IAF-99-A.5.10

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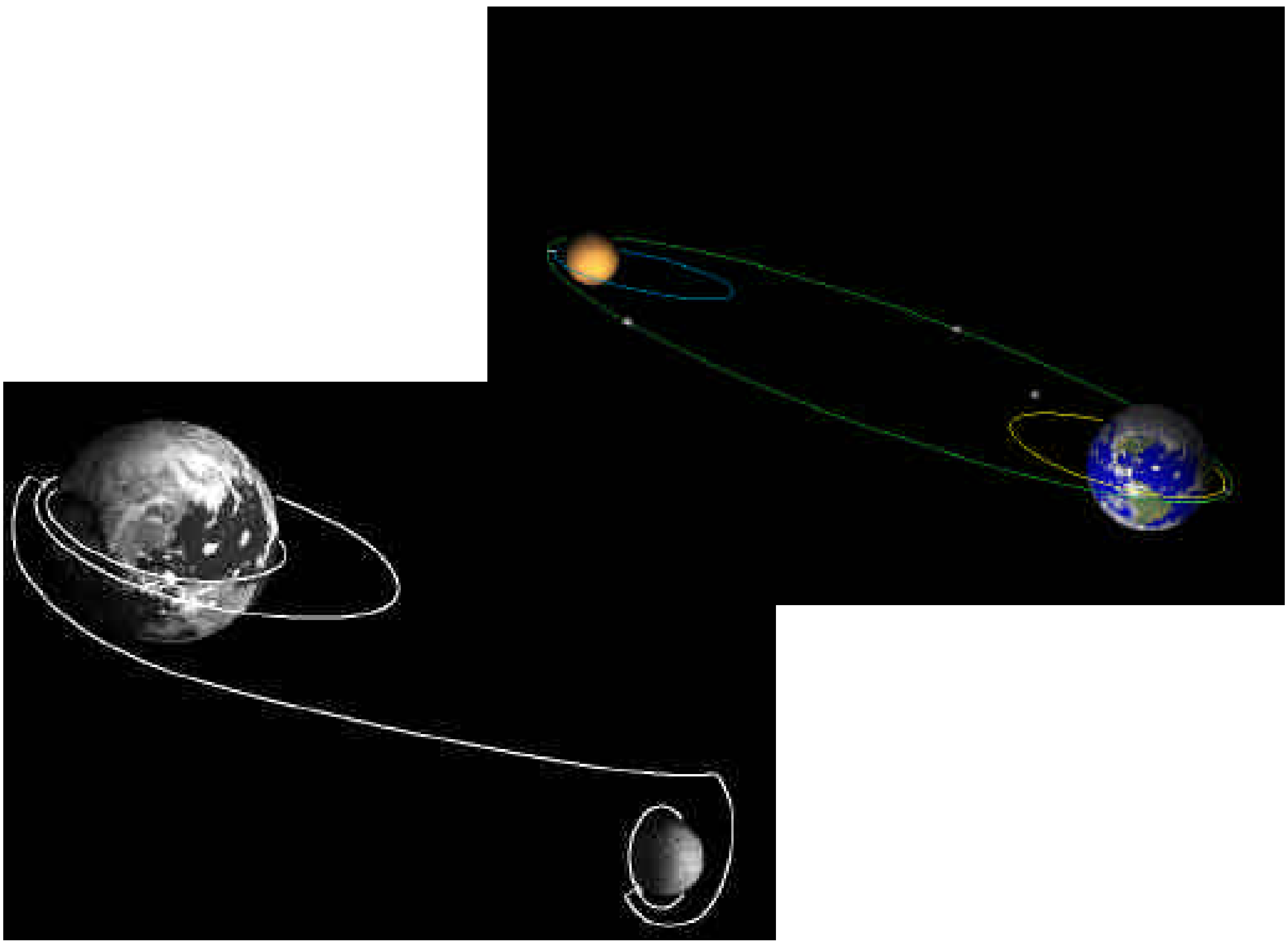

50th International Astronautical Congress
4-8 Oct 1999/Amsterdam, The Netherlands

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Abstract

Routine transport to and from Luna, Mars, and the other moons and planets in the solar system demands an efficient, rapid, low-cost transportation system. We have invented an innovative interplanetary transport architecture to meet that need. It consists of two rotating tethers in elliptical orbits, one around Earth and the other around the destination moon or planet. These two tethers, made of commercially available polymers, suffice to move payloads back and forth without the use of propellant except for midcourse corrections. For airless bodies, like Luna or Mercury, the payloads can be delivered to the surface of the body. We will describe two such architectures in detail, a Cislunar Tether Transport system and a Mars-Earth Rapid Interplanetary Tether Transport (MERITT) system. The Cislunar Tether Transport scenario takes into account the full complexities of the orbital mechanics of the Earth-Moon system, including non-spherical gravitational potentials, inclined orbit dynamics, and luni-solar perturbations. We also describe a design for the first stage of the system, a "rotating electrodynamic force tether" that combines the technology of electrodynamic tethers with the principles of rotating momentum-transfer tethers to enable multiple payloads to be boosted from LEO to higher orbits with no propellant needed. In the MERITT system, a payload capsule in LEO is picked up by the Earth orbiting tether as the tether nears perigee and is tossed a half-rotation later, slightly after perigee. The velocity increment given the payload deep in the gravity well of Earth is sufficient to send the payload on an escape trajectory to Mars, where it is caught by the Mars tether and placed in low Martian orbit. The mass of each tether system, using commercially available polymers and reasonable safety factors, including the central facility and ballast mass, can be as little as 15 times the mass of the payload being handled. Tethers with tip velocities of 2.5 km per second can send payloads to Mars in as little as 90 days if aerobraking is used dissipate some of the high relative velocity on the Mars end. Tether-to-tether transfers without aerobraking take 130 to 160 days.

Nomenclature & Units

a	semimajor axis, m
C_3	orbital energy, $\equiv V^2 - 2\mu/r$, km^2/s^2
d	density, kg/m^3
e	ellipse eccentricity
E	orbital energy, J
F	safety factor
h	specific angular momentum, m^2/s
i	orbit inclination, degrees
J_2	2nd geopotential coefficient
L	tether arm length, m
l	distance from facility to center of mass, m
M	mass, kg
N	orbital resonance parameter
p	orbit semiparameter, $= a(1-e^2)$, m
r	radius, m
R_e	Earth radius, m
r_p	perigee radius, m
T	tensile strength, Pa
V	velocity, m/s
V_C	characteristic velocity, m/s
λ	argument of tether perigee w.r.t. Earth-Moon line
μ_e	Earth's gravitational parameter $= GM_e$, m^3/s^2
μ_m	Moon's gravitational parameter $= GM_m$, m^3/s^2
ω	angular velocity, radians/s
θ	true anomaly
$\dot{\omega}$	Apsidal precession/regression rate, rad/s
$\dot{\Omega}$	Nodal regression rate, rad/s

subscripts:

$\square_a$	apoapse	$\square_p$	periapse
$\square_c$	critical	$\square_m$	moon
$\square_f$	facility	$\square_g$	grapple
$\square_P$	payload	$\square_t$	tether

Introduction

The possibility of using rotating "momentum-exchange" tethers to pick up payloads from one orbit and toss them into another orbit has been discussed conceptually numerous times over the past several decades.[1,2,3,4] In this paper, we investigate the design of specific tether system architectures for two important missions: first, transport between low Earth orbit (LEO) and the surface of the Moon, and second, transport of payloads between LEO and low Mars orbit.

The Cislunar Tether Transport System

A "Cislunar Tether Transport System" composed of one rotating momentum-exchange tether in elliptical, equatorial Earth orbit and a second rotating tether facility in a low lunar orbit can provide a means for repeatedly exchanging payloads between low Earth orbit (LEO) and the surface of the Moon, *with little or no propellant expenditure required*. In 1991, Forward[5] showed that such a system is theoretically possible from an energetics standpoint. A later study by Hoyt and Forward[6] 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. The purpose of this paper is to remove these assumptions and develop an architecture for such a system that takes into account the complexities of orbital mechanics in the Earth-Moon system.

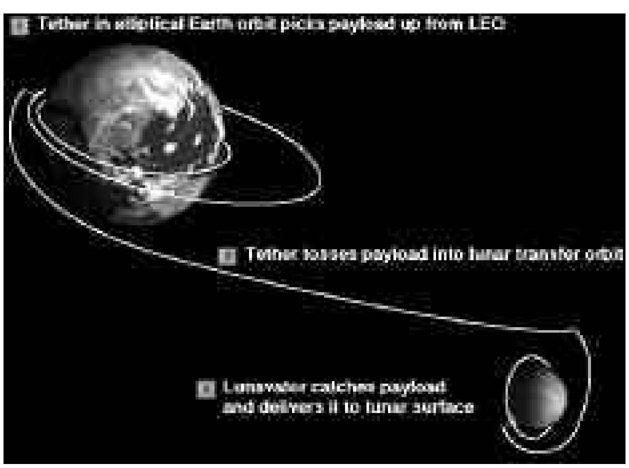

Figure 1. Conceptual illustration of the Cislunar Tether Transport System.

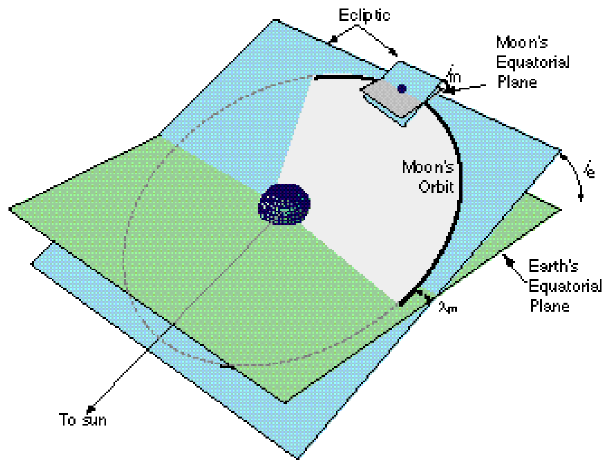

Figure 2. Schematic illustrating the geometry of the Earth-Moon system.

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.

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°.[7] 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 polar, circular 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 throw them towards one of the two points where the Moon crosses the Earth's equatorial plane. 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 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 Earth orbit capable of picking payloads up from low-LEO orbits and tossing them to the Moon. In order to determine an optimum configuration for this facility, we must balance the need to minimize the required masses of the tethers and facilities with the need to make the orbital dynamics of the system as manageable as possible.

The mission of the Earth-orbit portion of the Cislunar Tether Transport System 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 a trajectory with a C_3 of –1.9 would require a ΔV of approximately 3.1 km/s.

Design Considerations

Tether System Staging

From an operational standpoint, the most convenient design for the Earth-orbit portion of a Cislunar Tether Transport System would be to start with a single tether facility in a circular low-Earth-orbit, with the tether retracted. The facility would rendezvous with the payload, deploy the payload at the end of the tether, and then use propellantless electrodynamic tether propulsion to spin up the tether until the tip speed reached 3.1 km/s and the tether could inject the payload into a LTO. However, because the tether transfers some of its orbital momentum and energy to the payload when it boosts it, a tether facility in circular orbit would require a very large ballast mass so that its orbit would not drop into the upper atmosphere after it boosts a payload. Furthermore, the strong dependence of the required tether mass on the tether tip speed will likely make this approach impractical with current material technologies. The required mass for a tapered tether depends upon the tip mass and the ratio of the tip velocity to the tether material's critical velocity according to the relation derived by Moravec:[8]

$$M_t = M_p \sqrt{\pi} \frac{\Delta V}{V_C} e^{\frac{\Delta V^2}{V_C^2}} erf\left\{ \frac{\Delta V}{V_C} \right\}, \qquad (1)$$

where erf() is the error function. The critical velocity of a tether material depends upon the tensile strength, the material density, and the design safety factor according to:

$$V_C = \sqrt{\frac{2T}{Fd}}. \qquad (2)$$

The exponential dependence of the tether mass on the *square* of the velocity ratio results in a very rapid increase in tether mass with this ratio.

Currently, the best commercially-available tether material is Spectra® 2000, a form of highly oriented polyethlene manufactured by AlliedSignal. High-quality specimens of Spectra® 2000 have a room temperature tensile strength of 4 GPa, and a density of 0.97 g/cc. With a safety factor of 3, the material's critical velocity is 1.66 km/s. Using Eqn. (1), an optimally-tapered Spectra® tether capable of sustaining a tip velocity of 3.1 km/s would require a mass of over 100 times the payload mass. While this might be technically feasible for very small payloads, such a large tether mass probably would not be economically competitive with rocket technologies. In the future, very high strength materials such as "buckytube" yarns may become available with tensile strengths that will make a 3 km/s tether feasible; however, we will show that a different approach to the system architecture can utilize currently available materials to perform the mission with reasonable mass requirements.

The tether mass is reduced to reasonable levels if the $\Delta V/V_c$ ratio can be reduced to levels near unity or lower. In the Cislunar system, we can do this by placing the Earth-orbit tether into an elliptical orbit and arranging its rotation so that, at perigee, the tether tip can rendezvous with and capture the payload, imparting a 1.6 km/s ΔV to the payload. Then, when the tether returns to perigee, it can toss the payload ahead of it, giving it an additional 1.5 km/s ΔV. By breaking the 3.1 km/s ΔV up into two smaller boost operations with $\Delta V/V_c < 1$, we can reduce the required tether mass considerably. The drawback to this method is that it requires a challenging rendezvous between the payload and the tether tip; nonetheless, the mass advantages will likely outweigh that added risk.

Behavior of Elliptical Earth Orbits

One of the major challenges to designing a workable tether transportation system using elliptical orbits is motion of the orbit due to the oblateness of the Earth. The Earth's oblateness will cause the plane of an orbit to regress relative to the Earth's spin axis at a rate equal to:[9]

$$\dot{\Omega} = -\frac{3}{2} J_2 \frac{R_e^2}{p^2} \bar{n} \cos(i) \tag{3}$$

And the line of apsides (ie. the longitude of the perigee) to precess or regress relative to the orbit's nodes at a rate equal to:

$$\dot{\omega} = \frac{3}{4} J_2 \frac{R_e^2}{p^2} \bar{n} \,(5\cos^2 i - 1) \tag{4}$$

In equations (3) and (4), $\bar{n}$ is the "mean mean motion" of the orbit, defined as

$$\bar{n} = \sqrt{\frac{\mu_e}{a^3}} \left[1 - \frac{3}{4} J_2 \frac{R_e^2}{p^2} \sqrt{1-e^2}\,(1 - 3\cos^2 i) \right]. \tag{5}$$

For an equatorial orbit, the nodes are undefined, but we can calculate the rate of apsidal precession relative to inertial space as the sum $\dot{\Omega} + \dot{\omega}$ of the nodal and apsidal rates given by Eqs. (3) and (4).

In order to make the orbital mechanics of the Cislunar Tether Transport System manageable, we place two constraints on our system design:

- First, the orbits of the tether facility will be equatorial, so that i=0 and the nodal regression given by Eq. (3) will not be an issue.
- Second, the tether system will throw the payload into a lunar transfer trajectory that is in the equatorial plane. This means that it can perform transfer operations when the Moon is crossing either the ascending or descending node of its orbit.

Nonetheless, we still have the problem of precession of the line of apsides of an orbit. If the tether orbits are circular, this is not an issue, but it is an issue for systems that use elliptical orbits. In an elliptical orbit system we wish to perform all catch and throw operations at or near perigee. As illustrated in Figure 3, for the payload to reach the Moon's radius at the time when the Moon crosses the Earth's equatorial plane, the payload must be injected into an orbit that has a line of apsides at some small angle λ from the line through the Moon's nodes. If the orbit

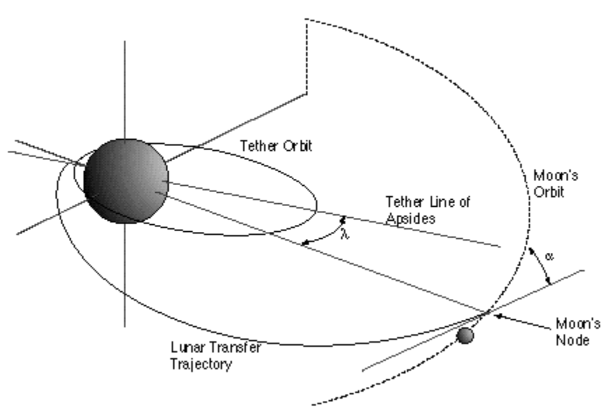

Figure 3. Geometry of the tether orbit and the Moon's orbit.

experiences apsidal precession, the angle λ will have the proper value only periodically. Consequently, in our designs we will seek to choose the orbital parameters such that the apsidal precession of the orbit will have a convenient resonance with the Moon's orbit.

Elliptical-Orbit Tether Boost Facility

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. First, 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 waits for one orbit and adjusts its rotation slightly (by reeling the tether in or out) so that when it returns to perigee, the tether is swinging above the facility and it can release the payload into a trajectory moving faster than the facility.

HEFT Tether Boost Facility

In order to enable the Earth-orbit tether facility to boost materials to the Moon before a lunar base has been established and begins sending return payloads back to LEO, we propose to combine the principle of rotating momentum-exchange tethers with the techniques of electrodynamic tether propulsion to create a facility capable of reboosting its orbit after each payload transfer without requiring return traffic or propellant expenditure. This concept, the "High-strength Electrodynamic Force Tether" (HEFT) Facility,[10] is illustrated in Figure 4. 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 increase 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, using propellantless electrodynamic propulsion to restore its orbit in between each payload boost operation.

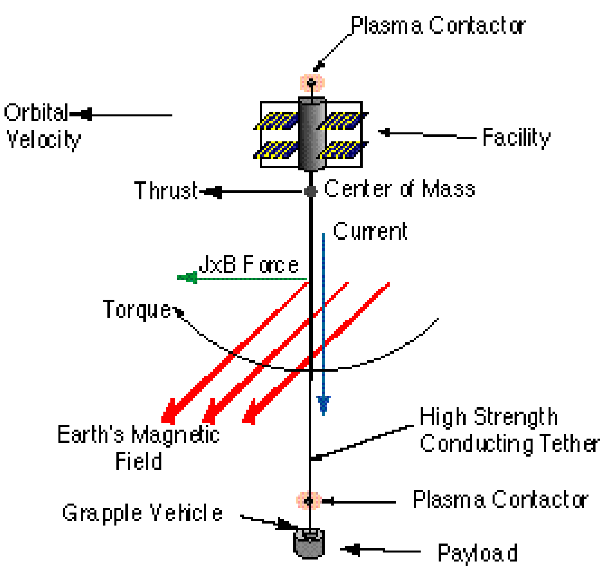

Figure 4. Schematic of the HEFT Facility design.

Tether Design

In order to design the tether boost facility, we must determine the tether length, rotation rate, and orbit characteristics that will permit the tether to rendezvous with the payload and throw it into the desired lunar transfer trajectory.

In the baseline design, the payload begins in a circular Initial Payload Orbit (IPO) with a velocity of

$$V_{p,0} = \sqrt{\frac{\mu_e}{r_{IPO}}}\,. \qquad (6)$$

The facility is placed into an elliptical orbit with a perigee above the payload's orbit, with the difference between the facility's initial perigee and the payload orbital radius equal to the distance from the tether tip to the center of mass of the facility and tether:

$$r_{p,0} = r_{IP0} + (L - l_{cm,unloaded}), \qquad (7)$$

where $l_{cm,unloaded}$ is the distance from the facility to the center of mass of the system before the payload arrives (this distance must be calculated numerically for a tapered tether).

The tether tip velocity is equal to the difference between the payload velocity and the facility's perigee velocity:

$$V_{t,0} = V_{p,0} - V_{IP0}. \tag{8}$$

In order to ensure that a payload will not be "lost" if it is not caught by the tether on its first opportunity, we choose the semimajor axis of the facility's orbit such that its orbital period will be some rational multiple N of the payload's orbital period:

$$P_{f,0} = NP_{IPO} \qquad a_{f,0} = N^{2/3}\ r_{IPO} \tag{9}$$

For example, if $N=5/2$, this condition means that every two orbits the facility will have an opportunity to rendezvous with the payload, because in the time the facility completes two orbits, the payload will have completed exactly five orbits.

An additional consideration in the design of the system are the masses of the facility and tether. A significant facility mass is required to provide "ballast mass." This ballast mass serves as a "battery" for storing the orbital momentum and energy that the tether transfers to and from payloads. If all catch and throw operations are performed at perigee, the momentum exchange results primarily in a drop in the facility's apogee. A certain minimum facility mass is necessary to keep the post catch and throw orbit above the Earth's upper atmosphere. Some of the "ballast mass" will be provided by the mass of the tether deployer and winch, the facility power supply and power processing hardware, and the mass of the tether itself. If additional mass is required, it could be provided by available material in LEO, such as spent upper stage rockets and shuttle external tanks.

The tether mass required will depend upon the maximum tip velocity and the choices of tether material and design safety factor, as described by Eq. 1. For a tapered tether, the tether's center-of-mass will be closer to the facility end of the tether. This can be an important factor when the tether mass is significant compared to the payload and facility masses. In the calculations below, we have used a model of a tether tapered in a stepwise manner to calculate tether masses and the tether center-of-mass.

By conservation of momentum, the perigee velocity of the center of mass of the tether and payload after rendezvous is:

$$V_{p,1} = \frac{V_{p,0}(M_f + M_t) + V_{IPO}M_P}{(M_f + M_t) + M_P}. \tag{10}$$

When the tether catches the payload, the center-of-mass of the tether system shifts downward slightly as the payload mass is added at the bottom of the tether:

$$r_{p,1} = \frac{r_{p,0}(M_f + M_t) + V_{IPO}M_P}{(M_f + M_t) + M_P} \tag{11}$$

In addition, when the tether catches the payload, the angular velocity of the tether does not change, but because the center-of-mass shifts closer to the tip of the tether when the tether catches the payload, the tether tip velocity decreases. The new tether tip velocity can be calculated as

$$V_t^{'} = V_t \frac{\left(L - l_{cm,loaded}\right)}{\left(L - l_{cm,unloaded}\right)} \tag{12}$$

At this point, it would be possible to specify the initial payload orbit, the payload/facility mass ratio, the facility/payload period ratio, and the desired LTO C_3, and derive a system of equations from which one particular tether length and one tether tip velocity can be calculated that determine an "exact" system where the tether tip velocity need not be adjusted to provide the desired C_3 of the payload lunar trajectory. However, the resulting system design is rather restrictive, working optimally for only one particular value of the facility and tether masses, and results in rather short tether lengths that will require very high tip acceleration levels. Fortunately, we can provide an additional flexibility to the system design by allowing the tether facility to adjust the tip velocity slightly by reeling the tether in or out a few percent. If, after catching the payload, the facility reels the tether in by an amount ΔL, the tip velocity will increase due to conservation of angular momentum:

$$V_t^{''} = \frac{V_t^{'}\left(L - l_{cm,loaded}\right)}{\left(L - l_{cm,loaded}\right) - \Delta L} \tag{13}$$

Then, when the facility returns to perigee, it can throw the payload into a lunar transfer trajectory with perigee characteristics:

$$r_{p,LTO} = r_{p,1} + \left(L - l_{cm,loaded}\right) - \Delta L$$
$$V_{p,LTO} = V_{p,1} + V_t' \tag{14}$$

Using the equations above, standard Keplerian orbital equations, and equations describing the shift in the system's center-of-mass as the payload is caught and released, we have calculated a design for a single-tether system capable of picking up payloads from a circular LEO orbit and throwing them to a minimal-energy lunar trajectory. During its initial period of operation, while a lunar facility is under construction and no return traffic exists, the tether system will use electrodynamic tether propulsion to reboost itself after throwing each payload. Once a lunar facility exists and return traffic can be used to conserve the facility's orbital momentum, the orbit of the tether will be modified slightly to permit round trip traffic. The system parameters are listed below.

Table 1:

Initial System Design: Outbound Traffic Only

Payload:
- mass M_p = 2500 kg
- altitude h_{IPO} = 308 km
- velocity V_{IPO} = 7.72 km/s

Tether Facility:
- tether length L = 80 km
- tether mass M_t = 15,000 kg
  (Spectra® 2000 fiber, safety factor of 3.5)
- tether center-of-mass $L_{t,com}$ = 17.6 km
  (from facility)
- central facility mass M_f = 11,000 kg
- grapple mass M_g = 250 kg
  (10% of payload mass)
- total system mass M = 26,250 kg
  = **10.5 x payload mass**
- facility power Pwr = 11 kW avg
- initial tip velocity: $V_{t,0}$ = 1530 m/s
- Pre-Catch Orbit:
  - perigee altitude $h_{p,0}$ = 378 km,
  - apogee altitude $h_{a,0}$ = 11,498 km
  - eccentricity e_0 = 0.451
  - period P_0 =5/2P_{IPO}
  (rendezvous opportunity every 7.55 hrs)
- Post-Catch Orbit:
  - perigee altitude $h_{p,1}$ = 371 km,
  - apogee altitude $h_{a,1}$ = 9687 km
  - eccentricity e_1 = 0.408

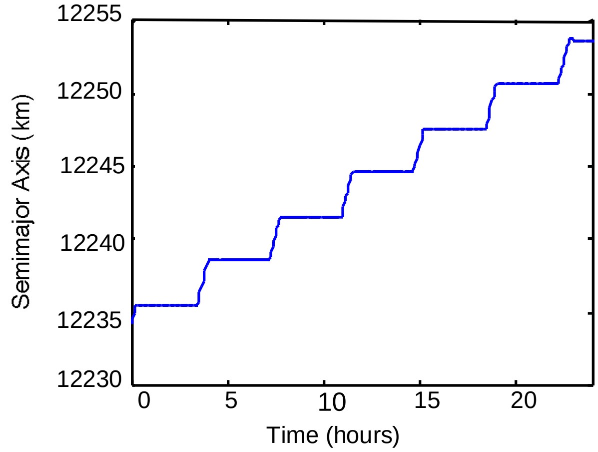

Figure 5. Electrodynamic propulsion reboost of the tether's orbit after the tether has boosted a payload into LTO.

After catching the payload, the facility reels in 2950 m of tether, increasing the tip velocity to 1607 m/s,
- Post-Throw Orbit:
  - perigee altitude $h_{p,2}$ = 365 km,
  - apogee altitude $h_{a,2}$ = 7941 km
  - eccentricity e_2 = 0.36

Lunar Transfer Trajectory:
- perigee altitude $h_{p,lto}$ = 438.7 km
- perigee velocity $V_{p,lto}$ = 10.73 km/s
- trajectory energy C_3 =-1.9 km^2/s^2

Note that for a particular system design, the tether and facility mass will scale roughly linearly with the payload mass, so an equivalent system designed for sending 250 kg payloads to the Moon could be constructed with a tether mass of 1,500 kg and a facility mass of 1,100 kg. Note also that the tether mass is not dependent upon the tether length, so longer tethers can be used to provide lower tip acceleration levels with no mass penalty.

Electrodynamic Reboost of the Tether Orbit

After boosting the payload, the tether facility will be left in a lower energy elliptical orbit with a semimajor axis that is approximately 1780 km less than its original orbit. Once a lunar base and a lunar tether facility have been established and begin to send return traffic down to LEO, the tether facility can restore its orbit by catching and de-boosting these return payloads. In the period before a lunar base is established, however, the tether facility will use electrodynamic propulsion to reboost its apogee by driving current through the tether when the tether is near perigee. 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. Figure 5 shows the reboost of the tether's orbit over one day, assuming that the tether facility has a power supply of 11 kW and is able to store up power during most of its orbit and expend it at a rate of 75 kW during the portion of the orbit when the tether is below 2000 km altitude. In one day, the facility can restore roughly 20 km to its orbit's semimajor axis; in roughly 85 days it could restore its orbit and be prepared to boost another payload to the Moon. More rapid reboost could be accomplished with a larger power supply.

Dealing with Apsidal Precession

As noted earlier, the oblateness of the Earth 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 two ways. First, we can utilize tether reeling maneuvers to counteract the apsidal precession.[11] By simply reeling the tether in and out slightly 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 Moon once per month.[12]

A second 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. Furthermore, we can use propellantless electrodynamic tether propulsion to "fine-tune" the precession rate, either by raising/lowering the orbit or by generating thrust perpendicular to the facility's velocity.

In the design given above, the mass and initial orbit of the tether facility was chosen such that after throwing a payload to the Moon, the tether enters a lower energy elliptical orbit which will precess at a rate of 2.28 degrees per day. The initial, high-energy orbit has a slower precession rate of approximately 1.58 degrees per day. These orbits were chosen so that in the 95.6 days it takes the Moon to orbit 3.5 times around the Earth, the tether facility can reboost itself from its low-energy orbit to its high-energy orbit using propellantless electrodynamic propulsion, and, by properly varying the reboost rate, the apsidal precession can be adjusted so that the line of apsides will rotate exactly 180°, lining the tether orbit up properly to boost another payload to the Moon.

System Design for Round-Trip Traffic

Once a lunar base is established and begins to send payloads back down to LEO, the orbit of the tether system can be modified slightly to enable frequent opportunities for round-trip travel. First, the facility's orbit will be raised so that its high-energy orbit has a semimajor axis of 12577.572 km, and an eccentricity of 0.41515. The tether will then pick up a payload from a circular, 450 km orbit and toss it to the Moon so that it will reach the Moon as the Moon crosses its ascending node. The facility will then drop to a lower energy orbit. At approximately the same time, the return payload will be released by the lunar tether and begin its trajectory down to LEO. When the return payload reaches LEO, the Earth-orbit tether facility will catch it at perigee, carry it for one orbit, and then place it into the 450 km initial payload orbit. Upon dropping the return payload, the facility will place itself back into the high-energy orbit. The perigee of this orbit will precess at a rate such that after 4.5 lunar months (123 days) it will have rotated 180°, and the system will be ready to perform another payload exchange, this time as the Moon crosses its descending node. If more frequent round-trip traffic is desired, tether reeling could again be used to hold the orientation of the tether's orbit fixed, providing transfer opportunities once per sidereal month.

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[8] 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 "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 could capture payloads from Earth as they passed perilune and then set them down on the surface of the Moon. Simultaneously, the tether could pick up payloads to be returned to Earth, and later throw them down to LEO.

Moravec found that the mass of the tether would be minimized if the tether had an arm length equal to one-sixth of the diameter of the Moon, rotating such that each of the two arms touched down on the surface of the Moon three times per orbit. Using data for the best material available in 1978, Kevlar, which has a density of 1.44 g/cc and a tensile strength of 2.8 GPa, Moravec found that a two-arm Skyhook with a design safety factor of F=2 would have to mass approximately 13 times the payload mass. Each arm of Moravec's tether would be 580 km long, for a total length of 1160 km, and the tether center-of-mass would orbit the Moon every 2.78 hours in a circular orbit with radius of 2,320 km. At that radius, the orbital velocity is 1.45 km/s, and so Moravec's Skyhook would rotate with a tip velocity of 1.45 km/s.

Using Moravec's minimal-mass solution, however, requires not only a very long tether but also requires that the payload have a very high velocity relative to the Moon at its perilune. Because the lunar tether in Moravec's design has an orbital velocity of 1.45 km/s and the tether tips have a velocity of 1.45 km/s relative to the center-of-mass, the payload's perilune velocity would need to be 2.9 km/s in order to match up with the tether tip at the top of their rotation. In order to achieve this high perilune velocity, the outbound lunar transfer trajectory would have to be a high-energy hyperbolic trajectory. This presented several drawbacks, the most significant being that if the lunar tether failed to capture the payload at perilune, it would continue on and leave Earth orbit on a hyperbolic trajectory. Moreover, as Hoyt and Forward[6] found, a high lunar trajectory energy would also place larger ΔV demands on the Earth-orbit tethers, requiring two tethers in Earth orbit to keep the system mass reasonable.

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

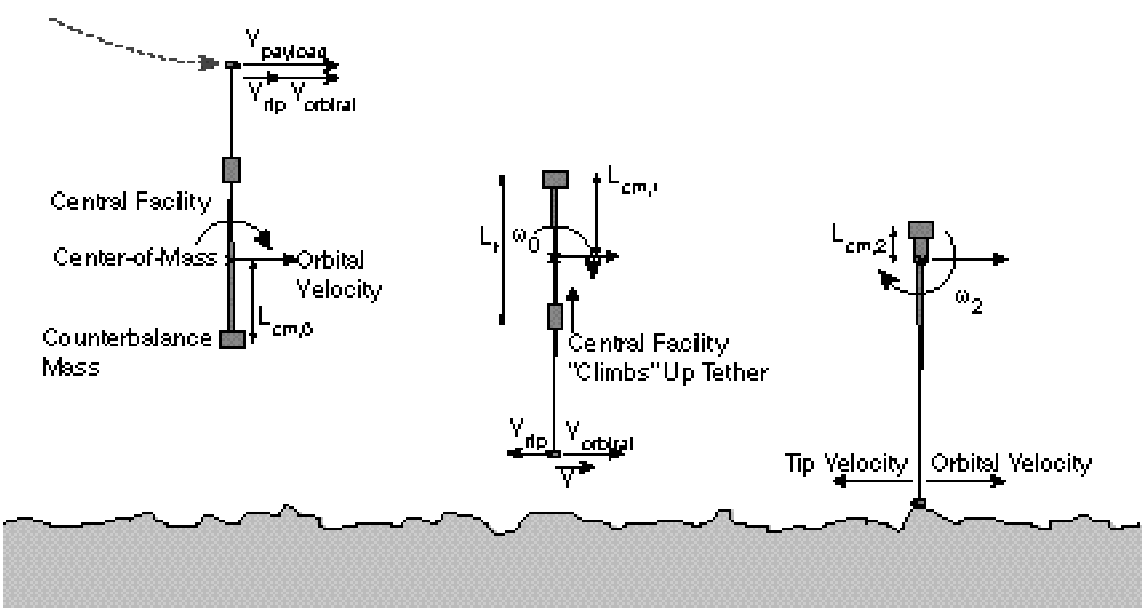

Figure 6. Method for a lunar tether to capture a payload from a minimal-energy LTO and deposit it on the Moon with zero velocity relative to the surface.

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 Moravec lunar Skyhook, which will 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 both 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 6. 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.

Analysis

A first-order design for the Lunavator™ can be obtained by calculating the shift in the system's center-of-mass as the central facility changes its position along the tether. We begin by specifying the payload mass, the counterbalance mass, the facility mass, and the tether length. The required tether mass cannot be calculated simply by using Moravec's tapered tether mass equation, because that equation was derived for a free-space tether. The Lunavator™ must support not only the forces due to centripetal acceleration of the payload and tether masses, but also the tidal forces due to the Moon's gravity. The equations for the tether mass with gravity-gradient forces included are not analytically integrable, so the tether mass must be calculated numerically.

Prior to capture of the payload, the distance from the counterbalance mass to the center-of-mass of the tether system is

$$L_{cm,0} = \frac{M_f L_f + M_t L_{cm,t}}{M_c + M_f + M_t}, \tag{15}$$

where L_f is the distance from the counterbalance to the facility and $L_{cm,t}$ is the distance from the counterbalance to the center-of-mass of the tether. $L_{cm,t}$ must be calculated numerically for a tapered tether.

If the Lunavator™ is initially in a circular orbit with radius a_0, it will have a center-of-mass velocity of

$$v_{cm,0} = \sqrt{\frac{\mu_m}{a_0}}. \tag{16}$$

At the top of the tether swing, it can capture a payload from a perilune radius of

$$r_p = a_0 + (L_t - L_{cm,0}). \tag{17}$$

A payload sent from Earth on a near-minimum energy transfer will have a $C_{3,m}$ of approximately 0.72 km^2/s^2. Its perilune velocity will thus be

$$v_p = \sqrt{\frac{2\mu_m}{a_0 + (L_t - L_{cm,0})} + C_{3,m}}. \tag{18}$$

In order for the tether tip's total velocity to match the payload velocity at rendezvous, the velocity of the tether tip relative to the center of mass must be

$$v_{t,0} = v_p - v_{cm,0}, \tag{19}$$

and the angular velocity of the tether system will be

$$\omega_{t,0} = \frac{v_{t,0}}{L_t - L_{cm,0}}. \tag{20}$$

When the tether captures the payload, the center of mass of the new system, including the payload, is at perigee of a new, slightly elliptical orbit, as illustrated in Figure 7 (it was in a circular orbit and caught a payload going faster than the center-of-mass). The perigee radius and velocity of the center–of-mass are

$$v_{p,1} = \frac{v_{cm,0}(M_c + M_f + M_t) + v_p M_p}{M_c + M_f + M_t + M_p}, \qquad (21)$$

$$r_{p,1} = \frac{a_0(M_c + M_f + M_t) + r_p M_p}{M_c + M_f + M_t + M_p}, \qquad (22)$$

and the new distance from the counterbalance mass to the system's center-of-mass of the system changes to

$$L_{cm,1} = \frac{M_f L_f + M_t L_{cm,t} + M_p L_t}{M_c + M_f + M_t + M_p}. \qquad (23)$$

To increase the rotation rate of the tether system and increase the distance from the system's center of mass to the tether tip, the facility climbs up the tether to the counterbalance mass, reducing the distance from the counterbalance to the center-of-mass to

$$L_{cm,2} = \frac{M_t L_{cm,t} + M_p L_t}{M_c + M_f + M_t + M_p}. \qquad (24)$$

By conservation of angular momentum, the angular velocity will increase to a new value of

$$\omega_2 = \omega_0 \frac{\begin{bmatrix} L_{cm,1}M_c + (L_f - L_{cm,1})M_f + \\ (L_{cm,t} - L_{cm,1})M_t + (L_t - L_{cm,1})M_p \end{bmatrix}}{\begin{bmatrix} L_{cm,2}M_f + (L_{cm,t} - L_{cm,2})M_t \\ + (L_t - L_{cm,2})M_p \end{bmatrix}} \qquad (25)$$

and the payload will then have a velocity relative to the center-of-mass of

$$v_{t,2} = \omega_2 (L_t - L_{cm,2}). \qquad (26)$$

If the initial orbit parameters, tether lengths, and facility and tether masses are chosen properly, then $v_{t,2}$ can be made equal to the perigee velocity of the tether system and the distance from the center of mass to the payload can be made equal to the perigee altitude. When the tether returns to its perigee it can then deposit the payload on the surface of the Moon and simultaneously pick up a payload to be thrown back to Earth.

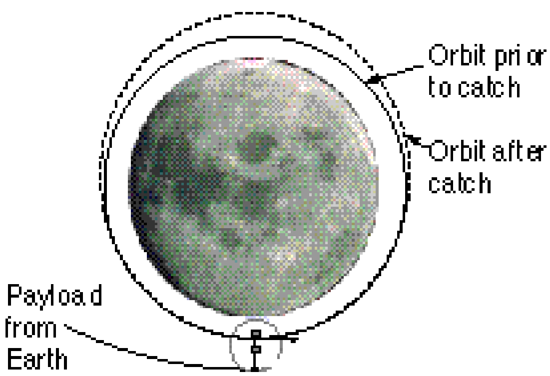

Figure 7. Lunavator™ orbits before and after payload capture.

Lunavator™ Design

Using the equations given above, 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:

Table 2: Baseline Lunavator™ Design

Payload Trajectory:
- mass M_p = 2500 kg
- perigee altitude h_p = 328.23 km
- Moon-relative energy $C_{3,M}$ = 0.719 km^2/s^2

Lunavator™:
- tether length L = 200 km
- counterbalance mass M_c = 15,000 kg
- facility mass M_f = 15,000 kg
- tether mass M_t = 11,765 kg
- Total Mass M = 41,765 kg
  = 16.7 x payload mass
- Orbit Before Catch:
  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
- Orbit After Catch:
  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 ω_0 = 0.00929rad/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

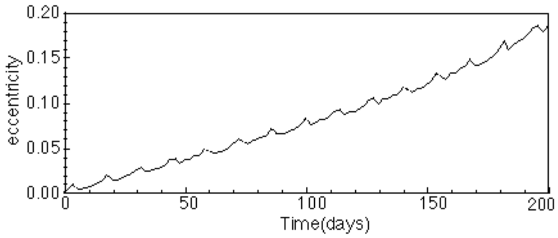

Figure 8. Evolution of the eccentricity of an initially circular 178 km polar lunar orbit, without tether reeling.

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. This ΔV can be provided either using a small rocket thrust or a lunar "slingshot" maneuver. These options will be discussed in more detail in a following section.

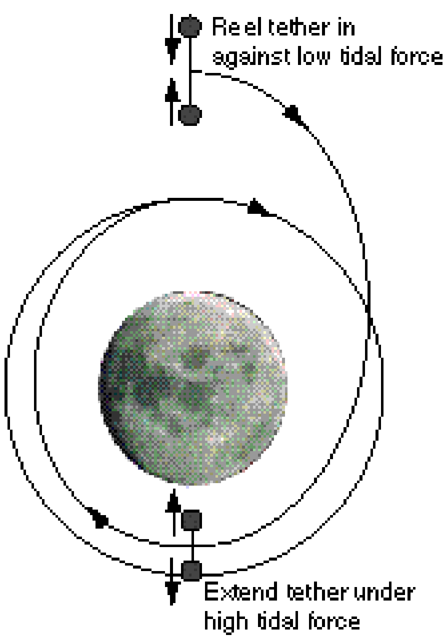

Figure 9. Schematic of tether reeling maneuver to reduce orbital eccentricity.

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. Polar lunar orbits, however, are unstable. The odd-harmonics of the Moon's potential cause a circular, low polar orbit to become eccentric, as illustrated in Figure 8. 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[11] and by Landis[13] 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 9. 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 11 and 13 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.[12] Using a tether reeling scheme in which the tether is reeled in and out once per orbit as shown in Figure 9, 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.[14]
- 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

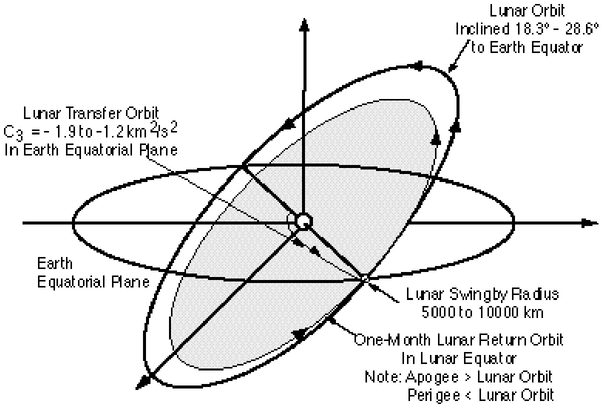

Figure 10. Schematic of one-month "resonance-hop" transfer to place payload in lunar equator without using propellant.

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***.

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,[15] 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.

Transfer to Equatorial Lunar Trajectories

Transfer of a payload from an equatorial Earth trajectory to an equatorial lunar trajectory can be achieved without propellant expenditure, but this requires use of a one-month "resonance hop" transfer, as illustrated in Figure 10. In a resonance hop maneuver, the payload is sent on a trajectory that passes the Moon in such a way that the lunar gravitational field slingshots the payload's orbit into a one-month Earth orbit that returns to the Moon in the lunar equatorial plane. Using MAESTRO, we have developed a lunar transfer scenario that achieves this maneuver.

In order to avoid the one-month transfer time, we can instead use a small impulsive thrust as the payload crosses the lunar equator to bend its trajectory into the equatorial plane. A patched-conic analysis of such a transfer predicts that such a maneuver would require 98 to 135 m/s of ΔV. However, our numerical simulations of the transfer revealed that under most conditions, luni-solar perturbations of the payload's trajectory will perform much of the needed bending for us, and the velocity impulse needed to place the payload in a lunar equatorial trajectory is only about 25 m/s. Figure 11 shows the time-history of a transfer of a payload from the Earth-orbit tether boost facility to the Moon, projected onto the Earth's equatorial plane.

Figure 12 shows this same transfer, projected onto the lunar equatorial plane in a Moon centered, rotating frame, with the x-axis pointing at the Earth. The motion of the payload relative to the lunar equator can be observed in Figure 13, which shows the trajectory projected onto the lunar x-z plane. The payload crosses the lunar equator approximately 10 hours before its closest

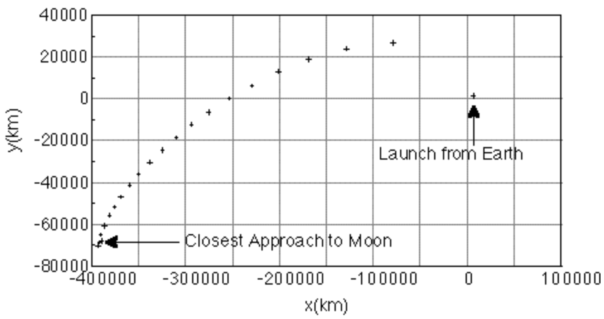

Figure 11. Transfer of payload to lunar equatorial trajectory, projected onto the True Earth Equator.

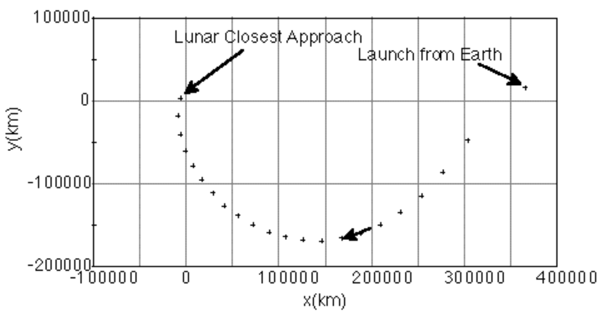

Figure 12. Projection of payload transfer onto Lunar Equatorial Plane (Moon centered frame).

approach to the Moon. Figure 14, which plots the Moon-relative velocity of the payload, shows that the payload's velocity at the time of lunar equatorial crossing is about 925 m/s. However, a plot of the declination of the payload's velocity with respect to the lunar equator, shown in Figure 15, reveals that that the declination of the Moon-relative velocity vector is only a few degrees, much less than the 18°-29° value predicted by a simple zero-patched conic analysis; the Moon's (or Sun's) gravity has bent the velocity vector closer to the lunar orbit plane.

At the time when the payload's trajectory crosses the lunar equator, the declination of the incoming velocity vector is only 1.52°. This dynamical situation permits us to bend the approach trajectory into the lunar equator with a very small amount of impulse supplied by the spacecraft propulsion system. In the case shown here, the amount of ΔV required is only 24.5 m/s, applied about 10 hours before closest approach to the Moon, as the spacecraft crosses the lunar equator.

Transfer to Polar Lunar Trajectories

Figure 16 shows a payload transfer targeted to a polar lunar trajectory with an ascending node (with respect to the lunar prime meridian) of –100.95°. This particular trajectory is a Type II

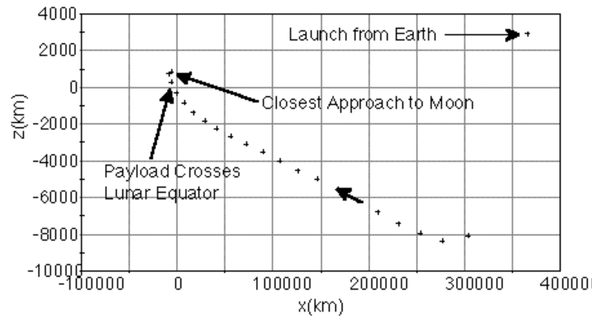

Figure 13. Projection of payload transfer onto Lunar x-z plane (Moon centered frame).

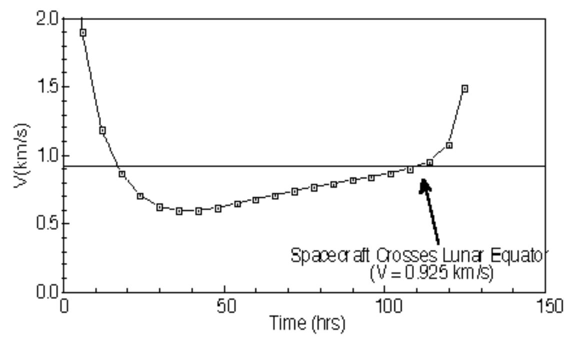

Figure 14. Moon-relative velocity of spacecraft.

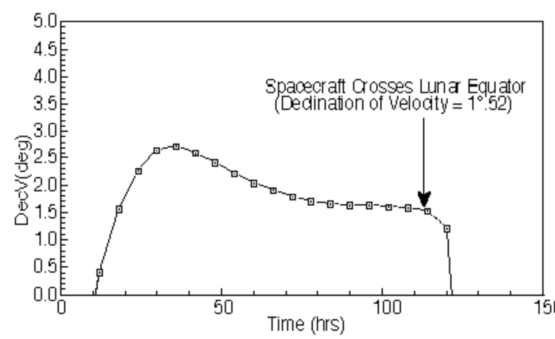

Figure 15. Declination of Moon-relative velocity vector with respect to Lunar Equator.

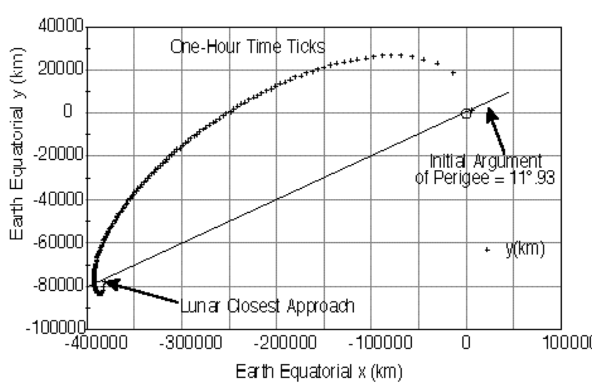

Figure 16. Time history of an Earth-Moon transfer targeted to a polar lunar trajectory.

transfer, with a central angle on the initial orbit of greater than 180°. Similar transfers can be achieved with Type I trajectories (central angle of less than 180°). Essentially, these transfers are achieved by injecting the payload into an orbit that just reaches the Moon's orbit near the point where the Moon will cross the Earth's equatorial plane. When the payload reaches its apogee, it is moving only a few hundred meters per second. As the payload slowly drifts towards its apogee, the Moon approaches, moving at just over 1 km/s. The Moon then "captures" the payload, pulling it into a trajectory that is just barely hyperbolic relative to the Moon.

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 28 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 a 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.

Mars-Earth Tether Transport System Architecture

In earlier work,[6] we developed a preliminary version of a LEO-Lunar Tether Transport System in which the Earth-orbit tethers were designed to throw the payload to the Moon on a fast trajectory. This provided short transit times and enabled a rendezvous with a standard Moravec Lunar Skyhook, but, as discussed earlier, it presented a problem in that if the payload failed to rendezvous with the tip of the Lunar Skyhook, the payload would leave the Earth-Moon system on a hyperbolic trajectory. This raised the question of how far a tether in a highly elliptical Earth orbit could throw a payload. A simple energetics-based calculation indicated that the answer was "All the way to Mars." The Mars-Earth Rapid Interplanetary Tether Transport (MERITT) System is the result. In the following sections, we develop a detailed design for a MERITT system architecture.

MERITT System Description

The MERITT system consists of two rapidly rotating tethers in highly elliptical orbits: EarthWhip around Earth and MarsWhip around Mars. A payload capsule is launched from Earth into a low orbit or suborbital trajectory. The payload is picked up by a grapple system on the EarthWhip tether as the tether nears perigee and the tether arm nears the lowest part of its swing. It is tossed later when the tether is still near perigee and the arm is near the highest point of its swing. The payload thus gains both velocity and potential energy at the expense of the tether system, and its resulting velocity is sufficient to send it on a high-speed trajectory to Mars with no onboard propulsion needed except for midcourse guidance.

At Mars, the incoming payload is caught in the vicinity of periapsis by the grapple end of the MarsWhip tether near the highest part of its rotation and greatest velocity with respect to Mars. The payload is released later when the tether is near periapsis and the grapple end is near the lowest part of its swing at a velocity and altitude which will cause the released payload to enter the Martian atmosphere. The system works in both directions.

The MERITT system can give shorter trip times with aerobraking at Mars because the incoming payload velocity is not limited by the

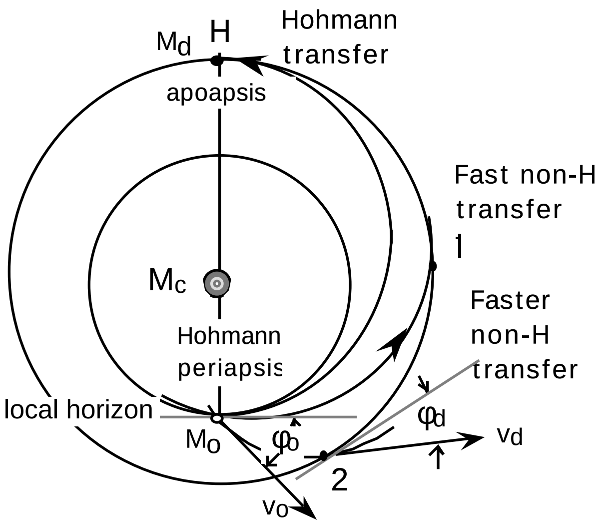

Figure 17. General Orbit Transfer Trajectories.

maximum tether tip velocity and thus payloads can use faster interplanetary trajectories.

In the following subsections we illustrate the general outlines of the system and define the terms used. This initial "feasibility" analysis has not dealt with the many problems of interplanetary phasing and trades. These issues will be addressed in future papers as time and funding allow.

Interplanetary Transfer Orbits

As shown in Figure 17, in the frame of reference of the Sun, acting as the central mass of the whole system, a payload leaves the origin planet, on a conic trajectory with a velocity v_o and flight path angle φ_o and crosses the orbit of the destination planet with a velocity v_d and flight path angle φ_d. Departure from the origin planet is timed so that the payload arrives at the orbit of the destination body when the destination body is at that point in its orbit. Many possible trajectories satisfy these conditions, creating a trade between trip time and initial velocity.

The classic Hohmann transfer ellipse (H) is a bounding condition with the least initial velocity and longest trip time. The Hohmann transfer is tangential to both the departure and destination orbits and the transfer orbits. The direction of the velocity vector is the same in both orbits at these "transfer" points and only differs in magnitude. A ΔV change in payload velocity (usually supplied by onboard propulsion) is required at these points for the payload to switch from one trajectory to another.

Faster non-Hohmann transfers may be tangential at origin, destination, or neither. They may be elliptical or hyperbolic. For a given injection velocity above the Hohmann minimum constraint, the minimum-time transfer orbit is generally non-tangential at both ends. An extensive discussion of the general orbit transfer problem may be found in Bate, Mueller and White.[16]

For reasons discussed below, using tethers in an elliptical orbit with a fixed tip velocity to propel payloads results in an injection velocity constrained to the vector sum of a hyperbolic excess velocity of the released payload and the orbital velocity of the origin planet. When a

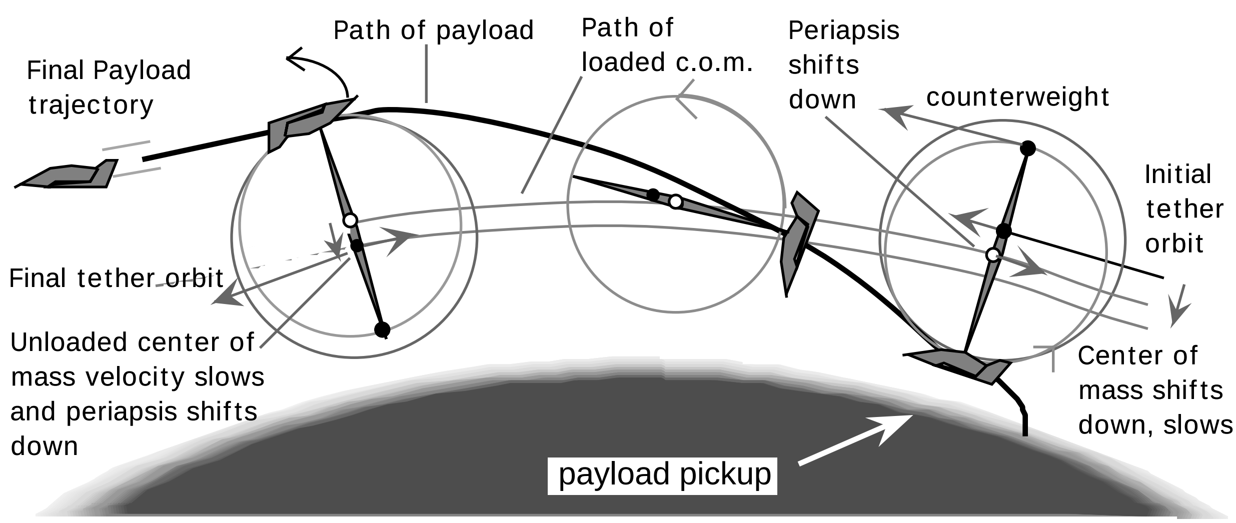

Figure 18. General geometry of tether pickup and throw orbital injection.

tether only is used to receive the payload, a similar constraint exists on the destination end; the incoming trajectory is a hyperbola and the periapsis velocity of the hyperbolic orbit must not exceed what the tether can handle. This periapsis velocity is determined by the vector sum of the orbital velocity of the destination planet, that of the intersecting payload orbit at the intersection, and the fall through the gravitational field of the destination planet.

When passage through the atmosphere of the destination planet (aerobraking) is used to remove some of the incoming velocity, the constraint becomes an engineering issue of how much velocity can be lost in the atmospheric passage. Experience with the Apollo mission returns (circa 12 km/s) and the Mars Pathfinder landing indicates that with proper design, much more velocity can be dissipated than is required to assist tether capture.

Real passages through space take place in three dimensions. To the first order, however, transfer orbits are constrained to a plane incorporating the Sun, the origin planet at launch and the destination planet at arrival. The injection vector must occur in this plane, or close enough to it that on-board payload propulsion can compensate for any differences. This analysis considers only coplanar trajectories, but, as discussed later, this is not a great handicap.

As the payload moves out from the influence of the mass of the origin planet, its trajectory becomes more and more influenced by the mass of the Sun, until the origin planet mass can be essentially neglected. Likewise, inbound payloads become more and more influenced by the destination planet mass until the mass of the Sun may be neglected. For first order Keplerian analysis it is customary to treat the change of influence as if it occurred at a single point, called the patch point. At this point, a coordinate transformation is made.

Payload Pickup and Injection

Figure 18 shows the general geometry of a tether picking up a payload from a suborbital trajectory at a point just outside the atmosphere of the origin planet and injecting it into an interplanetary transit trajectory. The payload is picked up, swung around the tether's center of mass along the circle as it moves along its orbit, and is released from the tip of the tether near the top of the circle. In the process, the tether center of mass loses both altitude and velocity, representing the loss of energy by the tether to the payload. This energy loss may be made up later by propulsion at the tether center and/or in the reverse process of catching incoming payloads.

Around the time of pick-up, the trajectory of the payload must be of equal velocity and should be very nearly tangential (no radial motion) to the circle of motion of the tether tip in the tether frame of reference. This tangential condition increases the time for a docking maneuver to be consummated. It is easy to see how this condition may be satisfied by rendezvous at the mutual apsides of the tether orbit and the payload pickup orbit, but other, more complex trajectories work as well. It is not a requirement, however, that the tether plane of rotation, the tether orbit, and the payload pickup orbit be coplanar. The mutual velocity vector at pick-up is essentially a straight line, and an infinite number of curves may be tangent to that line. The tether rendezvous acts as a kind of patch point, as the plane of the tether's rotation becomes dominant. The practical effect of this is to allow considerable leeway in rendezvous conditions. It also means that the kind of two dimensional analysis presented here has a wide range of validity.

Capturing of an incoming payload is essentially the time reversal of the outgoing scenario; the best place to add hyperbolic excess velocity is also the best place to subtract it. If the tether orbital period is an integral multiple of the rotation period following release of a payload, the tip will be pointed at the zenith at periapsis and the capture will be the mirror image of the release.

Capturing a payload after a pass through the destination body's atmosphere is more complex than a periapsis capture, but involves the same principle: matching the flight path angle of the payload exiting trajectory to the tether flight path angle at the moment of capture and the velocity to the vector sum of the tether velocity and tip velocity. Aerodynamic lift and energy management during the passage through the atmosphere provide propellant-free opportunities to accomplish this.

There is a trade in aerobraking capture between momentum gain by the capturing tether and mission redundancy. To make up for momentum loss from outgoing payloads, the tether would like to capture incoming payloads at similar velocities. That, however, involves hyperbolic trajectories in which, if the payload is not captured, it is lost in space. Also, in the early operations before extensive ballast mass is accumulated, care must be taken that the tether itself is not accelerated to hyperbolic velocities as a result of the momentum exchange.

Payload Release

The release orbit is tangential to the tether circle in the tether frame of reference by definition, but it is not necessarily tangential to the trajectory in the frame of reference of the origin planet. The injection velocity vector is simply the vector sum of the motion of the tether tip and the tether center, displaced to the location of the tether tip. Note in the third part of Figure 18 that this does not generally lie along the radius to the tether center of mass. For maximum velocity, if one picks up the payload at tether periapsis, one must wait for the tether to swing the payload around to a point where its tip velocity vector is near parallel to the tether center of mass orbital velocity vector. By this time, the tether has moved significantly beyond periapsis, and there will be a significant flight path angle, which both orbits will share at the instant of release. Large variations from this scenario will result in significant velocity losses, but velocity management in this manner could prove useful. If, on the other hand, maximum velocity transfer and minimum tether orbit periapsis rotation is desired, the payload can be retained and the tether arm length or period adjusted to release the payload in a purely azimuthal direction at the next periapsis.

Rendezvous of Grapple with Payload

The seemingly difficult problem of achieving rendezvous of the tether tip and payload is nearly identical to a similar problem solved daily by human beings at circuses around the world. The grapple mechanism on the end of a rotating tether is typically subjected to a centrifugal acceleration of one gee by the rotation of the tether. Although the grapple velocity vector direction is changing rapidly, its speed is constant and chosen to be the same speed as the payload, which is moving at nearly constant velocity in its separate free fall suborbital trajectory. The timing of the positions of the tether tip and the payload needs to be such that they are close to the same place (within a few meters) at close to the same time (within a few seconds), so their relative spacing and velocities are such that the grapple can compensate for any differences. This situation is nearly identical to the problem of two trapeze artists timing the swings of their separate trapeze bars so that that the "catcher," being supported in the 1 gee gravity field of the Earth by his bar, meets up with and grasps the "payload" after she has let go of her bar and is in a "free fall" trajectory accelerating with respect to the "catcher" at one gee. They time their swings, of course, so that they meet near the instant when both are at near zero relative velocity. The tether grapple system will have the advantages over the human grapple system of GPS guidance, radar Doppler and proximity sensors, onboard divert thrusters, electronic synapses and metallic grapples, which should insure that its catching performance is comparable to or better than the demonstrated human performance.

An essential first step in the development of the MERITT system would be the construction and flight test of a rotating tether-grapple system in LEO, having it demonstrate that it can accurately toss a dummy payload into a carefully selected orbit such that n orbits later the two meet again under conditions that will allow the grapple to catch the payload once again.

The Automated Rendezvous and Capture (AR&C) Project Office at Marshal Space Flight Center (MFSC) has been briefed on the AR&C requirements for the capture of a payload by a grapple vehicle at the end of a tether with a one-gee acceleration tip environment. MSFC has been working AR&C for over six years and has a great deal of experience in this area. It is their opinion [14] that their present Shuttle-tested [STS-87 & STS-95] Video Guidance Sensor (VGS) hardware, and Guidance, Global Positioning System (GPS) Relative Navigation, and Guidance, Navigation and Control (GN&C) software, should, with sufficient funding, be able to be modified for this tether application.

Tether Considerations

For a tether transport system to be economically advantageous, it must be capable of

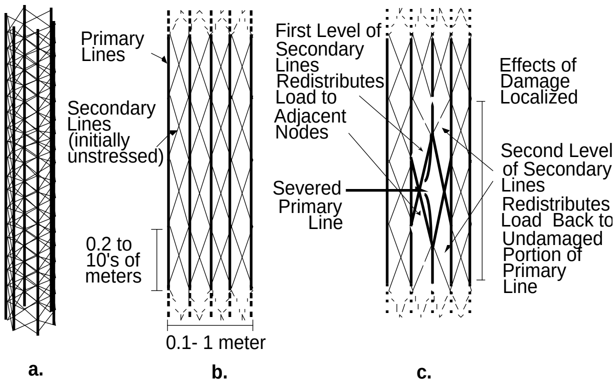

Figure 19. The Hoytether™ design and its response to a cut line.

handling frequent traffic for many years despite degradation due to impacts by meteorites and space debris. Fortunately, a survivable tether design exists, called the Hoytether™, which can balance the requirements of low weight and long life.[17] As shown in Figure 19, 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 slack initially, 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 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 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 retain a high margin of safety.[18]

Tether Mass Ratios

Assuming that the grapple on the end of the tether masses 20% of the payload mass, we can use Eqn. (1) to calculate the mass ratio of a one arm Spectra® 2000 Hoytether™ to the payload it is handling, assuming various different safety factors and various different tether tip velocities, to be:

Table 3:
Ratio of Spectra™ 2000 Tether Material Mass to Payload Mass (Grapple Mass 20% of Payload Mass)

	Tether Material Safety Factor (F)			
	1.75	2.0	2.4	3.0
Tip Speed V_T				
1.5 km/s	2.2	2.5	3.4	4.9
2.0 km/s	3.7	4.7	6.4	10.0
2.5 km/s	8.0	11.0	17.0	30.0

From this table we can see that by using Spectra™ 2000, we can achieve tether tip velocities of 2.0 km/s with reasonable tether mass ratios (<10) and good safety factors. Higher tip velocities than 2.0 km/s are achievable using higher mass ratios, lower safety factors, and stronger materials.

Tether Survivability

There are many objects in Earth space, ranging from micrometeorites to operational spacecraft with 10 meter wide solar electric arrays. 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 30 cm will impact all the strands at one time, cutting the tether. These large objects could include operational spacecraft, which would 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.

Depending upon the choice of the EarthWhip orbit, calculations show that there is a small (<1%) but finite chance of the EarthWhip tether striking one of the 600 operational spacecraft. It will therefore be incumbent on the tether system fabricators and operators to produce EarthWhip tether systems that maintain an accurate inventory of the known large objects and control the tether system center of mass 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.

MERITT Modeling

Calculations of the MERITT system performance were performed using the mathematical modeling software package "TK Solver" which allows the user to type in the relevant equations and get results without having to solve the model algebraically or structure it as a procedure, as long as the number of independent relationships equals the number of variables. This is very useful in a complex system when one may wish to constrain various variables for which it would be difficult, if not impossible, to solve and to perform numerical experiments to investigate the behavior of the system.

Two versions of a tether based interplanetary transfer system are being worked on, one for tether-only transfers and the other incorporating an aerobraking pass at the destination body to aid in capture and rotation of the line of apsides. It should be emphasized that the results presented here are very preliminary and much remains to be done with the software. Because of the ongoing work and the growing number of variables and lines of code, we will not try to go through this line by line here. Questions concerning the code should be referred to Gerald Nordley at the above address.

The general architecture of the models is sequential. A payload is picked up from a trajectory at the origin planet, and added to a rotating tether in a highly elliptical orbit around the origin planet. The pickup is accomplished by matching the position and velocity of the grapple end of the unloaded rotating tether to payload position and velocity.

This addition of the payload mass to one end of the tether shifts the center of mass of the tether toward the payload. The tether used in these examples is modeled as a rigid line with two arms, a grapple, a counterweight and a central mass. The tether is assumed to be designed for a payload with a given mass and a "safety factor" of two, as described in Hoyt and Forward[18] and to be dynamically symmetrical with a payload of that mass attached.

The mass distribution in the arms of the tether was determined by dividing the tether into ten segments, each massive enough to support the mass outward from its center; this was not needed for the loaded symmetric tether cases presented here, but will be useful in dealing with asymmetric counterweighted tethers. The total mass of each tether arm was determined from Eqn. (1). The continuously tapered mass defined by Eqn. (1) was found to differ by only a few percent from the summed segment mass of the 10 segment tether model used in the analysis, and the segment masses were adjusted accordingly until the summed mass fit the equation. The small size of this adjustment, incidentally, can be taken as independent confirmation of Eqn. (1).

We ended up designing many candidates for the EarthWhip and MarsWhip tethers, from some with very large central station masses that were almost unaffected by the pickup or toss of a payload, to those that were so light that the toss of an outgoing payload caused their orbits to shift enough that the tether tip hit the planetary atmospheres, or the catch of an incoming payload sent the tether (and payload) into an escape trajectory from the planet. After many trials, we found some examples of tethers that were massive enough that they could toss and catch payloads without shifting into undesirable orbits, but didn't mass too much more than the payloads they could handle. The tethers are assumed to be made of Spectra™ 2000 material braided into a Hoytube™ structure with a safety factor of 2. The tether design consists of a large central station with a solar array power supply, winches, and control systems, plus any ballast mass needed to bring the mass of the total system up to the desired final mass value. From the tether central station is extended two similar tethers, with a taper and mass determined by Eqn. (1) according to the loaded tip velocity desired. At the end of the tethers are grapples that each mass 20% of the payloads to be handled. To simplify this initial analysis, we assumed that one grapple is holding a dummy payload with a mass equal to the active payload, so that after the grapple on the active arm captures a payload, the tether system is symmetrically balanced. Later, more complex, analyses will probably determine that a one arm tether system will do the job equally well and cost less.

Shift in Tether Center of Mass

The shift of the center of mass of the tether system when a payload was attached or released was determined by adding the moments of the unloaded tether about the loaded center of symmetry and dividing by the unloaded mass.

Figure 20 illustrates the four general circumstances of tether operations: origin pickup, origin release, destination capture and destination release. The shift of the center of mass of the tether system when a payload was attached or released was determined by adding the moments of the unloaded tether about the loaded center of symmetry and dividing by the unloaded mass. Figure 20 illustrates the four general circumstances of tether operations; origin pickup, origin release, destination capture and destination release. It turns out that the dynamics of an ideal rigid tether system with a given payload can be fairly well modeled by simply accounting for the change in the position and motion of the tether's center of mass as the payload is caught and released.

When the payload is caught, the center of mass shifts toward the payload and the tether assumes a symmetrical state. The velocity of the tip around the loaded center of mass is simply its velocity around the unloaded center of mass minus the velocity of the point which became the new center of mass about the old center of mass. The change in the tether orbital vector is fully described by the sum of the vector of the old center of mass and the vector at the time of capture or release of the point that becomes the new center of mass relative to the old center of mass. Since the tether loses altitude with both the catch and the throw, its initial altitude must be high enough so that it does not enter the atmosphere after it throws the payload.

Once the payload is released, its velocity and position are converted to Keplerian orbital elements which are propagated to the outgoing patch point. At this point, they are converted back to position and velocity, and transformed to the Sun frame of reference.

The velocity of insertion into the orbit in the Sun's frame of reference is essentially the vector sum of the hyperbolic excess velocity with respect to the origin planet and the

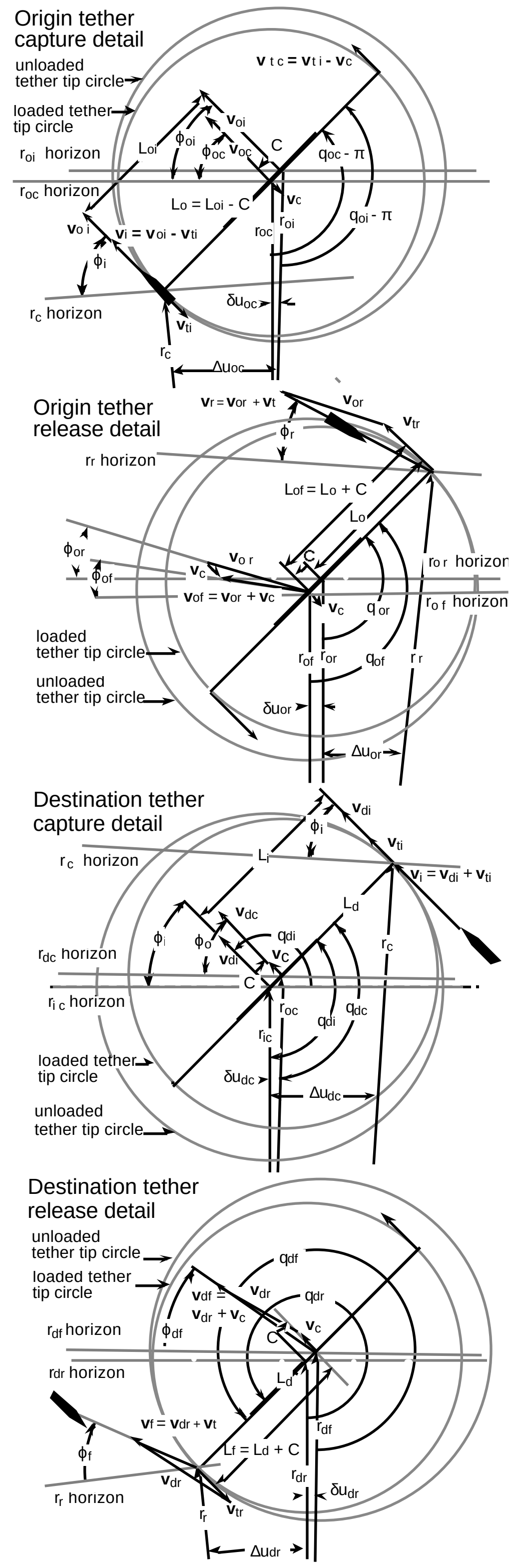

Figure 20. Tether Capture/Release Operations.

origin planet's orbital velocity about the Sun. This vector is done in polar coordinates, and the angle portion of this vector in the origin planet frame is, at this point, a free choice. For now, an estimate or "guess" of this quantity is made. The resulting vector is then converted into Sun frame orbital elements and propagated to the patch point near the orbit of the destination planet. There, it is transformed into the destination planet coordinates.

Tether-Only Incoming Payload Capture

For the tether-only capture scenario, the velocity and radius of the tip of the tether orbiting the destination mass are calculated and iteratively matched to the velocity of the payload on an orbit approaching the destination planet, as shown in Figure 21.

The distance of the patch point and the relative velocity there provide the energy of the orbit. The radius and velocity of the tether tip provide another pair of numbers and this is sufficient to define an approach orbit when they match. There are a large number of free parameters in this situation with respect to the tether orbit which can be varied to produce a capture. There is a good news/bad news aspect to this. The difficulty is that the problem is not self- defined and to make the model work, some arbitrary choices must be made. The good news is that this means there is a fair amount of operational flexibility in the problem and various criteria can be favored and trades made.

In this work, we have generally tried to select near-resonant tether orbits that might be "tied" to geopotential features so that they precess at the local solar rate and thus maintain their apsidal orientation with respect to the planet-Sun line. The Russian Molniya communications satellites about Earth and the Mars Global Surveyor spacecraft use such orbits.

The Sun-referenced arguments of periapsis, ω, in the figures are technically not constants, but can be treated as such for short spans of time when apsidal precession nearly cancels the angular rate of the planet's orbit about the Sun .

The fastest transfer times are generally associated with the fastest usable periapsis velocities. These are found when the tether is at

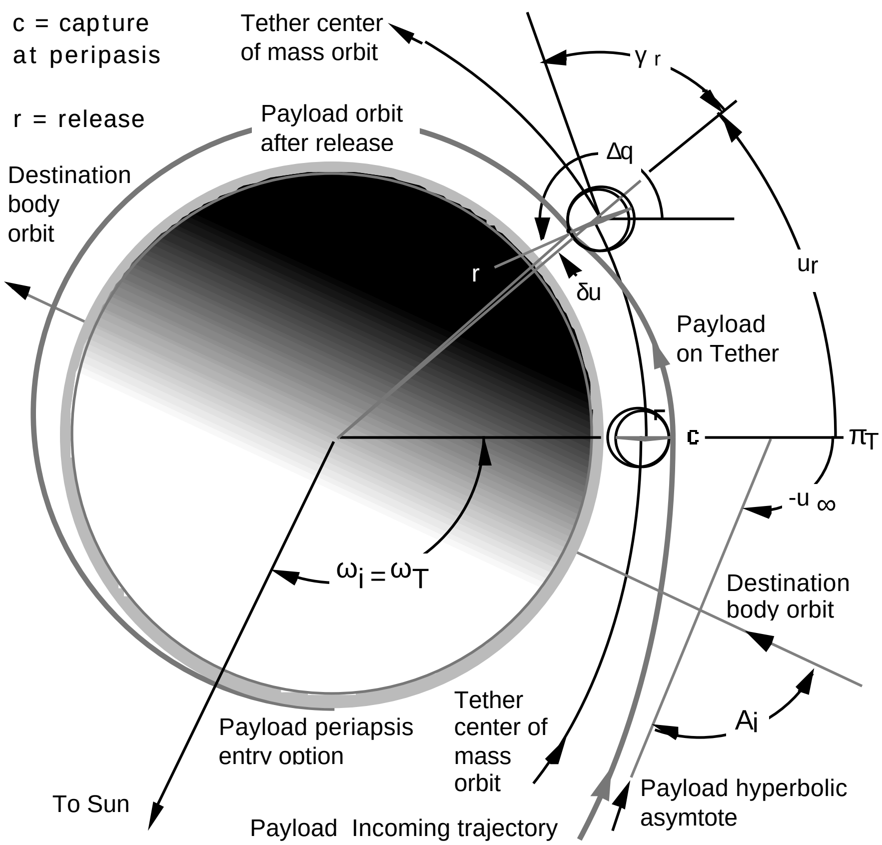

Figure 21. Tether-Only Capture Scenario.

periapsis and its tip at the zenith of its swing. In one approach to this model, these tether conditions are used to set the periapsis velocity and radius of the incoming orbit. This, in turn, defines the relative velocity at the patch point, and the origin planet injection angle can be iterated to produce a Sun frame orbit that produces that relative velocity at the destination planet patch point.

Aerobraking Payload Capture

In the case of using aerobraking in the planetary atmosphere, the injection angle can be optimized for minimum transfer time. As shown in Figure 22, the radius at which the atmosphere of the destination planet is dense enough to sustain an aerodynamic trajectory is used to define the periapsis of the approach orbit; there is no velocity limit.

In a similar manner, the tether tip at an estimated capture position and velocity, together with the radius at which the outgoing payload resumes a ballistic trajectory define an exit orbit which results in tether capture. The difference in the periapsis velocity of this orbit and the periapsis velocity of the inbound trajectory is the velocity that must be dissipated during the aerodynamic maneuver. For Mars bound trajectories, this aerobraking ΔV is on the order of 5 km/s, as compared to direct descent ΔV's of 9 km to 15 km/s. Also, payloads meant to be released into suborbital trajectories already carry heat shields, though designed for lower initial velocities.

After the tether tip and the incoming payload are iteratively matched in time, position and velocity, the center of mass orbit of the loaded tether is propagated to the release point. This is another free choice, and the position of the tether arm at release determines both the resulting payload and tether orbit. In this preliminary study, care was taken to ensure that the released payload did enter the planet's atmosphere, the tether tip did not, and that the tether was not boosted into an escape orbit.

Initial Planet Whip Analysis

We first carried out analyses of a number of MERITT missions using a wide range of assumptions for the tether tip speed and whether or not aerobraking was used. The trip times for the various scenarios are shown in Table 4. As can be seen from Table 4, the system has significant

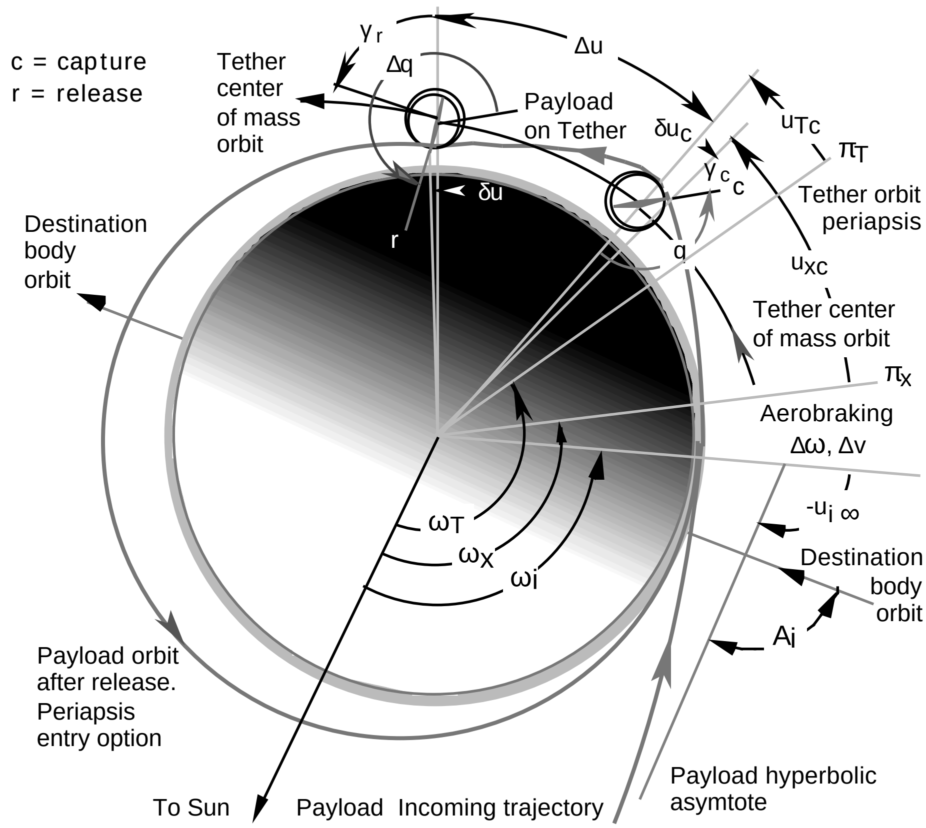

Figure 22. Aerobraking Tether Capture.

growth potential. If more massive tethers are used, or stronger materials become available, the tether tip speeds can be increased, cutting the transit time even further. The transit times in Table 4 give the number of days from payload pickup at one planet until payload reentry at the other planet, and include tether "hang time" and coast of the payload between the patch points and the planets. Faster transit times can be made with higher energy initial orbits for the payload and the tether. With a 2.5 km/s tip speed on the PlanetWhip tethers and using aerobraking at Mars (see Figure 22), the Earth orbit-Mars orbit transit time can be made about 94 days.

PlanetWhip Analysis

The periapsis of the tether orbit is pushed counterclockwise for where a tether-only capture would occur by the angular distance needed for aerobraking and the periapsis rotations caused by capturing and releasing the payload at non-zero true anomalies. If the periapsis is shifted enough, the tether may be able to inject a payload on a return trajectory without waiting for many months, or using substantial amounts of propellant to produce the needed alignment.

Detailed MERITT Example

There are a large number of variables in the MERITT system concept, and many of those variables can be freely chosen at the start of the system design. We have carried out dozens of complete round-trip scenarios under various different assumptions, such as: aerobraking before tether catch versus direct tether-to-tether catch; sub-, circular, and elliptical initial and final payload orbits; 1.5, 2.0, 2.5 and higher tether tip velocities; large, small and minimum tether central facility masses; etc. We will present here just one of the many possible MERITT scenarios using finite mass EarthWhip and MarsWhip tethers, but do it in extensive detail so the reader can understand where the broad assumptions are, while at the same time appreciating the accuracy of the simulations between the broad assumptions. In most cases, the matches between the payload trajectories and the tether tip trajectories are accurate to 3 and 4 decimal places.

Table 4.
Potential MERITT Interplanetary Transfer Times

Tip Speed (km/s)	System Mass Ratio	Transfer direction From->To	Tether-only (days)	Aero-braking (days)
1.5	15x	Earth->Mars	188	162
		Mars->Earth	187	168
2.0	15x	Earth->Mars	155	116
		Mars->Earth	155	137
2.5	30x	Earth->Mars	133	94
		Mars->Earth	142	126

Figure 23 is a diagram showing how a single tether toss and catch system would work on either the Earth or Mars end of the MERITT system, for a finite mass PlanetWhip tether. The incoming payload brushes the upper atmosphere of the planet, slows a little using aerobraking, and is caught by a rotating tether in a low energy elliptical orbit. After the payload is caught, the center of mass of the tether shifts and the effective length of the tether from center of mass to the payload catching tip is shortened, which is the reason for the two different radii circles for the rotating tether in the diagram. The orbit of the tether center of mass changes from a low energy elliptical orbit to a higher energy elliptical orbit with its periapsis shifted with respect to the initial orbit. The tether orbit would thus oscillate between two states:

1) a low energy state wherein it would be prepared to absorb the energy from an incoming payload without becoming hyperbolic

and

2) a high energy state for tossing an outgoing payload.

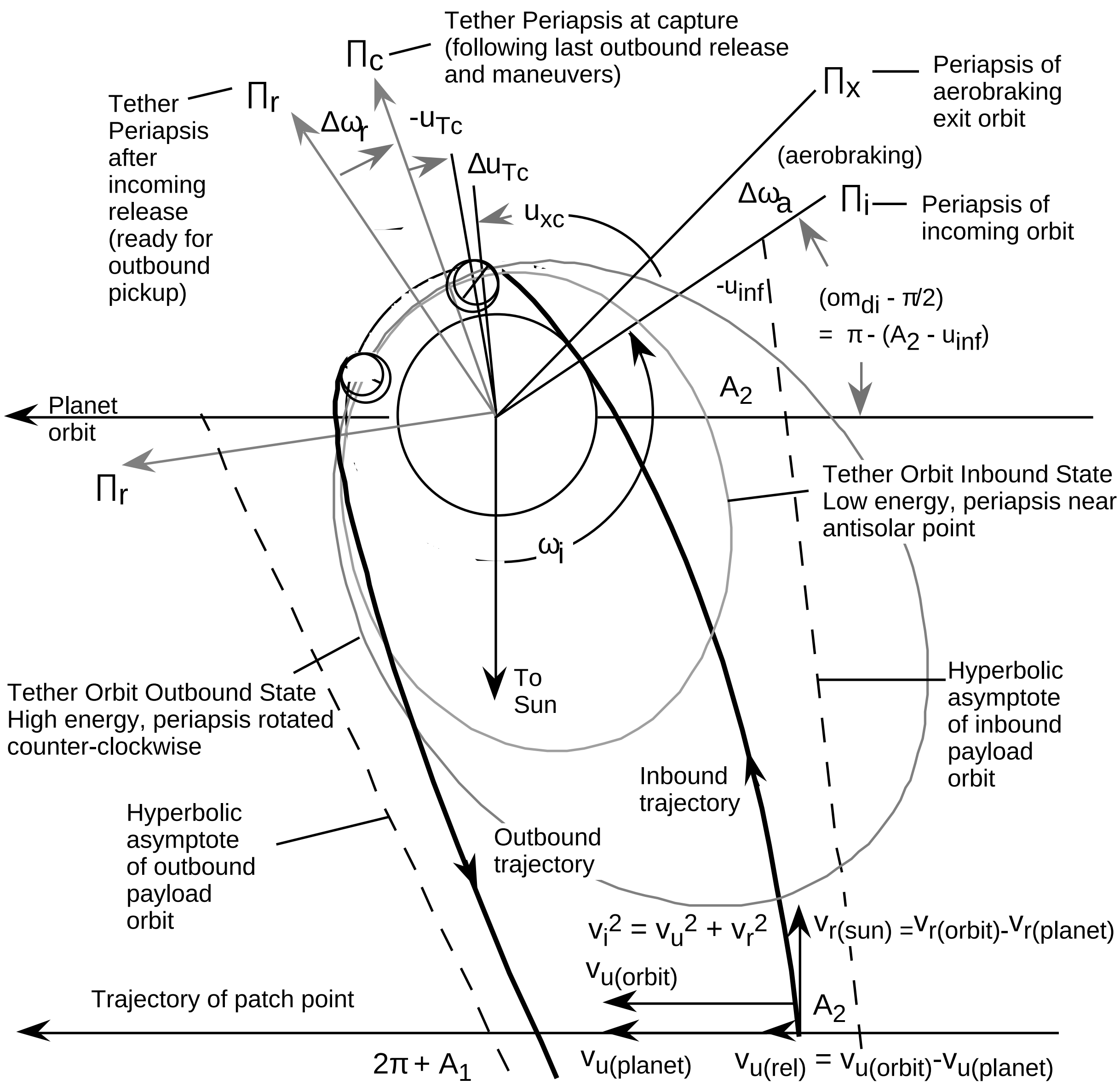

Figure 23. "Planet"Whip showing catch and toss states using aerobraking.

The scenario we will describe uses EarthWhip and MarsWhip tethers of near minimum mass made of Spectra™ 2000 with a tip speed of 2.0 km/s. Because they have small total masses, the toss and catch operations significantly affect the tether rotation speed, center of mass, and orbital parameters, all of which are taken into account in the simulation. The payload is assumed to be initially launched from Earth into a suborbital trajectory to demonstrate to the reader that the MERITT system has the capability to supply all of the energy and momentum needed to move the payload from the upper atmosphere of the Earth to the upper atmosphere of Mars and back again. We don't have ask the payload to climb to nearly Earth escape before the MERITT system takes over.

In practice, it would probably be wise to have the payload start off in an initial low circular orbit. The energy needed to put the payload into a low circular orbit is not that much greater than the energy needed to put the payload into a suborbital trajectory with an apogee just outside the Earth's atmosphere. The circular orbit option also has the advantage that there would be plenty of time to adjust the payload orbit to remove launch errors before the arrival of the EarthWhip tether.

In the example scenario, the payload, in its suborbital trajectory, is picked up by the EarthWhip tether and tossed from Earth to Mars. At Mars it is caught by the MarsWhip tether without the use of aerobraking, and put into a trajectory that enters the Martian atmosphere at low velocity. Since this scenario does not use aerobraking, the return scenario is just the reverse of the outgoing scenario.

Payload Mass

We have chosen a canonical mass for the payload of 1000 kg. If a larger payload mass is desired, the masses of the tethers scale proportionately. The scenario assumes that the payload is passive during the catch and throw operations. In practice, it might make sense for the payload to have some divert rocket propulsion capability to assist the grapple during the catch operations. In any case, the payload will need some divert rocket propulsion capability to be used at the midpoint of the transfer trajectory to correct for injection errors.

Tether Mass

Both the EarthWhip and MarsWhip tethers were assumed to consist of a robotic central station, two similar tethers, two grapples at the ends of the two tethers, and, to make the analysis simpler, one grapple would be holding a dummy payload so that when the active payload is caught, the tether would be symmetrically balanced.

The tether central station would consist of a solar electric power supply, tether winches, and command and control electronics. There may be no need to use center of mass rocket propulsion for ordinary tether operations. Both tethers can be adequately controlled in both their rotational parameters and center-of-mass orbital parameters by "gravity-gradient" propulsion forces and torques generated by changing the tether length at appropriate times in the tether orbit. [11,13,]

The EarthWhip tether would also have a small conductive portion of the tether that would use electrodynamic tether propulsion,[18] where electrical current pumped through the tether pushes against the magnetic field of the Earth to add or subtract both energy and angular momentum from the EarthWhip orbital dynamics, thus ultimately maintaining the total energy and angular momentum of the entire MERITT system against losses without the use of propellant.

The grapple mechanisms are assumed in this scenario to mass 20% of the mass of the payload, or 200 kg for a 1000 kg payload. It is expected, however, that the grapple mass will not grow proportionately as the payload mass increases to the many tens of tons needed for crewed Mars missions.

In the scenario presented here, it is assumed that the grapples remain at the ends of the tethers during the rendezvous procedure. In practice, the grapples will contain their own tether winches powered by storage batteries, plus some form of propulsion.

As the time for capture approaches, the grapple, under centrifugal repulsion from the rotation of the tether, will release its tether winches, activate its propulsion system, and fly ahead to the rendezvous point. It will then reel in tether as needed to counteract planetary gravity forces in order to "hover" along the rendezvous trajectory, while the divert thrusters match velocities with the approaching payload. In this manner, the rendezvous interval can be stretched to many tens of seconds.

If needed, the rendezvous interval can be extended past the time when the tip of the tether passes through the rendezvous point by having the grapple let out tether again, while using the divert thrusters to complete the payload capture. The grapple batteries can be recharged between missions by the grapple winch motor/dynamos, by allowing the grapple winches to reel out while the central winches are being reeled in using the central station power supply. The grapple rocket propellant will have to be resupplied either by bringing up "refueling" payloads or extracting residual fuel from payloads about to be deorbited into a planetary atmosphere.

For this scenario, we assumed that, when loaded with a payload, the EarthWhip and MarsWhip tethers were rotating with a tether tip speed of V_T = 2,000 m/s. The length of each tether arm was chosen as L=400 km in order to keep the acceleration on the payload, $G=V_T^2/L$, near one gee. We also assumed that the total mass of the Whips are 15,000 kg for a 1000 kg payload (16,000 kg total). This mass includes the central station, both tethers, the grapples at the ends of the tethers, and the dummy payload mass. This is about the minimum tether mass needed in order for the tether center-of-mass orbits to remain stable before and after a catch of a payload with a velocity difference of 2000 m/s.

The tether material was assumed to be Spectra™ 2000 with an ultimate tensile strength of U=4.0 GPa, a density d=970 kg/m^3, and an ultimate tip velocity for an untapered tether of $V_U=(2U/d)^{1/2}$ =2872 m/s. The tether safety factor was initially chosen at F=2.0, which results in a engineering characteristic velocity for the tether of $V_C = (2U/2d)^{1/2} = 2031$ m/s.

Using V_C and V_T in Eqn. (1), we find that the mass ratio of one arm of a tapered Spectra™ 2000 tether is 3.841 times the mass at the tip of the tether. Since the mass at the end of the tether consists of the 1000 kg payload and the 200 kg grapple, the minimum total mass of one tether arm is 4609 kg, or about 4.6 times the mass of the 1000 kg payload. The amount of taper is significant, but not large. The total cross-sectional area of the tether at the tip, where it is holding onto the payload, is 6 mm^2 or 2.8 mm in diameter, while the area at the base, near the station, is 17.3 mm^2 or 4.7 mm in diameter. This total cross-sectional area will be divided up by the Hoytether™ design into a large number of finer cables.

Eqn. (1), however, applies to a rotating tether far from a massive body. Since the EarthWhip and MarsWhip tethers are under the most stress near periapsis, when they are closest to their respective planets, we need to take into account the small additional stress induced by the gravity gradient forces of the planets, which raises the mass to about 4750 kg for a 1000 kg payload. We will round this up to 4800 kg for the tether material alone, corresponding to a free-space safety factor of 2.04, so that the total mass of the tether plus grapple is an even 5000 kg. With each tether arm massing 5000 kg including grapple, one arm holding a dummy payload of 1000 kg, and a total mass of 15,000 kg, the mass of the central station comes out at 4000 kg, which is a reasonable mass for its functions.

There are a large number of tether parameter variations that would work equally well, including shorter tethers with higher gee loads on the payloads, and more massive tethers with higher safety factors. All of these parameters will improve as stronger materials become commercially available, but the important thing to keep in mind is that the numbers used for the tethers assume the use of Spectra™ 2000, a commercial material sold in tonnage quantities as fishing nets, fishing line (SpiderWire), and kite line (LaserPro). We don't need to invoke magic materials to go to Mars using tethers.

Tether Rotational Parameters

When the EarthWhip or MarsWhip tethers are holding onto a payload, they are symmetrically balanced. The center-of-mass of the tether is at the center-of-mass of the tether central station. The effective arm length from the tether center-of-mass to the payload is 400,000 m, the tip speed is exactly 2000 m/s and the rotation period is P = 1256.64 s = 20.94 min = 0.3491 hr.

When the Whips are not holding onto a payload, then the center-of-mass of the Whip shifts 26,667 m toward the dummy mass tether arm, and the effective length of the active tether arm becomes 426,667 m, while the effective tip velocity at the end of this longer arm becomes 2,133 m/s. (Since there is no longer a payload on this arm, the higher tip velocity can easily be handled by the tether material.) The rotational period in this state is the same, 1256.64 s.

Payload Trajectory Parameters

The Earth-launched payload trajectory chosen for this example scenario is a suborbital trajectory with an apogee altitude of 203,333 m (6581.333 km radius) and a apogee velocity of 7,568 m/s. The circular orbit velocity for that radius is 7,782 m/s.

EarthWhip Before Payload Pickup

The EarthWhip starts out in an unloaded state with an effective length for its active arm of 426,667 m from the center-of-rotation, a tip velocity of 2,133 m/s and a rotational period of 1256.64 s. The center-of-mass of the EarthWhip is in a highly elliptical orbit with an apogee of 33,588 km (almost out to geosynchronous orbit), an eccentricity of 0.655, an orbital period of exactly 8 hours, a perigee radius of 7008 km (630 km altitude), and a perigee velocity of 9,701 m/s. The tether rotational phase is adjusted so that the active tether arm is pointing straight down at perigee, with the tether tip velocity opposing the center-of-mass velocity. The tip of the tether is thus at an altitude of 630 km-426.7 km = 203.3 km and a velocity with respect to the Earth of 9,701 m/s - 2,133 m/s = 7,568 m/s, which matches the payload altitude and velocity.

EarthWhip After Payload Pickup

After picking up the payload, the loaded EarthWhip tether is now symmetrically balanced. Since the added payload had both energy and momentum appropriate to its position on the rotating tether, the EarthWhip rotation angular rate does not change and the period of rotation remains at 1257 s. The center of mass of the loaded EarthWhip, however, has shifted to the center of the tether central station, so the effective length of the loaded tether arm is now at its design length of 400,000 km and tip velocity of 2,000 m/s. With the addition of the payload, however, the orbit of the tether center-of-mass has dropped 26.7 km to a perigee of 6981.3 km, while the perigee velocity has slowed to 9,568 m/s. The apogee of the new orbit is 28,182 km and the eccentricity is 0.603, indicating that this new orbit is less eccentric than the initial orbit due to the payload mass being added near perigee. The period is 23,197 s or 6.44 hours.

Payload Toss

The catch and toss operation at the Earth could have been arranged as shown in Figure 23, so that the payload catch was on one side of the perigee and the payload toss was on the other side of the perigee, a half-rotation of the tether later (10.5 minutes). To simplify the mathematics for this initial analysis, however, we assumed that the catch occurred right at the perigee, and that the tether holds onto the payload for a full orbit. The ratio of the tether center-of-mass orbital period of 23,197 s is very close to 18.5 times the tether rotational period of 1256.64 s, and by adjusting the length of the tether during the orbit, the phase of the tether rotation can be adjusted so that the tether arm holding the payload is passing through the zenith just as the tether center-of-mass reaches its perigee. The payload is thus tossed at an altitude of 603 km + 400 km =1003 km (7381 km radius), at a toss velocity equal to the tether center-of-mass perigee velocity plus the tether rotational velocity or 9,568 m/s + 2,000 m/s = 11,568 m/s. In the combined catch and toss maneuver, the payload has been given a total velocity increment of twice the tether tip velocity or Δv=4,000 m/s.

EarthWhip After Payload Toss

After tossing the payload, the EarthWhip tether is back to its original mass. It has given the payload a significant fraction of its energy and momentum. At this point in the analysis, it is important to insure that no portion of the tether will intersect the upper atmosphere and cause the EarthWhip to deorbit. We have selected the minimum total mass for the EarthWhip at 15,000 kg to insure that doesn't happen. The new orbit for the EarthWhip tether has a perigee of its center of mass of 6955 km (577 km altitude), apogee of 24,170 km, eccentricity of 0.552, and a period of 5.37 hours. With the new perigee at 577 km altitude, even if the tether rotational phase is not controlled, the tip of the active arm of the tether, which is at 426.67 km from the center-of-mass of the tether, does not get below 150 km from the surface of the Earth where it might experience atmospheric drag. In practice, the phase of the tether rotation will be adjusted so that at each perigee passage, the tether arms are roughly tangent to the surface of the Earth so that all parts of the tether are well above 500 km altitude, where the air drag and traffic concerns are much reduced.

With its new orbital parameters, the EarthWhip tether is in its "low energy" state. There are two options then possible. One option is to keep the EarthWhip in its low energy elliptical orbit to await the arrival of an incoming payload from Mars. The EarthWhip will then go through the reverse of the process that it used to send the payload from Earth on its way to Mars. In the process of capturing the incoming Mars payload, slowing it down, and depositing it gently into the Earth's atmosphere, the EarthWhip will gain energy which will put it back into the "high energy" elliptical orbit it started out in. If, however, it is desired to send another payload out from Earth before there is an incoming payload from Mars, then the solar electric power supply on the tether central station can be used to generate electrical power. This electrical power can then be used to restore the EarthWhip to its high energy elliptical orbit using either electrodynamic tether propulsion[18] or gravity-gradient propulsion. [11,13]

Payload Escape Trajectory

The velocity gain of $\Delta v \approx$4,000 m/s given the payload deep in the gravity well of Earth results in a hyperbolic excess velocity of 5,081 m/s. The payload moves rapidly away from Earth and in 3.3 days reaches the "patch point" on the boundary of the Earth's "sphere of influence," where the gravity attraction of the Earth on the payload becomes equal to the gravity attraction of the Sun on the payload. An accurate calculation of the payload trajectory would involve including the gravity field of both the Sun and the Earth (and the Moon) all along the payload trajectory. For this simplified first-order analysis, however, we have made the assumption that we can adequately model the situation by just using the Earth gravity field when the payload is near the Earth and only the Solar gravity field when we are far from the Earth, and that we can switch coordinate frames from an Earth-centered frame to a Sun-centered frame at the "patch point" on the Earth's "sphere of influence."

Payload Interplanetary Trajectory

When this transition is made at the patch point, we find that the payload is on a Solar orbit with an eccentricity of 0.25, a periapsis of 144 Gm and an apoapsis of 240 Gm. It is injected into that orbit at a radius of 151.3 Gm and a velocity of 32,600 m/s. (The velocity of Earth around the Sun is 29,784 m/s.) It then coasts from the Earth sphere-of-influence patch point to the Mars sphere-of-influence patch point, arriving at the Mars patch point at a radius of 226.6 Gm from the Sun and a velocity with respect to the Sun of 22,100 m/s. (The velocity of Mars in its orbit is 24,129 m/s.) The elapsed time from the Earth patch point to the Mars patch point is 148.9 days.

Payload Infall Toward Mars

At the patch point, the analysis switches to a Mars frame of reference. The payload starts its infall toward Mars at a distance of 1.297 Gm from Mars and a velocity of 4,643 m/s. It is on a hyperbolic trajectory with a periapsis radius of 4451 km (altitude above Mars of 1053 km) and a periapsis velocity of 6,370 m/s. The radius of Mars is 3398 km and because of the lower gravity, the atmosphere extends out 200 km to 3598 km. The infall time is 3.02 days.

MarsWhip Before Payload Catch

The MarsWhip tether is waiting for the arrival of the incoming high velocity payload in its "low energy" orbital state. The active tether arm is 426,667 m long and the tip speed is 2,133 m/s. The center-of-mass of the unbalanced tether is in an orbit with a periapsis radius of 4025 km (627 km altitude), periapsis velocity of 4,236 m/s, apoapsis of 21,707 km, eccentricity of 0.687, and a period close to 0.5 sol. (A "sol" is a Martian day of 88,775 s, about 39.6 minutes longer than an Earth day of 86,400 s. The sidereal sol is 88,643 s.) The orbit and rotation rate of the MarsWhip tether is adjusted so that the active arm of the MarsWhip is passing through the zenith just as the center-of-mass is passing through the perigee point. The grapple at the end of the active arm is thus at 4024.67+426.67 = 4,451.3 km, moving at 4,236 m/s + 2,133 m/s = 6,370 m/s, the same radius and velocity as that of the payload, ready for the catch.

MarsWhip After Payload Catch

After catching the payload, the MarsWhip tether is now in a balanced configuration. The effective arm length is 400,000 m and the tether tip speed is 2,000 m/s. In the process of catching the incoming payload, the periapsis of the center-of-mass of the tether has shifted upward 26,667 m to 4,051 km and the periapsis velocity has increased to 4,370 m/s, while the apoapsis has risen to 37,920 km, and the eccentricity to 0.807. The period is 1.04 sol.

Payload Release and Deorbit

The payload is kept for one orbit, while the phase of the tether rotation is adjusted so that when the tether center-of-mass reaches periapsis, the active tether arm holding the payload is approaching the nadir orientation. If it were kept all the way to nadir, the payload would reach a minimum altitude of about 250 km (3648 km radius) at a velocity with respect to the Martian surface of 4370 m/s - 2000 m/s = 2370 m/s. At 359.5 degrees (almost straight down), this condition is achieved to four significant figures. The payload is then moving at a flight path angle with respect to the local horizon of 0.048 radians and enters the atmosphere at a velocity of 2,442 km/s.

MarsWhip after Deorbit of Payload

After tossing the payload, the MarsWhip tether is back to its original mass. The process of catching the high energy incoming payload, and slowing it down for a gentle reentry into the Martian atmosphere, has given the MarsWhip a significant increase in its energy and momentum. At this point in the analysis, it is important to check that the MarsWhip started out with enough total mass so that it will not be driven into an escape orbit from Mars.

The final orbit for the tether is found to have a periapsis radius of 4078 km (676 km altitude so that the tether tip never goes below 253 km altitude), a periapsis velocity of 4,503 m/s, an apoapsis radius of 115,036 km, an eccentricity of 0.931, and a period of 6.65 sol. The tether remains within the gravity influence of Mars and is in its high energy state, ready to pick up a payload launched in a suborbital trajectory out of the Martian atmosphere, and toss it back to Earth.

Elapsed Time

The total elapsed transit time, from capture of the payload at Earth to release of the payload at Mars, is 157.9 days. This minimal mass PlanetWhip scenario is almost as fast as more massive PlanetWhip tethers since, although the smaller mass tethers cannot use extremely high or low eccentricity orbits without hitting the atmosphere or being thrown to escape, the time spent hanging on the tether during those longer orbit counts as well and the longer unbalanced grapple arm of the lightweight tether lets it grab a payload from a higher energy tether orbit.

Summary

We have developed tether system architectures for Earth-Luna and Earth-Mars payload transport. 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 preliminary design for a 80 km long Earth-orbit tether boost facility capable of picking payloads up from LEO and injecting them into a minimal-energy lunar transfer orbit. Using currently available tether materials, this facility would require a mass 10.5 times the mass of the payloads it can handle. 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. This tether facility will have the capability to reposition a significant portion of its “ballast” mass along the length of the tether, enabling it to catch the payload from a low-energy transfer trajectory and then “spin-up” so that it can deliver the payload to the Moon with zero velocity relative to the surface. This lunar tether facility would require a total mass of less than 17 times the payload mass. Both equatorial and polar lunar orbits are feasible for the Lunavator™. 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 with a total on-orbit mass requirement of less than 28 times the mass of the payloads it can handle, and this system could greatly reduce the cost of round-trip travel between LEO and the surface of the Moon by minimizing the need for propellant expenditure.

Using similar analytical techniques, we have shown that two rapidly spinning tethers in highly elliptical orbits about Earth and Mars can be combined to form a similar system that provides rapid interplanetary transport from a suborbital trajectory above the Earth's atmosphere to a suborbital trajectory above the Martian atmosphere and back.

Acknowledgments

This research was supported by a Contract 07600-011 from NASA’s Institute for Advanced Concepts, Dr. Robert A Cassanova, Director; and in part by the Tethers Unlimited, Inc. IR&D program.

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