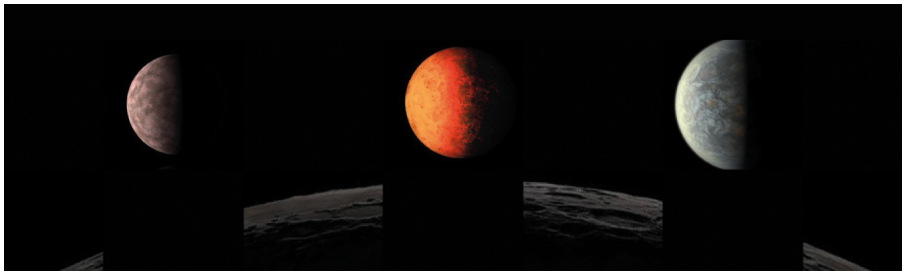

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Leveraging low-thrust propulsion and simulated Neptune gravity-assist maneuvers to redirect Trans-Neptunian Objects for Mars terraforming: a comparative assessment of ΔV and impact time requirements

Friday 24 October 2025 18:00 (1 hour)

Providing enough water remains a key challenge in the context of terraforming Mars. One interesting method is to redirect small water-rich bodies to hit the surface. While the prevailing focus of dynamical studies has been on Main Belt objects as the source, Trans-Neptunian Objects (TNOs) represent a more attractive source because of their significantly higher volatile content, including water ice.

In this study, we build on Czechowski (2025) [www.hou.usra.edu/meetings/lpsc2025/pdf/1858.pdf] analysis of the problem of redirecting TNOs onto collision trajectories with Mars. Two test cases were examined: a classical Kuiper Belt Object (KBO) and a Scattered Disk Object (SDO). A preliminary analysis of a non-optimal, retrograde thrust deceleration indicated prohibitive ΔV requirements in the range of 20-22 km/s. In order to drastically reduce these requirements, we performed a comprehensive optimization of the thrust vector over time for a very low thrust magnitude of $4{\times}10^{-10}$ km/s^2. We used advanced optimization algorithms, including the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) and the Differential Evolution algorithm. We also analyzed Neptune gravity-assist trajectories to evaluate possible energy savings. For bodies in the moderate-to-high eccentricity range, it was found that even a single Neptune assist provides a more pronounced ΔV reduction than the low-thrust maneuver alone.

The application of an optimized thrust profile, characterized by discrete changes in thrust direction, enabled a reduction of the total impulse required by nearly an order of magnitude. For the analyzed cases, the required ΔV was successfully reduced to below 3.5 km/s. A gravity assist from Neptune further reduced the ΔV requirements below this threshold.

These results show that the extremely low thrust requirements make missions aimed at steering TNOs onto collision trajectories with Mars feasible with emerging propulsion technologies.

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