Mission Options for NASA's Interstellar Probe

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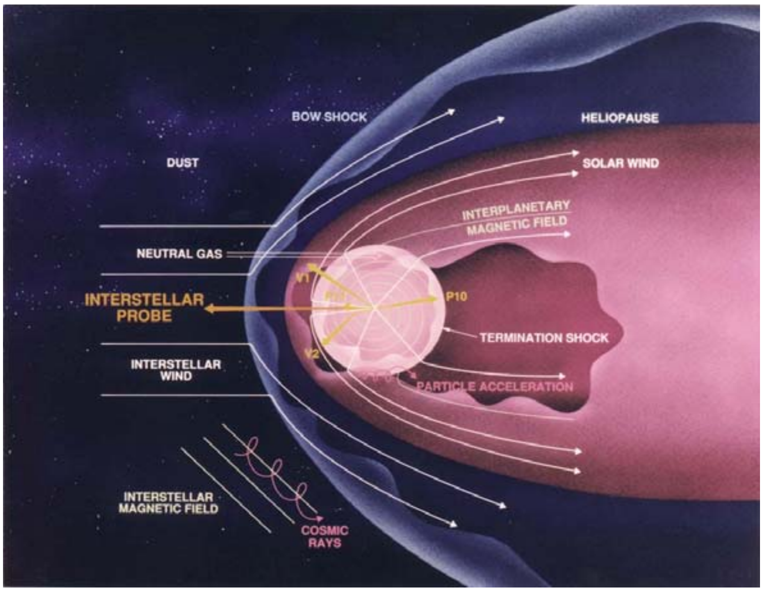
The present document represents a short abstract of the Chapter IV of NASA Contractor Report entitled: *The Interstellar Probe (ISP): Pre-Perihelion Trajectories and Application to Holography*, under NASA Contract H-29712D (continuation). Dr. Gregory L. Matloff led the related work in the time frame between February and September 2001. Dr. Giovanni Vulpetti developed Chapter IV from June 4 to September 21, 2001 by using his own solar-sail propulsion mission optimization computer code. He acted as NASA consultant at the Space Transportation Directorate of NASA George C. Marshall Space Flight Center (MSFC) in Huntsville, AL 35812. Dr. Les Johnson from MSFC was the team leader of this NASA contract. Chapter IV regards the computation of optimized trajectories and is entitled "*Sailcraft Trajectory Options for the Interstellar Probe: Mathematical Theory and Numerical Results*". Such work shall hereafter be called the ISP/STO, for short.

Content

The potential near-term exploration of the Kuiper belt, termination shock, heliopause and near interstellar medium will be among the main purposes of a joint COSPAR - IAF /IAA symposium (D1.2) at the 2nd World Space Congress to be held in Houston, Texas, October 2002.



(JPL Interstellar Probe)

1. Introduction

NASA Interstellar Probe (ISP) is an advanced concept of mission aimed at sending a spacecraft to the entrance direction of the interstellar wind as observed in the solar system. This direction is that of the so-called "heliopause nose". Very good introductions to the heliosphere and interstellar medium can be found at the following websites:

- http://web.mit.edu/space/www/helio.review/axford.suess.html
- http://interstellar.jpl.nasa.gov. This address contains the ISP spacecraft basic and mission rationale (November 2000).

ISP baseline mission includes the achievement of 200 AU ($1\ \mathrm{AU} = 149.59787\ 10^6\ km$) in 15 years (order of magnitude), whereas the extended mission, if any, should double this distance. Many propulsion systems have been considered for getting a high cruise speed compliant with mission and flight objectives. Among the best candidates, solar sail propulsion has been well analyzed and represents a very promising option. As mentioned above, ISP/STO refers to a work on sailcraft trajectory options & mission aspects for ISP as suggested to NASA Marshall Space Flight Center (September 2001).

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2. Mathematical Approach

References [1,2] describe what is the ISP mission as currently conceived by Jet Propulsion Laboratory, including preliminary design of sailcraft systems. The reader is invited to be aware of a short summary given at

http://www.lmsal.com/sec/Roadmap/AppendixA/isp.html.

The mission profile and the related trajectory baseline reflect a progress in solar sail dynamics occurred in the Nineties whereupon a sufficiently light sail-based spacecraft, or a sailcraft, could leave the solar system with a cruise speed higher than that by any other near-term propulsion system, including the nuclear-electric propulsion, provided that (i) the sailcraft decelerates once outside the Earth-Moon system, (ii) a fly-by sufficiently close to the Sun is performed, (iii) the total sailcraft mass on sail area ratio is no more than 2 g/m^2. This important parameter is usually named *the sailcraft sail loading* (σ). No planetary gravity-assist maneuvers are required. This allows the sailcraft launch to be independent of planets other than the Earth. One can found appropriate information on such aspects in [3-5].

ISP/STO is based on the mathematical theory developed in [3,4,6,7], based on the lightness vector (**L**) formalism, first introduced in 1996. **Section-2** of ISP/STO presents a background on fast solar sailing and considerations about modeling the translational motion of a sail in space. In addition to the full generality of the **L** formalism (that is able to describe all sailcraft trajectory classes in terms of the **L**'s components), one of the main outcomes from using such formalism was the discovery that there exist trajectory families of high speed characterized by the reversal of the spacecraft's orbital angular momentum (**H**).

In a nutshell, once the sailcraft "enters" the solar gravitational field, it is controlled to strongly decelerate until its motion is reversed from the usual counterclockwise mode to the clockwise one (with respect to the Sun); then, the sailcraft begins a sufficiently long flyby where it accelerates continuously. When it achieves the perihelion, orbital energy is high positive. Depending on $\mathbf{L}(\sigma)$, energy and speed can both increase asymptotically as the sailcraft recedes from the Sun, otherwise energy increases and speed passes through a local maximum. In any case, cruise speed is considerably higher than the departure-planet orbital speed about the Sun. Vehicle speed amplification could generally result in cruise speed ranging from 11 to 26 AU/yr[1] ($1\ \mathrm{AU/yr} \cong 4.74\ \mathrm{km/s}$) [3,8] with realistic values of σ and perihelion distance.

In the case of ISP, motion reversal entails that there is a second annual Sun flyby delivering the sailcraft to the heliopause target direction and satisfying mission requirements.

There are many effects to be taken into account in the so-called the *connection equations* (CEs), that is the model of the actual physical interaction between the solar photons and the sail material & configuration. Moreover, the set of CEs contains geometrical/physical features of the source(s) of light and the environment influence. **Section-3** of ISP/STO details CE and what are the principal effects to model. CEs are algebraic equations inasmuch as their main entries, the sail thermo-optical parameters, are not modeled as time-varying quantities, even though they depend on a number of other variables. The problem of relating the optical sail parameters entering the motion equations (as controls) to the classical optical parameters, which can be

[1] For comparison, the mean Earth orbital speed takes on about 6.283 AU/yr.

measured via the Optics techniques, was dealt with in [7]. Equations of sailcraft motion result in ordinary differential equations. However, **Section-4** of ISP/STO addresses the problem of the change of the sail optical parameters due to the bombardment by solar ultraviolet photons and solar wind particles. This has been done from the viewpoint of the impact onto the whole sailcraft trajectory. To such an aim, a sufficiently general optical-degradation model, starting from experimental data, has been set up. Due to the lacking of reliable *sail-oriented* experimental data about ultraviolet bombardment, only the solar wind contribution (via experiment) was taken into account. Nevertheless, the result has been impressive: the realistic sailcraft motion in the solar system is governed by *integro-differential* equations, which enhance the nonlinear-dynamics aspects of a <u>fast</u> sailcraft. It was necessary to modify the numerical code considerably for optimizing a sailcraft trajectory in the presence of non-negligible degradation of the reflective layer in the sail system.

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3. Computer Code

The computer code used to find new trajectories and optimize them for the ISP case is detailed in **Section-5** of ISP/STO. Such code is named Starship/Spaceship Mission Analysis Code (SMAC). The author has implemented SMAC on PC in the 1986-2001 timeframe. Very briefly, SMAC has been designed and is maintained for computing spacecraft trajectories related to propulsion modes such as solar sailing, nuclear/solar electric propulsion, laser/microwave sailing, plasma-driven sailing (and very advanced concepts such as antimatter propulsion and space ramjet). User can perform trajectory computation in either classical or (full) relativistic dynamics. SMAC is now in full Fortran-90/95 and currently runs under MS-Windows 98-SE. User graphic interface (GUI) has been designed in MS-Visual Basic 5. SMAC includes a true 3D-graphic module for quick output visualization. Current SMAC version (A.45.93a) consists of about 24,600 lines. Employed compiler is a commercial highly optimized compiler for Pentium-III. All computations are performed in double precision.

Solar-sail mode is one of the most detailed propulsion modes in SMAC. The whole of the solar sailing theory described in the previous sections comes from as the special case of a more general solar-sailing model embedded in a set of Fortran modules and procedures; these ones are designed to grow with the user needs.

The user can use SMAC in either propagation-mode or optimization-mode. High-precision numeric integrators are able to deal with ordinary differential equations and integro-differential equations. Trajectories can be optimized in the Non-Linear Programming sense, with linear/non-linear equality and inequality constraints. SMAC knows two robust optimization algorithms: the Marquardt method revised by Levenberg-Marquardt-Morrison (or the LMM algorithm), the Levenberg-Marquardt method improved by Moré (Argonne Lab., 1980) or the LME algorithm.

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4. Numerical Results on ISP Trajectory Optimization

Interstellar Probe mission opportunities involving sailcraft motion reversal have been studied. They might be added to the mission profiles already analyzed by JPL (Liewer, Mewaldt, 2000). The author has dealt with trajectories from sailcraft injection into the solar gravitational field to the target distance of 200 AU in the heliopause nose direction. **Section-6** of ISP/STO contains the problem statement and the discussion of results plotted in 84 Figures. **Section 7** reports a summary table with the optimized mission features case by case. The index of performance, here, is the sailcraft speed at 200 AU.

In addition to the time elapsed since sail deployment, the lightness vector depends generally on variables and parameters of different physical origin that one may group as follows:

a. Source-of-light parameters

b. Physical/geometrical sail parameters

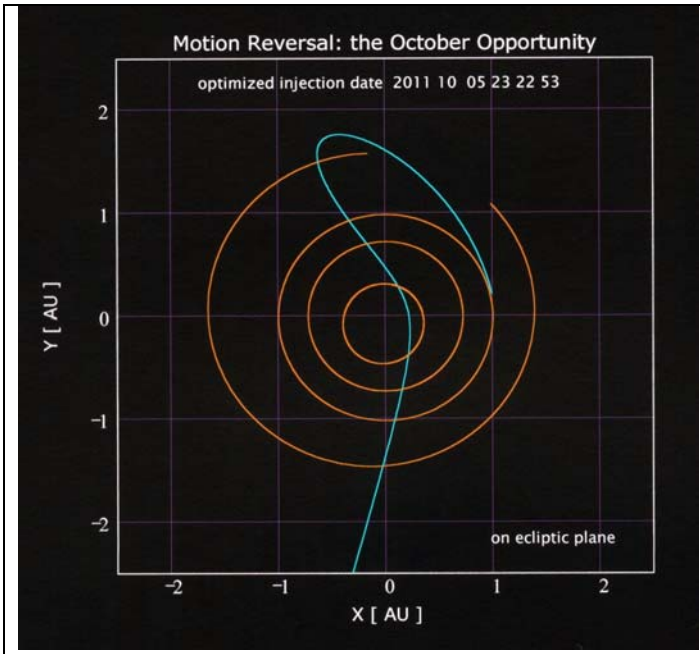
c. Sailcraft state variables (mass, position, velocity)

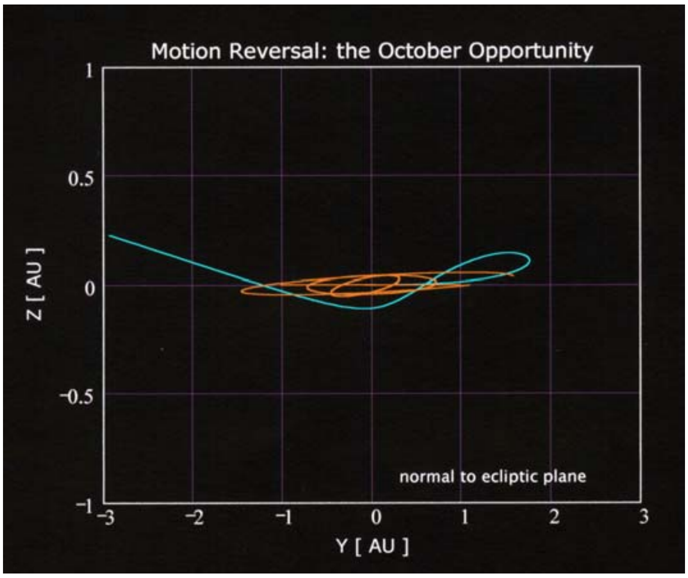
d. Environmental parameters.

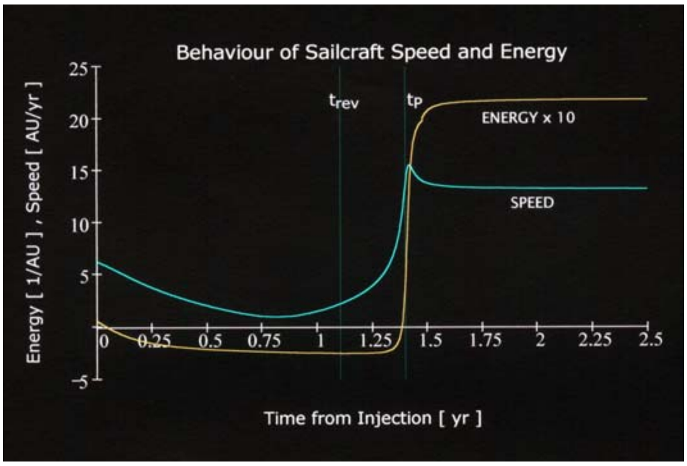
When (d)-set is not considered, one is in *ideal-optics* conditions, namely, the thermo-optical parameters are not time-dependent, even though they change along a trajectory because, for instance, photon incidence changes with the sail attitude. In contrast, optical degradation increases the absorption and reduces reflectance progressively as time goes by; it depends strongly on the trajectory profile. Modeling a high number of effects is required for accurate calculation of a fast sailcraft trajectory, even if one assumes ideal optics.

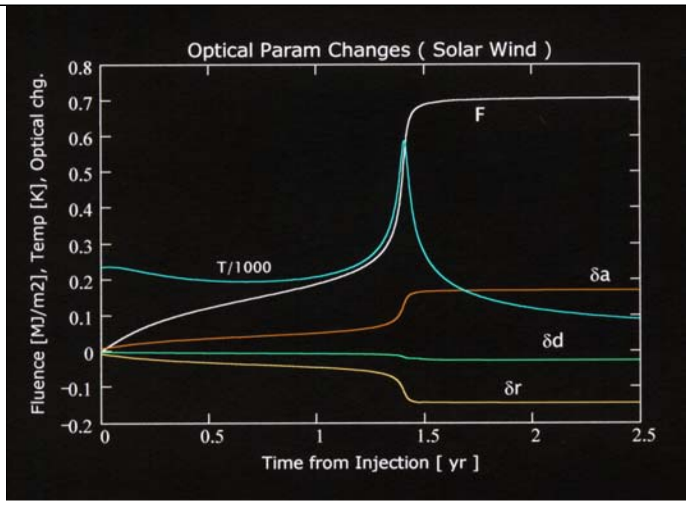
Aspects of the ISP mission concept through different values of the sailcraft sail loading have been analyzed. For each value of σ, typically there is discussed one (optimized) trajectory opportunity with ideal sail optics and, then, the corresponding opportunity with optical sail degradation. Optimized-trajectory sets for σ ranging from 2.2 to 1 g/m^2 have been considered. For the case $\sigma = 2\ \mathrm{g/m^2}$ (very close to the JPL-conceived spacecraft), more than one ideal-optics profiles are presented.

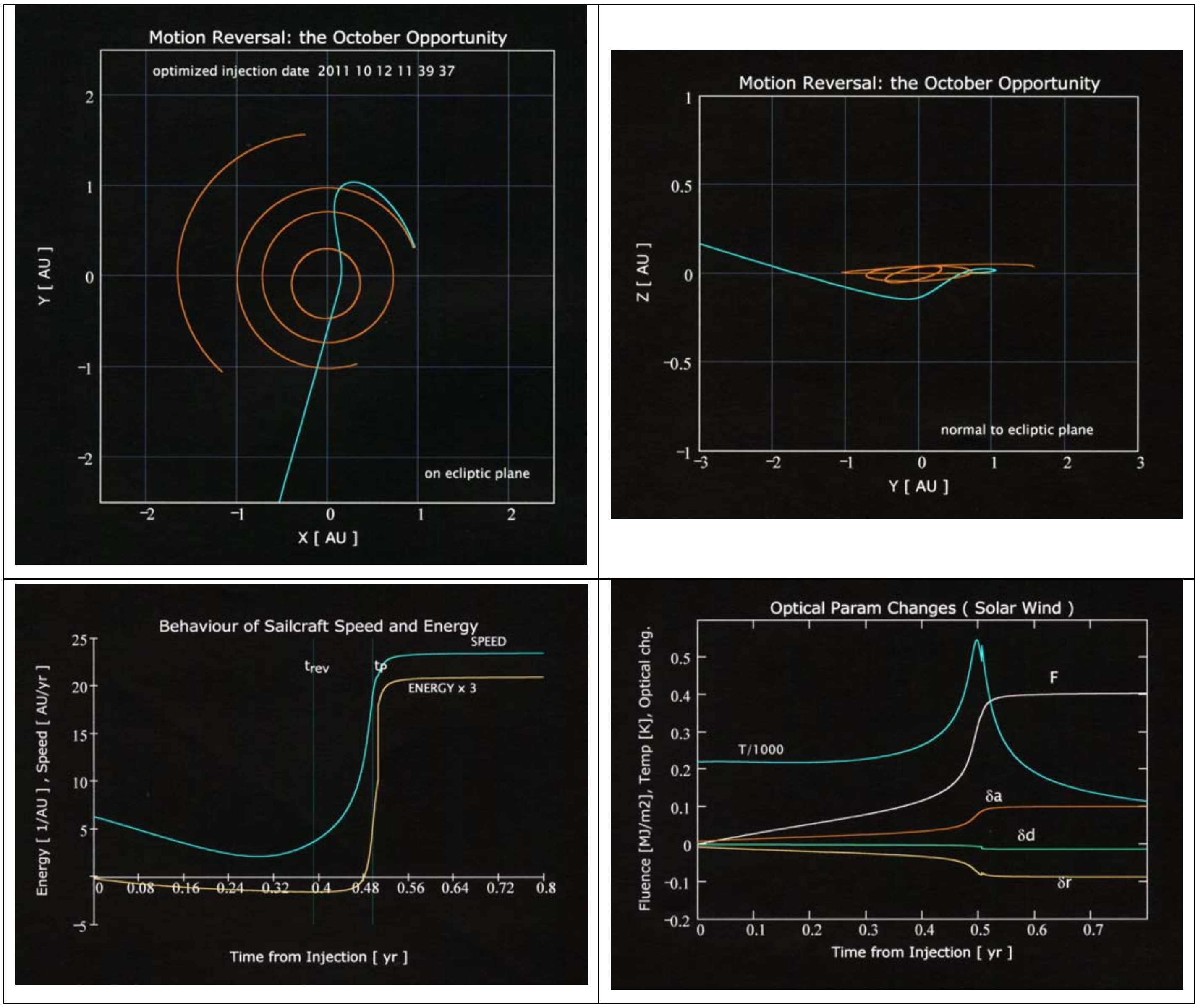
The complete analysis described in the NASA report is rather wide. Here, we want to report a few Figures to show the (unusual) profile of trajectory that would allow a sailcraft to travel realistically fast to very distant targets such as those of the ISP mission concept. Below one can find some of the Figures related to the cases of 2 g/m^2 and 1 g/m^2, respectively.











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5. Conclusions

Here are some of the considerations made in Sections 8-9 of the NASA report. Table shown in Section-7 is the basic overview of the ISP/STO results. Many other significant items are discussed in the mentioned report; reporting them here would be too long and, maybe, not sufficient clear without the theory presented in Sections 2-3-4.

"Interstellar Probe is not only a sophisticated scientific mission concept; among the main things, it should prove that it is possible to travel fast to distant targets with low cost and high reliability. These features generally depend on sailcraft operations, no additional propulsion (apart from lifting off, of course), strong increase of the launch window, higher number of missions per time unit (e.g. on a quinquennium basis) and so forth. The existence of an additional launch opportunity – *in October of every year* – for the ISP mission concept should be of high concern. This could be accomplished by utilizing one of the several peculiarities of space sailing: the fly-by of the Sun via motion reversal. A spectrum of fourteen optimized mission profiles have been computed by a code that takes into account a high number of real effects. Distinct trajectories correspond to different key parameters such as the sailcraft sail loading, sail roughness and optical sail degradation due to solar wind. (Ultraviolet-photon degradation was not considered by lack of experimental data appropriate to solar sailing). Solar wind fluence has been recognized relevant to a sailcraft approaching the Sun closely. A major item has consisted of dealing with integro-differential equations for modeling sailcraft motion appropriately. Optical degradation, with constraints on temperature, perihelion and flight time, has resulted in a key item for designing some fast sailcraft trajectory to many hundreds of AU. By considering both baseline and extended mission concepts, ISP is certainly feasible from *motion-reversal* trajectory viewpoint *if* the sailcraft sail loading is lower than 2.1 g/m². The current literature value of the ISP-sailcraft sail loading is very close to 2 g/m². This is a value sufficiently lower than the above threshold to allow the following time line (epoch=*injection into the solar field*): (1) launching in October, (2) flying-by the Sun at 0.24 AU after 1.40 years, (3) achieving 200 AU after 16.6 years, (4) extending the mission to 400 AU with a total flight time of 31.8 years. (A slightly lower value of the sailcraft sail loading in the range [1.9, 1.95] g/m² is suggested to balance some attitude control errors). Could one build a sailcraft with $\sigma = 1\,\mathrm{g/m^2}$ (not too low by considering the evolution of new materials), the ISP nominal mission to 200 AU would be carried out in 9.0 yr, whereas the extended mission would be completed in 17.6 yr (perihelion distance = 0.20 AU).

These ones and the other numerical results should be considered *realistic* enough due to the many key elements and detailed features included in the used dynamical model of sailcraft motion."

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6. References

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