DESIGNING SPACECRAFT TRAJECTORIES FROM LIBRATION POINT ORBIT TO NEAR-EARTH ASTEROIDS

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Abstract

The paper proposes an approach to designing transfer trajectories of a spacecraft from its initial orbit in the vicinity of the Sun-Earth libration point to near-Earth asteroids. The features of motion in bounded orbits around libration points, as well as invariant manifolds associated with them, open up the possibility of redirecting a spacecraft to trajectories of rendezvous with near-Earth asteroids almost without fuel consumption. The main focus of the research is to develop flight trajectories that involve a spacecraft initially approaching a celestial body and subsequently returning to the vicinity of the initial libration point.

The potentially hazardous asteroids Apophis and 2001 WN_5 were selected as target celestial bodies. The next close approaches of these asteroids to the Earth will take place in 2029 and 2028, respectively. It is worth noting that both near-Earth asteroids will first pass near the L_2 Sun-Earth libration point before approaching the Earth, and near the L_1 after the approach.

The James Webb Space Telescope, the Euclid spacecraft and the Spectrum-Roentgen-Gamma space observatory are spacecraft for which a concept of an asteroid exploration mission is proposed. All three spacecraft operate in orbits near the L_2 Sun-Earth libration point. As a result of the construction of invariant manifolds associated with halo orbits of these spacecraft, trajectories have been identified along which these spacecraft can approach the potentially hazardous asteroids Apophis and 2001 WN_5. Based on the analysis of obtained trajectories, necessary impulses for the close passage to these celestial bodies were calculated. Trajectories leading to bounded orbits in the vicinity of the L_2 Sun-Earth libration point, after asteroids approaching, were also calculated. Preliminary results show that there are a number of possible scenarios for such flights, in which the total cost of the characteristic velocity does not exceed 50 m/s. It is shown that in all cases, all three spacecraft do not leave the area bounded by the so-called Kislik sphere of influence of the Earth – a sphere with a radius of 2.5 million km centered at the center of mass of the Earth.

The proposed concept may be useful for future missions at the libration points of the Sun-Earth system, especially for small spacecraft due to the low fuel costs for such flights.

Keywords: *Sun-Earth libration points, near-Earth asteroids, invariant manifolds*

Introduction

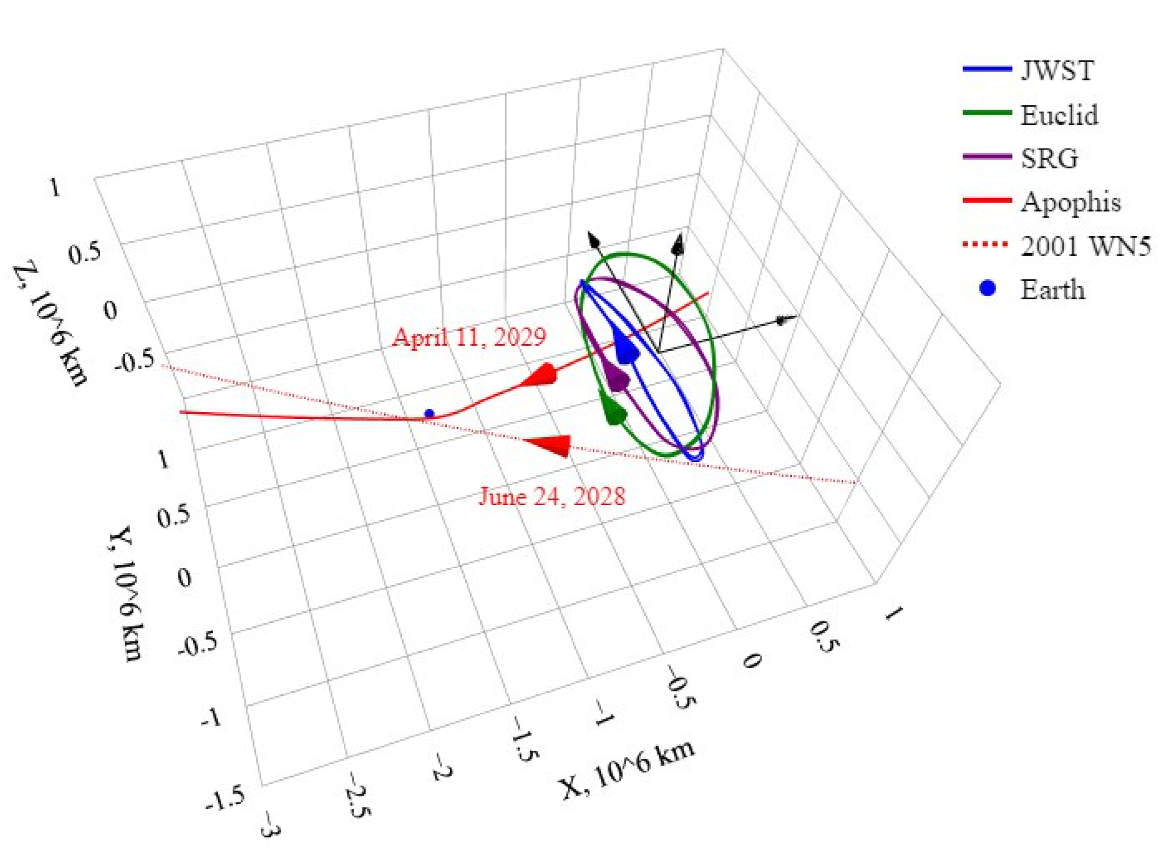

Fig. 1. Simulated JWST, Euclid, SRG, Apophis and 2001 WN_5 trajectories

The orbits of the James Webb Space Telescope [1], the Euclid observatory [2] and the Spectrum-Roentgen-Gamma space observatory [3] were chosen as the initial. These spacecraft are currently operating in the vicinity of the L_2 Sun-Earth libration point (see Fig. 1).

Asteroids Apophis and 2001 WN_5 [4] were selected as target celestial bodies.

The equations of a spacecraft motion in geocentric (index g) and heliocentric (index h) J2000 coordinate systems have the form:

$$\begin{cases} \ddot{r}_g = -\frac{\mu_E}{|r_g|^3} r_g + \mu_S \left(\frac{r_{gS} - r_g}{|r_{gS} - r_g|^3} - \frac{r_{gS}}{|r_{gS}|^3} \right) + \sum_{i=1}^{n} \mu_i \left(\frac{r_{gi} - r_g}{|r_{gi} - r_g|^3} - \frac{r_{gi}}{|r_{gi}|^3} \right), \\ \dot{r}_g = V_g, \end{cases}$$

$$\begin{cases} \ddot{r}_h = -\frac{\mu_S}{|r_h|^3} r_h + \mu_E \left(\frac{r_{hE} - r_h}{|r_{hE} - r_h|^3} - \frac{r_{hE}}{|r_{hE}|^3} \right) + \sum_{i=1}^{n} \mu_i \left(\frac{r_{hi} - r_h}{|r_{hi} - r_h|^3} - \frac{r_{hi}}{|r_{hi}|^3} \right), \\ \dot{r}_h = V_h. \end{cases}$$

The integration was carried out using the 8-order Runge-Kutta method in the JPL DE405 ephemeris model. All trajectories are represented in a rotating coordinate system centered at the L_2 Sun-Earth libration point

In this paper, we suggest a transfer scheme where a spacecraft, after applying ΔV_1 = 1 m/s along the escape direction [5], aligns with a trajectory from the unstable invariant manifold associated with its initial orbit near the libration point. For each pair of spacecraft-asteroid among the trajectories of the unstable manifold set, it is possible to determine one along which the spacecraft will pass at a minimum distance (Δr) from the target asteroid.

Asteroid / Spacecraft	JWST	Euclid	SRG
Apophis	61900 km	33500 km	17600 km
2001 WN_5	9900 km	94600 km	31800 km

The rendezvous of all three spacecraft with Apophis takes place on April 13, 2029.The encounter with the 2001 WN_5 asteroid for the JWST and SRG spacecraft takes place on June 27, 2028, while for the Euclid spacecraft - on June 26, 2028.

For the JWST-2001 WN_5 and SRG-Apophis cases, close approach trajectories (Δr < 1 km) after applying ΔV_2, as well as return trajectories (after applying ΔV_3 and ΔV_4) to the vicinities of the initial orbits, were calculated (see Fig. 3 and 6). All other schemes are shown in Fig. 2, 4, 5 and 7.

JWST transfers

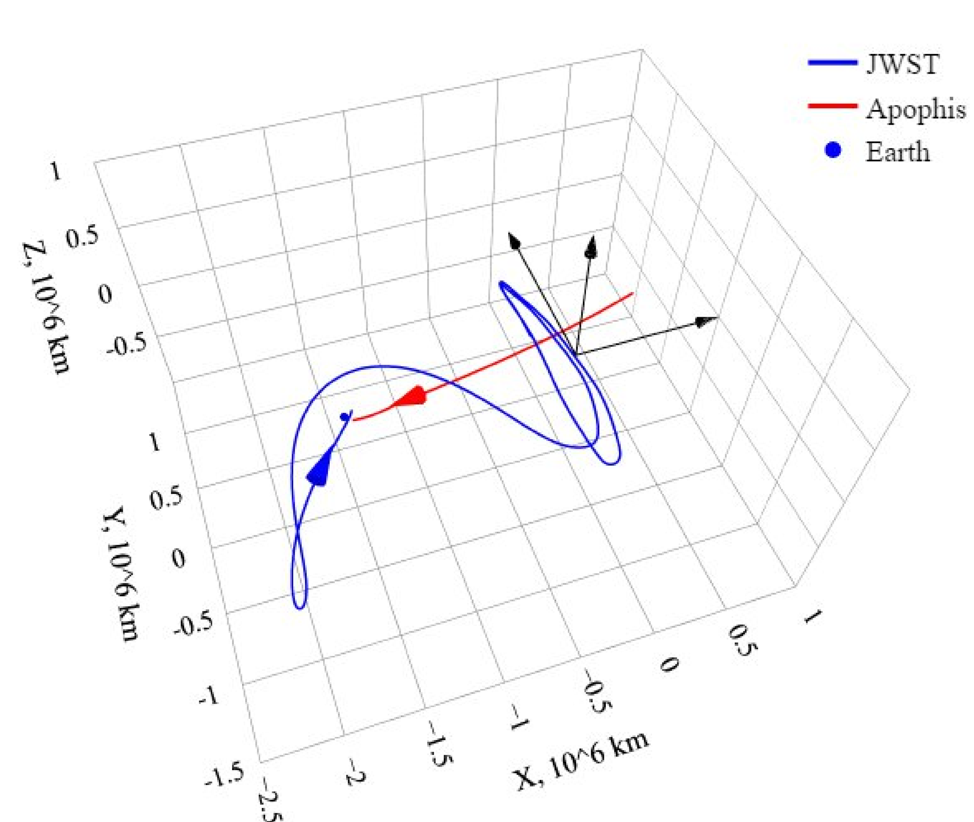

Fig. 2. Transfer trajectory of the JWST spacecraft to Apophis (ΔV_1 = 1 m/s, Δr = 61900 km)

JWST-Apophis	
Impulse value	Date of the impulse implementation
ΔV_1	September 2, 2028
JWST-2001 WN_5	
Impulse value	Date of the impulse implementation
ΔV_1	August 18, 2027
ΔV_2	June 6, 2028
ΔV_3	October 7, 2028

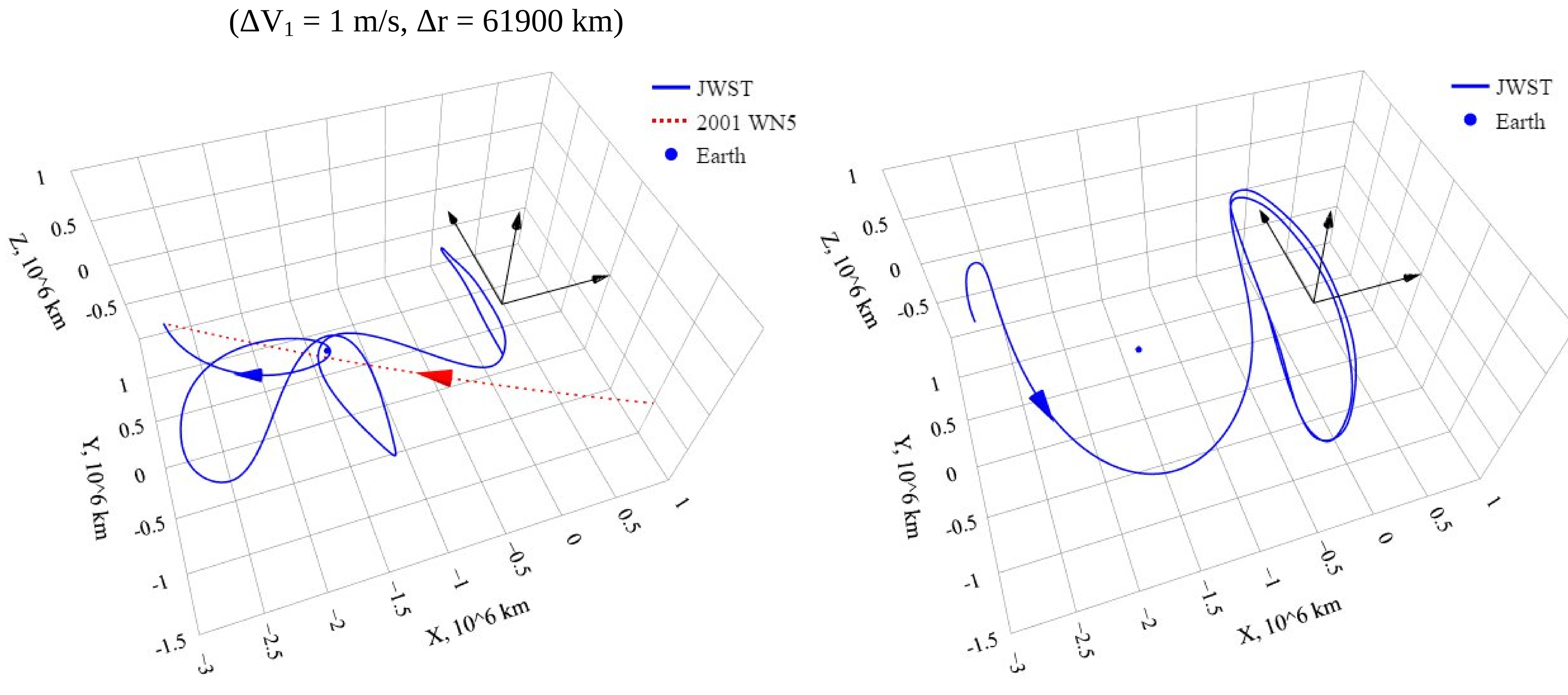

Fig. 3. Transfer trajectory of the JWST spacecraft to the 2001 WN_5 asteroid and return trajectory (ΔV_1 = 1 m/s, ΔV_2 = 6.7 m/s, Δr < 1 km, ΔV_3 = 2.2 m/s)

Euclid transfers

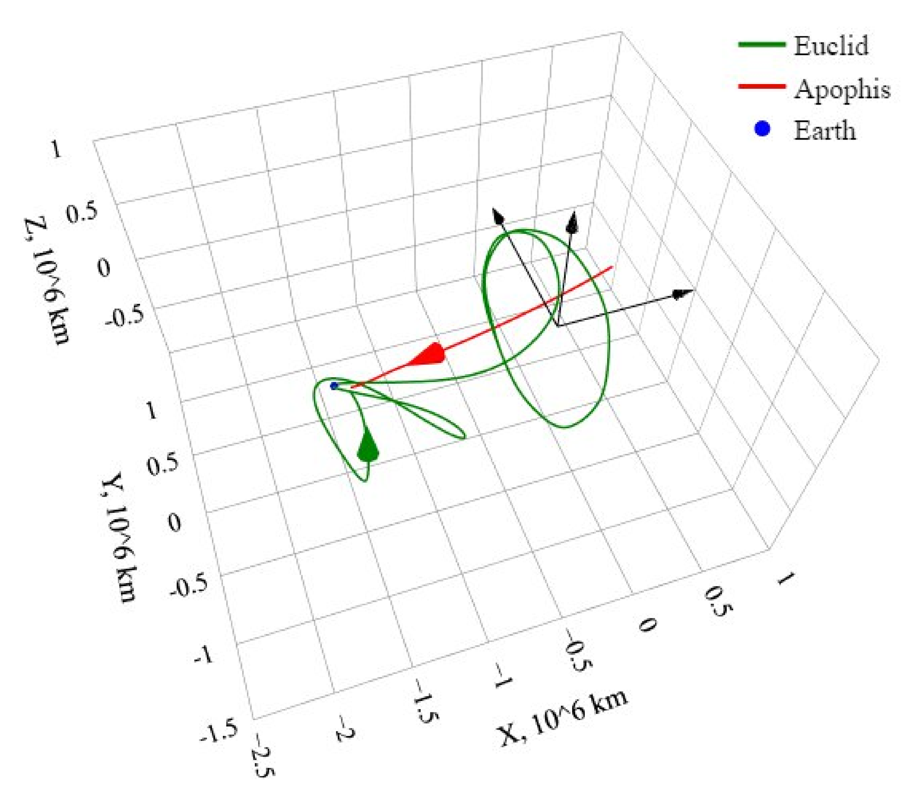

Fig. 4. Transfer trajectory of the Euclid spacecraft to Apophis (ΔV_1 = 1 m/s, Δr = 33500 km) Date of the impulse implementation - August 19, 2028

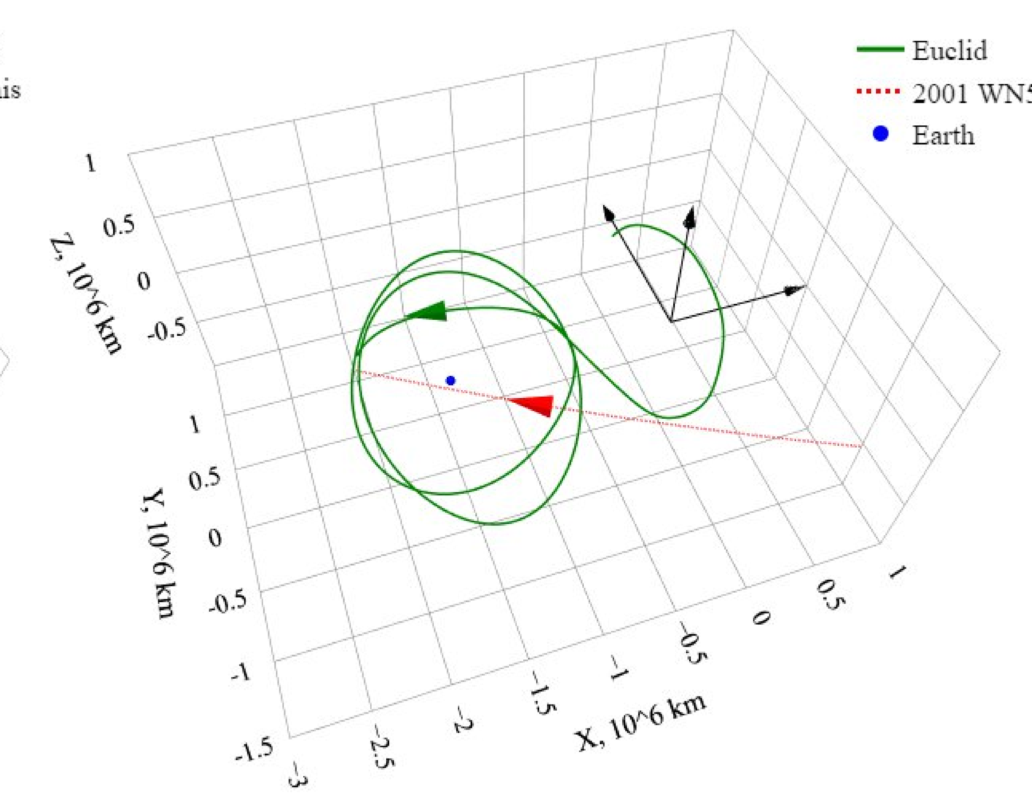

Fig. 5. Transfer trajectory of the Euclid spacecraft to the 2001 WN_5 asteroid (ΔV_1 = 1 m/s, Δr = 94600 km) Date of the impulse implementation - May 16, 2027

SRG transfers

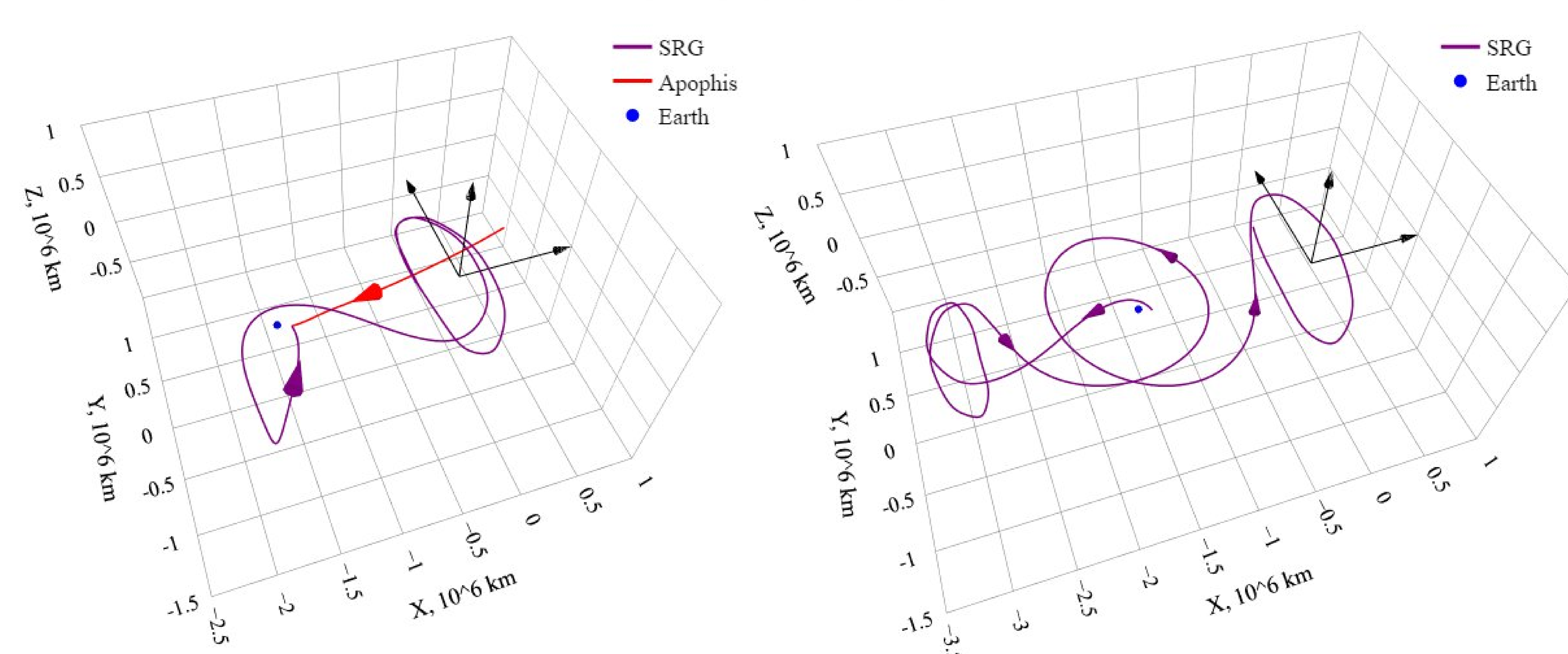

Fig. 6. Transfer trajectory of the SRG spacecraft to Apophis and return trajectory (ΔV_1 = 1 m/s, ΔV_2 = 35 m/s, Δr < 1 km, ΔV_3 = 6.2 m/s, ΔV_4 = 1 m/s)

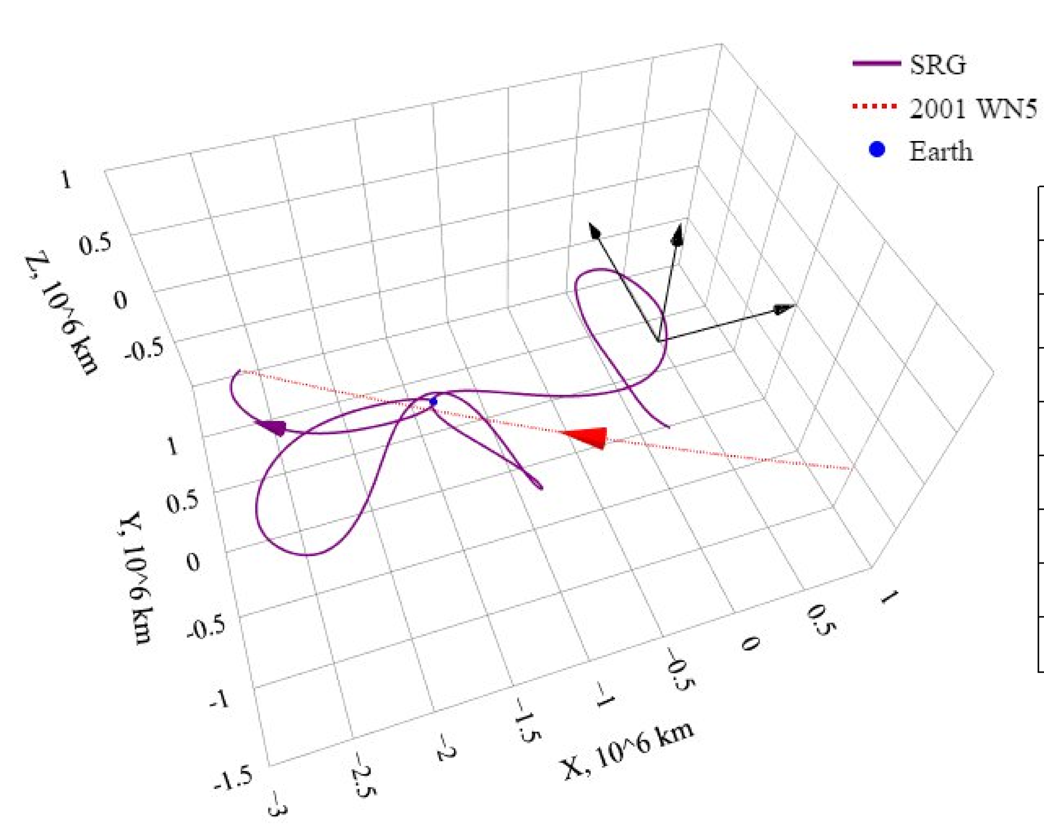

Fig. 7. Transfer trajectory of the SRG spacecraft to the 2001 WN_5 asteroid (ΔV_1 = 1 m/s, Δr = 31800 km)

SRG-Apophis	
Impulse value	Date of the impulse implementation
ΔV_1	September 13, 2028
ΔV_2	January 17, 2029
ΔV_3	April 14, 2029
ΔV_4	October 17, 2029
SRG-2001 WN_5	
Impulse value	Date of the impulse implementation
ΔV_1	August 21, 2027

Conclusion

This paper presents simulation results for spacecraft transfers to the Apophis and 2001 WN_5 asteroids using trajectories from invariant manifold sets. The study demonstrates that such transfers enable reaching the target celestial bodies with minimal propellant consumption. The proposed low-energy transfer concept could prove valuable for future missions to Sun-Earth libration points, particularly for small spacecraft where stringent fuel constraints apply.

References

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