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MARS-EARTH RAPID INTERPLANETARY TETHER TRANSPORT (MERITT) SYSTEM: I. Initial Feasibility Analysis

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ABSTRACT

Routine travel to and from Mars demands an efficient, rapid, low cost means of two-way transportation. To answer this need, we have invented a system of two rotating tethers in highly elliptical orbits about each planet. At Earth, a payload is picked up near periapsis and tossed a half-rotation later, still near periapsis, at a velocity sufficient to send the payload on a high-speed trajectory to Mars. At Mars, it is caught near periapsis and is released a short time later on a suborbital reentry trajectory. The system works in both directions and is reusable. Kinetic energy lost by the throwing tethers can be restored either by catching incoming payloads or by propellantless tether propulsion methods. 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 at Mars. Tether-to-tether transfers without aerobraking may be accomplished in about 130 to 160 days. Tether systems using commercially available tether materials at reasonable safety factors can be as little as 15 times the mass of the payload being handled. This is a relatively new concept and tasks needing further study are listed in the final section of the paper.

BACKGROUND

The idea of using rotating tethers to pick up and toss payloads has been in the tether literature for decades [1-7]. In 1991, Forward [8] combined a number of rotating tether concepts published by others [2,6,7] to show that three rotating tethers would suffice to move payloads from a suborbital trajectory just above the Earth's atmosphere to the surface of the Moon and back again, without any use of rockets except to get out of the Earth's atmosphere. The three tethers consisted of a "LEO" rotating tether in a nearly circular Low Earth Orbit, an "EEO" rotating tether in a highly Elliptical Earth Orbit, and a "Lunavator" rotating tether cartwheeling around the Moon in a circular orbit whose altitude is equal to the tether length, resulting in the tip of the tether touching down on the lunar surface. This concept has since been examined in detail by Hoyt and Forward [9-12], and is presently the subject of a Tethers Unlimited, Inc. Phase I Contract from the NASA Institute for Advanced Concepts, Dr. Robert A. Cassanova, Director.

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In the process of thinking about ways to improve the performance of the system, Forward realized that much of the gain in the three tether system came from the EEO tether, since its center-of-mass velocity at perigee was quite high, and when the tether tip rotational velocity was added, the toss velocity was not only very high, but was taking place deep in the gravity well of Earth. It is well known in rocketry that it always pays to make your Δv burns deep in the gravity well of a planet, and this rule of thumb applies equally well to tether tosses. In fact, in the LEO-Lunar papers [9-12], the EEO tether throws the payload so hard toward the moon that if the Lunavator does not catch it, the payload leaves the Earth-Moon system in a hyperbolic orbit. Forward then wondered how far a single EEO tether could throw a payload if the tether were in a Highly Elliptical Orbit and rotating near the maximum tether tip velocity possible with presently available commercial tether materials. After a few back-of-the-envelope calculations, the answer was found to be: "All the way to Mars... and beyond." Not believing the answer, Forward enlisted the aid of his co-author, an experienced orbital “mechanic,” who confirmed the back of the envelope calculations with more detailed calculations. The Mars-Earth Rapid Interplanetary Tether Transport (MERITT) System is the result.

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 that 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 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 1, 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.

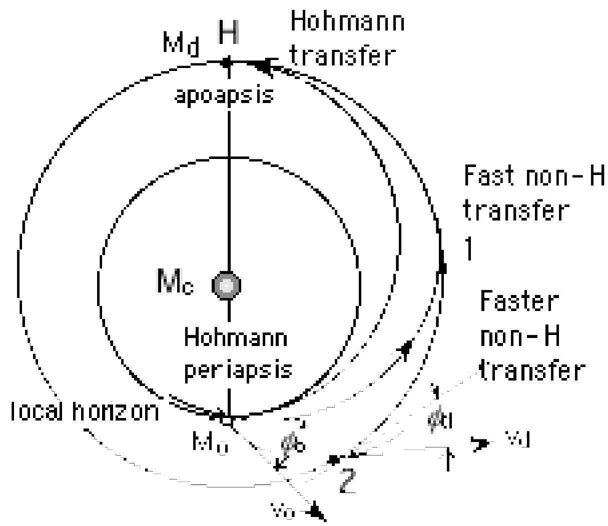

Figure 1. General Orbit Transfer Trajectories.

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 [13]

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 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.

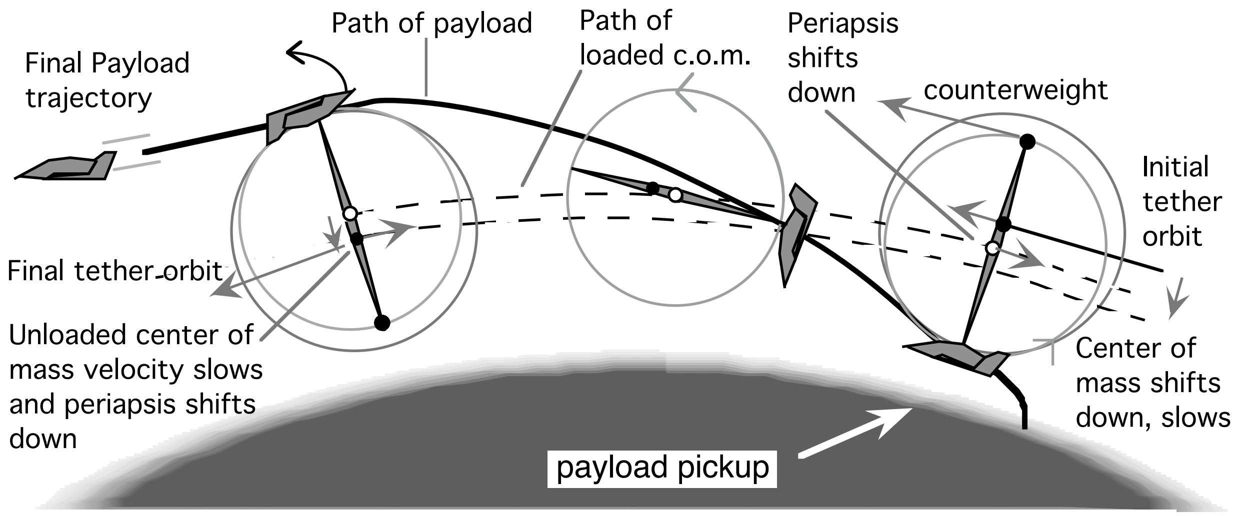

Figure 2: General geometry of tether pickup and throw orbital injection.

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, 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 2 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 2 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 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 [14,15]. As shown in Figure 3, 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.

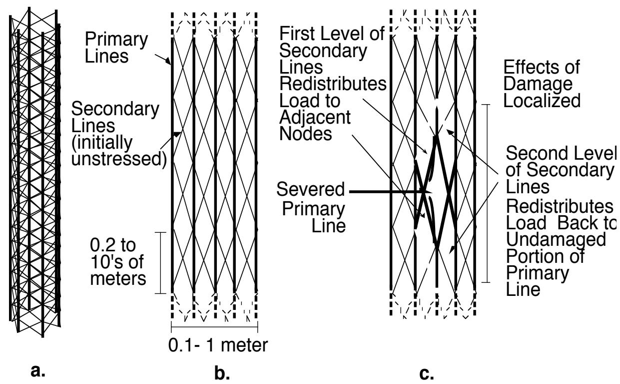

Figure 3 - The Hoytether™ design and its response to a cut line.

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 [9].

Tether Mass Ratio

The mass of a rapidly spinning tether is determined primarily by the tip speed of the tether, not the tether length or the tether tip acceleration. In a rotating tether system, where the tether mass itself is part of the mass being rotated, adding mass to a tether to increase its strength also increases the load, thus limiting the tip motion to a given velocity level, not acceleration level. A short, fat tether will have the same tip velocity V_T as a long, skinny tether of the same mass. The acceleration level G felt by the payload at the tip of the tether will vary as the tether length L with $G = V_T^2/L$.

The basic equation for the ratio of the mass M_T of one arm of a spinning tether to the mass M_P of the payload plus grapple on the end of the tether arm is [2,9]:

$$M_T/M_P = \pi^{1/2}(V_T/V_C) \exp[(V_T/V_C)^2] \operatorname{erf}(V_T/V_C) \quad (1)$$

Where the error function $\operatorname{erf}(V_T/V_C) \approx 1$ for $V_T/V_C>1$, V_T is the tether tip speed, and $V_C=(2U/Fd)^{1/2}$ is the maximum tip speed of an untapered tether, where U is the ultimate tensile strength of the tether material, d is its density, and F >1 is an engineering safety factor derating the "ultimate" tensile strength to a safer "practical" value. The engineering safety factor F to be used in different applications is discussed in detail by Hoyt[9] and is typically between 1.75 and 3.0.

The material presently used for space tethers is a polyethylene polymer called Spectra™, which is commercially available in tonnage quantities as fishing net line. Although slightly stronger materials exist, and should be used when they become commercially available, we do not need them to make the MERITT system feasible. Spectra™ 2000 has an ultimate tensile strength of U=4.0 GPa, a density of 970 kg/m^3, and an ultimate (F=1) characteristic velocity of $V_U=(2U/d)^{1/2}$ = 2.9 m/s. Assuming that the grapple on the end of the tether masses 20% of the payload mass, we can use Equation (1) to calculate the mass ratio of a one arm Spectra™ tether to the payload it is handling, assuming various different safety factors and various different tether tip velocities, to be:

Table 1. Ratio of Spectra™ Tether Mass to Payload Mass (Grapple 20% of Payload)

	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 [9] 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 equation (1). The continuously tapered mass defined by equation (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 equation (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 equation (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 4. 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 4. 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 that 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 that 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.

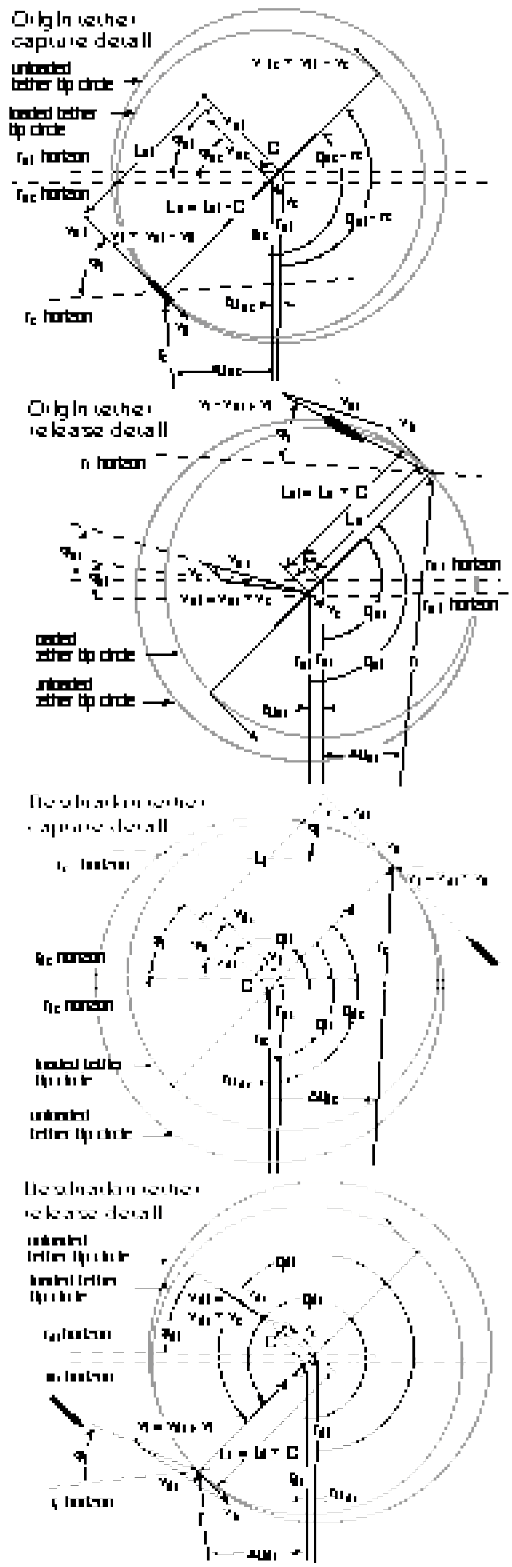

Figure 4. Tether Capture/Release Operations

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 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 5.

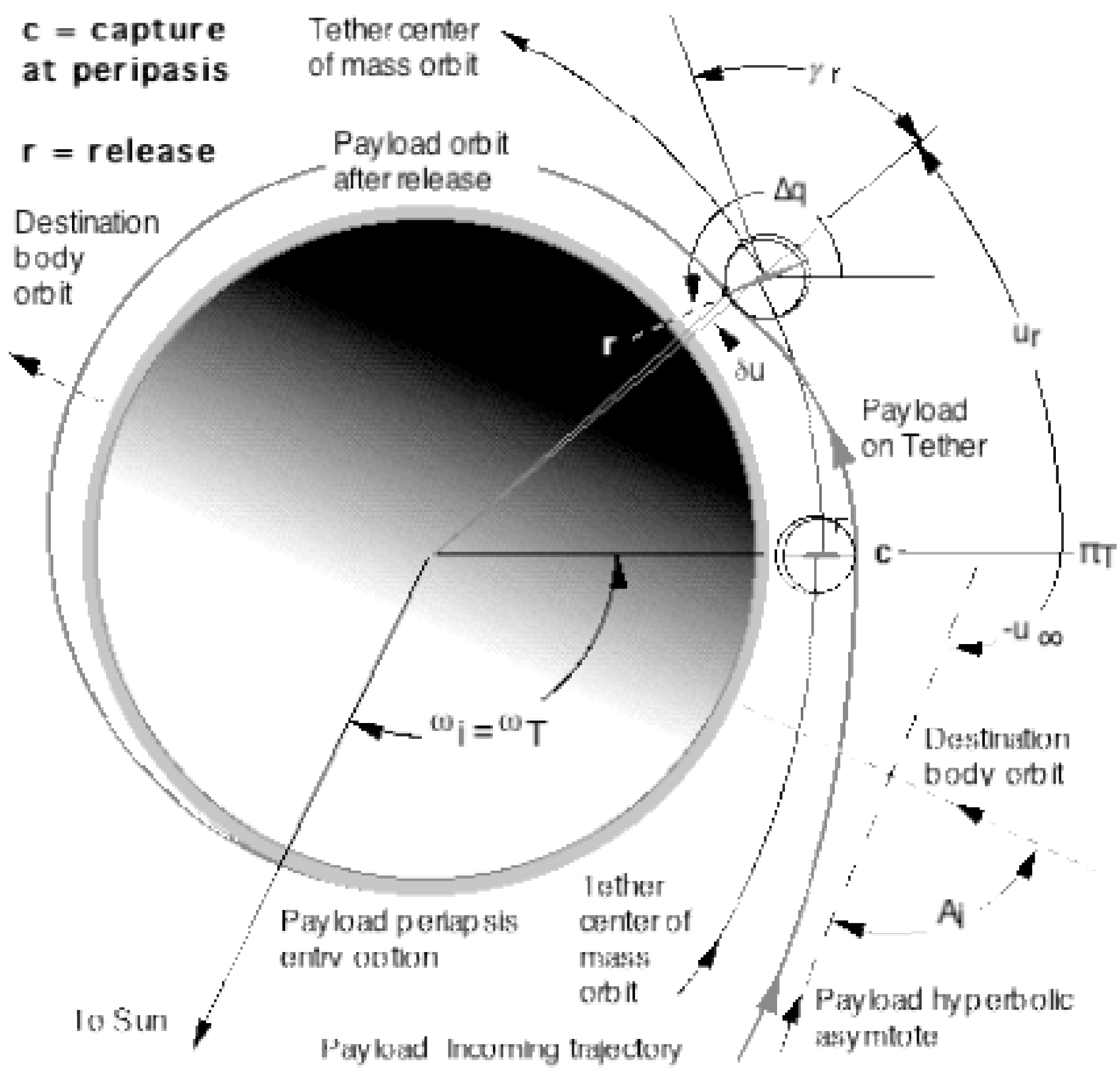

Figure 5. Tether-Only Capture Scenario

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 that 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 figures 5, 6, and 7 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 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 6, 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.

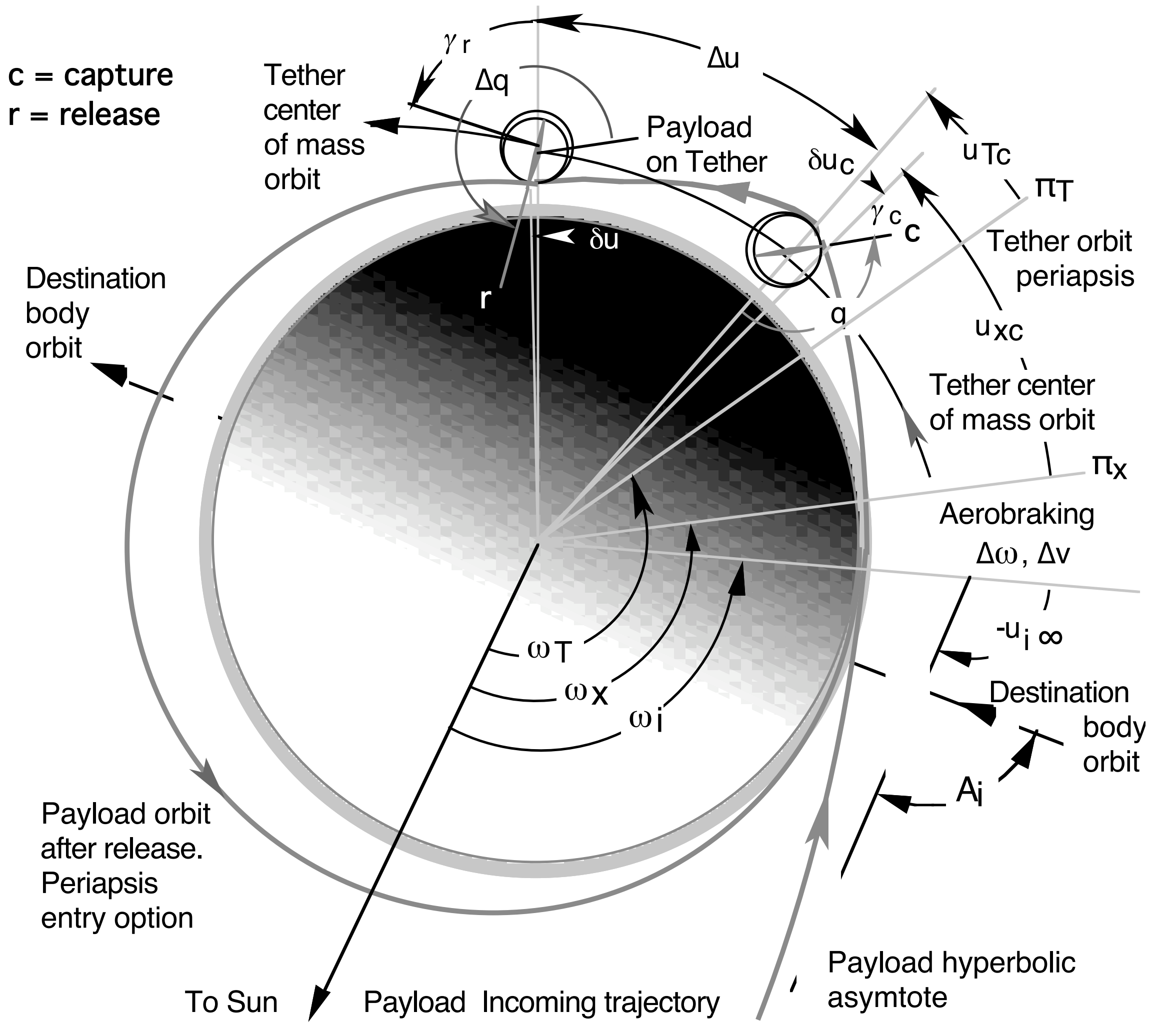

Figure 6. Aerobraking Tether Capture

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 3. As can be seen from Table 3, the system has significant 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 3 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 Fig. 6), the Earth orbit-Mars orbit transit time can be made about 94 days.

Table 3. 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

PlanetWhip Analysis

The initial mathematical model program made many simplifying assumptions, which are gradually being removed. One issue that was not addressed was the apsidal orientation of a tether expected to both catch and throw payloads.

Figure 7 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.

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.

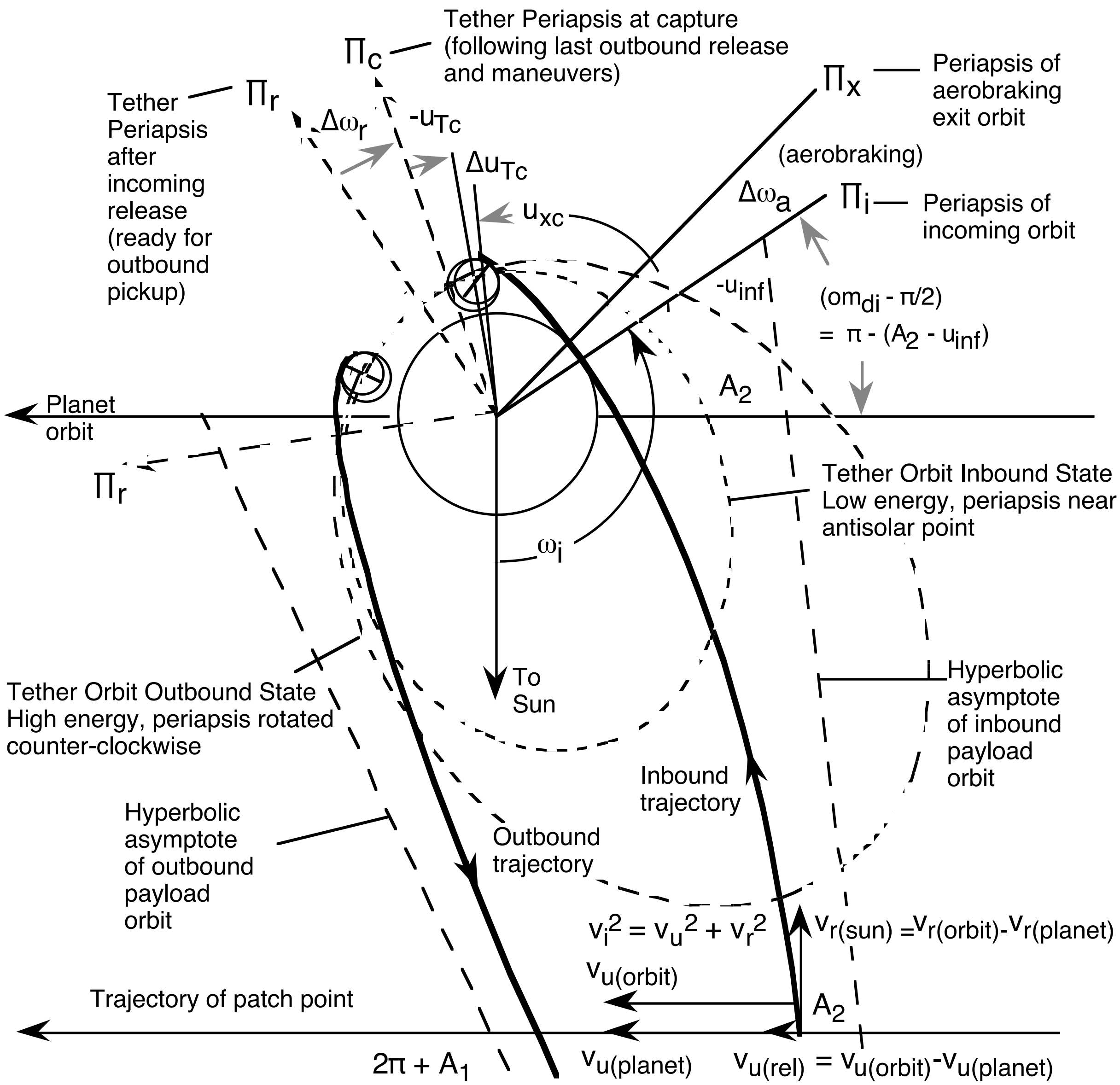

Figure 7 - "PlanetWhip" showing catch and toss states using aerobraking.

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.

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 to 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 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 [7,16,17].

The EarthWhip tether would also have a small conductive portion of the tether that would use electrodynamic tether propulsion[9], 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 is 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 an engineering characteristic velocity for the tether of $V_C = (2U/2d)^{1/2}$ = 2031 m/s.

Using V_C and V_T in equation (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.

Equation (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 is 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 km, the tip speed is exactly 2 km/s and the rotation period is P = 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 an 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 6, 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 [9] or gravity-gradient propulsion [16,17].

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.

FUTURE MERITT STUDIES

As emphasized before, this paper is only the first of a series of papers that will continue to demonstrate the engineering and economic feasibility of the MERITT concept by finding optimum solutions to the various technical challenges, and illustrating ways to augment and expand the concept. The follow-on papers, numbered II to VII, will cover the following topics:

II - Finite PlanetWhip Mass Analysis

This paper will document the detailed effects of the finite mass of the EarthWhip and MarsWhip tethers on the operation of the MERITT system, especially the capture and toss phases. Special attention will be given to scenarios where the payload "helps" in the transfer by starting out in circular or elliptical orbits with significant energy and angular momentum in them, so the PlanetWhip does not shoulder the whole transport burden. Then, for various values of interplanetary travel time and transit velocity, this paper will determine the minimum mass needed by the PlanetWhip to prevent it from being deorbited during a toss or recoiling to escape during a catch.

III - Full Trajectory Analysis

This paper will remove the simplifying assumptions made during the initial feasibility analysis concerning the gravity fields of the planets, the orbits of the planets, the tilt of the planet axes, the interplanetary trajectory, and the actual positions of the planets in the coming two decades. It is not expected that including these corrections will affect the feasibility of the concept. It will, however, result in an accurate estimate of the width of the launch windows, optimum launch times for different toss velocities and resultant transit times, and, hopefully, some attractive case studies.

IV - Tether Dynamics Analysis

This paper has assumed ideal rigid tethers. Real tether materials have both elasticity and damping. The Hoytether™ structure then adds its own damping and a non-linear elasticity and strength response as the secondary strands come into play after sufficient elongation. Then, depending upon the placement of intermediate masses along the tether, the long tether structure has libration, pendulum, and skip-rope modes, plus longitudinal, transverse, and torsional vibrational modes. The analysis would study the effect of the catch and throw operations on the excitation of those modes, ways to minimize the excitation, and how the existence of high amplitude oscillations of those modes could affect the accuracy of the catch and throw operations.

V - Energy/Momentum Management

One of the major advantages of the MERITT system over rocket methods for getting to Mars is that once two-way traffic is established, the system can, in principle, be self-powered, with incoming payload capsules restoring energy and angular momentum lost by the tethers when throwing outgoing payloads. A payload thrown to Mars from a tether on Earth typically arrives with much more velocity than the tether can handle at feasible tip velocities, and trajectories have to use aerobraking or be deliberately deoptimized to allow capture. Energy will be needed to make up drag losses, for tether damping, for periapsis rotation, and for phasing maneuvers, so we need to study methods for restoring that energy and momentum. The EarthWhip tether can supply both of these by including a Hoyt Electrodynamic Force Tether (HEFT™) system[9] in its structure. MarsWhip tether energy management can be accomplished by including a solar electric power supply on the central facility and using the electrical energy to power a tether winch to periodically change the tether length at the proper point in the MarsWhip elliptical trajectory [15,16], making the orbit more or less elliptical for the same angular momentum.

VI - Incremental Construction

The objective of this paper would be to show how the EarthWhip tether can be built up incrementally, first serving to send small science payloads to Mars, while at the same time accumulating central facility mass by keeping upper stages and other unwanted masses. The Hoytether™ design also lends itself to incremental construction, not only in length but in thickness and taper, so that a 10, 20 or even 100 ton tether can be built out of a large number of 1 to 5 ton deploy-only canisters each containing a 10-20 km long section of tether.

Preliminary analysis also shows that a minimal mass MarsWhip can be tossed to Mars by a similar mass EarthWhip tether, arriving at Mars 180 days after toss. The MarsWhip could halt itself by use of an aerobraking module. Alternatively, it could employ the Landis [18] tether assisted planetary orbital capture procedure, where prior to close approach to Mars, the tether is deployed so that one end is ahead of and much closer to Mars than the other, pulling that end of the tether into a different trajectory than the other end. If properly done, the tether system gains rotational energy and angular momentum from the non-linear gravity-whip interaction, at the expense of its center-of-mass orbital energy and angular momentum, and thus ends up rotating around its center-of-mass, with the center-of-mass in a highly elliptical capture orbit around Mars. Once in the capture orbit, the MarsWhip tether can use tether pumping [15,16] to change the rotation rate of the tether and the ellipticity of its orbit to the desired values. After the MarsWhip is ready to receive incoming payloads, its tether and central facility can then be built up by additional incremental payloads.

VII - Spinning Tether Payload

Once the MERITT system has proved its reliability in handling science probes, sample return missions, and cargo missions, to robotically build up a Mars orbital station and surface base camp, then it could be considered for delivery of crewed interplanetary transit capsules. For these missions, the short trip times available using the MERITT system will minimize the radiation exposure to the crew. In addition, the MERITT system could also provide a method of completely eliminating the biological effects of long periods in zero gee. The payload tossed by the EarthWhip and caught by the MarsWhip would consist of two capsules connected by a tether and put into slow rotation during the toss operation. After the toss, a solar electric powered winch on one of the payload capsules would change the length of the tether to attain any desired artificial gravity level during the transit time interval. Since the payload can be caught by the tether grapple at either capsule end, and the capsule velocity can add or subtract from the MarsWhip tether tip velocity, the existence of a spinning payload opens up a whole new series of system optimizations to be explored.

VIII - Transport to Other Planets

Although Mars is the obvious first target for a Rapid Interplanetary Tether Transport (RITT) system, there is no reason why the RITT concept couldn't be used for rapid transport among other planets and moons in the Solar System, as well as between planets and moons. The objective of this study would be to define "Planet"Whip tether systems for each planet that could provide two-way transport not only between that planet and Earth, but between that planet and other planets, ultimately resulting in a solar-system-wide tether transportation network.

CONCLUSIONS

We have shown that two rapidly spinning tethers in highly elliptical orbits about Earth and Mars, can be combined into a 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.

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