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Extension of the Mission of a Spacecraft Operating at a Vicinity of the Sun-Earth Libration Point for Asteroids Exploration

Maxim V. Pupkov*, Natan A. Eismont, Konstantin S. Fedyaev, Vladislav A. Zubko

Department of Space Dynamics and Mathematical Information Processing, Space Research Institute of Russian Academy of Sciences (IKI), 84/32 Profsoyuznaya Street, Moscow, Russia 117997
* Corresponding Author, m.pupkov@iki.rssi.ru

Abstract

This paper considers the possibility of extending the mission of a spacecraft currently operating at a vicinity of the collinear Sun-Earth libration point for observing potentially hazardous asteroids. If, after the completion of the planned part of the mission, propellant reserves remain in the fuel tanks of the spacecraft, and main onboard systems have not out of order yet, then it is possible to carry out a number of maneuvers for the close flyby of some asteroids. At the present time there are a number of spacecraft functioning at vicinities of collinear Sun-Earth libration points. One of them is the Spectrum-Roentgen-Gamma Space Observatory. According to preliminary estimates, after completing the main tasks of this observatory by 2026, there will be enough fuel in the spacecraft tanks to perform the orbital maneuvers necessary for a sufficiently close flyby of some potentially hazardous asteroids. It is confirmed that with appropriate orbital maneuvers satisfying the limits on the characteristic velocity, the Spectrum-Roentgen-Gamma spacecraft can approach Apophis in 2029 at any necessary distance and, after flyby, return in an orbit around the Sun-Earth libration point L_2. In addition, it is possible to consider the asteroid 1990 MU, the next close approach to the Earth of which will take place in 2027, as a candidate for such a mission. Another example is the Deep Space Climate Observatory spacecraft. As an extended part of its mission this spacecraft can approach the asteroid 1997 XF_{11} in 2028 under the same restrictions on the required characteristic velocity as for the Spectrum-Roentgen-Gamma observatory. It is also shown that the Gaia spacecraft in 2026 can be redirected to the asteroid 1997 NC_1, if the main mission of the spacecraft is completed by that time.
Keywords: Spectrum-Roentgen-Gamma, Potentially Hazardous Asteroids, Asteroid Flyby

Nomenclature

ΔV – the minimum required impulse value,
V_{rel} – the relative velocity of the asteroid flyby at the moment of the close approach.

Acronyms/Abbreviations

International Cometary Explorer (ICE),
International Sun-Earth Explorer-3 (ISEE-3),
Spectrum-Roentgen-Gamma (SRG),
Deep Space Climate Observatory (DSCOVR).

1. Introduction

The first spacecraft that operated in an orbit around a Sun-Earth libration point (specifically around L_1) was the ICE (ISEE-3) [1]. Its initial goal was to examine the structure of the solar wind near the Earth. The ISEE-3 spacecraft was also used in an extended mission to study the interaction of the solar wind with the comet atmosphere. After completing the original mission, several gravitational maneuvers near the Moon were performed, and the spacecraft was successfully sent first to Giacobini-Zinner, and then to Halley comets.

In current research, it is proposed to redirect the spacecraft on a trajectory of a close approach to the asteroid, which will allow to obtain a number of new scientific data about it. Using the existing navigation capabilities, orientation and orbital control systems of spacecraft data, we get the opportunity to conduct a number of experiments. For example, in June 1997, the interplanetary station NEAR Shoemaker [2] flew at a distance of 1200 km from the asteroid Matilda at a relative velocity of 10 km/s and received more than 500 images of this celestial body, as well as measured its magnetic field and mass.

We consider the Spectrum-Roentgen-Gamma Space Observatory [3] as a possible candidate that can be redirected to the trajectories of a close approach to some asteroids for the extended mission. The spacecraft was launched in July

2019 and currently operating in an orbit around the Sun-Earth libration point L_2. The main scientific goal of the SRG spacecraft is to create a map of the visible Universe in the X-rays.

Two more spacecraft were considered for similar extended tasks. The first one is the Deep Space Climate Observatory [4], currently located in the vicinity of the Sun-Earth libration point L_1. This spacecraft is designed to monitor the solar wind and to provide advanced warnings about geomagnetic storms. The last one is the Gaia spacecraft – an optical–band space telescope located in the vicinity of the Sun-Earth libration point L_2 [5]. The most important scientific mission of Gaia is to survey stars in order to clarify the origin and development of our Galaxy.

2. Material and methods

According to [6], there are 271 kg of propellant in the SRG fuel tanks. It is expected to be enough to perform a total impulse of 200 m/s after completing the main mission by 2026. While considering the DSCOVR and the Gaia spacecraft, we assumed the same fuel reserves to be available by the end of their tasks.

The simulation of the SRG motion is carried out in the gravitational field of the Earth and the Sun, taking into account the main perturbations: the attraction of the Moon and the planets of the Solar system. The simulation was performed using NASA General Mission Analysis Tool software package [7] using the Runge–Kutta integration method of the 9th order with a variable step. Required station-keeping correction maneuvers were calculated using technique provided by [8].

Figure 1 shows the simulated trajectory of the SRG (the trajectory is shown in blue, its projections on planes are shown in green) in a rotating coordinate system associated with the Sun-Earth libration point L_2 (the X-axis is aligned with the Sun-Earth line and directed to the Earth, the Z-axis is orthogonal to the ecliptic plane and directed to the North ecliptic pole, the Y-axis completes to the right-handed set) for the period of time from February 05, 2023 until September 15, 2030.

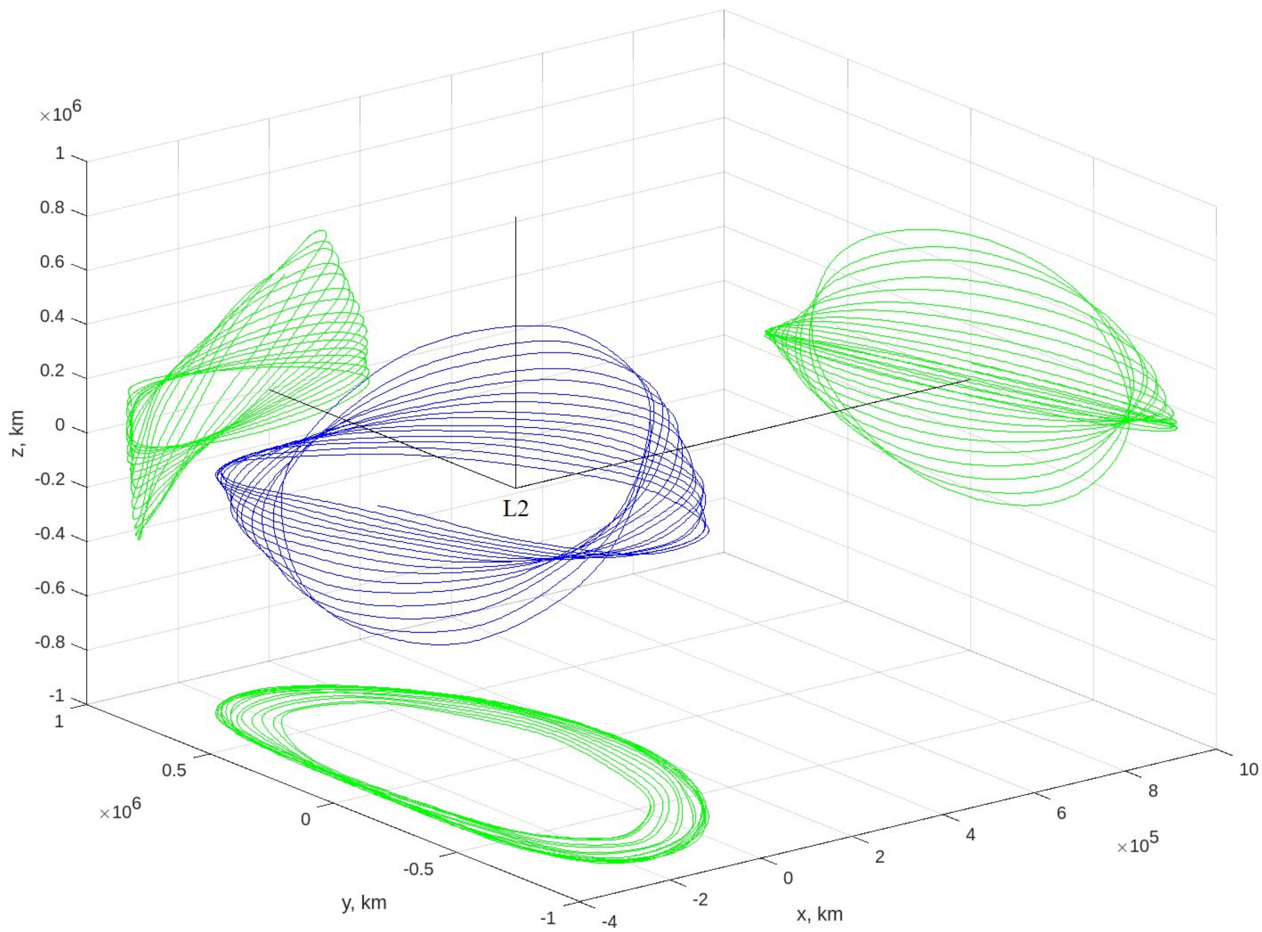

Fig. 1. Simulated trajectory of the SRG spacecraft

3. Theory and calculation

Since the end of the SRG main mission is currently planned at the end of 2025, we discuss the perspectives of redirecting the spacecraft to asteroids encountering the Earth after this year. Therefore, we consider asteroids 1997 NC_1, 1990 MU, 1997 XF_{11} and Apophis [9], which will approach the Earth in 2026, 2027, 2028 and 2029, respectively.

At first, we considered a direct flight of the spacecraft from its initial orbit to the approach to the asteroid. The flight was carried out by a single impulse in the initial bounded orbit of the spacecraft. A minimum value of the impulse for each possible date of its implementation was determined by varying the date of approach to the asteroid. This scheme is used to transfer the SRG spacecraft to the Apophis asteroid and the DSCOVR spacecraft to the asteroid 1997 XF_{11}.

Another scheme requires two impulses. The first small impulse is needed to led the spacecraft to left the bounded orbit. The set of such trajectories form an unstable manifold (see Fig. 2). The second impulse is a transfer one. Such a scheme is used to redirect the SRG observatory to the asteroid 1990 MU and the Gaia spacecraft to the asteroid 1997 NC_1.

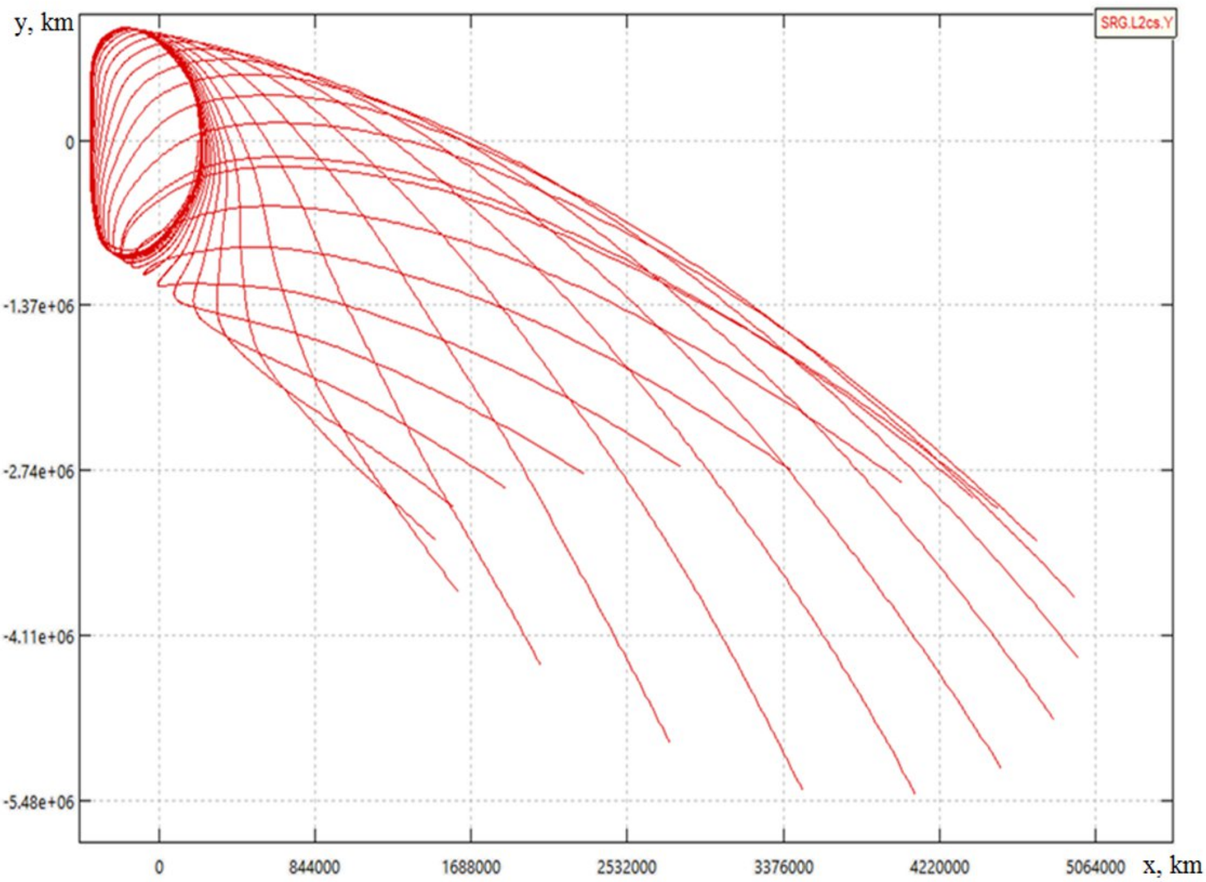

Fig. 2. An example of an unstable manifold

4. Results

4.1 The SRG transfers

Figure 3 shows the trajectory of the SRG spacecraft transfer to the Apophis asteroid (the trajectory before the impulse implementation is shown in blue, the ones after is shown in green; the trajectory of the asteroid is shown in red). The date of the impulse implementation is March 01, 2029. The date of the close approach to the Apophis asteroid is April 11, 2029. $\Delta V \approx 171.7$ m/s, $V_{rel} \approx 6$ km/s. After asteroid flyby, it is possible to keep the SRG spacecraft in an orbit around Sun-Earth libration point L_2. This scenario is shown in Fig. 4 (the trajectory after the close approach is shown in purple).

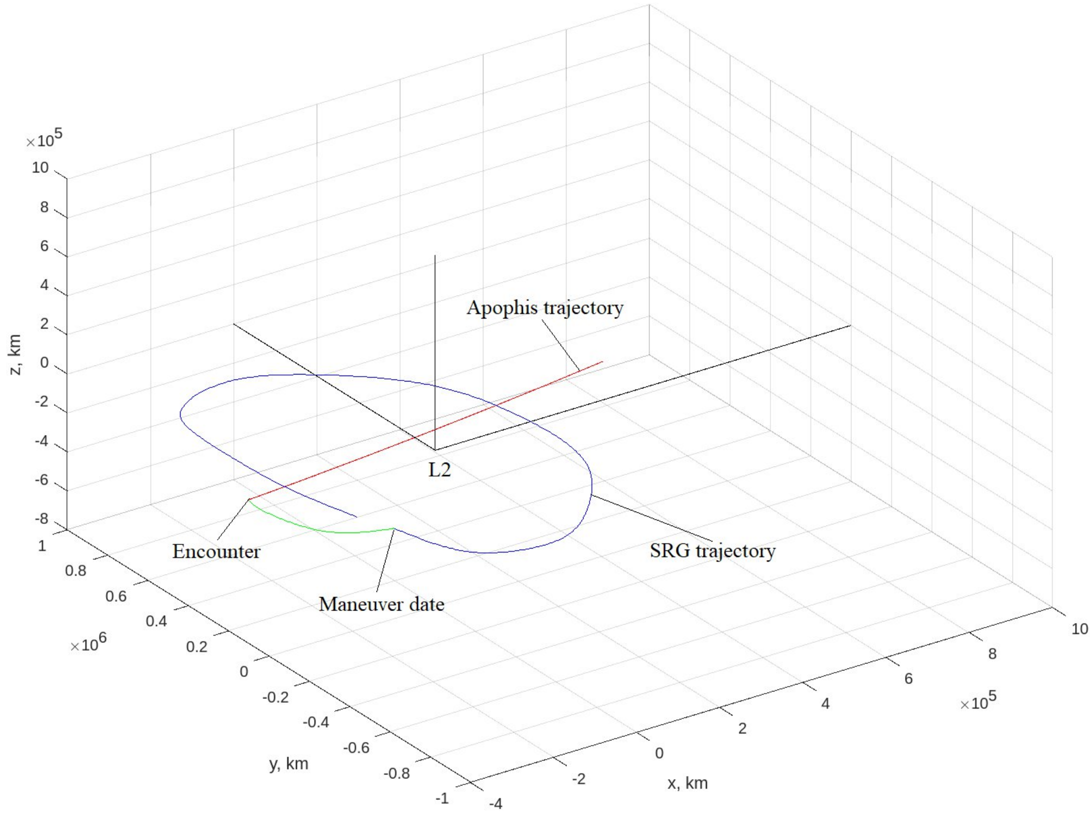

Fig. 3. Transfer trajectory of the SRG spacecraft to a close approach to the Apophis asteroid in 2029

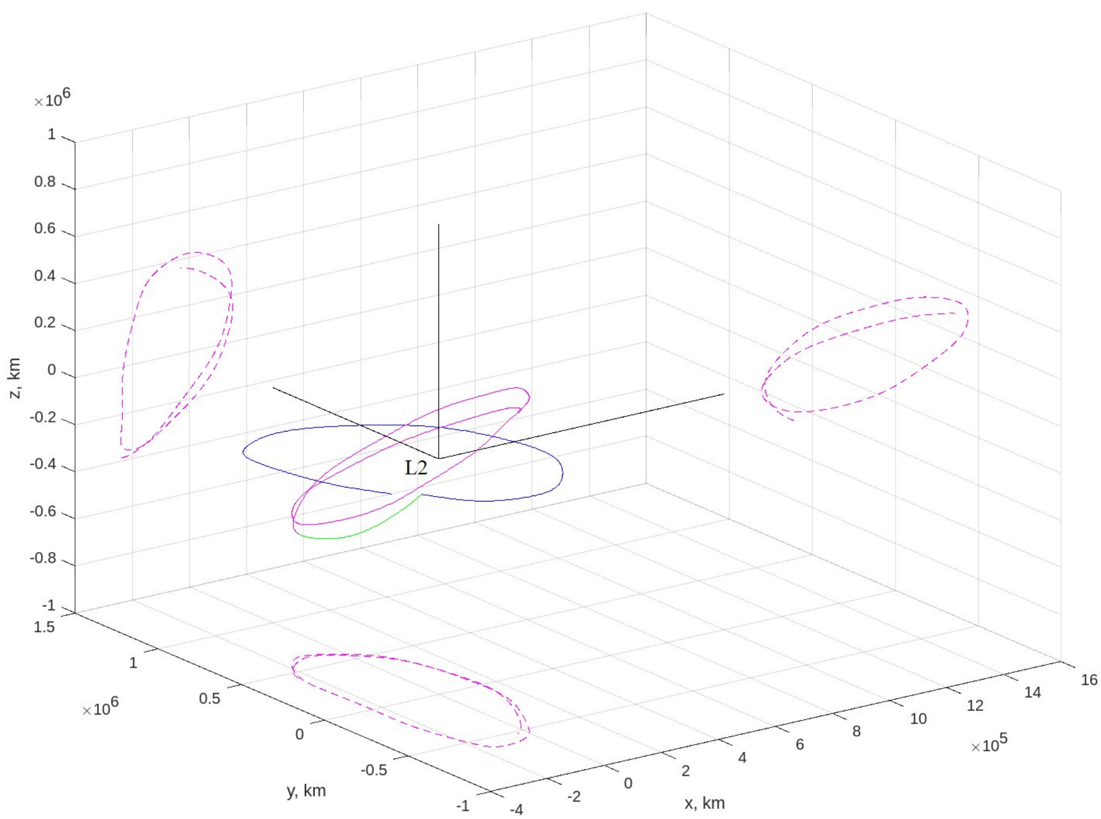

Fig. 4. The trajectory of the SRG spacecraft after the close approach to the Apophis asteroid

Figure 5 shows the trajectory of the SRG transfer to the asteroid 1990 MU. The first small impulse ($\Delta V_1 \approx 6$ mm/s) is given at June 10, 2026 (a part of the trajectory after the first impulse is shown in blue). Then, at March 21, 2027 the second impulse is applied ($\Delta V_2 \approx 126.1$ m/s), and the spacecraft is redirected to the asteroid (a part of the trajectory after the second impulse is shown in green). The date of the close approach is June 10, 2027. $V_{rel} \approx 22$ km/s.

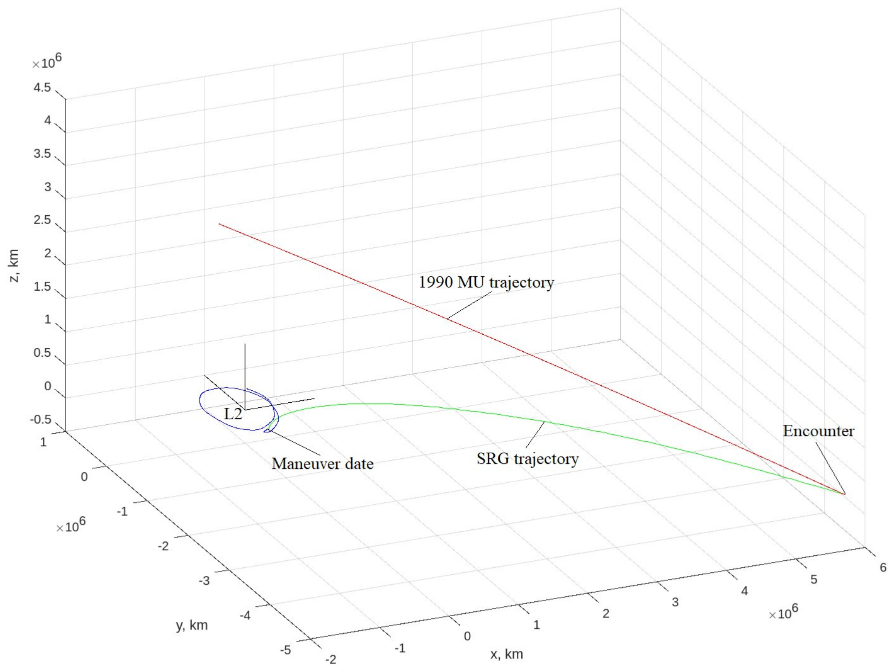

Fig. 5. Transfer trajectory of the SRG spacecraft to a close approach to the asteroid 1990 MU in 2027

4.2 The DSCOVR and the Gaia transfers

Figure 6 shows the trajectories of the DSCOVR and the asteroid 1997 XF_{11}. The date of the impulse implementation is September 25, 2028; the date of the close approach to the asteroid is October 25, 2028. $\Delta V \approx 178$ m/s. $V_{rel} \approx 14$ km/s.

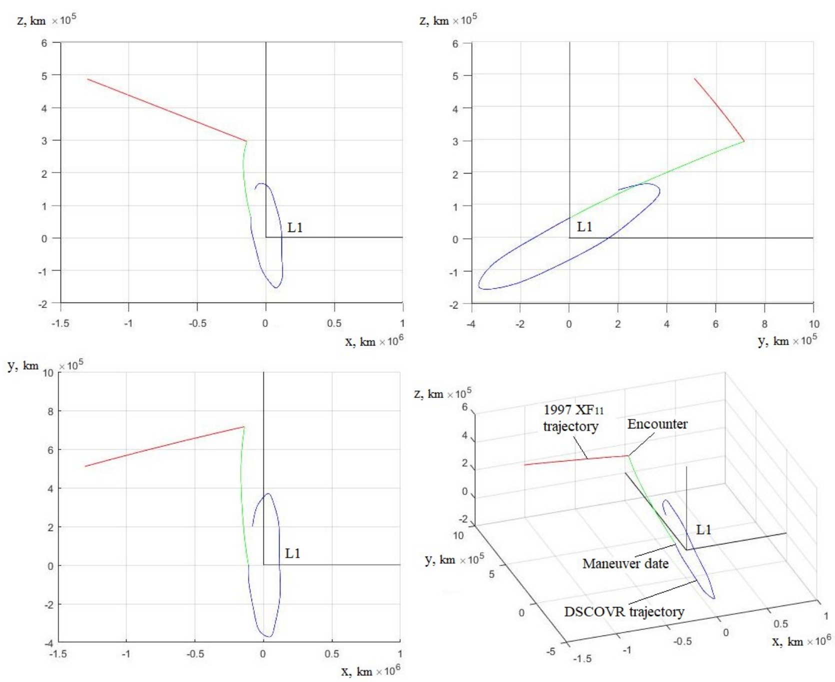

Fig. 6. Transfer trajectory of the DSCOVR spacecraft to a close approach to the asteroid 1997 XF_{11} in 2028

Figure 7 shows the trajectory of the Gaia spacecraft transfer to the asteroid 1997 NC_1. The value of the first small impulse is $\Delta V_1 \approx 0.8$ m/s, which is given at November 23, 2025. The date of the second impulse implementation is May 25, 2026, $\Delta V_2 \approx 29.5$ m/s. The date of the close approach is June 28, 2026. $V_{rel} \approx 9$ km/s.

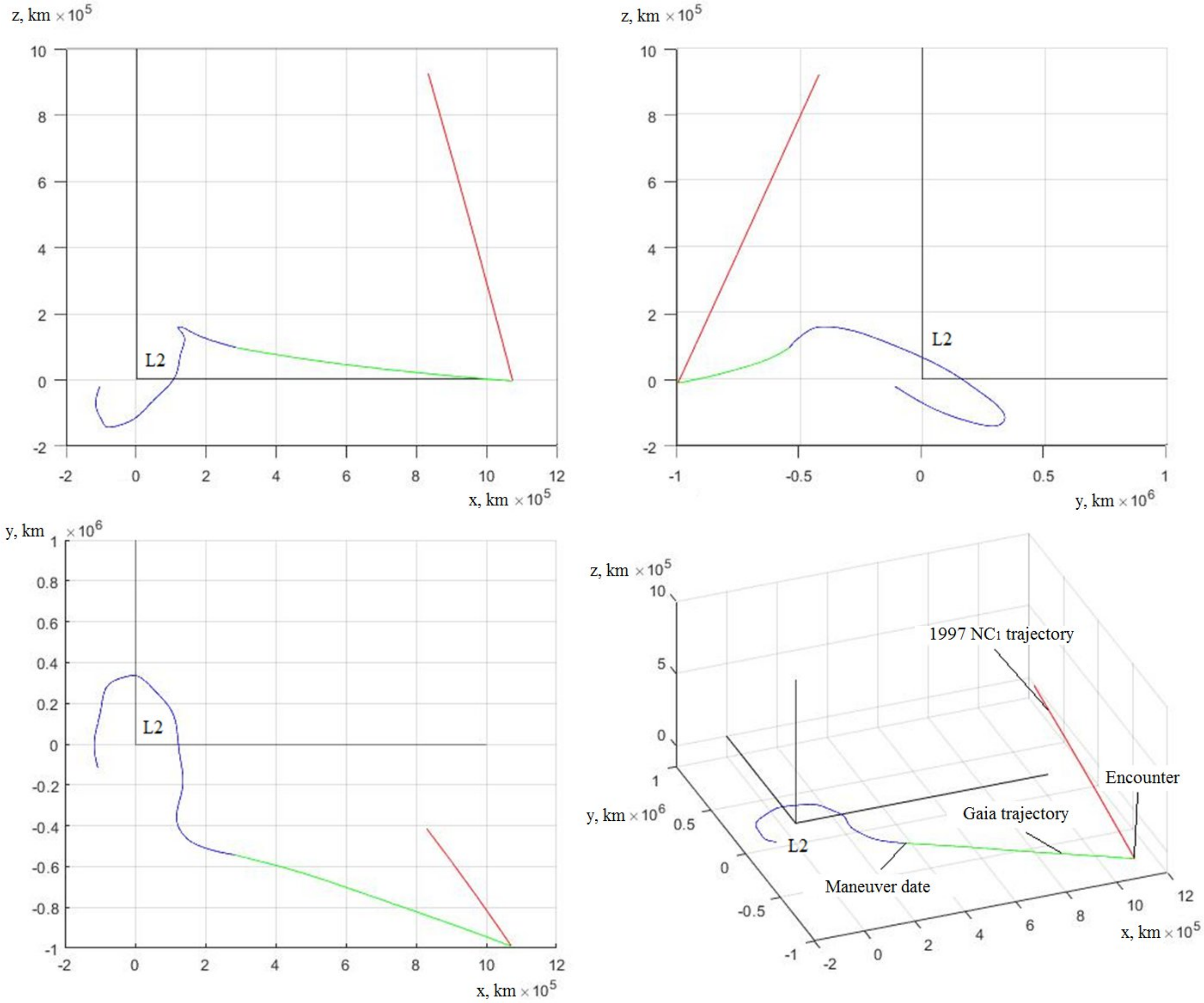

Fig. 7. Transfer trajectory of the Gaia spacecraft to a close approach to the asteroid 1997 NC_1 in 2026

All calculated flight schemes satisfy the imposed restriction on the maximum costs of the characteristic velocity.

5. Discussion

As the considered examples show, this approach can lead to a number of interesting scientific ideas. In particular, the spacecraft can be redirected not only to near-Earth asteroids, but also to other celestial bodies more distant from the Earth. Examples of such missions are given in [10], where scenarios of possible approach of the SRG spacecraft to comets 289P/Blanpain and 300P/Catalina in 2035 and 2036 are considered. It is shown that under the same restrictions on the onboard fuel amount, such extended missions are possible.

The advantages of the proposed approach also include the possibility of carrying out such an extended mission at the expense of a spacecraft already in an orbit. This makes it possible to organize this mission in a very short time – for example, immediately after the discovery of a new unknown object approaching the Earth.

6. Conclusions

In this paper, the technical feasibility of the extended mission of a spacecraft in a bounded orbit around the Sun-Earth libration point is discussed. It is shown that after completing the main mission the spacecraft can be used to study potentially hazardous asteroids from a close distance. The preliminary calculations presented above show the prospects of the proposed approach, the advantages of which are the efficiency of the mission and the economy of terrestrial resources.

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