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Mars–Earth Rapid Interplanetary Tether Transport System: I. Initial Feasibility Analysis

Gerald D. Nordley*
Sunnyvale, California 94089-2334
and
Robert L. Forward†
Tethers Unlimited, Inc., Clinton, Washington 98236

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/s can send payloads to Mars in as little as 94 days if aerobraking is used at Mars. Tether-to-tether transfers without aerobraking may be accomplished in about 130–160 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.

Nomenclature

A = payload approach or departure angle from planetary orbital path
a_c = centripetal acceleration
d = density of tether material
F = factor by which tether material is derated for safety
L = length of rotating tether arm from center of mass to tip
M_P = mass of payload and grapple at tip of tether
M_T = mass of tether material from center of mass to tip
q = rotation angle of tether from vertical
U = ultimate strength of tether material (force per unit area at failure)
u = true anomaly of payload
u_c = true anomaly of tether/payload system at payload capture
u_r = true anomaly of tether/payload system at payload release
u_T = true anomaly of tether center of mass
u_∞ = true anomaly of hyperbolic orbit at infinity (hyperbolic asymptote)
v_c = characteristic (maximum) tip velocity of derated tether material
v_d = velocity at destination of interplanetary trajectory
v_o = velocity at origin of interplanetary trajectory
v_t = tip velocity of rotating tether
v_U = maximum tip velocity of tether material at ultimate strength
γ_c = tether-payload system flight-path angle from zenith at payload capture
γ_r = tether-payload system flight-path angle from zenith at payload release
Δq = change in rotation angle of tether
Δv = velocity change
$\Delta \omega$ = change in payload orbit argument of periapsis
δu = Earth-centered arc from u_r to tether tip
Π = periapsis of payload orbit
ϕ_d = flight-path elevation angle of interplanetary trajectory at destination
ϕ_o = flight-path elevation angle at interplanetary trajectory at origin
ω = argument of periapsis of payload orbit from Sun–planet line
ωT = argument of periapsis of tether orbit from Sun–planet line

Introduction

THE idea of using rotating tethers to pick up and toss payloads has been in the tether literature for decades[1–6] (see also Hans Moravec, "Free Space Skyhooks," URL:http//www.frc.ri.cmu.edu/~hpm/hpm.cv.html, Nov. 1978). In 1991 Forward[7] combined a number of rotating tether concepts published by others[2,5] 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 rotating tether in a nearly circular low Earth orbit (LEO), a rotating tether in a highly elliptical Earth orbit (EEO), and a rotating "Lunavator" tether cartwheeling around the Moon in a circular orbit whose altitude is equal to the tether arm 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[8,9] and Hoyt.[10,11]

In 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 because 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 astronautics that it pays to make a Δv deep in a gravity well of a planet, and this rule of thumb also applies to tether tosses. In fact, in the LEO–Lunar papers,[8–11] 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 available commercial tether materials. After a few back-of-the-envelope calculations, the

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*Consultant, 1238 Prescott Avenue; gdnordley@aol.com. Member AIAA.
†Chief Scientist, 8114 Pebble Court; TU@tethers.com. Associate Fellow AIAA.

answer was found to be: "All the way to Mars... and beyond." Not believing the answer, Forward enlisted the aid of his coauthor, an astronautical engineer, 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. The rotating systems would consist of long (hundreds of kilometers), thin (a few square centimeters in cross sectional area) cables of high strength material with a grapple at one end and a counterweight at the other. A service module would be attached to the tether and include a solar electric power supply, tether winches, command and control electronics, and propulsion systems. This might be positioned near the center of mass, for ballast, or at the end opposite the grapple as part of the counterweight.

A payload 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 released from the tether 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 or elsewhere. Payload rocket propulsion is needed only for attitude control and velocity corrections.

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 can be designed to work in both directions.

With aerobraking the MERITT system can give even shorter trip times because the incoming payload velocity change is not limited by the maximum tether tip velocity.

Energy and momentum lost by the tethers can be replenished over time by either of two different highly efficient propulsion systems that use electrical energy but little or even no propellant.[12] The system thus acts as a propulsive energy-momentum bank, which delivers the propellant efficiency of advanced propulsion systems with the dynamic advantages of impulsive deep-gravity-well maneuvers.

In the following subsections we describe the system in detail, discuss the modeling of the system, provide a detailed point example, and present some preliminary results for different tip speeds.

Payload Pickup and Release

Figure 1 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 and swung around the tether's center of mass in a circle over angle q as the tether/payload system moves along its orbit. The payload 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 twice, representing the transfer of energy by the tether to the payload.

Around the time of pickup, the trajectory of the payload must be of equal speed and should be very nearly tangential (no radial motion) to the circle of motion of the tether tip in the tether frame of reference. It is easy to see how this condition can 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 pickup is essentially a straight line, and an infinite number of curves may be tangent to that line. The practical effect of this is to allow considerable leeway in rendezvous conditions. It also means that the general conclusions reached from the kind of two-dimensional analysis presented here should hold for more complicated geometries.

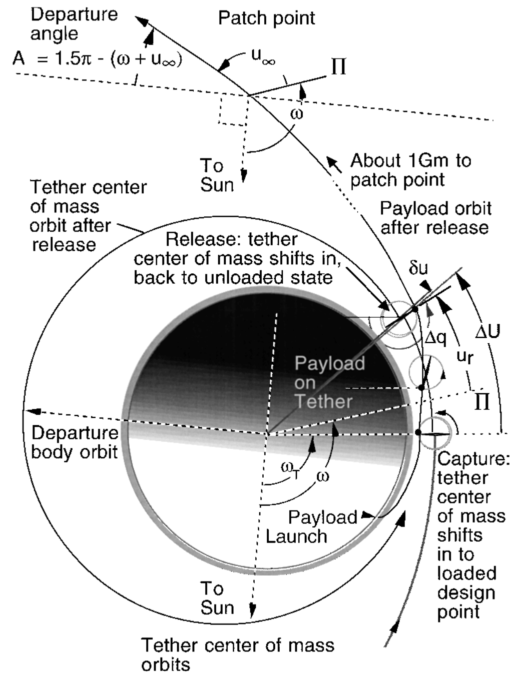

Fig. 1 Payload pickup and release to an interplanetary trajectory.

The release orbit is tangential to the tether tip 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. By this time, the tether has moved beyond periapsis through angle Δu, and there will be a significant flight-path angle.

Large variations from this scenario will result in significant velocity losses, but velocity management in this manner could also 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.

Following payload release, tethers could also provide artificial gravity for crewed missions. 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.

Because the payload can be caught by the tether grapple at either capsule end, the capsule velocity can add or subtract from the MarsWhip tether tip velocity.

Interplanetary Transfer Orbits

The MERITT system achieves its rapid transfer times because its interplanetary trajectories result from high, essentially fixed velocity increments and are not subject to the mass/Δv trade that pushes other propulsion systems toward minimum Δv trajectories with low flight-path angles at injection. For fast tip velocities interplanetary injection flight-path angles do not need to be small.

As shown in Fig. 2, 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.

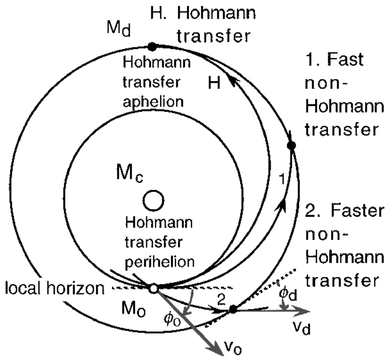

Fig. 2 Interplanetary trajectories.

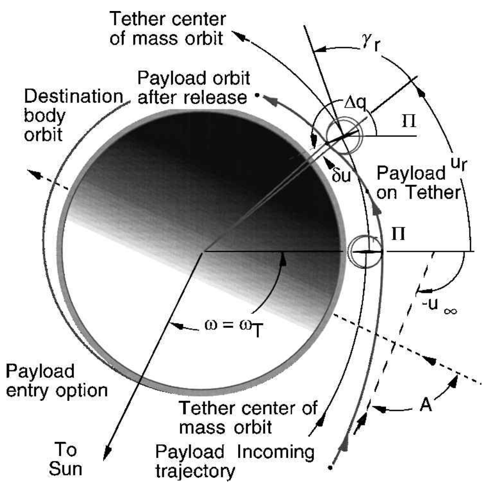

Fig. 3 Payload capture by tether only.

A change in payload velocity (Δv, usually supplied by onboard propulsion) is required at these points for the payload to switch from one trajectory to another.

Faster non-Hohmann transfers, 1) and 2) in Fig. 2, can be tangential at origin, destination, or neither. They can be elliptical or hyperbolic. For a given injection velocity above the Hohmann minimum constraint, the minimum-time transfer orbit is generally nontangential at both ends. An extensive discussion of the general orbit transfer problem may be found in Bate et al.[13]

Capture and Release at Destination

Capturing of an incoming payload with a tether (Fig. 3) 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.

Capture after a pass through the destination body's atmosphere (Fig. 4) 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 do this.

After capture the payload swings around the tether and is released into a trajectory that either orbits the destination planet or intersects its atmosphere so that the payload can land. The tether center of mass shifts outward and its velocity increases in this process, leaving the tether orbit in a higher energy state. It is, in some ways, as if the incoming payload had "bounced" off the tether.

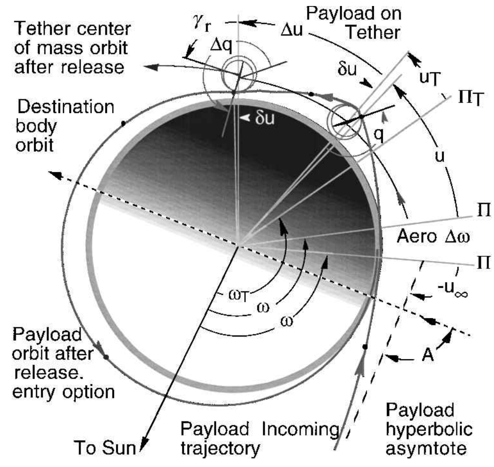

Fig. 4 Payload capture with aerobraking.

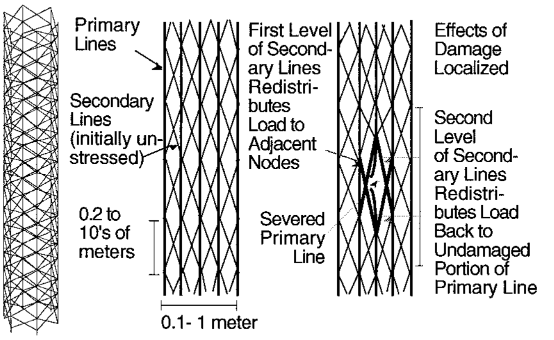

Fig. 5 Hoytether damage resistance.

Tether Engineering

For a tether transport system to be economically advantageous, it must be capable of handling frequent traffic for many years despite degradation caused by 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 Fig. 5, the Hoytether is an open net structure where the primary load bearing lines are interlinked by redundant secondary lines. The secondary lines are designed to be 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.

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 0.4–0.5 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 because of meteorite strikes or material failure. Consequently, the Hoytether structure can be loaded at high stress levels, yet retain a high margin of safety.[8]

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 felt by the payload at the tip of the tether will vary as the tether length L with

$$a_c = v_t^2 / L \tag{1}$$

Table 1 Ratio of Spectra 2000 tether material mass to payload mass (grapple mass assumed to be 20% of payload mass)

Tip speed, km/s	Tether material safety factor, F			
	1.75	2.0	2.4	3.0
2.0	3.7	4.7	6.4	10.0
2.5	8.0	11.0	17.0	30.0

Tether material has a "characteristic velocity," which depends on the ultimate strength and density of the material[2,8]

$$v_u = (2U/d)^{\frac{1}{2}} \tag{2}$$

For safety, this velocity can be reduced by dividing the ultimate strength by an engineering safety factor so that the characteristic velocity for the derated material is

$$v_c = [2(U/F)/d]^{\frac{1}{2}} \tag{3}$$

The engineering safety factor F to be used in different applications is discussed in detail by Hoyt and Forward[9] and is typically between 1.75 and 3.0.

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[2,8]

$$M_T/M_P = \pi^{\frac{1}{2}}(v_t/v_c)\exp\left[(v_t/v_c)^2\right]\operatorname{erf}(v_t/v_c) \tag{4}$$

where the error function $\operatorname{erf}(v_t/v_c) \approx 1$ for $v_t/v_c > 1$

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 4.0 GPa, a density of 970 kg/m^3, and an ultimate ($F = 1$) characteristic velocity of 2.9 m/s. Assuming that the grapple on the end of the tether masses is 20% of the payload mass, we can use Eq. (4) to calculate the mass ratio of a Spectra tether from its center of mass to the payload for various different safety factors and tether tip velocities, as in Table 1.

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 Orbital Energy Maintenance

Following payload release the tether system will be left in a less energetic orbit. To throw another payload, the lost orbital energy should be made up.

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.

But 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.

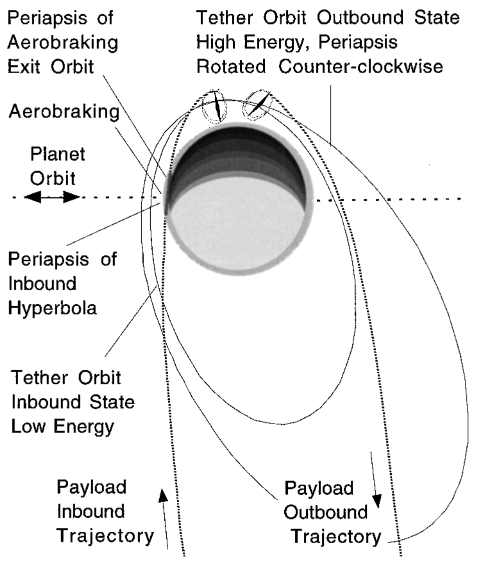

Fig. 6 Tether concept for inbound and outbound payloads at Earth or Mars.

The EarthWhip tether can also have a small conductive portion of the tether that would use electrodynamic tether propulsion,[8,12] 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 with minimal propellant requirements.

MarsWhip tether energy management can be aided by including a solar array to power a tether winch to periodically change the tether length at the proper point in the MarsWhip elliptical trajectory,[16,17] making the orbit more or less elliptical for the same angular momentum. This power could also run a fuel-efficient electric propulsion system using in situ resources from Mars or its moons.

We have not modeled long-term orbit perturbations of the planetwhip tethers; however, the changes made to the tether orbits from frequent payload capture and release would dwarf any perturbation effects, and minor adjustments in release angles and timing could be used to counter or enhance such effects as needed.

The large number of free parameters in this system produce a "good news/bad news aspect to analysis. The difficulty is that the problem is not self-defined, and to make the model work a number of 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.

Figure 6 shows how a single tether toss and catch system might work on either the Earth or Mars end of the MERITT system for a finite mass PlanetWhip tether.

Rendezvous of Grapple with Payload

The tether rendezvous problem resembles one solved daily by trapeze acrobats, where one is caught in midair by a colleague hanging from a trapeze bar. The catcher meets up with and grasps the "payload" after she has let go of her bar and is in a "freefall" trajectory accelerating with respect to the "catcher" at one g. They time their swings, of course, so that they meet near the instant when both are at near zero relative velocity.

In tether rendezvous the grapple velocity vector is arranged to match, as closely as possible, that of the payload at the time of rendezvous. Though their accelerations are different, the large radius of curvature of both trajectories makes the differential vertical motion near the time the curves are small (ideally, zero). The grapple mechanism on the end of a rotating tether is subjected to a centrifugal acceleration by the rotation of the tether, but may change its radial position by reeling itself in or out and change its lateral position with thrusters. As the time for capture approaches, the grapple could reel out and use its propulsion to fly ahead to the rendezvous point. As the payload comes along, it can reel tether in and out to match the curvature of the payload trajectory and adjust its position with thrusters to compensate for any lateral errors. In this manner the rendezvous interval can be stretched to many tens of seconds.

The grapple batteries can be recharged from a solar array or from 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.

In addition to having more time to perform its task, the tether grapple system will have many advantages over its human analog: global positioning system (GPS) guidance, radar Doppler and proximity sensors, onboard divert thrusters, and the speed of electronic "synapses."

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. Preliminary discussions were held by Dr. Forward with staff at the Automated Rendezvous and Capture Project Office at Marshall Space Flight Center, and it appears that the present Shuttle-tested (STS-87 & STS-95) video guidance sensor hardware; guidance GPS relative navigation; and Guidance, Navigation, and Control software could be modified for tether operations.

Tether System Construction

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 nonlinear 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[16,17] 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 incrementally by catching additional tether and power modules.

Meritt System Simulation Model

Calculations of the MERITT system performance were performed on Macintosh personal computers 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.

These initial models were intended to provide a quick, top-level look at the performance potential of the system and contained simplifying assumptions for speed and generality, including coplanar Keplerian orbits about point masses, Earth and Mars in circular orbits with a radius equal to their semimajor axes, and rigid tethers of constant length.

Two versions of a tether-based interplanetary transfer system were modeled: 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. The general architecture of the models is sequential. A payload is added to a rotating tether in a highly elliptical orbit around the origin planet, released from the tether on an interplanetary trajectory, captured at the destination planet by another tether, and released to a trajectory that allows descent to the target planet.

Tether Model

The tether 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[8] 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 10 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 Eq. (4). The continuously tapered mass defined by Eq. (4) 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 Eq. (4).

Shift in Tether Center of Mass with Payload Pickup and 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. The position and velocity of the grapple end of the unloaded rotating tether is matched to the payload position and velocity of the payload as shown in the lower right part of Fig. 1.

When the payload is caught, the center of mass shifts toward the payload, and the tether assumes its "design" state, with maximum tension at the center of rotation. The amount of the shift is determined by adding the moments of the unloaded tether about the loaded center of symmetry and dividing by the unloaded mass. The tip speed around this new loaded center of mass is simply its speed around the unloaded center of mass minus the speed of the point, which became the new center of mass about the old center of mass and which is the angular rate times the shift distance.

This speed and the rotation angle at capture define a velocity vector, which is transformed to the planetary frame and added to the velocity vector of the old center of mass to give the new velocity vector of the loaded tether system. The center-of-mass displacement and the rotation angle also provide a position vector in the frame of the old center of mass. This is transformed to the planetary frame of reference and added to the radius vector of the old center of mass to get the radius vector to the new center of mass in the planetary frame. These two vectors constitute the orbital state vector for the combined payload/tether system.

This state vector is converted to orbital elements, which are propagated until the payload is released. At release, the center of mass shifts away from the grapple end of the tether by the same amount, and the model calculates the final tether orbit , essentially by reversing the preceding procedure.

Because, in the outgoing case, 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. This was done by defining the periapsis of the initial tether center-of-mass orbit as the sum of the planet's radius, the height of the sensible atmosphere (taken as 140 km for both Earth and Mars), the length of the unloaded tether arm, and two center-of-mass shifts.

Released Payload Trajectory

The injection velocity vector in the planetary frame is simply the vector sum of the motion of the tether tip as a function of its rotation angle and that of the tether center of mass, displaced to the location of the tether tip. This velocity and position are converted to Keplerian orbital elements.

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 onboard payload propulsion can compensate for any differences. This analysis considered only coplanar trajectories, but, given the foregoing flexibility, 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's 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. For this model the locus of patch points about a planet is approximated as a circle, the radius of which is equal to the distance from the planet away from the sun (inner planet) or toward the sun (outer planet) at which the combination of solar gravity, planetary gravity, and solar frame centrifugal acceleration result in zero radial force. We call this the patch radius.

The outbound trajectory is propagated to this distance, the orbital elements are converted to a state vector, the vector is transformed to solar inertial coordinates, and the solar frame orbital elements are generated.

The angle the state vector at the patch point makes with a vector normal to the radius vector of the sun to the planet's orbit A is a free choice at this point. 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. The solar radius of the patch point is estimated by dividing the patch radius by the sine of the flight-path angle (ϕ_d in Fig. 5) of the solar frame trajectory at the planet's semimajor axis and subtracting that from the semimajor axis. There, it is transformed into the destination planet coordinates.

When a tether only is used to receive the payload (Fig. 3), a constraint exists on the destination end; the incoming trajectory is a hyperbola, and the periapsis velocity of the hyperbolic orbit must not exceed the maximum tip velocity of the capture tether. This periapsis velocity is determined by the vector sum of the capture tether's orbital motion and the tip velocity as a function of the tether rotation angle, q. This defines the hyperbolic excess velocity of the incoming payload. The argument of periapsis of the destination tether center of mass can be found from the true anomaly of the incoming orbit at the patch point (essentially u_∞) and the angle that transfer orbit makes with the sun–planet radius transformed to the planet's frame of reference.

The inbound hyperbolic excess velocity is also given by the vector sum of the orbital velocity of the destination planet and that of the intersecting payload orbit at the patch point. The angle of injection at the Earth end A in Fig. 1 is iterated until a match exists.

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. 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, and minimum time transfers can be used. In this case, the injection angle A is iterated until a minimum time is found.

Once A is determined, it can be used to define the argument of periapsis of the departure orbit with respect to the sun–planet radius. This, with the tether rotation rate, the time of release, and the initial tether orbit are used to define the argument of periapsis of the initial tether orbit.

Payload Capture and Release at Destination

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.

In capture, the estimated tether tip capture position and velocity, together with the radius at which the outgoing payload resumes a ballistic trajectory, define a post aerobraking 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. The angle traversed is a free parameter that depends on choices for deceleration limits and the aerodynamic capabilities of the atmosphere transiting payload. For Mars-bound trajectories this aerobraking Δv is on the order of 5 km/s, as compared to direct descent Δv 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.

As shown in Fig. 4, 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. The capture of a payload exiting the atmosphere at the high end of the tether is necessarily off the vertical line, and so rotates the periapsis of the tether/payload system center of mass.

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.

Detailed MERITT Example

There are many variables in the MERITT system, which 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 vs direct tether-to-tether catch; suborbital and orbital initial and final payload trajectories; 1.5, 2.0, 2.5, and higher tether tip velocities; large, small, and minimum tether central facility masses; etc. We will present here one of the many possible MERITT scenarios using finite mass EarthWhip and MarsWhip tethers to illustrate the process in quantitative detail.

Payload

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, the payload may perform minor maneuvers to assist the grapple during the catch operations.

A suborbital trajectory was chosen to demonstrate the MERITT system's ability to reduce boost velocity requirements as well as perform the interplanetary transfer. In practice, however, a initial circular orbit may be preferred to allow time for a postboost checkout, schedule flexibility, and prerendezvous orbit adjustments. The payload apogee chosen was 6581.333-km radius (203.333 km altitude above Earth's mean radius) with an apogee velocity of 7568 m/s. The circular orbit velocity for that radius is 7782 m/s.

Tethers

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. Both the EarthWhip and MarsWhip tethers were assumed to consist of a robotic central station with identical tether arms and a counterweight at the end of one arm equal in mass to the design payload and grapple so that when the active payload is caught the resulting tether-payload system would be symmetrical.

Numerical experiments revealed problems with keeping the tether tips out of the atmosphere following payload release for masses under 15 metric tons, and so the total unloaded tether system mass was set at an even 15 metric tons.

The length of the arms with payload attached was chosen to be 400 km in order to keep the acceleration on the payload from Eq. (1) near one g. The tether material was assumed to be Spectra 2000 with an ultimate tensile strength of 4.0 GPa, a density of 970 kg/m^3, and an ultimate tip velocity for an untapered tether of 2872 m/s. The tether safety factor was initially chosen at 2.0, which results in a engineering characteristic velocity for the tether from Eq. (3) of 2031 m/s. Using v_c and v_t in Eq. (4), 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. Because that consists of 1000 kg for payload and 200 kg (20% of the payload) for the grapple, the minimum total mass of one tether arm is 4609 kg, or about 4.6 times the mass of the 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 (2.8 mm in diameter for a single fiber) while the area at the base, near the station, is 17.3 mm^2 (4.7 mm diam). This total cross-sectional area would actually be divided up by the Hoytether design into a large number of finer cables.

Equation (4), however, applies to a rotating tether far from a massive body. Near a planet there are small additional stresses on the tether proportional to the gravity gradient and the tether length. Because the EarthWhip and MarsWhip tethers are under the most additional gravity gradient stress near periapsis, when they are closest to their respective planets, we estimated a mass allowance for the small additional stress induced by the gravity gradient forces of the planets, which raised the mass to about 4750 kg for a 1000-kg payload. We rounded 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 counterweight of 1000 kg, and a total (unloaded) mass of 15,000 kg, the mass of the central station comes out at 4000 kg.

There are a large number of tether parameter variations that would work equally well, including shorter tethers with higher g 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).

With a payload attached the center of mass of a symmetric tether is at its center. 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 1256.64 s = 20.94 min = 0.3491 h.

Without a payload attached the center of mass of the tethers shifts 26,667 m toward the counterweighted tether arm, and the effective length of the grapple arm becomes 426,667 m, while the tip speed relative to its new center of mass becomes 2133 m/s. (With no payload the higher tip velocity can easily be handled by the tether material.) The rotational period remains 1256.64 s.

EarthWhip Orbits at Payload Pickup

The center of mass of the EarthWhip is initially 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 h, a perigee radius of 7008 km (630-km altitude), and a perigee velocity of 9701 m/s. The tether rotational phase is adjusted so that at rendezvous the grapple 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 − 426.7 = 203.3 km and a velocity with respect to the Earth of 9701 − 2133 = 7568 m/s, which matches the payload altitude and velocity.

At payload pickup the center of mass of the loaded EarthWhip shifts downward 26.7 km to a perigee of 6981.3 km, while its perigee velocity has slown to 9568 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 as a result of the payload mass being added near perigee. The period becomes 23,197 s, or 6.44 h.

Payload Toss

The capture and release operations at the Earth could have been arranged as shown in Fig. 2 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 min). 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's 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 + 400 = 1003 km (7381-km radius), at a toss velocity equal to the tether center-of-mass perigee velocity plus the tether rotational velocity or 9568 + 2000 = 11,568 m/s. In swinging on the tether from nadir to zenith, the payload has been given a total velocity increment of twice the tether tip velocity or $\Delta v = 4000$ m/s, as well as gaining potential energy from 203 to 1003 km.

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. 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 h. 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.

Payload Escape Trajectory

The velocity gain of $\Delta v \approx 4000$ m/s given the payload deep in the gravity well of Earth results in a hyperbolic excess velocity of 5081 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.

Payload Interplanetary Trajectory

When the 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 4643 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 6370 m/s. The radius of Mars is 3398 km, and because of the lower gravity the atmosphere extends out 200–3598 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 2133 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 4236 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 min 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 $4024.67 + 426.67 = 4451.3$ km, moving at $4236 + 2133 = 6370$ 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 2000 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 4051 km, and the periapsis velocity has increased to 4370 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 of 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 $4370 - 2000 = 2370$ m/s. At 359.5 deg (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 rad and enters the atmosphere at a velocity of 2442 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 4503 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 because, 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.

Table 2 Potential MERITT interplanetary transfer times

Tip speed, km/s	System mass ratio	Transfer direction, from → to	Tether only, days	Aerobraking, days
2.0	15*x*	Earth → Mars	155	116
		Mars → Earth	155	137
2.5	30*x*	Earth → Mars	133	94
		Mars → Earth	142	126

Additional PlanetWhip Analyses

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 so 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 did not mass too much more than the payloads they could handle.

We then looked at 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 2. As can be seen from Table 2, 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 2 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.

Conclusions

We have shown that two ideal rigid rotating tethers in highly elliptical orbits about Earth and Mars can provide rapid interplanetary transport from a suborbital trajectory above the Earth's atmosphere to a suborbital trajectory above the Martian atmosphere and back. Real tether materials have both elasticity and damping. The Hoytether structure then adds its own damping and a nonlinear 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 would have libration, pendulum, and skip-rope modes, plus longitudinal, transverse, and torsional vibrational modes. Additional analysis is needed to study 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.

Synergistic use of a rotating tether between parts of a payload for artificial gravity for additional velocity increments sounds attractive but needs further study. Use of reels and grappling fixtures already developed for MERITT would reduce the technological risk.

Although Mars is the obvious first target for a Rapid Interplanetary Tether Transport (RITT) system, there is no reason why the RITT concept could not be used for rapid transport among other planets and moons in the solar system, as well as between planets and moons.

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