# A SISTEMATIC STUDY ABOUT SUN PERTURBATIONS ON LOW ENERGY EARTH-TO-MOON TRANSFERS

**Sandro da Silva Fernandes**(1) **and Cleverson Maranhão Porto Marinho**(2)
(1) (2) *Instituto Tecnológico de Aeronáutica, São José dos Campos – 12228-900 – SP – Brazil, (+55)(12)3947-5953,sandro@ita.br,cmarinho@ita.br*

***Keywords:*** *bicircular problem, low energy transfers, optimal trajectories, three-body problem*

## ABSTRACT

In the last decades, new types of Earth-to-Moon transfers have been designed and used in lunar missions which could not be possible using traditional approaches (Belbruno, 2004; Koon et al, 2007). New methods make use of the nonlinear dynamics of the circular restricted three-body problem and the bi-circular restricted four-body problem to design low energy transfers.

Low energy Earth-Moon transfers can be classified into exterior or interior, according to the geometry (Topputo, 2013). In the exterior transfers the spacecraft is injected into an orbit with large apogee which crosses the Moon orbit. The apogee distance is approximately four times the Earth-Moon distance. This kind of trajectories exploits the Sun's gravitational attraction (Yamakawa et al, 1992, 1993). In the interior transfers most part of the trajectory occurs within the Moon orbit.

In this work, a systematic analysis about the perturbation of the Sun on the problem of transferring a space vehicle from a circular low Earth orbit (LEO) to a circular low Moon orbit (LMO) with minimum fuel consumption is presented considering only interior transfers. It is assumed that the velocity changes are instantaneous, that is, the propulsion system is capable of delivering impulses. Two-impulse trajectories are considered in the analysis: a first accelerating velocity impulse ($\Delta v_{LEO}$) tangential to the space vehicle velocity relative to Earth is applied at a circular low Earth orbit and a second braking velocity impulse ($\Delta v_{LMO}$) tangential to the space vehicle velocity relative to Moon is applied at a circular low Moon orbit (Miele and Mancuso, 2001). The minimization of fuel consumption is equivalent to the minimization of the total characteristic velocity which is defined by the arithmetic sum of velocity changes (Marec, 1979), that is, $\Delta v_T = \Delta v_{LEO} + \Delta v_{LMO}$. The optimization problem has been formulated using the classic planar circular restricted three-body problem (PCR3BP) and the planar bi-circular restricted four-body problem (PBR4BP). Numerical results are obtained for several final altitudes of a clockwise or counterclockwise circular low Moon orbit for a specified altitude of a counterclockwise circular low Earth orbit. Direct ascent trajectories, with time of flight of approximately 4.5 days, and multiple revolution trajectories with moderate time of flight (lesser than 60 days), are considered in this study. The initial position of the Sun $\theta_{S0}$ is taken as a parameter and the major parameters of the optimal trajectories – first and second delta-v, time of flight and initial position of the spacecraft – are calculated as function of $\theta_{S0}$. The results show that Sun perturbation effects are significant for trajectories with three or more revolutions; fuel consumption can vary significantly according the initial position of the Sun; swing-by maneuvers with the Moon are made in the trajectories with three or more revolutions, for the both dynamical models; the second delta-v is significantly affected by the presence of the Sun for trajectories

with three or more revolutions; and, for missions with multiple revolutions, fuel can be saved if a lunar swing-by occurs.

## REFERENCES


1. Belbruno, E. A., 2004. *Capture Dynamics and Chaotic Motions in Celestial Mechanics*, Princeton University Press, Princeton, N.J., USA.
2. Koon, W.S., Lo, M.W., Marsden, J.E. and Ross, S.D., 2007. *Dynamical Systems, the Three-Body Problem and Space Mission Design*, Springer.
3. Marec, J.P., 1979. *Optimal Space Trajectories*, Elsevier, New York.
4. Miele, A. and Mancuso, S., 2001, “Optimal Trajectories for Earth-Moon-Earth Flight”, *Acta Astronautica*, Vol 49, pp. 59-71.
5. Topputo, F., 2013, “On Optimal Two-Impulse Earth-Moon Transfers in a Four-Body Model”, *Celestial Mechanics and Dynamical Astronomy*, doi: 10.1007/s10569-013-9513-8.
6. Yamakawa, H., Kawaguchi, J., Ishii, N. and Matsuo, H., 1992, “A Numerical Study of Gravitational Capture in the Earth-Moon System”. In: Spaceflight Mechanics 1992, Proceedings of the 2nd AAS/AIAA Meeting, Colorado Springs, CO, pp. 1113-1132.
7. Yamakawa, H., Kawaguchi, J., Ishii, N. and Matsuo, H., 1993, “On Earth-Moon Transfer Trajectory with Gravitational Capture”, Advances Astronautical Sciences 85, pp. 397-397.