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EXTENSION OF THE EARTH LIBRATION POINT MISSIONS BY TARGETING A SPACECRAFT TO NEAR-EARTH ASTEROIDS

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A possibility of studying potentially hazardous Near-Earth object by redirecting a spacecraft from a bounded orbit around a Sun-Earth libration point to a close approach with the object is discussed. During the flyby some physical and/or orbital parameters of the object can be determined. In particular, it is possible to estimate its mass by measuring the spacecraft trajectory deflection caused by gravitational attraction of the object.

As an example of this approach some possible perspectives of extending the Spectrum-Roentgen-Gamma mission is considered. It is shown that after the completion of the main mission the spacecraft may be redirected to a close approach with one of the asteroids (35396) 1997 XF11 and (99942) Apophis, or the comets 289P/Blanpain and 300P/Catalina. In all cases all the necessary maneuvers may be performed using propellant left in tanks of the spacecraft.

Keywords: *Near-Earth Object, potentially hazardous asteroid, asteroid flyby, Sun-Earth libration point*

1. Introduction

This article discusses an approach to estimate properties of a potentially hazardous object (an asteroid) using a spacecraft in a bounded orbit around a collinear Sun-Earth libration point. In particular, the spacecraft can be used for this purpose after the completion of the main mission. If on-board systems of the spacecraft are still functioning and there is a sufficient amount of propellant left in tanks, the spacecraft may be sent to one of the Near-Earth asteroids to explore its physical properties and orbital characteristics from a close distance. Such an extended mission has a number of significant advantages. At first, it uses a spacecraft that is already in the Near-Earth space, that may be critically important, if the hazardous object is discovered shortly before the possible impact and there is no time left for creating a special mission. At second, this mission does not require any additional resources. Only these two aspects can be crucial in developing an operational strategy when detecting a potentially hazardous object.

An idea of an extended mission of a spacecraft after the completion of the main mission was initially used in the ISEE-3/ICE project [1], which was originally aimed at studying the solar wind in the vicinity of the Sun-Earth libration point L_1. After completing the planned scientific program, the spacecraft was successfully targeted to the Giacobini-Zinner and Halley comets by performing several Lunar gravity assist maneuvers.

One of the possible scenarios of the extended mission of a spacecraft may be its redirection to the trajectory of approach to a potentially hazardous asteroid. During the asteroid flyby it is possible to obtain a new scientific data about the asteroid. In particular, some physical characteristics or orbital parameters can be estimated using measurements made by onboard spacecraft equipment or flight dynamics methods. For example, mass of the asteroid can be estimated by assessing its gravitational influence on the spacecraft trajectory.

A possible method for measuring the mass of the asteroid was proposed by A. Perret [2]. This method consists of sending a probe mass in the direction of the asteroid several tens of thousands of kilometers before the approach. Since the gravitational attraction of the asteroid is insignificant up to its immediate proximity, then during the phase of approach to the asteroid, relative measurements make it possible to accurately determine the separation conditions and disturbing forces. During the removal phase, the differential deviation can be measured using the amplifying effect.

As a spacecraft which can be retargeted to asteroid exploration after completion of the main mission we considered the Spectrum-Roentgen-Gamma (SRG) spacecraft currently located at a vicinity of the collinear Sun-Earth libration point L_2. SRG is a Russian-German high-energy space astrophysical observatory [3] launched on 13.07.2019. The main scientific goal of SRG with its telescopes is to measure X-rays from celestial objects. In addition, the observatory is equipped with optical instruments to determine its orientation [4]. According to preliminary estimates, by approximately 2029, after completing its mission objectives, the SRG observatory is expected to have enough onboard propellant for the orbital and orientation maneuvers necessary for a fairly close flyby of some asteroids.

2. SRG trajectory simulating

To describe the motion of the SRG spacecraft a rotating coordinate system with a fixed Sun-Earth direction is used, the center of which is located at the point L_2, the X-axis is directed along the straight line connecting the Sun and the Earth in the direction from the Sun to the Earth, the Z-axis is directed to the north pole of the ecliptic, the Y-axis complements the system to the right triple.

The equations of motion of the SRG in the system of two massive bodies, the Sun and the Earth, can be represented as [5]:

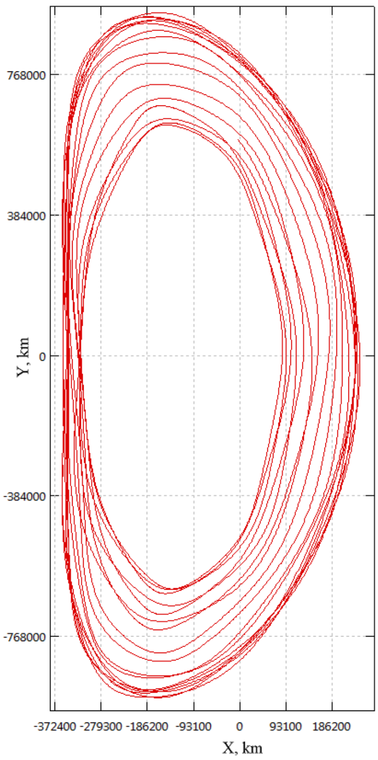
$$
\begin{cases}
\ddot{x} - 2\dot{y} - (2c_2 + 1)x = 0 \\
\ddot{y} + 2\dot{x} - (1 - c_2)y = 0 \\
\ddot{z} + c_2 z = 0
\end{cases}
$$

where c_2 is a parameter depended on the masses of the Sun and the Earth. This system of equations has a solution that can be written in the form

$$
\begin{cases}
x(t) = A_1 e^{\lambda t} + A_2 e^{-\lambda t} + A_{xy} \cos(\omega t + \varphi_{xy}) \\
y(t) = k_1 A_1 e^{\lambda t} - k_1 A_2 e^{-\lambda t} - k_2 A_{xy} \cos(\omega t + \varphi_{xy}) \\
z(t) = A_z \cos(\nu t + \varphi_z)
\end{cases}
$$

where $\lambda, \omega, v, k_1, k_2$ are parameters depending on c_2.

The SRG's velocity correction algorithm consists in selecting such initial conditions for the system of equations that ensure that the coefficient A_1 is equal to zero in its solution [6]. At the first step, one needs to choose two planes $X=X_{max}$ and $X=X_{min}$ ($X_{min} < 0 < X_{max}$), so that the bounded orbit of the spacecraft is located between them. For a given state vector, the numerical integration of the orbit is performed up to the moment of intersection with one of the planes X_{max} or X_{min}. The final coordinate X_f is a function of the initial state vector of the spacecraft, and if $A_1 > 0$, $X_f = X_{max}$, if $A_1 < 0$, $X_f = X_{min}$. On the set of state vectors providing a bounded orbit, the function X_f has a discontinuity. Thus, the problem of finding the initial conditions leading to a bounded orbit is reduced to the problem of finding the point of discontinuity of the function X_f, determined numerically. Simulated trajectory of SRG with correction impulses is illustrated on Figure 1.



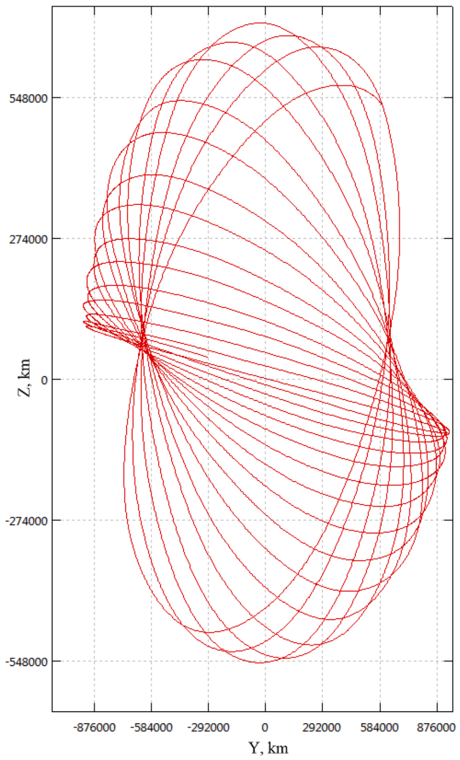


Figure 1. Simulated trajectory of SRG in 2021-2029 using correction impulses

The simulations of the SRG trajectory in the heliocentric frame were carried out in the NASA GMAT (General Mission Analysis Tool) [7]. It allows to numerically integrate the equations of motion of the spacecraft in a realistic force model using the Runge-Kutta methods of various orders, Prince-Dormand, and others. The GMAT scripting language allows to implement algorithms for calculating the initial velocity of the SRG and the required correction impulses.

After the completion of the main mission, the SRG spacecraft is expected to have enough propellant to perform a total impulse of 200 m/s. Thus, the SRG space observatory can be redirected towards exploration of some near-Earth asteroids using its existing navigation, attitude control and orbit control systems. Examples of this approach will be considered below.

3. Possible close approaches

3.1. Asteroid (35396) 1997 XF11

An asteroid (35396) 1997 XF11 is considered as a potentially hazardous [8]. According to NASA report, this asteroid should approach the Earth on 26.10.2028 at a distance of 930,000 km. Its mean diameter is estimated to be between 0.7 and 1.4 km, with a current absolute magnitude of 16.9. During the rendezvous on 28.10.2028, the stellar magnitude is expected to be 8.2 units. This asteroid could be a good candidate as a potential object of study, in particular, to verify the size and mass with the help of the SRG.

In our study, the dependence of the minimum required impulse (**ΔV**) value on the date of its application was calculated. The results are shown at Figure 2.

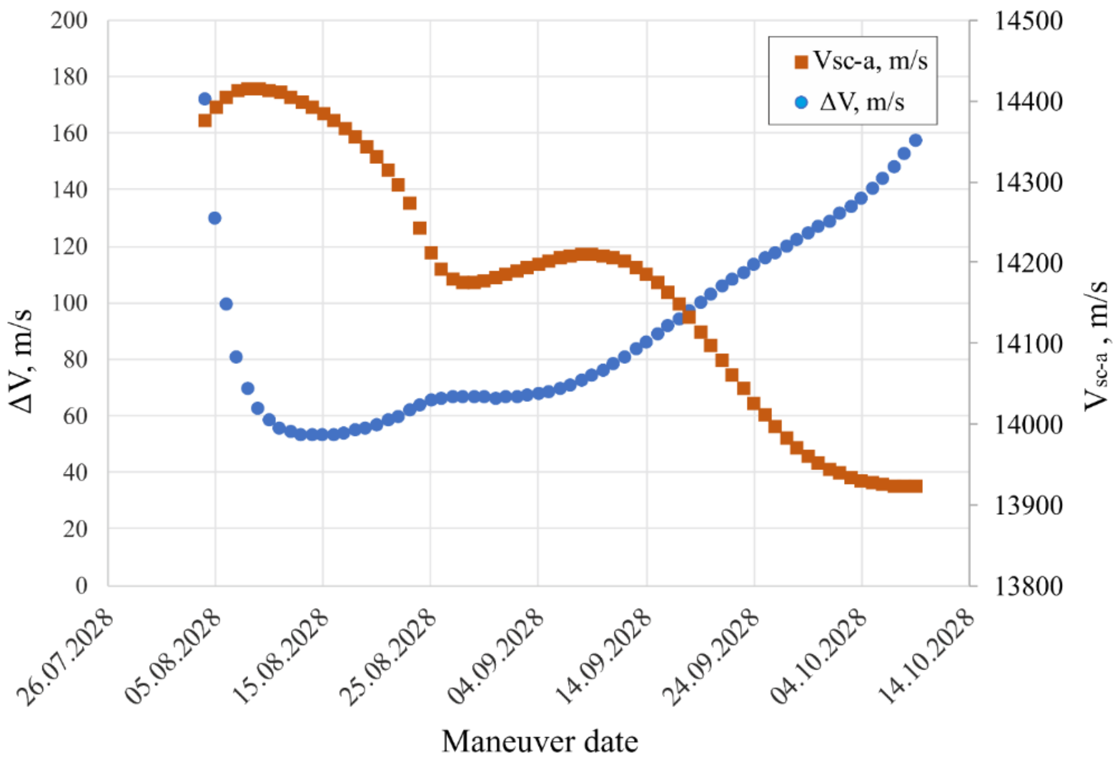


Figure 2. Dependence of the minimal ΔV required for the SRG transfer to the 1997 XF11 asteroid on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in blue)

As it is seen from the Figure 2, during the period from 04.08.2028 until 18.09.2028 the required impulse value does not exceed 100 m/s, that is completely satisfies the restriction on a maximum ΔV at 200 m/s. The relative velocity of the spacecraft during the close approach is about 13.9-14.5 km/s.

The transfer trajectory of SRG to the asteroid 1997 XF11 for the optimal date 14.08.2028 is shown at Figure 3.

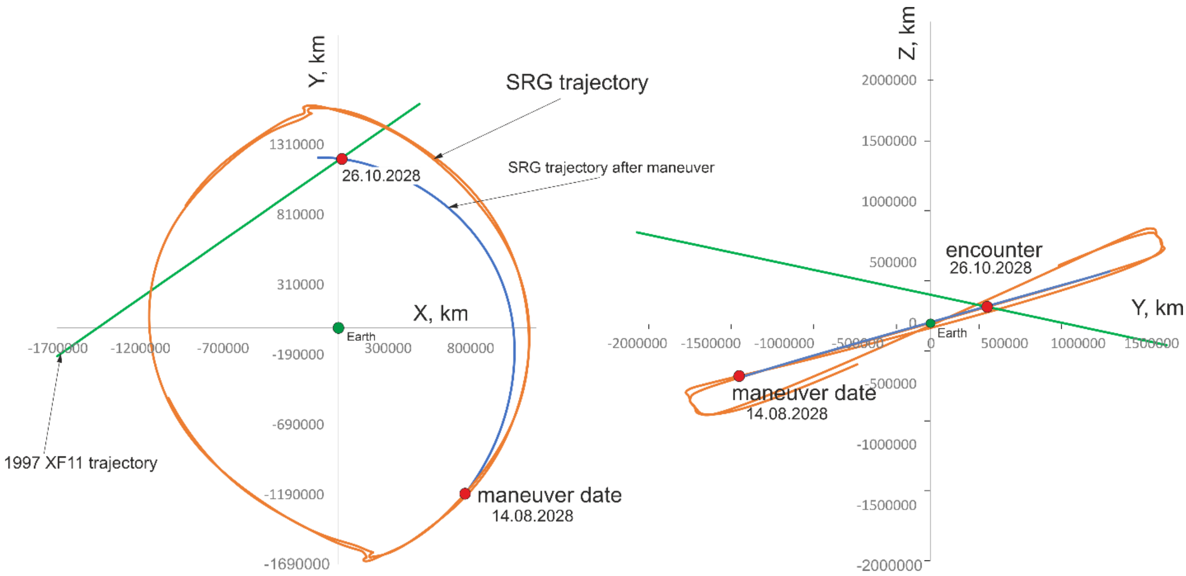


Figure 3. The SRG orbit around the Sun-Earth L_2 libration point (shown in orange) with the subsequent transition to the trajectory of an approach with 1997 XF11 (shown in blue) with the maneuver on 14.08.2028 and the flyby of the asteroid on 26.10.2028 in the geocentric inertial equatorial coordinate system

3.2. Asteroid (99942) Apophis

Another possible target for the extended mission of the SRG is the Apophis asteroid, since on 13.04.2029, it will approach the Earth at a distance of about 31,000 km [9, 10]. Due to this, Apophis, including the estimation of its mass, is considered as one of the most preferred targets for an additional research.

For the simulation of the close approach, Apophis ephemeris data obtained using NASA Horizons interface [11] were used. During the simulation we considered several possible scenarios of the extended mission.

3.2.1. Direct transfer to the close approach

The simplest way to approach Apophis for the SRG spacecraft is the direct flight from the libration point vicinity. Figure 4 shows the dependence of the minimum required impulse value on the date of its application for this transfer.

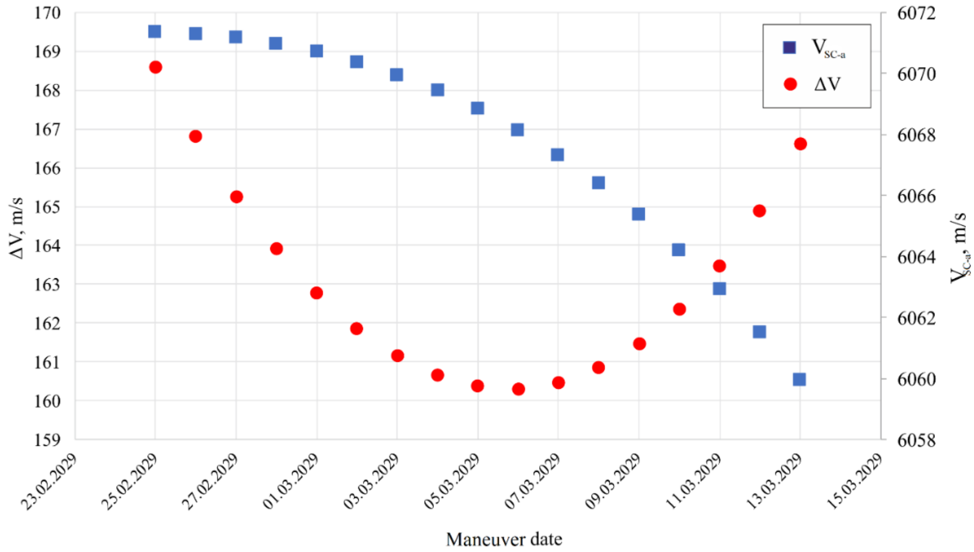


Figure 4. Dependence of the minimal ΔV required for the SRG transfer to Apophis on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in blue)

As one can see from the Figure 4, ΔV required satisfies the imposed restriction on its maximum value at 200 m/s only for dates between 25.02.2029 and 15.03.2029, for other dates of the impulse application the transfer requires very large values of ΔV.

The trajectory of the SRG approach to Apophis for the optimal date of the impulse application is shown at Figure 5. In this case the approach takes place before the Apophis perigee, at a distance of about 1 bil. km from the Earth, the relative velocity of the spacecraft is about 6 km/s.

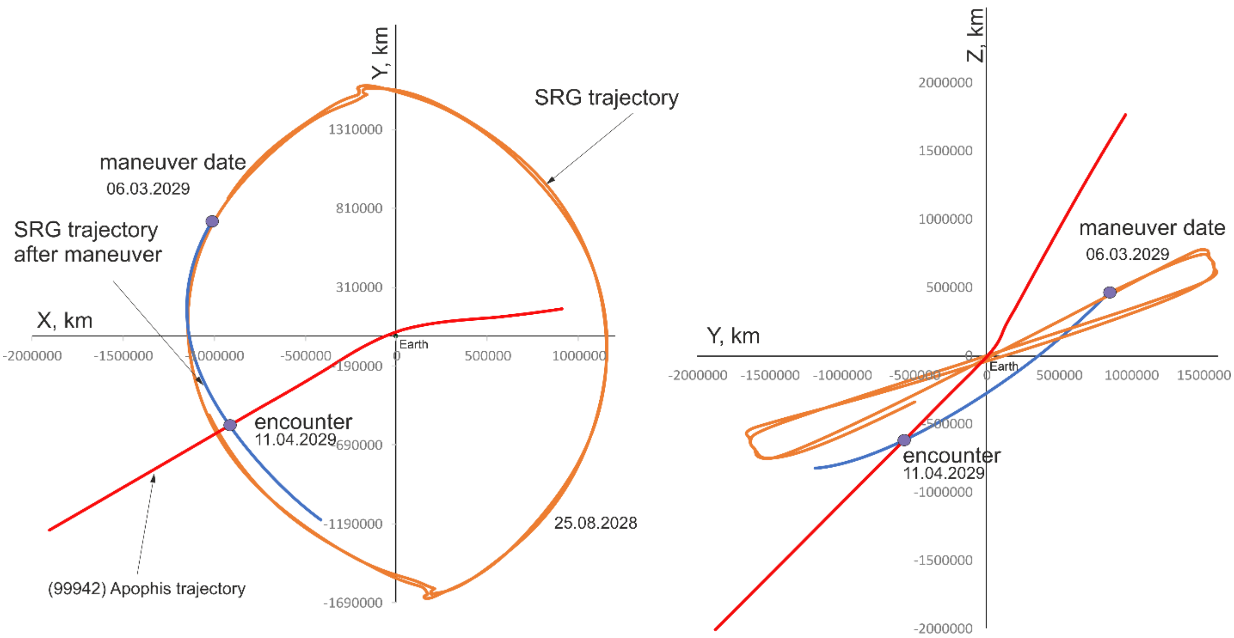


Figure 5. The SRG orbit around the L2 libration point (shown in orange) with the subsequent transition to the trajectory of an approach with Apophis (shown in blue) with the maneuver on 06.03.2029 and the flyby of the asteroid on 11.04.2029 in the geocentric inertial equatorial coordinate system

3.2.2. Observing Apophis from the SRG initial orbit

Another possibility of observing Apophis by the SRG is to study it from the current orbit in the vicinity of the Sun-Earth libration point L_2. Preliminary calculations show that in this case SRG will approach Apophis at a distance of about 300,000 km on 11.04.2029, the relative velocity of the SRG is about 6 km/s. This option only requires orbit maintenance corrections; see Figure 6.

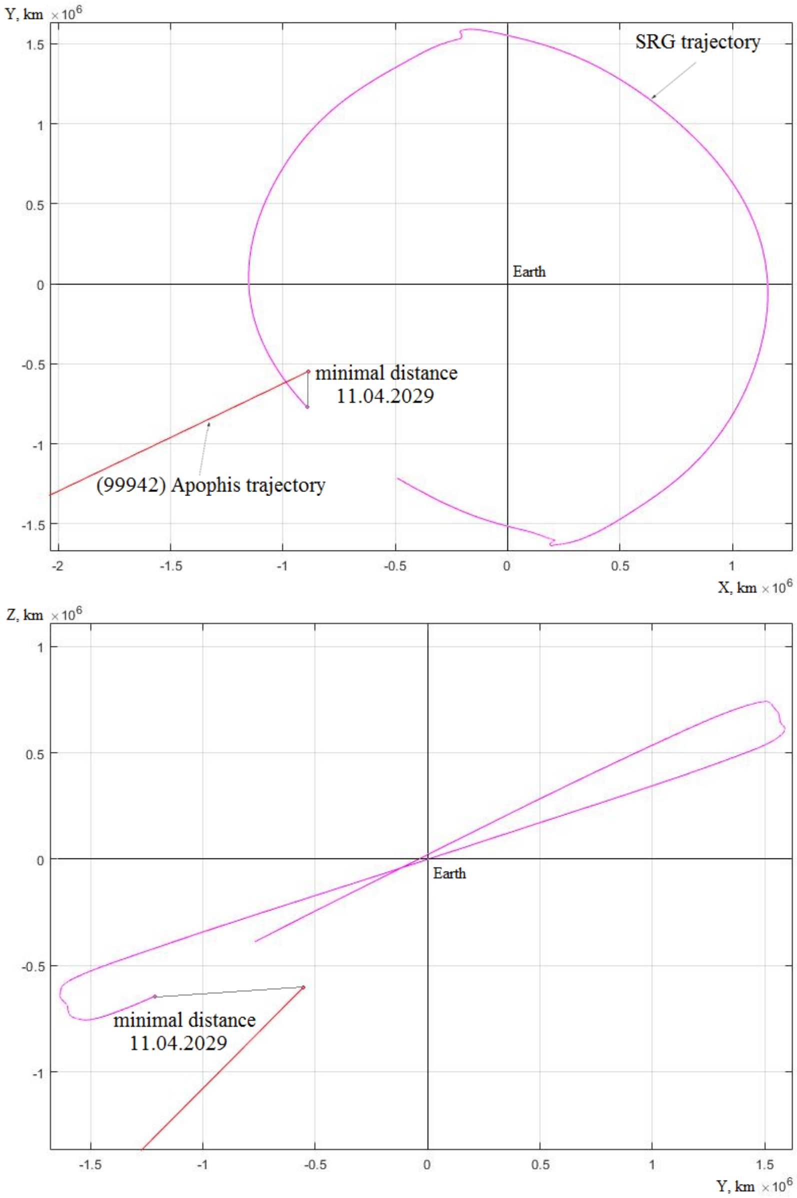


Figure 6. The SRG orbit around the L2 libration point (shown in violet) and Apophis' trajectory (shown in red) in the geocentric inertial equatorial coordinate system

3.3. Comets 289P/Blanpain and 300P/Catalina.

This section discusses perspectives of the SRG flight to comets 289P/Blanpain and 300P/Catalina. These comets are expected to approach the Earth at 2035-2036, respectively. Since the SRG can be maintained in a limited orbit by low impulses for quite a long time, these comets are of interest as objects to study by the spacecraft.

The comets will approach the Earth at a distance 0.05-0.08 a.u., so the use of a Moon gravity assist to reach these comets was considered to approach them. The results were obtained using the method of patched conics approximation. The ephemerides obtained with GMAT were used as the model of SRG motion, the ephemerides of the comets were obtained with high-precision integration in the JPL Horizons system.

Figures 7 and 8 show the dependences of the required momentum (ΔV) on the maneuver date. Note that the flight to 289P/Blanpain required two gravity assist maneuvers of the Moon, while the flight to 300P/Catalina required only one such maneuver.

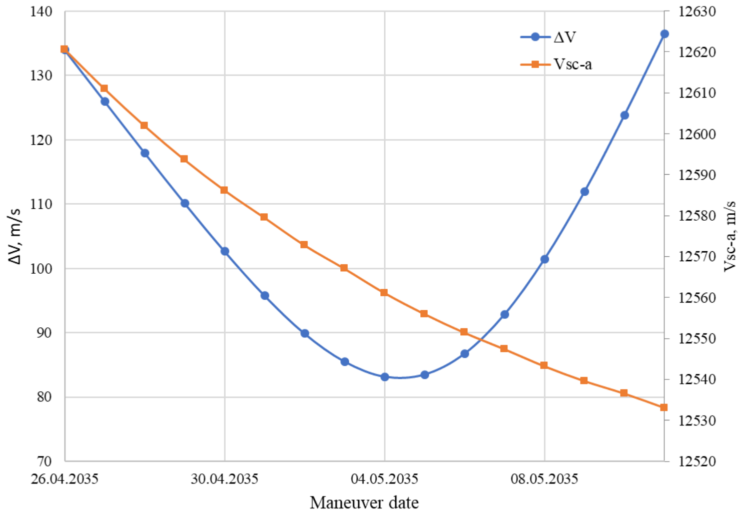


Figure 7. Dependence of the minimal ΔV required for the SRG transfer to 289P/Blanpain on the date of the impulse application (shown in blue), and the relative velocity of the spacecraft (shown in orange)

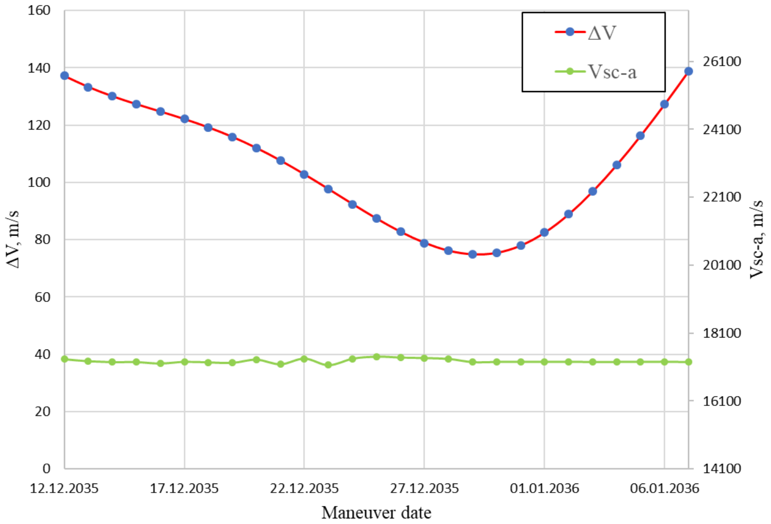


Figure 8. Dependence of the minimal ΔV required for the SRG transfer to 300P/Catalina on the date of the impulse application (shown in red), and the relative velocity of the spacecraft (shown in green)

As can be seen from Fig. 7 and 8, the SRG transfer to the comets 289P/Blanpain and 300P/Catalina for the considered entire time interval ΔV is always less than 200 m/s, and the relative velocity of the flyby 300P/Catalina in 2036 will always be 5 km/s greater than that of 289P/Blanpain in 2035.

4. Conclusion

As the considered examples show, an approach of studying potentially hazardous Near-Earth objects by a spacecraft after the completion of its main mission may lead to a number of interesting scientific ideas. In particular, the possibility of a spacecraft flyby in order to estimate masses of some asteroids and comets with sufficient accuracy has been confirmed, and it was shown that corresponding orbital maneuvers meet the Delta-V constraints and provide a spacecraft approach close enough for the minimum detectable deviation of their trajectories. It should also be noted that the proposed concept can be applied to other spacecraft for additional use at the final stages of their missions. The preliminary calculations presented above show that this approach is promising.

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