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Solar Sails for Mars Cargo Missions

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Abstract. This paper presents an analysis of Solar Sails for the Mars Cargo Mission. The figures-of-merit used are the total system Initial Mass in Low Earth Orbit (IMLEO) and Trip Time. The total IMLEO includes the payload, solar sail, and any orbit transfer vehicle (OTV) required to move the sail and its payload to the operational altitude of the sail (e.g., 2,000 km minimum altitude Earth orbit for the solar sail due to air drag). Once the sail and its payload are transported to the sail's minimum operational orbit by the OTV, the sail begins its Earth-escape spiral and heliocentric transfer to the orbit of Mars. In order to minimize the payload's Earth-to-Mars trip time, the sail does not perform a Mars orbit insertion capture spiral but rather deploys its payload during Mars flyby. The payload then aerobrakes into Mars orbit or to the surface to await arrival of the crewed portion of the mission. The sail loiters in heliocentric space until it is time to return to Earth. Note that one important constraint on the payload's Earth-to-Mars trip time is the requirement that the payload be delivered to Mars (and be checked-out and verified operational) before the crew departs Earth at the next Earth-Mars launch opportunity. We further assumed that the solar sail would be a reusable system; thus, in addition to delivering the payload to Mars prior to the next crew departure, the solar sail must return to Earth before the next sail Earth-departure opportunity. With these constraints, the solar sail areas required for a 58 and 72 metric ton (MT) payload are, respectively, 20 and 25 km^2. The corresponding IMLEO values are 149 and 185 MT, such that the total transportation system (sail and OTV) is only 1.6 times the payload mass.

INTRODUCTION

Solar sails use sunlight pressure to provide propulsive force. As such, they are a "propellantless" propulsion system. However, because sunlight pressure is very low, solar sails are typically large-area, low-acceleration systems. They have been considered as a highly mass efficient transportation systems for a variety of robotic missions and as a cargo vehicle to support piloted missions. Generally, they are not considered for crew transportation for near-term piloted missions because of the long trip times required. However, in the role of cargo vehicles they are the deep space analog of terrestrial Supertankers for the slow, but very fuel-efficient transport of bulk cargo.

In this study, we evaluated the use of solar sails to transport cargo in support of a piloted Mars mission. We assumed that the crew would be delivered on a separate vehicle, such as a nuclear thermal rocket, to provide for rapid trip times (e.g., 1-year crew round trip) for the crew. Of particular importance in evaluating the benefit of solar sails for a Mars cargo mission is the total initial mass in low Earth orbit (IMLEO) and the total trip time. As will be shown below, because of the slow, long trip time of the solar sail vehicle, trip time becomes an important consideration in determining the overall mission operations of the solar sail transportation system.

MISSION ANALYSIS ASSUMPTIONS

In this section, we describe the various assumptions used in the study. This includes the overall mission scenario, the mission scenario's impact on the sail trajectory, the level of solar sail technology (characterized by the sail's area and mass-per-unit-area or area density), the mass of the cargo transported, and finally, any supporting infrastructure required in either Earth or Mars orbit.

Mission Scenario

The solar sail Mars cargo mission starts in a 400-km low Earth orbit (LEO). Each sail carries one payload unit (a Mars Lander). The sail, along with its cargo, is boosted to a 2,000-km circular Earth orbit by a reusable chemical rocket Orbit Transfer Vehicle (OTV). A 2,000-km altitude was selected in order to minimize air drag on the sail. It may be possible to operate a sail as low as 1,000 km; however, this will be a function of the overall sail performance, as well as atmospheric conditions in a given year (i.e., atmosphere density as a function of the solar cycle). The sail then transfers from a 2,000-km circular Earth orbit to Earth escape, followed by a heliocentric transfer a Mars heliocentric orbit. An optional trajectory involves the sail then transferring down to a 6,000-km circular Mars orbit, which is the same altitude as that of Phobos. The cargo is then deployed and aerobrakes into Mars orbit. The sail then returns (empty) to a 2,000-km circular Earth orbit for reuse. A chemical OTV then transfers only cargo payload from the 400-km LEO to the sail in its 2,000-km minimum altitude.

Additionally, we (Drake, 2000) required that the sail be able to deliver the cargo to Mars before the next crew Earth departure (about 2.1 years), so as to check out the landers prior to crew Earth departure, and also be able return the sail (empty) to the minimum sail altitude at Earth (2,000 km circular orbit) before the next sail Earth departure (about 4.2 years). This makes it possible to reuse the sail for subsequent Mars missions. However, because of the long trip times involved, we found that two sails (or two sets of sails depending on the number of landers required per mission) would be needed, with each being used for alternating Earth-Mars mission opportunities (about every 2.1 years). Thus, by using two sets of sails, a Mars cargo mission can be flown every opportunity with a mission time phasing such as that shown in Table 1.

TABLE 1. Solar Sail Time Phasing for the Mars Cargo Mission.

OPPORTUNITY	DATE	ACTIVITY
Opportunity 1 (T = 0)	12/27/2014	Sail 1 departs Earth
Opportunity 2 (T ~ 2.1 years)	3/6/2017 2/26/2017 6/15/2018	Sail 2 departs Earth Sail 1 arrives at Mars Crew 1 leaves Earth
Opportunity 3 (T ~ 4.2 years)	3/7/2019 5/8/2019 4/21/2019 12/15/2019	Sail 1 returns to Earth, picks up next payload Sail 1 departs Earth Sail 2 arrives at Mars Crew 2 leaves Earth
Opportunity 4 (T ~ 6.3 years)	5/11/2021 6/23/2021 8/13/2021 2/15/2022	Sail 2 returns to Earth, picks up next payload Sail 2 departs Earth Sail 1 arrives at Mars Crew 3 leaves Earth

Sail Trajectory

For a given a sail trajectory, the trip time is a function of the total sail plus cargo payload areal density in units of grams per square meter (g/m^2) or, equivalently, metric tons (MT) per square kilometer (MT/km^2) of sail. Lower areal density results in a lowered trip time and IMLEO for a given sail. The heliocentric transferred was calculated by Carl Sauer of JPL (Sauer, 2000), and the Earth and Mars escape/capture spirals calculated by the method of Sands (Sands, 1961). The IMLEO is equal to the sail plus its payload, plus the wet mass of the chemical stage used to transfer the sail and payload from the 400-km LEO to the 2,000-km minimum sail altitude, plus the dry mass of any propellant tankers required to transport chemical propellants from Earth to LEO.

Sail Technology

One of the critical factors affecting solar sail performance is the achievable sail areal density. In the context used here, the sail areal density consists of the mass of the sail (sail film, structure, attitude control, avionics, etc.) divided by the effective area of the sail. We have treated the sail areal density parametrically, with areal densities ranging from 10 g/m^2, corresponding to a moderately near-term sail, to 0.1 g/m^2, corresponding to the sail areal density required for interstellar missions (Forward, 1984). For the purposes of comparison, we have assumed a nominal sail areal density of 3 g/m^2 based on the demonstration of carbon-carbon (C-C) based sail substrates of 1 g/m^2 (Knowles, 1999). In fact, as will be discussed below, there is an upper limit of sail areal density of about 4.5 g/m^2 for a Mars cargo sail so that it has a short enough trip time to enable the sail to be reused on a subsequent mission opportunity.

Once a given sail areal density is selected, we then add a payload mass and select a total sail area to calculate the sail mass, total vehicle mass with payload, and total areal density. The total areal density with payload is then used to determine the characteristic acceleration (A_c) (Garner, 1999):

$$A_c = (4.5\ \mathrm{N/km^2})\ (1 + \text{Sail Reflectivity } [\eta])\ /\ (\text{Total Sail+Paylod Areal Density}) \qquad (1)$$

A_c is then input to the trajectory codes to determine trip time. We have assumed a sail reflectivity (η) of 0.8 in all calculations. Finally, note that the sail photon reflection term in Equation 1 is $(1+\eta)$; some earlier authors (Forward, 1984) had erroneously used a term 2η for their calculations, introducing a small error in calculations.

Cargo Payload

Based on discussions (Drake, 2000) with Brent Drake (NASA JSC), two general classes of cargo payloads were considered. The first was a 58 metric ton (MT) lander; the second was a 72 MT lander. For a fast, 1-year round-trip crew mission, the 58 MT lander contains a 30-day surface habitat and an ascent vehicle capable of transferring to a 500-km circular Mars orbit; the 72 MT lander contains the same 30-day surface habitat and an ascent vehicle capable of transferring to a 1-Sol elliptical Mars orbit. For a long, minimum energy multi-year mission, a 58 MT lander with a 580-day surface habitat (but no assent vehicle) would be used in conjunction with a second Lander with ascent vehicle.

For the solar sail mission, the landers would aerobrake from Mars heliocentric space into a Mars orbit to await crew arrival and rendezvous with the landers. The landers then aerobrake to the Mars surface. By deploying the landers from the heliocentric space near Mars, the sail avoids the long spiral that would otherwise be required to place it in a 6,000-km circular Mars orbit.

Supporting Infrastructure

As discussed above, a chemical propellant OTV is required to transport the sail and its cargo from a 400-km circular Earth orbit to a 2,000-km circular Earth orbit. For this requirement, a reusable oxygen/hydrogen (O_2/H_2) stage with a specific impulse of 460 lb_f-s/lb_m is used. The overall stage has a 1-MT fixed mass and a 12% propellant tankage fraction. A propellant tanker for this stage, used to transport propellant from Earth to LEO; has a tankage fraction of 6%. The mission ΔV for either the up or down leg is a 795 m/s which includes the ideal ΔV, a flight performance reserve of 2% of the ideal ΔV, and a 10 m/s contingency for trajectory correction maneuvers, rendezvous and docking, etc. Note that in order to prevent damage to the sail, we must use a low-thrust chemical stage with a thrust on the order of 50 to 100 lbs. of thrust depending on the sail size and payload mass. Typically, the chemical OTV and its supporting propellant tanker are less than 20% of the total IMLEO.

MISSION ANALYSIS RESULTS

In this section, we describe the results of the trajectory analysis, and introduce the requirement on the trajectory such that a sail launched in one Earth departure opportunity delivers the cargo to Mars prior to the crew departing Earth on the subsequent Earth departure opportunity. This ensures that the landers can be checked out in Mars orbit prior to committing the crew to the mission (Drake, 2000). Additionally, the sail is required to return to Earth on a schedule that allows the sail to be used for a subsequent cargo mission. These mission timing requirements impose significant constraints on the required sail areal densities and sizes.

Trajectory Analysis

The planetary escape or capture spirals were calculated based on the total vehicle areal density (sail plus payload) using the method of Sands. Figures 1 and 2 illustrate the trip time as a function of characteristic acceleration (A_c) for the planetary escape/capture spirals, and the heliocentric transfers, respectively. For comparison, for the nominal sail areal density of 3 g/m^2, the outbound (Earth-to-Mars) sail has a characteristic acceleration of 1.4 mm/s^2 and the returning (Mars-to-Earth) empty sail has a characteristic acceleration of 2.7 mm/s^2. Note that for the Mars-to-Earth leg, the sail is empty; its characteristic acceleration depends only on the sail areal density and is independent of sail area. Thus, the sail area is determined primarily by the characteristic acceleration needed for the Earth-to-Mars step with the loaded sail, such that the overall mission time constraints are satisfied.

Figure 1 shows that the Earth capture and escape spiral has a very long trip time in part due to the large gravity of Earth and the low starting or ending altitude (2,000 km). By contrast, the capture and escape spirals for Mars are much quicker due to the lower gravity of Mars and the higher assumed altitude at Mars (6,000 km), even though sunlight intensity, and thus sail acceleration, is less than half that at Earth.

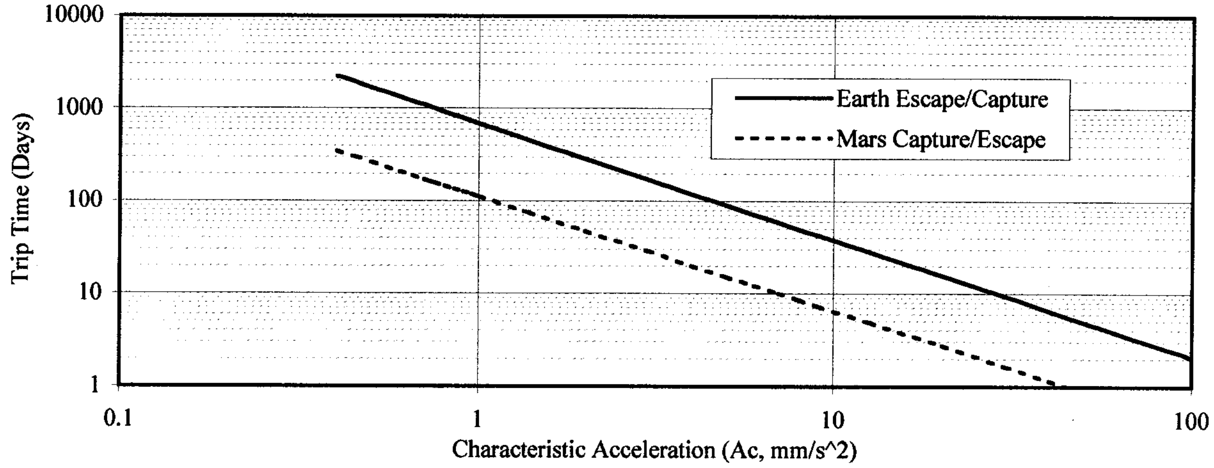

FIGURE 1. Solar Sail Earth and Mars Escape and Capture Spiral Times as a Function of Characteristic Acceleration (A_c).

Figure 2 shows the heliocentric transfer between Earth orbit (1.0 AU) and Mars (1.5 AU). The elliptical orbits of Earth and Mars result in a 15-year cycle of trajectories; i.e., the orbital geometries and thus trip times between Earth and Mars repeat every 15 years. This is illustrated in Figure 2 where we see that the worst year (i.e., longest trip time) is in 2026. Interestingly, there is less than a 100 day spread in trip time between the best (2018) and worst (2026) years. It is also interesting to note that the total heliocentric trip time is relatively insensitive to a given year, in part because of the varying Mars layover time required to satisfy the planetary alignments needed for the two legs of the trip. For our calculations, we assumed a worst year (2026) trajectory for the heliocentric portion. (The Earth or Mars escape and capture spirals are independent of year.)

Determination of Sail Area

To determine the required sail area, we first select a payload mass (58 or 72 MT). We then vary the sail-only areal density from 0.1to 10 g/m^2 with a nominal value of 3 g/m^2. By trial and error we then select a sail area that results in a characteristic acceleration for the total vehicle that makes it possible to deliver the cargo to Mars before the next crew Earth departure and also return (empty) to the minimum sail altitude at Earth (2,000 km circular orbit) before the next sail Earth departure. For these trip time constraints, we found that for a nominal 3 g/m^2 sail, a 58 MT lander payload requires the sail with an area of 20 km^2 (which weighs 60 MT) and a 72 MT lander requires a sail area of 25 km^2 (which weighs 75 MT).

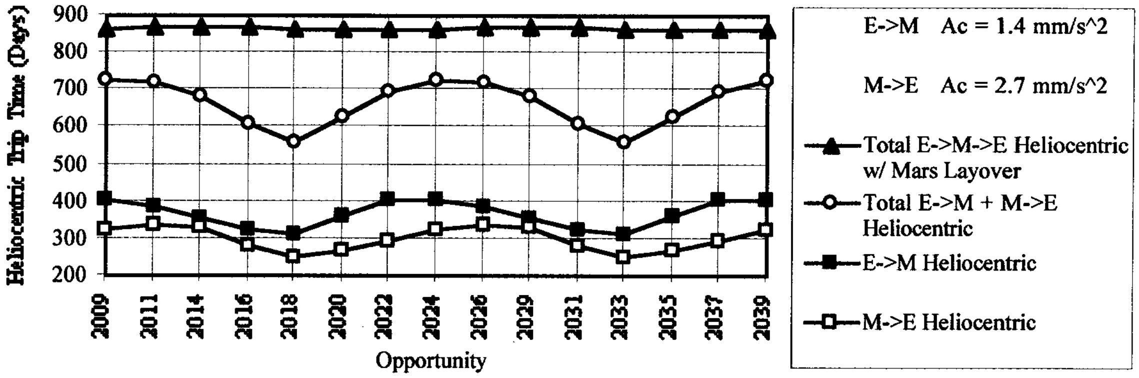

FIGURE 2. Solar Sail Heliocentric Trip Times for the Nominal Sail Areal Density.

The variation in sail area as a function of payload mass and sail areal density is shown in Figure 3. For the time-phasing constraints listed above, the limiting (maximum) sail areal density is 4.5 g/m^2; this case would correspond to the limit of zero payload for both the outbound and return legs of the trip.

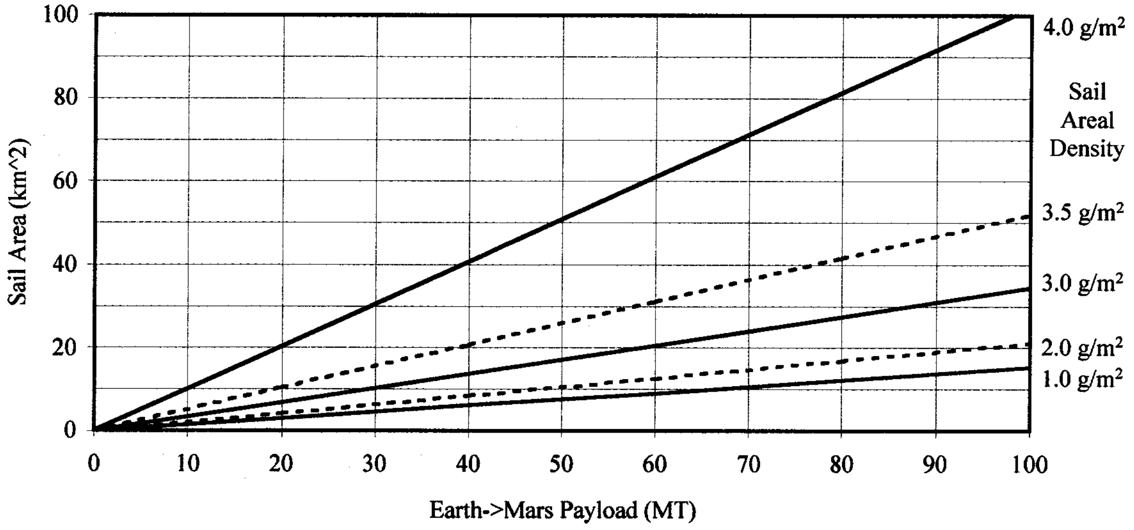

FIGURE 3. Sail Area Required to Meet Mission Timeline Constraints vs. Payload Mass as a Function of Sail Areal Density.

Supporting Infrastructure

To determine the total initial mass in low Earth orbit (IMLEO), we then add the mass of the chemical OTV (and any required chemical propellant tankers for the chemical OTV and landers) to the total sail plus payload mass. For the nominal sail areal density (3 g/m^2), this is about one-fourth of the mass of the sail and (wet) lander. The trip time required for the LEO-to-2,000 km transfer (less than four days round trip) is negligible compared to the sail trip times.

Amortization of Sail Transportation System Over Multiple Missions

For the first sail mission, the total IMLEO required is about 1.6 times the mass of the payload delivered to Mars (for a nominal sails areal density of 3 g/m^2). This is because it is necessary to deliver the sail and its payload, chemical OTV, and chemical OTV propellants to LEO for the first mission. However, on subsequent missions, only the payload and chemical OTV propellant need be delivered to LEO. Thus, the total per-mission IMLEO is only 0.9 times the payload mass for an amortized system after only two missions per sail, suggesting that the reusability of a solar sail transportation system can result in significant savings over multiple Mars missions. This is illustrated in Table 2, where we show the mass values for the two payloads on sails with the nominal areal density.

TABLE 2. Solar Sail Mars Cargo Mission IMLEO.

PAYLOAD (LANDER) MASS SAIL AREA (AREAL DENSITY)	**58.0 MT (Light Lander) 20 km^2 (3.0 g/m^2)**		**72.0 MT (Heavy Lander) 25 km^2 (3.0 g/m^2)**	
ITEM	**First Mission**	**Subsequent Missions**	**First Mission**	**Subsequent Missions**
	IMLEO (MT)	IMLEO (MT)	IMLEO (MT)	IMLEO (MT)
Sail	60.0		75.0	
Lander (Wet)	58.0	58.0	72.0	72.0
Lander Tanker (Dry)	0.8	0.8	1.4	1.4
Chem OTV (Dry)	3.9		4.6	
Chem OTV Propellants	24.4	12.9	30.3	15.9
Chem OTV Propellant Tanker (Dry)	1.5	0.8	1.8	1.0
Subtotal	*148.6*	*72.4*	*185.2*	*90.2*

SUMMARY

Solar sails have the potential of being a highly mass-efficient, propellantless Mars cargo transportation system. Solar sails can ultimately become the supertankers of the solar system - slow, but very mass efficient. They are also reusable, which results in a significant amortization over multiple missions for additional mass savings. Finally, development of solar sails for robotic planetary and interstellar precursor missions is synergistic with the development of the large, lightweight solar sails required to support human missions, and both robotic- and piloted-mission sails are part of a technology roadmap that ultimately can lead to interstellar mission capabilities. For example, the large size sails required for Mars cargo missions are comparable to the size of sails required for a laser-driven 0.1-c interstellar flyby (Forward, 1984).

Many of the major solar sail technology issues such as sail film, structures, deployment, etc. are already being addressed for applications for robotic missions. This includes technology areas such as advanced C-C sail fabrics and ultra-thin plastic films, sail deployment by carbon booms, inflatable struts, or spinning, as well as general technology issues for large space structures such as stability, dynamics, and controls.

Finally, one area identified in this study that requires additional work is in the area of modeling tools to calculate spiral times for planetary escape and capture. Specifically, the method of Sands does not take into account variations in planetary escape or capture spirals with respect to orbit eccentricity or inclination. For example, a Sun-synchronous polar orbit might dramatically reduce escape and capture spiral times, which ultimately impact the required sail area, although it would adversely impact Earth-to-orbit launch capability.

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