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Venturing to Near-Earth Asteroid systems using Nuclear Electric Propulsion

F. Damme (1), J. Oberst (1,2), F. Jansen (3)
(1) Technical University of Berlin, Germany (friedrich.damme@tu-berlin.de, +49 (0)30 314 28840), (2) DLR Institute of Planetary Research, Berlin, Germany, (3) DLR Institute of Space Systems, Bremen, Germany

Abstract

In an effort to explore mission opportunities made possible by Nuclear Electric Propulsion (NEP) systems we studied a transfer of a NEP spacecraft from a low-earth orbit (LEO) to the near-earth binary 1866 Sisyphus. Using a simple analytical approximation we find the required launch window and thrust to meet the asteroid at the point of ecliptic intersection. Numerical methods are used to find a physically possible transfer model, also taking into account various gravitational perturbations. Assuming a departure from Earth (i.e., entry to hyperbolic path) in August 2023, we find a transit time to the target of 510 days.

1. Introduction

The International Nuclear Power and Propulsion System (INPPS) spacecraft will be launched for a testing of Nuclear Electric Propulsion in Earth orbit. After commissioning the spacecraft it is foreseen to venture into near-Earth space, where Near-Earth asteroids pose attractive targets of opportunity. Here, we study a mission to the binary NEO 1866 Sisyphus. The challenge is that the point of Sisyphus ecliptic intersection must be met by the spacecraft at some exact time due to Sisyphus rather high inclination of 41.2°

1.1 Objectives

The goal of the mission is to reach the binary NEO 1866 Sisyphus for a flyby starting from a circular low-Earth orbit with 7,800 km radius. The encounter is possible when Sisyphus crosses the ecliptic plane at 1.104 AU distance from the Sun (Figure 1). This maneuver should be done using only electric propulsion.

2. Method

To reduce complexity of the problem, electric propulsion is simulated to accelerate the spacecraft continuously in the direction of flight. As a reference we used spacecraft parameters similar to the BepiColombo mission which is equipped with electric thrusters (T6, Kaufman-type) providing 290 mN of thrust; the spacecraft has a total mass of 2,900 kg [3]. Until more accurate parameters of the INPPS spacecraft are known we neglect the decrease of mass due to fuel consumption.

2.1 Analytic approximation

An analytical approximation for the two body problem with continuous thrust (a_θ) in angular direction can be obtained under the assumption of a circular orbit. The change of the orbital radius r with time t is then given by the approximation:

$$r(t) = r_0 \ / \ (1 - a_\Theta t / v_0)^2 \qquad (1)$$

with r_0 and v_0 being the initial radius and velocity respectively. As the orbit will increase in eccentricity with time and since leaving Earth requires an hyperbolic orbit, the assumption does not hold for longer time periods. Validation of the results with numerical methods is necessary. Nevertheless analysis provides the means to determine the required time and thrust to reach a given helio- of geocentric radius.

2.2 Numerical solution

For high-accuracy determination of the spacecraft trajectory, we apply numerical methods. The initial position and velocity together with all perturbing and propelling forces pose a second-order ordinary differential equation (ODE) for the spacecraft motion. It is solved by numeric integration. The differential equation must be sufficiently smooth for efficient error estimation and error minimization. Therefore it is beneficial for the accuracy to simulate the propulsion as continuously and not impulsive. To simulate the perturbing gravitational forces of Sun, Moon, Mars and Jupiter we included ephemeris data into the numeric simulation. The positional data of the planetary bodies are taken from standard ephemerides (DE 421 [1]).

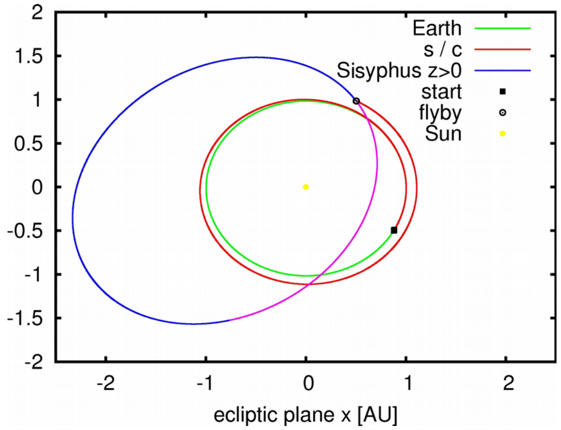

Figure 1: Transfer trajectory of the spacecraft (s/c) in the ecliptic plane. Starting outside Earth's sphere of influence on 24-AUG-2023 00:00 UTC, the encounter is on 06-JAN-2025 06:00 UTC. Sisyphus ecliptic ascending node indicated by color change violet to blue.

3. Results

Phase I of the maneuver is to reach a hyperbolic orbit relative to Earth. The initial orbit has a radius of 7,800 km and is assumed to be within the ecliptic. Assuming the full acceleration of 0.1 mm/s² of the electric thrusters (see 2.1) it takes 766 day of "orbit climbing" to increase the eccentricity to 1 and leave Earth. Despite the increasing eccentricity the analytic approximation holds up well and is accurate (Figure 2; top), except when the s/c passes the orbital height of the moon. Collision with the moon can be avoided by appropriate timing. In our simulations the inclination increased to 1° when passing the moon. With stronger thrusters the time required for Phase I is proportionally shorter. Starting in a geostationary transfer orbit will reduce the transit time about 600.

Phase II is the transfer to Sisyphus. Because the spacecraft mean motion changes with the radius according to Kepler's law we need a_θ to be an adjustable parameter to meet the longitude of the target intersection point at the correct time. Given the constellation of Earth and asteroid the acceleration through propulsion a_θ was decreased to 0.042 mm/s². The approximation (1) suggested a time of transfer of 396 days as first iteration. Starting with the eccentricity of Earth's orbit the actual solar distance differed significantly from (1) (Figure 2, bottom). Iterating numeric simulations gave a successful transfer arc (Figure 1,2). The time of travel is 510 days and 6 hours, accumulating a total delta-v of 2.18 km/s. We pass Sisyphus with a relative velocity of 24.43 km/s. The flyby distance can be chosen freely.

4. Summary and Conclusions

Even with the low acceleration provided by electrical propulsion it is possible, given sufficient time, to leave the low-Earth orbits and reach an asteroid such as Sisyphus. If the reduced acceleration of phase II is implemented by using the thrusters periodically the total operating time is approximately 980 days. We expect to find other favorable asteroid encounter opportunities, which require shorter transit times.

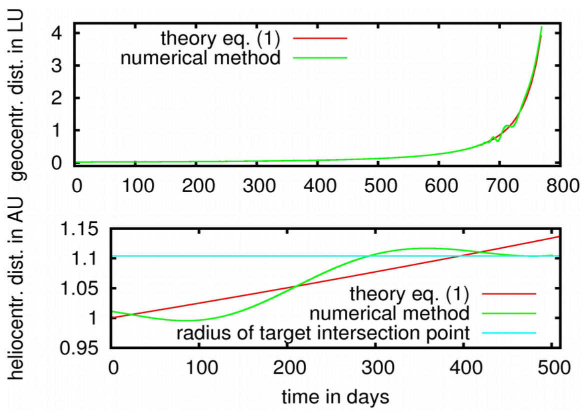

Figure 2: Change in radius during "orbital climb". Phase I (top) from LEO to hyperbolic escape. Distance shown in Lunar units LU. Phase II (bottom) from Earth orbit to Sisyphus encounter. Solution using numerical integration (green) is compared with analytical approximation (red).

References

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