EARTH AND MARS BASED SEP TUGS FOR INCREASED PAYLOAD DELIVERY TO MARS. T. P. McElrath[1], J. O. Elliott[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: Modern Hall thrusters have nearly infinite lifetimes, but their potential application on a solar electric propulsion (SEP) stages generally don't make full use of this capability, and typically end up with excess solar array capability at arrival. Re-usable SEP tugs based at the Earth and optionally at Mars would make full use of the SEP hardware, while significantly increasing the payload transfer capability to Mars. Trajectories exist that would allow a SEP tug based at the Earth to deliver a Mars-bound payload every 26 months (1 synodic period), while Mars-based tugs would be better-suited to 52 month sequences.

Mission Sequence: The sequence of events is shown on Table 1. The Earth-based tug would wait in a 12-hour orbit for payload launch. Once launch occurs, the tug would dock with the payload and connect to one of two xenon tanks attached to the payload. Using that xenon supply, the tug would raise the orbit quickly above the van Allen belts (in ~2 months, incurring less than 10 krads), and then ascend more slowly until the apogee reached lunar altitude, as shown in Figure 1. The trajectory would have a lunar flyby, followed by a ~3.5-month trajectory to a final pair of lunar flybys, thus enabling an Earth departure at a excess hyperbolic velocity (V_∞) of 2 km/sec.

Table 1: Timeline and example masses

Time (months)	Tot. mass	Tank 1/2 Xe	Comments
0	1120	-/0	Staging pre-launch
1	4820	750/615	Launch & docking
7-10.5	4377	307/615	Lunar flybys
14.5	4294	224/615	Pre-separation
14.5	1418	224/-	Post-sep, Earth-tug
24	1317	125/-	Lunar flyby
25.5	1199	8/-	Pre-launch orbit
26	1120	-/-	Tank drop
23.5-30	2875	-/615	Earth, Mars flyby
24	1331	-/133	Mars departure
33	1200	-/2	Pre-catch
33	1120	-/-	Tank drop
33	3995	-/615	Docking
57	3659	-/279	Mars rendezvous
63	3550	-/173	Pre-aerobraking
63	2179	-/-	Post-separation
63	1371	-/173	Mars ascent start
69	1331	-/133	Mars ascent end
24+52=76	1331	-/133	Depart (7m margin)

Within 4 months of departure, the tug would typically supply 500 m/s, putting the payload on an Earth-return trajectory with a V_∞ of 3+ km/sec. Figure 2 shows an example trajectory for the 2016 Mars opportunity. This opportunity is challenging, with high Earth departure/Mars arrival energy, so it was chosen as a bounding case. Other Mars opportunities would show similar benefits, and better overall performance.

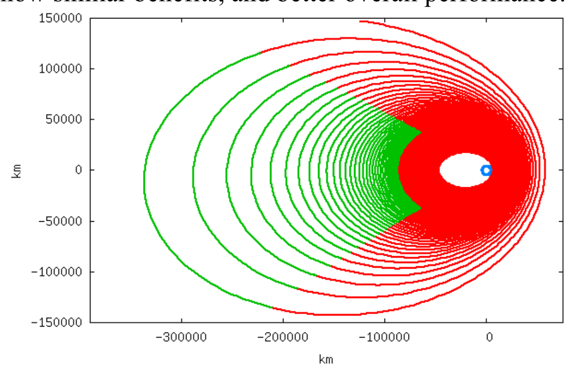

Figure 1: Ascent to lunar altitude. Thrust arcs are in red, coast arcs in green

Once the payload was put on a Mars-bound trajectory, the tug would separate, retaining one xenon tank, and perform SEP thrusting to return to the Earth 13.5 months after departure, at a V_∞ of only 1 km/sec, as shown in Figure 3. At that velocity, a single lunar flyby would suffice to return the tug to the ending conditions shown in Figure 1, such that 1.5 months of thrusting (at a much lower mass, using the remaining xenon in the tank) would permit the tug to return to the starting conditions, with a 0.5-month margin before the start of the next launch opportunity. Note that more time margin could be obtained by optimizing the Δ-V usage between the geocentric and heliocentric phases.

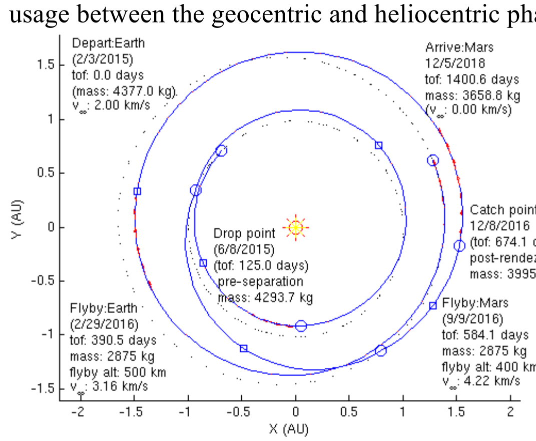

Figure 2: Complete trajectory

Meanwhile, the payload would continue to an Earth and Mars flyby, using the optimum point in the 2016 launch-arrival space. Note that the payload would have to perform statistical maneuvers and provide other housekeeping functions during this 550-day trajectory segment, but no large Δ-Vs would be required, so a small mono-prop system should be sufficient.

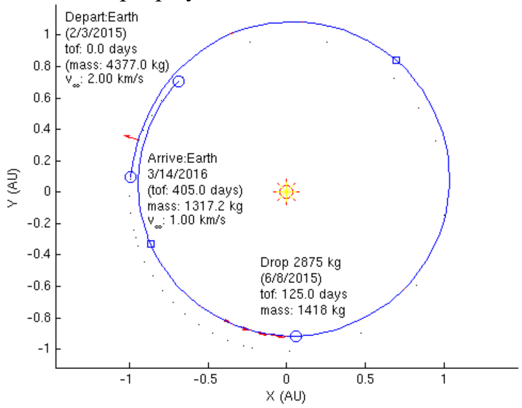

Figure 3: Earth-return tug trajectory

Six months befor the payload's Mars flyby, the Mars-based tug would depart Mars, as shown in Figure 4. Three months after the Mars flyby, the Mars tug would rendezvous with the payload, and connect to the payload xenon tank. The Mars tug would use that propellant to fly both vehicles to a Mars rendezvous, as shown in Figure 2. Such long trajectories allow the Mars-relative V∞ to be efficiently removed, at a 2:1 or better ratio, with respect to the SEP Δ-V supplied.

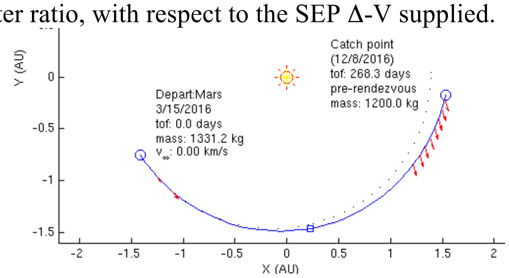

Figure 4: Mars tug rendezvous trajectory

Following Mars arrival, the tug could proceed to drop the payload to a 2-day orbit with a low periapsis, suitable to start aerobraking, as shown in Figure 5. From that point, the payload would be separated to perform aerobraking, typically taking 6 months to reach a low Mars orbit. The tug would keep the xenon tank, and use the remaining propellant to climb back out of Mars orbit and prepare to start a new payload capture cycle. Note that there is margin in the Mars tug sequence, such that a different orbit (perhaps Phobos or Deimos rendezvous) could be reached, or propellant saved through a slower transfer. The Mars tug would retain enough propellant to reach the capture point for the next payload, as shown in Table 1.

Table 2: Performance comparisons, delivered mass

Scenario	To Mars	To aerobraking
Direct launch	1480 kg*	887 kg**
Earth tug	2875 kg	1725 kg**
Both tugs	n/a	2179 kg

*V_∞ 4 km/s from Earth ** V_∞ 4 km/s at Mars, Isp 320s impulsive, useful mass lower due to prop system

Discussion: For this example, the launch capabilities of a Falcon 9 (blk 2) are used, although the relative benefits would be similar for any other launch vehicle, with proper tug sizing. As shown in Table 2, the benefits of using one or both tugs would be substantial.

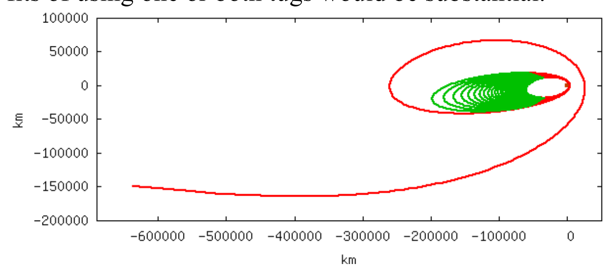

Figure 5: Mars descent trajectory

The tugs themselves would be very similar for this example. The Earth tug would have 30 kW of solar array power, and 6 BPT-4000 thrusters (examples of which are currently flying), with an estimated total mass (with margin) of 1120 kg. The Mars tug would have 35 kW of (1-AU) solar power and 3 BPT-4000s, with the same mass. The only significant development item would be the docking port, which would make a xenon connection at 100 psi (downstream of the regulator, which would be discarded with each spent tank). The low acceleration levels would make the loads negligible. The relatively low mass of the two tugs would allow them to be launched together on a Falcon 9-sized vehicle to establish this transportation infrastructure.

As with many SEP uses, this approach would trade increased payload mass for increased flight time. While the upfront investment would be increased, the payoff over several cycles could be significant, in a combination of increased payload and reduced launch costs. Note that the Earth tug could also perform Mars insertions on a cycle longer than 26 months, either missing every other Mars opportunity or having two Earth-based tugs (and of course these tugs could perform other tasks). The 12-hour orbit might not prove to be the optimum staging point between the launch vehicle and the Earth-based tug, but it appears to be a useful balance of injected mass and van Allen belt radiation penalty.

Conclusion: Earth- and Mars-based SEP tugs would provide a significant mass benefit for Mars-bound payloads. Their development would be a stepping stone for larger SEP spacecraft that may be useful for future human exploration of the solar system.