SAILCRAFT-BASED MISSION TO THE SOLAR GRAVITATIONAL LENS

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Abstract. This paper shows that current or near-term technology together with the *H*-reversal mode for solar sailing would allow designing a 22-year flight-time mission to the *minimum* Solar Gravitational Lens (550 AU from the Sun). Sailcraft mass can be as low as 345 kg with a net payload of 100 kg. Al-Cr sail is 0.287 km^2 large and 0.14 μm thick. Sailcraft mass breakdown and trajectory profiles are detailed.

INTRODUCTION

In this decade, three new large classes of solar-sail trajectories have been found out (Vulpetti, 1996-99). Their excellent properties are based on a new solar-sailing concept: the sailcraft motion reversal or the *H*-reversal mode. The Aurora Collaboration (AC), that has been studying high-speed low-mass sailcraft since 1994, adopted such a potential strategy to propose new missions to the Italian Space Agency for scientific investigation beyond the planetary range. Wider aim is to try to make the solar-sail propulsion *feasible* for scientific, utilitarian and, subsequently, commercial use in space. In addition to spiral trajectories and halo-orbits (in the Earth-Moon system or inner/outer Solar System), the trajectory classes related to the *H*-reversal mode would dramatically allow expanding low-cost high-frequency low-mass scientific missions to very distant targets. It is based on the following properties, strictly proved from an astrodynamic viewpoint:

1. Sailcraft can escape the Earth-Moon system without the need of any other propulsion system or any lunar fly-by
2. If the sail loading is 2 grams/m^2 (or lower), then the sailcraft can decelerate down to reverse its orbital angular momentum; this allows the vehicle to point close to the Sun in acceleration mode for weeks and so getting the absolute (not a relative or strong) maximum of energy for a technology-given sailcraft
3. Perihelion distance and time can be tuned by design to meet different constraints, including temperature
4. The cruise phase is characterized by a speed practically independent of the distance from the Sun
5. High heliocentric speed is achieved by no planetary fly-by; sail is open at a parking orbit about the Earth, instead of at solar perihelion, thus avoiding strong jumps of thrust or impulses that may either damage the sail or induce unrecoverable attitude errors.

The first basic concept for performing smart sailcraft control was to turn the lightness-number concept as one fixed parameter into the concept of time-varying lightness vector. The second basic concept consisted of investigating what happens to a decelerating heliocentric sailcraft with a sail loading sufficiently low to allow a progressive decrease of the orbital angular momentum down to its reversal. Perihelion ranges from 0.30 to 0.15 AU whereas cruise speed spans in 11-17 AU/yr by 2 grams/m^2 (or 1.30 times the critical density) for a mission to the heliopause.

In the AC context, a further significant improvement of the *H*-reversal concept is in progress. On keeping the same range of admissible perihelion, an all-metal sail is under investigation with a sail loading as low as 1.20 grams/m^2 (or 0.78 times the critical density). A strong example mission such as the flight to the *minimum* Solar Gravitational Lens (SGL), or 550 AU, is the subject of this paper.

BASIC CONCEPTS OF SOLAR SAILING

We remind the reader a minimal set of solar-sailing concepts for a better understanding of the SGL mission. For a full treatment of dynamics and technology of solar sailing, one can refer to (McInnes, 1999) in general, and to (Vulpetti, 1996-99a) for high-speed trajectories, in particular.

There are two basic points: (*a*) in general, the force field actually acting on sailcraft is not conservative, (*b*) the sailcraft motion can be controlled by steering the normal-to-sail axis of symmetry. For our purposes, we need two frames of reference to describe the sailcraft motion: the heliocentric inertial frame (HIF) and the extended heliocentric orbital frame (EHOF). HIF may be identified with the Dynamical-Equinox and Ecliptic at J2000. EHOF is the generalization of the usual orbital frame by including trajectory branches separated by a finite number of points where the sailcraft's orbital angular momentum per unit mass (**H**) vanishes. The EHOF axes are given by the columns of the matrix ($\mathbf{r}\ \ \mathbf{h}\times\mathbf{r}\ \ \mathbf{h}$), where **r** denotes the direction of the sailcraft position vector, say, **R** in HIF and **h** is either the **H** direction for direct trajectory arc or the -**H** direction for retrograde trajectory arc or their (common) limit when **H=0**. (From here the phrase *H*-reversal mode). Motion reversal can take place even if **H** does not vanish. In such cases, the magnitude of **H** passes through a minimum (strictly, time of sailcraft motion reversal comes before this minimum of **H,** usually a few hours). The strict definition and properties of EHOF can be found in (Vulpetti, 1999a). One can write general sailcraft motion equations by introducing the time-dependent vector function named *the lightness vector* (Vulpetti, 1996-97), denoted by **L,** as follows:

$$\mathbf{L} \equiv \begin{pmatrix} \lambda_r & \lambda_t & \lambda_n \end{pmatrix}^T \qquad\qquad \lambda \equiv |\mathbf{L}| \tag{1}$$

L is defined in EHOF. Its components (also called the *radial*, the *transversal* and the *normal* lightness numbers, respectively) represent the solar-pressure-induced vector acceleration in units of the *local* solar gravitational acceleration or μ/R^2, where μ denotes the solar gravitational constant. Thus, the classical-dynamics equations of sailcraft motion can be written as

$$\begin{aligned} \frac{d}{dt}\mathbf{R} &= \mathbf{V} \\ \frac{d}{dt}\mathbf{V} &= \frac{\mu}{R^2}\left[-\left(1-\lambda_r\right)\mathbf{r} + \lambda_t\,\mathbf{h}\times\mathbf{r} + \lambda_n\,\mathbf{h}\right] \end{aligned} \tag{2}$$

(Here, for simplicity, Equations (2) do not contain the mass rate equation; actually, if a sailcraft is controlled by small attitude rockets then $d\mathrm{M}/dt < 0$, where M is the vehicle mass). One then realizes that sailcraft trajectory can be analyzed in terms of the **L** vector only, even though the actual control shall operate on the sail orientation. In order to highlight the different roles of the **L** components, we report the main equations for orbital sailcraft energy *E,* angular momentum and their time rates:

$$\begin{aligned} &E = \tfrac{1}{2}V^2 - \left(1-\lambda_r\right)\frac{\mu}{R}\,, && \frac{d}{dt}E = \frac{H}{R^2}\frac{d}{dt}H\,, \\ &\mathbf{H}\times\frac{d}{dt}\mathbf{H} = H\,\lambda_n\frac{\mu}{R}\mathbf{r}\,, && \frac{d}{dt}\mathbf{H} = \frac{\mu}{R}\left(\lambda_t\,\mathbf{h} - \lambda_n\,\mathbf{h}\times\mathbf{r}\right), \\ &\frac{d}{dt}H = \lambda_t\frac{\mu}{R}\,, && \mathbf{H} = H\,\mathbf{h}\,. \end{aligned} \tag{3}$$

An extended discussion of Equations (3) and their consequences for sailcraft dynamics can be found in (Vulpetti, 1996-97). The quantity *H* in Equations (3) is an invariant; it is the projection of **H** (defined in HIF) onto the Z-axis of EHOF. It can be of any sign and its derivative depends on the *transversal* lightness number. dH/dt drives the *E* change and determines the history of **H**. Note that the *normal* lightness number governs the bending of **H**. How to control a heliocentric sailcraft trajectory by *H* is explained in (Vulpetti, 1999a). In general, **L** is a complicated function of the sailcraft mass (M) on sail area (*S*) ratio (or the spacecraft *sail loading*, usually denoted by σ), the thermo-optical properties of the sail materials, the sail axis control angles, the spacecraft velocity and the source-of-light characteristics (McInnes, 1999) and (Vulpetti, 1999b). As usually conceived, a practical sail consists of a multi-layer film: the *reflective* layer, the *emissive* layer and the *substrate* the other two layers are deposited on. The reflective (or front-side) layer is always facing the Sun in a heliocentric trajectory, whereas the emissive (or backside) layer allows keeping the sail temperature sufficiently low. Although specular reflection is the dominant effect for photon-sail momentum exchange, other non-negligible effects have to be taken into account. If the substrate (which is the heaviest component of a sailcraft) is removed, then one has an all-metal sail capable to achieve very high speed. We shall consider this configuration for a fast mission to SGL.

Neglecting the sail irradiance reduction due to both the Sun finite-size and limb darkening - some models can be found in (McInnes, 1999) - and additionally retaining the linear terms in the sailcraft velocity results in the following simplified link between the direct control variables & parameters and the lightness numbers that enter the motion equations, or *the connection equations*:

$$\mathbf{L} = \lambda_0 \cos\alpha \, \cos\delta \left\{ \begin{bmatrix} \left(2r\cos\alpha \, \cos\delta + \chi_f \, d + \kappa a\right)\left(1-2\beta_x\right) - \\ 2r\sin\alpha \, \cos\delta \, \beta_y \end{bmatrix} \mathbf{n} + \left(a+d\right) \begin{bmatrix} 1-2\beta_x \\ -\beta_y \\ 0 \end{bmatrix} \right\}$$

where

$$\mathbf{n} \equiv \begin{bmatrix} \cos\alpha \, \cos\delta \\ \sin\alpha \, \cos\delta \\ \sin\delta \end{bmatrix}, \qquad \boldsymbol{\beta} \equiv \frac{V}{C} \begin{bmatrix} \cos\varphi \\ \sin\varphi \\ 0 \end{bmatrix}, \qquad \varphi \equiv angle\left(\mathbf{R},\mathbf{V}\right), \qquad V \equiv \left|\mathbf{V}\right| , \tag{4}$$

$$\lambda_0 \equiv \tfrac{1}{2}\sigma_c \frac{S}{M} , \quad \sigma_c \equiv 2\frac{W_{1AU}}{g_{1AU}\, C} = 0.001539 \ kg \ m^{-2} , \quad W_{1AU} = 1368 \ W m^{-2} , \quad g_{1AU} = 0.00593 \ m\, s^{-2} .$$

In Equations (4), α and δ denote the azimuth and elevation of the sail axis **n** (oriented backward with respect to the reflective sail side) in EHOF. The set (r, d, a) denote the specularly reflected, the diffused reflected and the absorbed fractions of the solar incident flux by the sail materials, respectively. Their exact meaning, numeric handling and relationship to orbit determination can be found extensively in (Vulpetti, 1999b). χ_f denotes the surface coefficient of the front side, whereas κ is a known function of the sail temperature. The vector $\boldsymbol{\beta}$ (resolved in EHOF) accounts for the aberration effect, which is not negligible for a high-speed flight. The quantity σ_c represents the so-called *critical* density. One has the following important relationship

$$\sigma = \sigma_c \, \tau / \lambda \ , \tag{5}$$

where τ is the thrust efficiency. Note that g_{1AU} is the solar gravitational acceleration at 1 AU, whereas W_{1AU} denotes the solar constant; the above value is compliant with some other reference (Wright, 1993). W_{1AU} has to be measured accurately for space sailing (probably as part of the orbit determination process); this could be performed in experimental sailcraft missions.

SAILCRAFT FOR SGL MISSION

If the sailcraft sail loading is sufficiently low, then by appropriately orienting the sail axis it is always possible to meet the following conditions: $\frac{1}{2} \le \lambda < 1, \ \ \lambda_t \le 0$ for the first branch of heliocentric flight, even though, in principle, the sailcraft is able to accelerate considerably already at 1 AU. These necessary conditions plus a sufficiently long deceleration time are sufficient to force **H** to zero and then reverse it. This is the only way to approach the Sun closely in the continuous accelerating mode. Roughly, this may be thought as a very long burn around the perihelion. Solar sail, however, consume no propellant and can be controlled such a way the along-track component of the total vector acceleration is positive past the reversal point. The sailcraft energy no longer decreases and can achieve its *absolute* maximum for a given sailcraft technology. Such an overall non-linear effect is mathematically detailed in (Vulpetti, 1996-99a). The technology to achieve the *H*-reversal condition consists of in-orbit removing the plastic support from the multi-layer sail made, for instance, of Al-Kapton-Cr. Some successful methods are in progress in laboratory (Scaglione, 1999). Given a very light bare sail, the other systems, including the deployment & keeping sub-systems, of sailcraft should be comparable in mass while exhibiting mission-appropriate features. For the SGL mission, AC has selected and sized the following main systems:

A. Hydrostatic Beam-based Deployment System with load-supporting web (Genta, 1999)

B. Attitude Control System (ACS), based on the Field Emission Electric Propulsion developed by the European Space Agency. The current ACS has been sized by using a jet speed of 7 km/s for keeping power low

C. Main Power System (MPS), based on the Pu^{238} Radioisotope Thermo-Photo Voltaic Generator (Shock, 1997)

D. Small CO_2 Laser Power Transmission System (SLPTS) delivering part of the electric energy from MPS (located close to the sailcraft center-of-mass) to four two-engine packages the ACS consists of. They are positioned at the rim of the sail system. SLPTS can produce a regular input to ACS independently of the Sun-sailcraft distance

E. Communication System based on Nd-YAG. It is sized to yield a bit rate (with coding) of 200 baudes at 750 AU

F. Scientific Payload.

Mass values of the subsystems and systems composing the systems A-F plus other structures and contingency are reported in Fig. 1 for the SGL mission envisaged here. Note that the above system choice allows designing a sailcraft with a net payload of 29 percent.

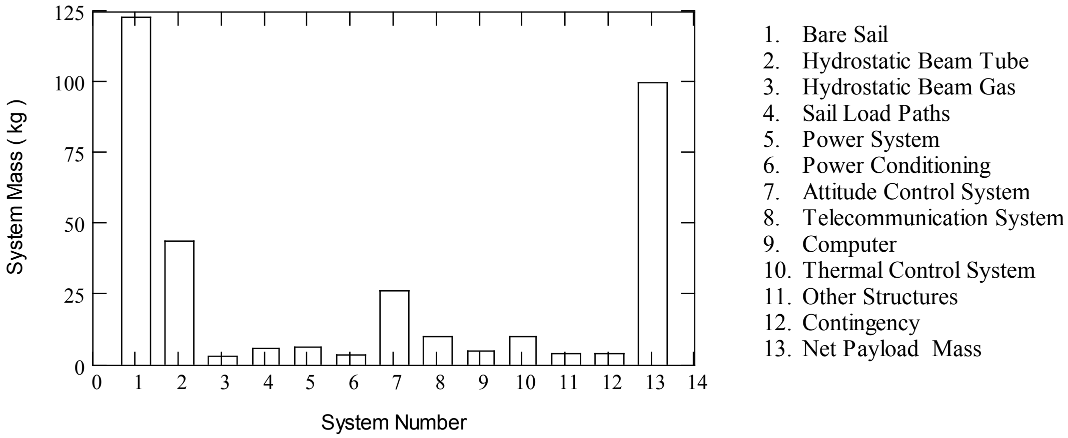

FIGURE 1. Sailcraft mass breakdown for the SGL mission.

H-REVERSAL FLIGHT TO SGL

One wants to reach the so-called galactic anti-center direction (Maccone, 1997), that has (approximate) Ecliptic Longitude = 86.83^{O}, Latitude = 5.537^{O}, with a minimum operational distance of 550 AU. These three numbers represent the current SGL-target. The flight design we are going to discuss is the solution to the following problem:

" *Given* the above sailcraft, find the three-dimensional **L**'s history that minimizes the flight time to the SGL-target by using Sun fly-by *only* with the sail peak temperature not exceeding 60 percent of the aluminum melting point ".

The temperature constraint preserves the mechanical properties of the aluminum film and determines a lower limit on the reachable perihelion. We have used non-linear programming, in particular two versions of the Levenberg-Marquardt method, for minimizing the (Euclidean) norm of a penalty vector function. We shall show *nominal* time behaviors of meaningful quantities zoomed on the intervals where they vary appreciably. Outside, quantities are either constant or asymptotically flat. Figure 2 shows the time behavior of sail azimuth and elevation in EHOF. The duration of the thrusting arcs (t_1-t_0, t_2-t_1, t_3-t_2, t_4-t_3) is optimized according to the theory (Vulpetti, 1999a). Table 1 reports the complete optimal control and other meaningful flight information. How the above control affects the vector **L** is shown in Fig. 3. Note that at t_3 an attitude maneuver is performed such that $\lambda_r > 1$. That, induced by a

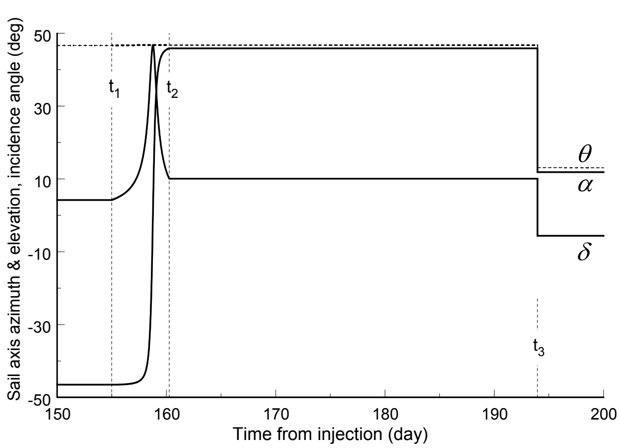

FIGURE 2. History of the direct control variables in the sailcraft orbital frame; also, the incidence angle (θ) behavior and trajectory arc time tags are shown.

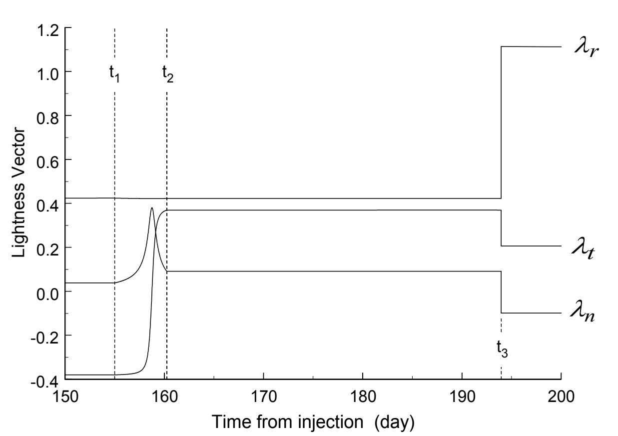

FIGURE 3. Profile of the lightness numbers, induced by the direct sail axis control, which minimize the flight time to the galactic anti-center direction in SGL.

sub-critical sail loading, causes a continuous increase of vehicle speed, thus avoiding a local maximum characterizing the *H*-reversal classes previously analyzed.

TABLE 1. Optimal control driving the initial state to the current SGL target by *H*-reversal mode (1 yr=365.25 d). Note that a control direction specified as constant in either frame is variable in the other one, thus producing the optimal history of Fig. 2. The initial sailcraft longitude has been optimized.

Arc	Reference frame	Duration	Sail azimuth	Sail elevation	Mode	Model of Sun
T1	EHOF	155.00 d	-46.50°	4.2299°	constant	point-like
T2	HIF (J2000)	5.2515 d	236.6055°	-7.2596°	constant, patched	point-like
T3	EHOF	33.7010 d	45.8728°	10.0913°	constant, patched	finite-size & limb-darkening.
T4	EHOF	21.300 yr	11.8516°	-5.5919°	constant	point-like
Mass [kg]	**X** [AU]	**Y** [AU]	**Z** [AU]	**VX** [AU / yr]	**VY** [AU / yr]	**VZ** [AU / yr]
344.4	-0.8704494	-0.4922579	0	3.1152469	-5.5086268	0
330.1	30.248	546.60	53.055	1.425	25.659	2.501
time to min-speed	**time to reversal,**	**time to perihelion**	**perihelion distance&speed**	**perihelion long. & latitude**	**cruise speed**	**flight time**
114.06 d	158.676 d	191.950 d	0.151 AU 22.04 AU/yr	194.61° -49.26°	25.82 AU/yr	21.831 yr

The above control generates the trajectory graphed in Fig. 4. Note that the sailcraft-to-Earth vector is always sufficiently distant from the Sun to allow safe communication. (The minimum of the Earth-sailcraft line-of-sight distance from the solar photosphere is 14.4 solar radii, 50.7 days past the sailcraft perihelion). Along such a trajectory, the vector **H** evolves a way shown in Fig. 5. According to the theory, **H** does not vanish at the reversal

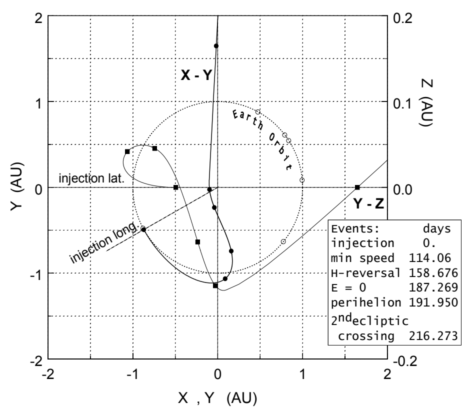

FIGURE 4. Zoomed projections of the sailcraft's 3D trajectory to the SGL target. Special events and the corresponding Earth positions are marked.

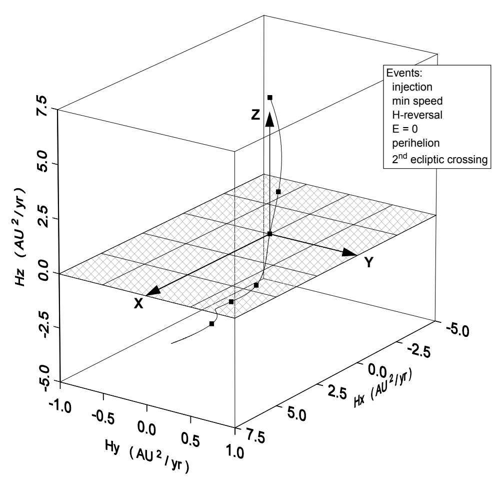

FIGURE 5. Hodograph of the orbital angular momentum in HIF. Flight begins with positive Hz. Special events are indicated.

point. Its magnitude is 313 times lower than the value at injection. Strong decrease is necessary to achieve the absolute maximum of energy. The stronger this reduction is the higher the cruise speed is achievable. Histories of the invariant and energy are shown in Fig. 6. Note the significant energy jump as a result of the optimal attitude maneuver (in intensity and time allocation). The overall effect of the *H*-reversal mode, a sub-critical sail loading and final attitude maneuver is displayed quantitatively in Fig. 7, in terms of Sun-sailcraft distance and speed. The shown information box is self-explaining; it adds to data reported in the last row of Table 1. This high cruise speed would allow the payload mission to extend from 550 AU over 200 AU (at least) in 7.75 years. Note that, strongly enhancing previous results, speed takes on a *square-root-like* profile; in other words, (not only energy but also) speed gets increased asymptotically. Such behavior can be considered the current dynamical output of the non-linear

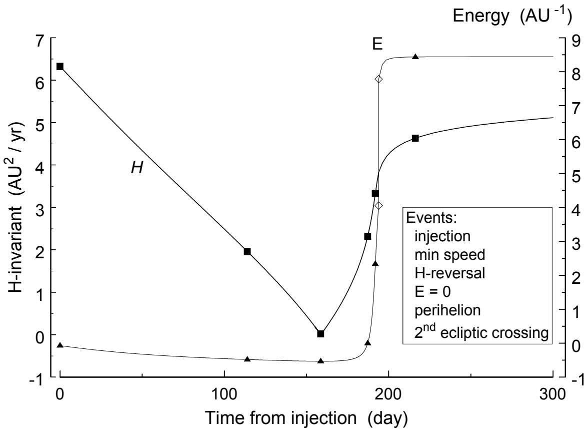

FIGURE 6. Time profiles of the sailcraft energy E and *H*-invariant with special events marked. Empty diamonds denote the E values before and after the optimal attitude maneuver.

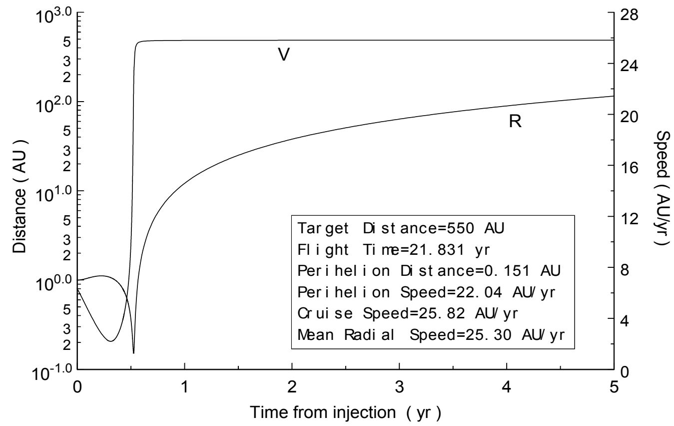

FIGURE 7. Histories of Sun-sailcraft distance and speed in HIF. Meaningful flight values have been reported in the information box.

range of solar sailing. It may foster studying other sail materials and sailcraft systems capable to lessen the sail loading still further, once experiments on sailcraft begin in space. What ultimately matters for a mission to a very far target is the mean radial speed of the spacecraft. In our case, it is very close to the cruise speed (Fig. 7); this means that the time to achieve the acceleration point is rather short (114 days from Tab. 1, instead of 4-5 years by using planetary fly-by techniques). With regard to launch window, preliminary results indicate that the present SGL-target has a launch window at least of 16 days (from 11^{th} to 27^{th} April) every year. This baseline flight profile can be widely "deformed" to balance the off-optimal Earth longitude. Flight-time charge varies from few weeks to 1.2 yr.

CONCLUSION

This paper shows that *current* or near-term technology and *advanced* solar-sailing astrodynamics should be able to accomplish a highly scientific mission to the solar gravitational lens with a flight time less than 22 years with no planetary/lunar launch windows. Its perihelion distance (0.15 AU) is affordable, whereas the cruise speed (near 26 AU/yr) is sufficiently high to allow a scientific payload to get data for 8 years or, equivalently, up to 750 AU. Mission window spans 16 days every year.

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