PRELIMINARY TRAJECTORY DESIGN FOR A SOLAR POLAR OBSERVATORY USING SEP AND MULTIPLE GRAVITY ASSISTS

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Abstract

Heliophysics has always been a subject of great relevance, with strong implications on many fields of study, including climatology, metereology, and spacecraft design. Due to the complexity of the subject matter, and relatively poor models of the Sun's activity and composition, heliophysics relies on continuous direct observations on the Sun.

Over the last 20 years there have been over 15 missions whose objective was to observe the Sun and its interaction with the Earth's environment. While they have all collected a wealth of information, in most cases these missions have operated in Earth orbit. Few exceptions include ESA's SOHO, at the Sun-Earth L_1 point, NASA's STEREO, operating in a 1 AU circular orbit, as well as other missions under development, such as ESA's SoIO and NASA's Solar Probe Plus, both planning to fly more ambitious orbits. In the case of the former, reaching a perihelion of 0.28 AU and inclination of 34 degrees with respect to the ecliptic, and of the latter, grazing the Sun's surface at 0.034 AU.

A spacecraft which deserves special mention is NASA's Ulysses: launched in 1990, it is the only satellite which managed to directly observe the Sun's poles. This severe lack of data with respect to the solar poles is in part explained by the extremely high energies needed to reach such orbits, requiring to drastically increase the inclination with respect to the Sun's equator. Ulysses could only achieve this by performing a gravity assist around Jupiter, allowing it to reach an inclination of more than 80 degrees; unfortunately this also implied its orbital period was extremely long, and therefore it only observed the poles three times (latest was in 2008) at which point the Radioisotope Thermoelectric Generator (RTG) power and hydrazine levels were too low for a fourth pass.

After more than twenty years since Ulysses launched, the Sun's poles still remain an extremely attractive, yet underachieved, goal. Flying a mission with a polar orbit combined with relatively low altitudes will allow for repeated and continuous observations not only of the poles, but of the entire star. Furthermore, recent developments in low-thrust technology, in particular Solar Electric

Propulsion (SEP), open up many new previously unexplored trajectory opportunities. The objective of this research is to expand existing studies in polar observatories [1, 2, 3], by taking advantage of both SEP and multiple gravity assists.

The low-thrust modeling is done using a direct method similar to Sims-Flanagan [4], as implemented in the Boulder Optimization of Low-Thrust Trajectories (BOLTT) [5, 6, 7]. The algorithm models the trajectory using multiple legs connected by planetary fly-bys, which in turn are computed using patched conics. On each of these legs, the trajectory is discretized into segments where a small impulsive ΔV maneuver is performed, thus approximating continuous low-thrust. The numerical optimization of this problem is performed using a Sparse Nonlinear OPTimizer (SNOPT) [8].

A limiting factor to BOLTT (and any other method using this optimizer) is that it remains a local tool, requiring proper initial guesses, especially in the case of many gravity assists. To this end, an initial guess tool based on the Gravity Assist Space Pruning method (GASP [9]) is utilized. This tool for space pruning looks at a series of gravity assists (assuming ballistic trajectories, with impulses applied only at a planet's periapse), and uses constraints on fly-by radius and required ΔV of the current flyby to restrict the possible dates of the next fly-by. This produces a cascade of "fly-by pork-chop plots" which allows to sequentially prune away unfeasible dates. Some modifications are made to the classic method, wherein the feasible "islands" are identified using a contour following algorithm, rather than computing the entire pork chop search space. Using GASP, proper bounds of feasible impulsive trajectories will be produced, which in turn will be fed into BOLTT, to optimize the SEP trajectory. The trajectories formulated with GASP will be verified using Copernicus v2.3 [10], a trajectory software suite initially developed at the University of Texas, and expanded at NASA.

This research offers many innovations, on many fronts. First and foremost, it furthers the field of heliophysics, by presenting potentially competitive trajectory alternatives for future solar observatories. It also showcases more uses of SEP and low-thrust, by applying it to cases with more gravity assists (some of which are expected to be resonant). On the theoretical side, it improves low-thrust modeling capabilities, by testing new methods of forming initial guesses, and seeing how the optimizer is able to deal with many gravity assists. Lastly, it presents the interesting problem wherein the objective of the optimization is not to reach a particular planet, but rather match heliocentric parameters, which not only are subject to mission design and optimization themselves, but which also conflict with other more traditional goals (such as minimizing propellant consumption).

1. References

[1] Herman, J. and Noomen, R. "Preliminary Mission Design for a Far-Side Solar Observatory using Low-Thrust Propulsion." Charleston, SC, Jan 29 - Feb 2, 2012. 22nd AAS/AIAA Space Flight Mechanics Meeting - AAS 12-210.

[2] Kawakatsu, Y. and Kawaguchi, J. "Trajectory Options for Solar Polar Region Observation Mission." Journal of Aerospace Engineering, Sciences and Applications, Vol. 4, No. 3, pp. 93–103, jul 2012.

[3] Janin, G. "Trajectory design for the Solar Orbiter mission." Jornadas de Trabajo en Mecnica Celeste, , No. 25, pp. 177–218, 2004.

[4] Sims, J., Finlayson, P., Rinderle, E., Vavrina, M., and Kowalkowski, T. "Implementation of a Low-Thrust Trajectory Optimization Algorithm for Preliminary Design." Vol. 3, pp. 1872–1881. Keystone, CO, August 21-24, 2006. Collection of Technical Papers - AIAA/AAS Astrodynamics Specialist Conference.

[5] De Smet, S., Parker, J., Herman, J., and Noomen, R. "Preliminary Design of a Crewed Mars Flyby Mission using Solar Electric Propulsion." Santa Fe, NM, January 26-30, 2014. 24th AAS/AIAA Space Flight Mechanics meeting - AAS 14-366.

[6] De Smet, S. Preliminary Design of a Crewed Mars Flyby Solar Electric Propulsion Mission. Master's thesis, Delft University of Technology, December 2014. Http://repository.tudelft.nl/view/ir/uuid

[7] De Smet, S., Parker, J., Herman, J., and Noomen, R. "Mission Design for a Crewed Earth-Venus-Mars-Flyby Mission using Solar Electric Propulsion." Breckenridge, CO, January 30 - February 4, 2015. 32nd annual AAS Guidance and Control Conference - AAS 15-091.

[8] Gill, P. "Users Guide for SNOPT Version 7: Software for Large-Scale Nonlinear Programming." Tech. rep., University of California, San Diego, 2008.

[9] Izzo, D., Becerra, V. M., Myatt, D., Nasuto, S. J., and Bishop, J. M. "Search space pruning and global optimisation of multiple gravity assist spacecraft trajectories." Journal of Global Optimization, Vol. 38, No. 2, pp. 283–296, 2007.

[10] Trajectory Optimization Group. "Copernicus: a generalized spacecraft trajectory design and optimization system." Tech. rep., Department of Aerospace Engineering and Engineering Mechanics, the University of Texas, Austin., 2010.