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Minimum Time Planetary Rendezvous with an Electric Sail

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Abstract

Electric sail based missions towards Mercury, Venus, and Mars are discussed. The analysis takes into account both the real three-dimensional shape of the starting and arrival orbits and the ephemeris constraints. Each mission is parameterized with different values of the sailcraft characteristic acceleration.

1. Introduction

Similar to a solar sail, an electric sail is capable of generating a propelling thrust without the need of any propellant. Unlike a solar sail, which is accelerated by momentum transfer from photons emitted by the Sun that strike the sail, an electric sail exploits the interaction between the flux of charged particles from the Sun (the solar wind) with an artificial electric field, created around the spacecraft through long charged tethers [1].

From a trajectory analysis standpoint, an e-sail (that is, a spacecraft whose thrust is produced by an electric sail) can be thought of as equivalent to a constant mass system, capable of generating a propelling thrust whose magnitude varies with the distance r from the Sun as $1/r^n$. The value of n is usually set equal to $7/6$, even if recent plasma dynamics simulations have shown that n is close to unity [2]. The sail performance is typically characterized through the value of the characteristic acceleration $a_\oplus$, that is, the maximum propelling thrust at $r = 1\,\mathrm{AU}$ [3]. Taking into account that for a solar sail the thrust varies with $n = 2$, for a given characteristic acceleration an e-sail provides a maximum propelling thrust greater (smaller) than a solar sail for solar distances greater (smaller) than $1\,\mathrm{AU}$. Moreover, a second important difference between an e-sail and a solar sail for the trajectory analysis is constituted by the allowable thrust direction. In fact, if $\hat{\boldsymbol{a}}$ and $\hat{\boldsymbol{r}}$ are the unit vectors of thrust and distance, respectively, a solar sail is capable of orienting the thrust in the half-space $\hat{\boldsymbol{a}} \cdot \hat{\boldsymbol{r}} > 0$, while the thrust for an e-sail is restricted by a constraint in the form $\hat{\boldsymbol{a}} \cdot \hat{\boldsymbol{r}} \le \cos\alpha_{\max}$, where α is the cone angle and $\alpha_{\max} \simeq 35\,\mathrm{deg}$. The upper value of $\alpha_{\max}$ affects substantially the e-sail performance.

In the last few years several studies concerning the analysis of optimal trajectories for an e-sail have been conducted by the authors. In particular, using an indirect approach, minimum time trajectories have been investigated in different mission scenarios, such as an interplanetary transfer [3], an asteroid rendezvous [4] and a Solar System escape [5]. In this paper we discuss the preliminary results regarding the e-sail performance for missions towards an inner planet (Mercury, Venus, and Mars). The analysis aims at quantifying the minimum flight time and the better launch windows to transfer an e-sail from one planet to another. In particular, both the minimum required performance and the corresponding launch date will be calculated to accomplish a tour of the planets with a possible Earth return of the probe. Such an analysis is performed by taking into account the actual three-dimensional shape of the planetary orbits and the ephemeris constraints. In addition, each mission is parameterized by varying the e-sail characteristic acceleration to generate a wide mission database. As a result, it is possible to quantify the impact of the e-sail configuration on the global mission performance.

2. Minimum-time rendezvous

The minimum flight times necessary to reach Mercury, Venus, and Mars (starting from an Earth's heliocentric orbit) are now summarized. The results correspond to an optimal orbit-to-orbit rendezvous (with zero hyperbolic excess energy at both departure and arrival) in which the true three dimensionality of the planetary orbits is taken into account, see Table 1, but without any ephemeris constraint. In other terms, the optimization process selects the best starting and arrival points on the two orbits in such a way that the total flight time is minimized. The simulation results have been summarized in Fig. 1 that, for each mission scenario, shows two curves. The continuous line corresponds to the minimum flight time, that is, the best true anomaly on the Earth's starting orbit. The dotted line, instead, corresponds to the worst starting position. In this context,

	Mercury	Venus	Earth	Mars
a [AU]	0.38709	0.72333	0.99953	0.15237
$e \times 10^3$	205.6	6.8096	17.246	93.3062
i [deg]	7.0043	3.3944	2.0639×10^{-3}	1.8488
ω [deg]	29.1531	54.9191	354.1466	286.5823
Ω [deg]	48.3175	76.6505	108.9205	49.5244

Table 1: Inner planets osculating orbital elements at June 1st 2010 (JPL DE-406/LE-406 ephemeris model).

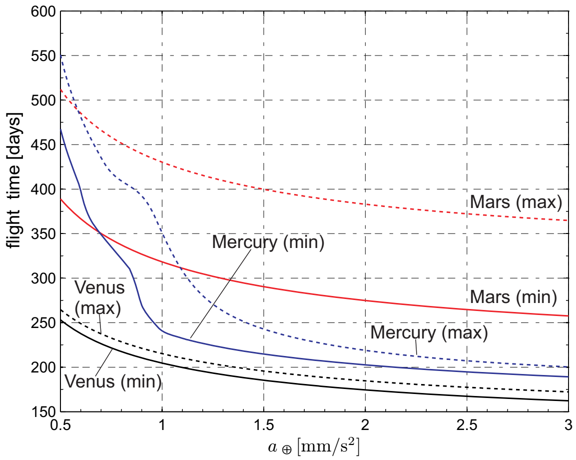

Figure 1: Orbit-to-orbit minimum flight time.

Fig. 1 represents the e-sail counterpart of an analogous picture obtained by Sauer for a solar sail [6]. Note that the corresponding flight time, which takes into account the true ephemeris constraint, might be (and, in general, is) much greater than the value shown on the continuous line. Accordingly, the information from Fig. 1 guarantees an approximation by defect of the flight times necessary to accomplish an interplanetary rendezvous. The dimensionless flight time variation (for $a_\oplus = 1\,\mathrm{mm/s^2}$) is shown in Fig. 2 as a function of the starting true anomaly. The considerable eccentricity of Mercury's orbit causes a flight time variation of about 45%.

3. Conclusions

Electric sail based missions towards Mercury, Venus, and Mars have been investigated. The analysis takes into account both the real three-dimensional shape of the starting and arrival orbits and the ephemeris constraints. Each mission is parameterized with different values of the sailcraft characteristic acceleration. The obtained results show interesting similarities with the same missions previously studied for solar sails.

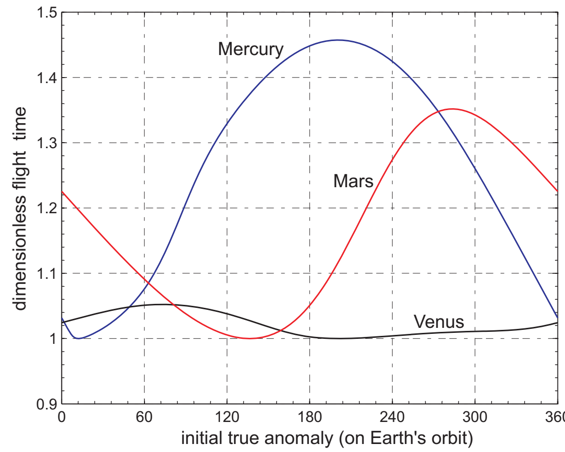

Figure 2: Dimensionless ($t/t_{\min}$) flight time as a function of the starting true anomaly ($a_\oplus = 1\,\mathrm{m/s^2}$).

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References

[1] Janhunen, P. and Sandroos, A., "Simulation Study of Solar Wind Push on a Charged Wire: Basis of Solar Wind Electric Sail Propulsion," *Annales Geophysicae*, Vol. 25, No. 3, 2007, pp. 755–767.

[2] Janhunen, P., "Increased electric sail thrust through removal of trapped shielding electrons by orbit chaotisation due to spacecraft body," *Annales Geophysicae*, Vol. 27, No. 8, 2009, pp. 3089–3100.

[3] Mengali, G., Quarta, A. A., and Janhunen, P., "Electric Sail Performance Analysis," *Journal of Spacecraft and Rockets*, Vol. 45, No. 1, January–February 2008, pp. 122–129. doi: 10.2514/1.31769.

[4] Quarta, A. A. and Mengali, G., "Electric Sail Missions to Potentially Hazardous Asteroids," *Acta Astronautica*, Vol. 66, No. 9-10, May-June 2010, pp. 1506–1519. doi: 10.1016/j.actaastro.2009.11.021.

[5] Quarta, A. A. and Mengali, G., "Electric Sail Mission Analysis for Outer Solar System Exploration," *Journal of Guidance, Control, and Dynamics*, Vol. 33, No. 3, May-June 2010, pp. 740–755. doi: 10.2514/1.47006.

[6] Sauer, Jr, C. G., "Optimum Solar-Sail Interplanetary Trajectories," *AIAA/AAS Astrodynamics Conference*, AIAA Paper 76–792, San Diego, CA, August 18–20 1976.