Optimal Trajectories for Solar Bow Shock Mission

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Abstract—This paper deals a Solar Bow Shock mission, a phenomenon of interaction between the solar wind and the interstellar medium, due to the relative motion of our star with respect to the enormous interstellar matter cloud that contains it. This phenomenon occurs at boundary of the solar system (200 AU), and it is preferable a mission in situ that could examine in detail what actually happens on-the-spot, to understand its effect on the planets of the solar system. *Voyager 1 & 2* reached the area where the phenomenon takes place after 30 years. The target is to arrive there optimizing both the transfer time, and the propellant mass consumption. Therefore, the trajectory will be optimized using different propulsion systems and appropriate flyby sequences. The approach techniques that will be used foresee executions of impulsive or ballistic gravity assists with the utilisation of high thrust engine only, or low thrust engine only, or both engines in two different phases of the mission. By comparing all the solutions obtained imposing different initial conditions the optimal trajectory to arrive at Solar Bow Shock is presented.

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1. INTRODUCTION

The area typically known as Termination Shock is where a slowing down of the solar wind occurs, due to interstellar matter; the area known as Bow Shock is where a slowing down of interstellar matter occurs, due to the solar wind. The area where the two effects counterbalance each other is called Heliopause (see Fig. 1) [1]. Termination Shock, Heliopause and Bow Shock are three parts of a unique and complex physical phenomenon. We generally refer to this interaction with Solar Bow Shock (SBS), because of the analogies with the planetary Bow Shock. The interest for the SBS was born in 2005, when *Voyager 1* began to penetrate the boundary of our solar system (at about 200 AU from the Sun) [2, 3]. Data transmitted by the probe inspired further studies, including those made by *Cassini*, which has carried out, during its principal mission, important surveys regarding the Heliosphere [4], and *IBEX*, a NASA mission with the aim of mapping the outer solar system, including the SBS [5].

The principal scientific targets of a study of the SBS are [6, 7]: studying the nature of interstellar medium and its implications regarding the origin of matter and its evolution in our galaxy and universe; studying the influence of interstellar medium on the solar system; studying the impact of the solar system on the interstellar medium as an example of the interaction between a solar system and the environment that surrounds it; studying the outer solar system, in order to understand better its origins and to study the nature of outer planets and trans-neptunian objects.

The definition of an arrival point is given by the results of the *IBEX* probe [8]. This mission had the aim to find the direction of the relative motion between the solar system and the local cloud. This information was found thanks to the trajectories of ENAs (Energetic Neutral Atoms) coming from interstellar space. Since these particles aren’t influenced by the phenomenon of the SBS, they arrive on the Earth approximately with the same trajectory they had when entering the solar system. Therefore, the detection of these particles gives an index of the direction of relative motion between the solar system and the local cloud, defining a stagnation point of the phenomenon, that is the point where the SBS has its maximum intensity due to the frontal encounter between the solar wind and interstellar matter. Between these particles, *IBEX* probe uses only helium atoms, because the hydrogen is ionized by the solar wind before arriving near to Earth, getting carried by the magnetic solar field towards the outer solar system. The target of the mission will be the area of the Bow Shock because it is the outer of the three areas: leaving from the Earth, arriving on it means to cross the Termination Shock and the Heliopause, having the possibility of studying the whole phenomenon. Recent studies have demonstrated how different kind of mission can be performed by using advanced propulsive systems [9–13]. Using solar sails with a characteristic acceleration of $1.5 \text{ mm/s}^2$ it is possible to reach the target in about 25 years [14–16]. Using electric sails with characteristic acceleration of $1.15–1.25 \text{ mm/s}^2$, it is possible to reach the destination in 19.6 years. In order to obtain this value of characteristic acceleration, we should have cables of the

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1 The article is published in the original.
The length of 2500 km [17, 18]. The deployment and maintenance in position of these cables could be problematic for a probe which must cross the whole solar system. During the planning phase of the HERMES probe (HEliosphere Research Mission Escaping the Solar system), it was assumed to use electric sails, and these performances were confirmed. If the target of the mission is extended up to the SBS, the flight time will be around 20 years [19].

In this paper we will search a solution that allows a probe to reach a distance of 200 AU, with a flight time lower than the 25 years expected with the solar sails, by using chemical and electric engines, and appropriate gravity assists. Centering the reference frame on the Sun, the stagnation point is defined in polar coordinates as [8]:

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\begin{align*}
    r &= 200 \text{ AU}, \\
    \lambda &= 75.4^\circ, \\
    \mu &= -7.5^\circ,
\end{align*}
\]

where \( r \) is the radial distance from the Sun, \( \lambda \) is the longitude counter-clockwise measured by the line connecting the Sun and the vernal point, and \( \mu \) is the latitude measured on the ecliptic plane.

2. MISSION ANALYSIS

Because of the high number of variables the optimization is not based on patented software which provide a global optimization, but it is based on an initial selection over the structure mission (see section 2.1). The optimal trajectory strongly depends on the following initial constraints:

—Time constraints: date of launch included between 2015/01/01 and 2025/12/31; duration of mission not longer than 25 years.

—Propulsion constraints: specific impulse of chemical engine 300 s; specific impulse of electric engine 3000 s.

—Mass constraints: probe’s total mass 1000 kg; probe’s dry mass 200 kg.

—Launch constraints: maximum impulse of velocity obtainable from the launcher: 15 km/s (value obtainable with Ariane 5 and Atlas V launchers) [20, 21].

In Fig. 2 there is a summarizing scheme of the trajectory optimization algorithm. The program takes as inputs the departure planet (the Earth), a flyby sequence, the mission constraints (time constraints, propulsion constraints, mass constraints and launch constraints) and the coordinates of the arrival point (the stagnation point of SBS); it uses the JPL/DE405 ephemeris generator to calculate the position of celest-