PDC2025
Stellenbosch, Cape Town, South Africa

Space Mission & Campaign Design

Accessibility of Earth Impactors for Planetary Defense Rendezvous Missions

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Keywords: *solar electric propulsion, mission design*

Planetary defense (PD) scenarios present unique mission design challenges compared to typical interplanetary missions. Critically, the target body cannot be selected to conform to predefined science or technology demonstration objectives. Instead, cosmic chance dictates the impending Earth impact, with the orbit of the body strongly influencing the difficulty and complexity of an Earth impact prevention campaign. The semi-major axis (SMA), eccentricity, and inclination of potentially hazardous orbits vary widely and drive the ΔV requirements of space missions for reconnaissance and Earth impact prevention space missions. The histograms in Figure 1 illustrate the expected distributions of SMA, eccentricity, and inclination for a synthetic pool of Earth impactors based on Reference 1. While the mean SMA of impactors is relatively low, the mean inclination and eccentricity are markedly higher than any historical or planned small-body or planetary rendezvous mission outside of New Horizons' flyby of Pluto.

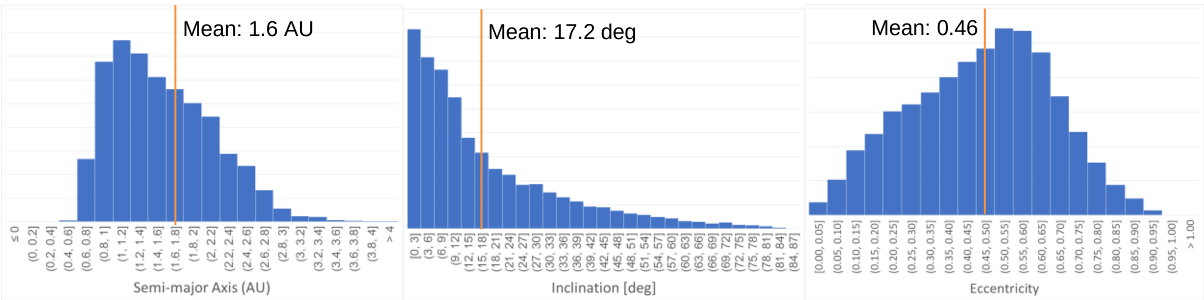

Figure 1: Distributions of semi-major axis (left), inclination (middle), and eccentricity (right) of a synthetic population of impactors

In addition to potentially challenging orbits, many planetary defense campaigns require or benefit from rendezvous missions, further increasing mission design difficulty as compared to high-speed flyby missions. For reconnaissance missions, rendezvous enables accurate measurement of the impactor's mass, comprehensive surface mapping, and maintenance of an observing spacecraft at the body, all of which can be critical for a subsequent mitigation mission. Moreover, impact mitigation techniques such as ion beam deflection (IBD), gravity tractor deflection, laser ablation deflection, and some nuclear explosive device (NED) strategies require rendezvous rather than a high-speed encounter. While flyby missions can minimize mission ΔV by timing the encounter at the ecliptic crossing, rendezvous missions necessitate a plane change to the impactor's inclined orbit and are subject to significant ΔV costs, driving the potential for high propellant demand, long flight times, and stressing the capability of heavy lift launch vehicles. These rendezvous challenges can be exacerbated by high eccentricity, which can introduce phasing challenges and substantial ΔV cost for periapsis lowering or apoapsis raising. On the other hand, the low SMA of most impactors keeps the bodies relatively close to the Sun and is beneficial for solar power.

This work examines the accessibility of rendezvous PD missions given the high degree of variation in impactor orbital elements and the demanding time constraints associated with warning time. Viable mission architectures in terms of launch vehicle and propulsion system combinations that can address different statistical realizations of impactors are established and compared to past space missions. Solar electric propulsion (SEP) system configurations and chemical propulsion are contrasted, demonstrating the benefit of SEP for impactor rendezvous. Furthermore, we illustrate the advantage of gravity assist combinations to reduce propellant demand and assess the compromise between trajectory time of flight (TOF) and propulsion system parameters such as propellant and solar array size for SEP. This evaluation is enabled by application of a stochastic optimization approach that resolves the optimal Pareto front of multiple mission objectives such as minimizing TOF, maximizing delivered mass, minimizing launch vehicle class, and minimizing solar array size for SEP. An example comparison of the optimal trade space between chemical propulsion and SEP for the 80th percentile inclination body in the synthetic population is highlighted in Figure 2.

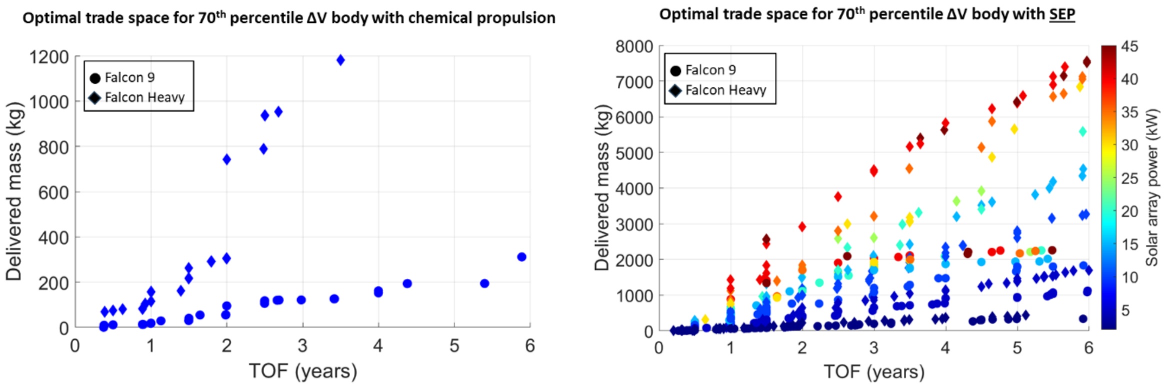

Figure 2: Optimal mission design solution space for chemical propulsion (left) and solar electric propulsion (right) designs for a 70th percentile ΔV impactor

References:

[1] S. R. Chesley, G. B. Valsecchi, S. Eggl, M. Granvik, D. Farnocchia and R. Jedicke, "Development of a Realistic Set of Synthetic Earth Impactor Orbits," 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-7, doi: 10.1109/AERO.2019.8742172.

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Comments: *Poster*