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Mass breakdown model of solar-photon sail shuttle: The case for Mars

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ABSTRACT

The main aim of this paper is to set up a many-parameter model of mass breakdown to be applied to a reusable Earth–Mars–Earth solar-photon sail shuttle, and analyze the system behavior in two sub-problems: (1) the zero-payload shuttle, and (2) given the sailcraft sail loading and the gross payload mass, find the sail area of the shuttle. The solution to the subproblem-1 is of technological and programmatic importance. The general analysis of subproblem-2 is presented as a function of the sail side length, system mass, sail loading and thickness. In addition to the behaviors of the main system masses, useful information for future work on the sailcraft trajectory optimization is obtained via (a) a detailed mass model for the descent/ascent Martian Excursion Module, and (b) the fifty–fifty solution to the sailcraft sail loading breakdown equation. Of considerable importance is the evaluation of the minimum altitude for the rendezvous between the ascent rocket vehicle and the solar-photon sail propulsion module, a task performed via the Mars Climate Database 2014–2015. The analysis shows that such altitude is 300 km; below it, the atmospheric drag prevails over the solar-radiation thrust. By this value, an example of excursion module of 1500 kg in total mass is built, and the sailcraft sail loading and the return payload are calculated. Finally, the concept of launch opportunity-wide for a shuttle driven by solar-photon sail is introduced. The previous fifty–fifty solution may be a good initial guess for the trajectory optimization of this type of shuttle.

1. Introduction

Solar-Photon Sailing (SPS) is a reality after IKAROS (JAXA) and NanoSail-D2 (NASA). At least three more projects of sailcraft about the Earth, to the Moon, and to NEAs are in progress with launches planned within a couple of years or so. These important projects should further contribute to the strong expectation and belief that SPS could be the propellantless in-space propulsion mode capable to overcome the restrictions of rocket propulsion beyond the low Earth orbits. This takes place by using an appropriate *low*-fluctuation external source of energy and momentum, namely, the Total Solar Irradiance (TSI).

Plenty of conceptual work has been done for SPS in the four decades before IKAROS, and many other system/subsystem concepts, innovations, simulations, and system realizations are needed [1] for SPS can be considered mature and safe for most of the future Astronautics. SPS can be regarded as a strict propellantless propulsion; as a point of fact, not only the translational motion of sailcraft can accomplished with no propellant, but also modern concepts of sail attitude control, or more generally thrust vectoring control, benefit sailcraft inasmuch as they entail no fuel consumption even as backup control system, e.g. [2–6]. Therefore, it is expected that SPS-based Interplanetary Space

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Nomenclature

a	semi-major axis of Mars orbit
A	actual sail membrane area
A_V	actual area of the control vanes
AU	Astronomical Unit
c	speed of light in vacuum
C_d	drag coefficient
f_L	net return payload on landed payload ratio
f_V	fraction A_V/A
h	rendezvous orbit altitude
H	angular momentum of Mars orbit
I_{sp}	specific impulse
k	averaged effect of non-orthogonal flow impingement on solar sail
l	$\sqrt{A}$, length of the sail side
$l_\blacksquare$	length of the sail side in the fifty–fifty condition
$\mathbf{L}$	lightness vector
$\mathscr{L}$	lightness number
m	total mass of the sailcraft at departure from Earth
m_B	mass of the beam subsystem
$m_{dry}^{(a)}$	ascent-stage dry mass
m_D	deployment subsystem mass
m_L	gross payload mass
m_{mem}	Martian Excursion Module mass
$m_{mem}^{(d)}$	descent stage (aerobraking and rocket) mass
$m_{mem}^{(L1)}$	net payload delivered to Mars surface
$m_{mem}^{(L2)}$	net payload returned to the Earth
$m_{mem}^{(2)}$	total mass at launch from Martian ground
$m_p^{(a)}$	propellant for ascent and rendezvous
$m^{(ret)}$	return sailcraft mass
m_S	sail system mass
$q^{(d)}$	landed mass ratio
$r^{(a)}$	propulsion mass ratio related to the ascent and docking phase
R	Sun–Mars distance
SPS	Solar-Photon Sailing
SSI	Spectral Solar Irradiance
TSI	Total Solar Irradiance
ϕ	sub-satellite point longitude
η_{thr}	thrust efficiency
φ	sub-satellite point latitude
μ_{Sun}	solar gravitational mass
ν_{ch}	boom spatial frequency
ρ	Martian local atmospheric density
ρ_{sps}	solar-sail stall density
σ	sailcraft sail loading
$\sigma_\blacksquare$	sailcraft sail loading in the fifty–fifty condition
σ_{BS}	bare-sail loading
$\sigma_{(cr)}$	critical sailcraft sail loading
σ_{mem}	descent/ascent Martian Excursion Module (MEM) sail loading
σ_V	vane sail loading
υ_{rel}	relative speed between sailcraft and atmosphere
ξ_{ch}	chord linear density
ξ_B	supporting beam linear density
Ξ	SPS overall payload ratio
ζ	ascent-stage structure on propellant mass ratio

Vehicles (ISVs), aimed at traveling from a celestial body P_1 to another celestial body P_2, can have wider launch windows with respect to rocket-based vehicles designed for running between P_1 and P_2 with the same mission goals.

In this context, a team of teachers and graduate students at the University of Rome 'La Sapienza' has been pursuing a research into a concept of SPS shuttle between Earth and Mars. They began by considering a *robotic* shuttle concept (as described below) with some preliminary calculations carried out by graduate students [6,7]. The case for *human* Mars exploration – as currently conceived by NASA via rocket propulsion missions – is detailed in [8], while a more general vision about planetary science can be found in [9]. The heliocentric branch of sailcraft trajectories depends also on the sailcraft sail loading (i.e. the sailcraft mass on sail area ratio), which in the first analysis [7] was varied parametrically. In this paper, we moved to a detailed analysis of the mass of the shuttle, which includes the Mars Excursion Module (MEM). Developing the shuttle mass breakdown in a sufficiently general way is the most important aim of this paper.

There are two additional purposes to the current work. First, evaluating the minimum altitude (in the Mars atmosphere) allowing rendezvous between the Martian ascent vehicle and the main sailcraft parked about Mars. Second, analyzing briefly if the particular concept of interplanetary reusable and launch opportunity-wide (LOW) shuttle may be compliant with the general equations for the shuttle system loading (this will be help us for the strategies of trajectory optimization in a subsequent paper). Let us clarify this concept of shuttle. The attribute of reusability is plain. Let us see what LOW means in the current context. Suppose that the above celestial bodies P_1 and P_2 are planets, and some ISV is aimed at traveling from P_1 to P_2 and back. Its transfer trajectories are characterized by a certain index of performance J to be minimized/maximized as function of the launch dates, say, τ_1 and τ_2 from P_1 to P_2 and subsequently from P_2 to P_1, respectively. If J^* denotes the strict optimal value, then ISV as *launch opportunity-wide* vehicle is meant here as a vehicle designed for accomplishing the transfer with a penalty $\Delta J = J(\tau_1,\ \tau_2) - J^*$ entailing *no appreciable* modification of the complete propulsion system. An important restriction to this concept comes from the upper limit of the total exposure time of payload subject to interplanetary radiations. More generally, the LOW attribute may entail missions between different types of celestial bodies in the solar system; for instance, P_2 may be an asteroid, a short-period comet, or some P_1's satellite.

The following sections are arranged as follows. Section 2 states the current problem, which consists of two main