An Automated Search Procedure to Generate Optimal Low-Thrust Rendezvous Tours of the Sun-Jupiter Trojan Asteroids

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Keywords: *Trojan asteroid tour, optimal low-thrust, variable specific impulse, automated trajectory design, asteroid rendezvous*

ABSTRACT

Asteroids in the vicinity of the Sun-Jupiter equilateral equilibrium points, commonly termed “Greek” or “Trojan” asteroids, offer insight into the primordial composition of the solar system. Additionally, these asteroids are potential resources offering water, possible propellant materials, and other mineral resources for long-term human exploration of the solar system. An increasing number of studies examine transfers to Near Earth Objects and to the equilateral Lagrange points, but comparatively little investigation of transfers within the neighborhood of the L4 and L5 points is available. Because of the dynamical stability and comparatively low relative velocities near the equilateral libration points, low-thrust systems are particularly attractive for long-term missions in these regions. Low-thrust orbit transfers that are optimized in terms of propellant potentially offer years or even decades of mission lifetime while simultaneously ensuring a relatively large number of asteroid encounters. Conservation of propellant is also a critical objective for sample return missions from the vicinity of the Sun-Jupiter Lagrange points.

Given the potential of this relatively unexplored region of the solar system, this investigation considers the addition of the natural dynamics within the context of the circular restricted three-body problem (CR3BP) and a variable specific impulse (VSI) engine into a primer vector-based, optimal transfer and rendezvous strategy. Asteroid tours in higher-fidelity models are also constructed. A multiple shooting procedure with analytical gradients yields rapid solutions and generates a framework for an investigation into the trade space between flight time and propellant consumption. The primer vector, propellant-minimizing multiple shooting formulation, when combined with parameter optimization schemes, comprises an extremely useful hybrid optimization approach. This type of algorithm readily allows for the application of path constraints at node points along the thrust arc, where constraints are formulated to satisfy mission requirements or engine operation limitations. Thruster operation is easily scaled by spacecraft parameters such as initial mass and engine maximum power, simplifying preliminary analysis while retaining the ability to modify the spacecraft characteristics. Additionally, the results from the VSI engine simulations offer insight into the optimal placement of conventional impulsive maneuvers to seed other types of design options. The symmetry in the CR3BP ensures that solutions in the vicinity of the L4 point are easily translated to initiate investigation of the L5 region as well.

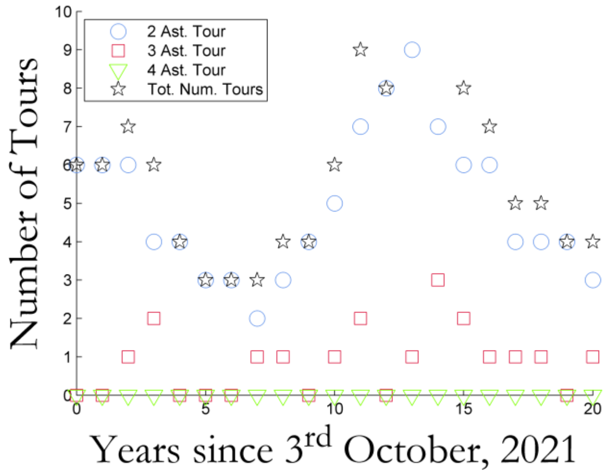

Figure 1: Tours originating at 1143 Odysseus, year-by-year, categorized by number of asteroids encountered

Rendezvous solutions are initially computed between quasi-periodic tracks representing the asteroid motion in the CR3BP, but the trajectories are readily transitioned to higher fidelity ephemeris models. Numerical simulations incorporate VSI engine operation and predict the propellant consumption and the thrust durations for a variety of independently generated rendezvous trajectories between pairs of asteroids. Subsequent combinations by an autonomous search algorithm of the pre-generated coast and thrust arcs offer potential trajectories with multiple asteroid encounters. The results of one such search appear in Fig. 1, where ten-year tours with the number of asteroids encounters are plotted over a twenty year window of initial insertion epochs into the L4 vicinity. The blue circles indicate the number of tours that visit two asteroids while the three asteroid tours are marked by the red square. Black stars reflect the total number of tours for a given initial epoch. A sample trajectory encountering the asteroids 1143 Odysseus, 4057 Demophon, and 1869 Philoctetes over the ten-year interval between 3rd October 2024 and 3rd October 2034 is plotted in Fig. 2. Arcs along the spacecraft trajectory when thrust is active are colored in gold while coast intervals, in the vicinity of the asteroids, are light-blue. Also plotted are the full asteroid tracks of 1143 Odysseus (navy), 4057 Demophon (yellow), and 1869 Philoctetes (magenta) in the forty-year window from 3rd October 2021 to 3rd October 2061. Propellant consumption and asteroid encounter timing are initially approximated from the independent thrust arcs generated in the CR3BP, but these estimates are closely aligned with results from ephemeris models.

Potential transfer legs from Earth to the Sun-Jupiter L4 region are also investigated for incorporation into a complete mission scenario. Impulsive burns will almost certainly be required if mission times are to remain practical, but the inclusion of the VSI engine opens the possibilities for additional trajectory concepts and applications of hybrid system optimization techniques. Additionally, the selection of specific asteroid tours enables sample return missions or extended trajectories that encounter other solar system bodies, such as Mars or main belt asteroids. The automated combination of pre-computed, independently generated rendezvous arcs between Trojan asteroids, outbound legs from Earth, and extended mission segments enables rapid examination of mission scenarios and readily offers end-to-end trajectory options in higher fidelity models.

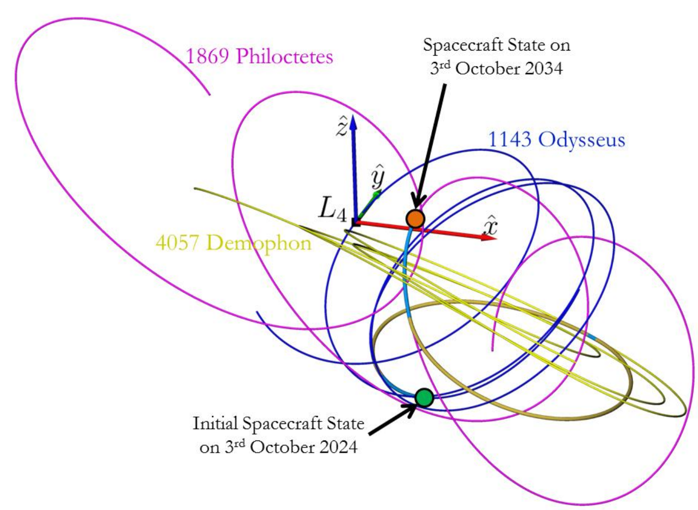

Figure 2. Spacecraft trajectory, converged in the Sun-Jupiter CR3BP, with long-term motion of target asteroids.