Dramatically Reduced Launch Costs for Mars Missions using a Reusable Momentum Exchange Tether with Electrodynamic Reboost as the Upper Stage

Simon Rowland[1], Robert Hoyt, Ph.D[2]

1. Direct Leap Technologies, Inc. Toronto, Ontario, Canada, (416) 771-1132
2. Tethers Unlimited, Inc. Lynnwood, Washington, United States, (425) 744-0400

Summary

We propose to develop a reusable in-space orbital transfer stage using a small momentum exchange tether with propellantless electrodynamic reboost. Imagine Mars Odyssey, Mars Pathfinder, and a large penetrator delivered to Mars during a single transfer opportunity, all launched using a single reusable in-space transfer stage.

The momentum-exchange tether system will enable subsequent Mars spacecraft to be launched into Low Earth Orbit as low-cost secondary payloads. The tether facility will mate with the payload at low speed, and then toss them into a direct transfer to Mars re-entry, or to Low Lunar Orbit using a weak stability boundary trajectory. The facility can also provide most of the transfer energy for Delta-class Mars Orbital or Near-Earth Asteroid rendezvous missions. This infrastructure is less costly to design, build and launch than even the first Delta-class launch.

System Concept and Operation

The basic concept is to connect a Mars-bound spacecraft to a larger, reusable central facility using a long, high-strength tether (cable). The system is then set into rotation and the payload released, transferring momentum from the central facility to the payload without the consumption of propellant. To restore the momentum after each payload transfer operation, the tether facility drives a current along a conducting wire in the tether, generating thrust through electrodynamic interactions with the Earth's magnetic field. The tether facility converts energy from solar panels into orbital energy over many weeks, which is then transferred to the payload upon release.

The facility will be launched into LEO with its first three payloads well before the launch window. It deploys a 50 km electrodynamic tether, and over a period of 6 months, the system boosts itself into a 343 km x 24,000 km orbit, and spins up to a tip speed of 1.04 km/s. It releases the first 650 kg fuelled Mars Orbiter into a Belbrunno weak stability boundary transfer to L4, the Lagrangian Earth-Moon gravitational balance point. Over the next several months it reboosts its orbit and then tosses the 650 kg fuelled Mars Lander into the same L4 holding orbit.

The tether boost reduces the fuel needed for a Mars insertion trajectory by a factor greater than 10. The Mars Orbiter spacecraft waits for the launch window to execute a 511 m/s Trans-Mars Insertion, and on arrival it performs an orbit insertion burn. Using a hydrogen peroxide bipropellant and the Mars '96 trajectory results in a final weight of 400 kg in Mars orbit.

The Mars Lander is launched with a Thiokol Star 17A solid rocket motor weighing 112 kg. This puts the Mars Lander on a direct re-entry trajectory, with a weight approaching Mars of 540 kg and a landed weight of perhaps 270 kg. The two spacecraft are comparable to the Mars Odyssey and Mars Pathfinder missions, each of which was launched using a US$50 million Delta 7925.

After releasing the first two payloads into a high earth orbit, the tether facility deploys the smaller surface payload to the end of the tether and raises the tip speed, releasing a 300 kg penetrator, lander or balloon — or a cluster of smaller devices — directly into a Mars re-entry trajectory. The package requires only minor course corrections, perhaps using a solar sail.

Much larger Mars Lander payloads can be accommodated. By lifting a 1,500 kg fuelled lander to GTO, a peroxide bipropellant is able to deliver a re-entry capsule of about 1,000 kg.

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Dry Spacecraft Weight at Mars		Mission Profile	Trajectory Provided
300 kg	Balloon or Penetrator	Inserted directly into Mars re-entry course, needs only course corrections. Five times the size of Beagle 2. Up to 150 kg soft-landed.	Trans-Mars Insertion
540 kg	Lander or Aircraft	Uses a Star 17A for trans-Mars insertion followed by re-entry. Same size as the Mars Pathfinder mission. Up to 270 kg soft-landed.	L4
1000 kg	Lander	Uses a H_2O_2 bipropellant thruster to transit to L4 for holding, and later for Trans-Mars Insertion. Even larger missions are easily transferred.	GTO
190 kg	Orbital	Uses a Star 17 and its attitude thrusters for Mars orbit insertion. Same size as Clementine lunar mission.	Trans-Mars Insertion
265 kg	Orbital	Uses a Star 17A for trans-Mars insertion, and monopropellant for orbit insertion. Ideal for a low-cost spacecraft fleet, like the Cluster mission.	L4
400 kg	Orbital	Uses a H_2O_2 bipropellant thruster for Trans-Mars Insertion and orbit insertion burns. Same size as 2001 Mars Odyssey mission.	L4
200 kg	Deimos Lander	Uses a H_2O_2 monopropellant thruster for orbit insertion and landing. This is low-cost secondary mission is made easy by the tether facility.	Trans-Mars Insertion
450 kg	Deimos Lander	Uses a H_2O_2 bipropellant thruster for transfer and landing. Same size as the Near Earth Asteroid Rendezvous mission.	L4
Ten at 15 kg	Orbital Relay	Ten UoSat-style UHF repeaters provide global access to the 128 kbit relays on low-orbiting NASA missions. Uses H_2O_2 monopropellant.	Trans-Mars Insertion

Fig. 1 Selected missions using proposed tether facility, with spacecraft dry weight compared

System Sizing and Cost Estimates

The facility is launched at a cost of US$10 million on a Russian Dnepr, which places 4,500 kg into Low Earth Orbit. The 2,000 kg upper stage is retained as ballast. Using a commercially available satellite bus, the control and power system will mass approximately 1,750 kg, with a solar concentrator array power of 24 kW. Using Spectra 2000™ with a 350% safety margin, the multi-stranded Hoytether™ will mass 1,154 kg, including the tether deployer.

Following a small initial study, designing the tether facility will cost US$2 million, with about another US$20 million to build and test. A single Dnepr launches the facility together with the first three payloads. Thus, the total cost of a reusable infrastructure which substitutes for multiple Delta-class launches is $32 million — slightly less than the very cheapest upper stage launches.

The concept of Orbiter, Lander and Penetrator missions is simply illustrative — an excellent practical approach would be to build and launch two copies of the major mission selected.

Payoff

This reusable in-space transportation infrastructure will achieve dramatic reductions in the cost of delivering spacecraft to Mars. Once this tether facility is in place, subsequent missions can be built with less attention to weight, and launched as a 300 or 650 kg secondary payload on low cost vehicles. Even 1,500 kg on a shared Dnepr launch is only about $4 million.

In addition to Mars missions, the tether facility can service commercial and scientific markets such as GEO spacecraft and lunar missions. By adjusting the rotation of the tether, the system can boost payloads massing approximately 1,500 kg to GTO, allowing low-cost launchers with a negligible payload beyond LEO to orbit two or three satellites, in place of a more expensive launcher with an upper-stage deploying just one. Capacity can be built up by launching extra modules, making the potential for private operations and export clear.

Achieving significant reductions in the cost of space exploration will give smaller countries a new opportunity to mount small interplanetary missions as a matter of routine. This mission design makes any space program's commitment to permanently advancing access to space clear.

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