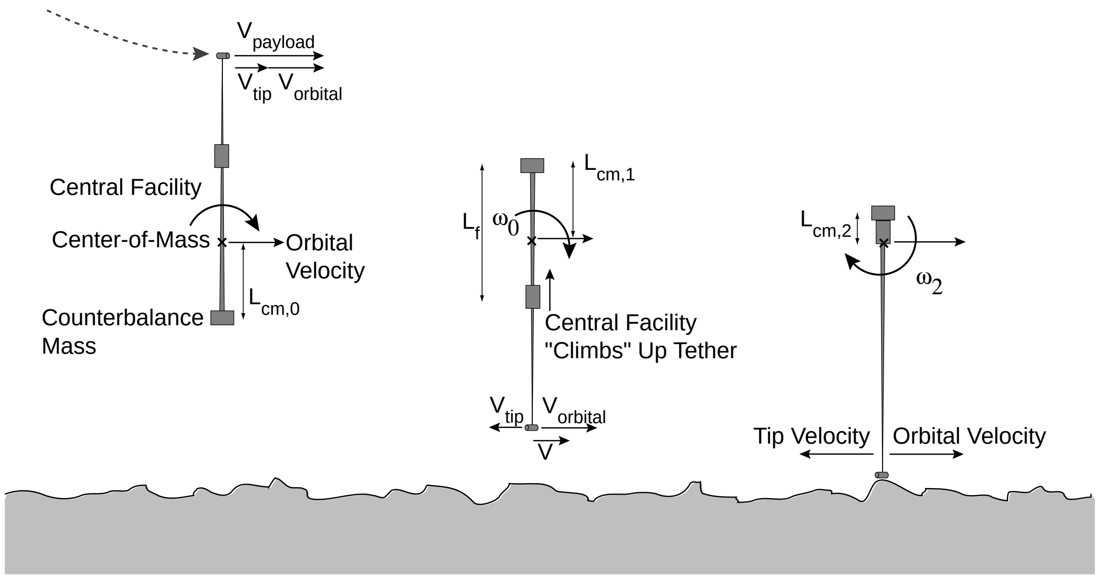

Figure 8. Method for a lunar tether to capture a payload from a minimal-energy LTO and deposit it on the Moon with zero velocity relative to the surface.

Moravec lunar Skyhook, which would have a tip velocity of 2.9 km/s at the top of its rotation. Consequently, the design of the lunar tether system must be modified to permit a tether orbiting the Moon at approximately 1.5 km/s to catch a payload to at perilune when the payload's velocity is approximately 2.3 km/s, then increase <u>both</u> the tether length and the angular velocity so that the payload can be set down on the surface of the Moon with zero velocity relative to the surface. Simply reeling the tether in or out from a central facility will not suffice, because reeling out the tether will cause the rotation rate to decrease due to conservation of angular momentum.

A method that can enable the tether to catch a payload and then increase the tether rotation rate while lowering the payload is illustrated in Figure 8. The "Lunavator™" tether system is composed of a long tether, a counterbalance mass at one end, and a central facility that has the capability to climb up or down the tether. Initially, the facility would locate itself near the center of the tether, and the system would rotate slowly around the center-of-mass of the system, which would be located roughly halfway between the facility and the counterbalance mass. The facility could then capture an inbound payload at its perilune. The facility would then use energy from solar cells or other power supply to climb up the tether towards the counterbalance mass. The center-of-mass of the system will remain at the same altitude, but the distance from the tether tip to the center-of-mass will increase, and conservation of angular momentum will cause the angular velocity of the system to increase as the facility mass moves closer to the center-of-mass.

Lunavator™ Design

Using analyses of the orbital mechanics of the system, we have found the following first-order design for a Lunavator™ capable of catching payloads from minimal-energy lunar transfer orbits and depositing them on the surface of the Moon:

<u>Payload Trajectory:</u>

- mass M_p = 1000 kg
- perigee altitude h_p = 328.23 km
- Moon-relative energy $C_{3,M}$ = 0.719 km²/s²

<u>Lunavator™:</u>

- tether length L = 200 km
- counterbalance mass M_c = 6,000 kg
- facility mass M_f = 6,000 kg
- tether mass M_t = 4,706 kg
- Total Mass M = 16,706 kg
  = 16.7 x payload mass
- <u>Orbit Before Catch:</u>
  central facility position L_f = 155 km
  tether tip velocity $V_{t,0}$ = 0.748 km/s
  rotation rate ω_0 = 0.00566 rad/s
  circular orbit altitude $h_{p,0}$ = 170.5 km
- <u>Orbit After Catch</u>:
  perigee altitude $h_{p,0}$ = 178 km,

apogee altitude $h_{a,0} = 411.8$ km
eccentricity $e_0 = 0.0575$

After catching the payload, the central facility climbs up the tether to the counterbalance mass, changing the rotation rate to:

- adjusted rotation rate $\omega_0 = 0.00929$ rad/s
- adjusted tip velocity $V_{t,2} = 1.645$ km/s

Payload Delivery:

- drop-off altitude $h = 1$ km (top of a lunar mountain)
- velocity w.r.t. surface $v = 0$ m/s

Lunavator™ Orbit: Polar vs. Equatorial

In order to provide the most consistent transfer scenarios, it is desirable to place the Lunavator™ into either a polar or equatorial lunar orbit. Each choice has relative advantages and drawbacks, but both are viable options.

Equatorial Lunar Orbit

The primary advantage of an equatorial orbit for the Lunavator™ is that equatorial lunar orbits are relatively stable. An equatorial Lunavator™, however, would only be able to service traffic to bases on the lunar equator. Because the lunar equatorial plane is tilted with respect to the Earth's equatorial plane, a payload boosted by the Earth-orbit tether facility will require a ΔV maneuver to bend its trajectory into the lunar equatorial plane. For most transfer opportunities, this correction can be accomplished by a small rocket thrust on the order of 25 m/s.

Polar Lunar Orbit

A polar orbit would be preferable for the Lunavator™ for several reasons. First, direct transfers to polar lunar trajectories are possible with little or no propellant expenditure required. Second, because a polar lunar orbit will remain oriented in the same direction while the Moon rotates inside of it, a polar Lunavator™ could service traffic to any point on the surface of the Moon, including the potentially ice-rich lunar poles. Low polar lunar orbits, however, are unstable. The odd-harmonics of the Moon's potential cause a circular, low polar orbit to become eccentric. Eventually, the eccentricity becomes large enough that the perilune is at or below the lunar surface. For the 178 km circular orbit, the rate of eccentricity growth is approximately 0.00088 per day.

Fortunately, the techniques of orbital modification using tether reeling, proposed by Martínez-Sánchez and Gavit[7] and by Landis[10]

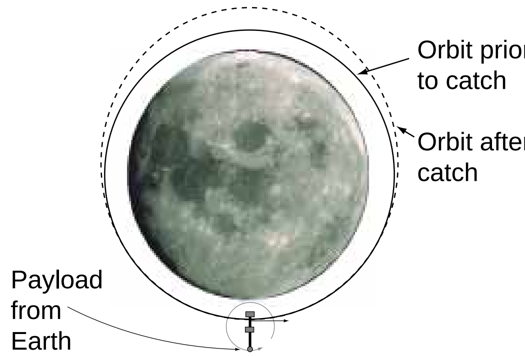

Figure 9. Lunavator™ orbits before and after payload capture.

may provide a means of stabilizing the orbit of the Lunavator™ without requiring expenditure of propellant. Tether reeling can add or remove energy from a tether's orbit by working against the non-linearity of a gravitational field. The basic concept of orbital modification using tether reeling is illustrated in Figure 10. When a tether is near the apoapsis of its orbit, the tidal forces on the tether are low. When it is near periapsis, the tidal forces on the tether are high. If it is desired to reduce the eccentricity of the tether's orbit, then the tether can be reeled in when it is near apoapsis, under low tension, and then allowed to unreel under higher tension when it is at periapsis. Since the tidal forces that cause the tether tension are, to first order, proportional to the inverse radial distance cubed, more energy is dissipated as the tether is unreeled at periapsis than is restored to the tether's orbit when it is reeled back in at apoapsis. Thus, energy is removed from the orbit. Conversely, energy can be added to the orbit by reeling in at periapsis and reeling out at apoapsis. Although energy is removed (or added) to the orbit by the reeling maneuvers, the orbital angular momentum of the orbit does not change. Thus the eccentricity of the orbit can be changed.

The theories developed in references 7 and 10 assumed that the tether is hanging (rotating once per orbit). Because the Lunavator™ will be rotating several times per orbit, we have extended the theory to apply to rapidly rotating tethers.[8] Using a tether reeling scheme in which the tether is reeled in and out once per orbit as shown in Figure 10, we find that a reeling rate of 1 m/s will reduce the eccentricity of the Lunavator™'s orbit by 0.0011 per day, which should be more than enough to counteract the effects of lunar perturbations to the tether's orbit. Thus tether reeling may provide a means of stabilizing the orbit of a polar Lunavator™ without requiring propellant expenditure. This tether reeling, however, would add additional complexity to the system.

Cislunar System Simulations

Tether System Modeling

In order to verify the design of the orbital dynamics of the Cislunar Tether Transport System, we have developed a numerical simulation called "TetherSim" that includes:

- The 3D orbital mechanics of the tethers and payloads in the Earth-Moon system, including the effects of Earth oblateness, using Runge-Kutta integration of Cowell's method.
- Modeling of the dynamical behavior of the tethers, using a bead-and-spring model similar to that developed by Kim and Vadali.[11]
- Modeling of the electrodynamic interaction of the Earth-orbit tether with the ionosphere.

Using this simulation tool, we have developed a scenario for transferring a payload from a circular low-LEO orbit to the surface of the Moon using the tether system designs outlined above. We have found that for an average transfer scenario, mid-course trajectory corrections of approximately 25 m/s are necessary to target the payload into the desired polar lunar trajectory to enable rendezvous with the Lunavator™. A simulation of a transfer from LEO to the surface of the Moon can be viewed at *www.tethers.com*.

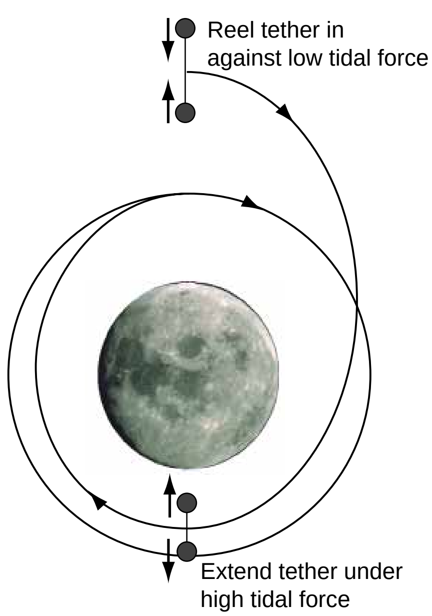

Figure 10. Schematic of tether reeling maneuver to reduce orbital eccentricity.

Targeting the Lunar Transfer

In addition to the modeling conducted with TetherSim™, we have also conducted a study of the Earth-Moon transfer to verify that the payload can be targeted to arrive at the Moon in the proper plane to rendezvous with the Lunavator™. This study was performed with the MAESTRO code,[12] which includes the effects of luni-solar perturbations as well as the oblateness of the Earth. In this work we studied targeting to both equatorial and polar lunar trajectories.

We have found that by varying the energy of the translunar trajectory and adjusting the argument of perigee, it is possible to target the payload to rendezvous with a polar orbit Lunavator™ with a wide range of ascending node positions of the Lunavator™ orbit. Our simulations indicate that the viable nodal positions ranges at least ±10° from the normal to the Earth-Moon line.

Comparison to Rocket Transport

Travelling from LEO to the surface of the Moon and back requires a total ΔV of more than 10 km/s. To perform this mission using storable chemical rockets, which have an exhaust velocity of roughly 3.5 km/s, the standard rocket equation requires that a rocket system consume a propellant mass equal to 16 times the mass of the payload for each mission. The Cislunar Tether Transport System would require an on-orbit mass of less than 37 times the payload mass, but it would be able to transport many payloads. In practice, the tether system will require some propellant for trajectory corrections and rendezvous maneuvers, but the total ΔV for these maneuvers will likely be less than 100 m/s. Thus a simple comparison of rocket propellant mass to tether system mass indicates that the fully reusable tether transport system could provide significant launch mass savings after only a few round trips. Although the development and deployment costs associated with a tether system would present a larger up-front expense than an existing rocket-based system, for frequent, high-volume round trip traffic to the Moon, a tether system could achieve large reductions in transportation costs by eliminating the need to launch large quantities of propellant into Earth orbit.

Summary

Our analyses have concluded that the optimum architecture for a tether system designed to transfer payloads between LEO and the lunar surface will utilize one tether facility in an elliptical, equatorial Earth orbit and one tether in low lunar orbit. We have developed a system concept design for a 100 km long Earth-orbit Tether Boost Facility capable of picking 1,000 kg payloads up from LEO and injecting them into a minimal-energy lunar transfer orbit. This system will also boost 2,500 kg payloads to GTO. The payload capacity of the system can be built incrementally by deploying additional tether modules. After boosting a payload, the facility can use electrodynamic propulsion to reboost its orbit, enabling the system to repeatedly send payloads to the Moon without requiring propellant or return traffic. When the payload reaches the Moon, it will be caught and transferred to the surface by a 200 km long lunar tether. Using two different numerical simulations, we have tested the feasibility of this design and developed scenarios for transferring payloads from a low-LEO orbit to the surface of the Moon, with only 25 m/s of ΔV needed for small trajectory corrections. Thus, it appears feasible to construct a Cislunar Tether Transport System that can greatly reduce the cost of round-trip travel between LEO and the surface of the Moon by minimizing the need for propellant expenditure.

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