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About some transfer trajectories of spacecraft to potentially hazardous asteroids

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With the development of cosmonautics, it has become possible to fly to asteroids approaching the Earth within the Earth's sphere of action. To date, several flights to asteroids have been completed. Their duration took years. During this time, ephemeris tracking of the spacecraft and consideration of disturbances from the large planets of the Solar system are required. We built a transfer trajectory of the spacecraft from the near-Earth parking orbit to the target asteroid located inside the sphere of action of the Earth. The trajectories of the spacecraft between the near-Earth parking orbit and the target asteroid were built by computer simulation. Two models of the spacecrafts flight to potentially hazardous asteroids (PHA) inside the Earth's sphere of action are proposed. The calculations were performed in approximation of the geocentric problem of five bodies: The Earth, the Sun, the asteroid, the Moon and the spacecraft. The problem was solved numerically by the 15th-order Everhart method in Cartesian coordinates. The necessary short-term increments of speed are calculated using the example of three asteroids $2016RD34$, $2018NX$ and $2001AV43$, approaching the Earth in the coming decades. In our models, the duration of flights did not exceed two days. The results allow us to conclude that it is possible in principle to fly to potentially hazardous asteroids.

Keywords: Movement of spacecraft, transfer trajectory, numerical integration of the equations of motion, asteroids approaching the Earth

1 Introduction

To date, the number of space missions to bodies of the Solar system are more than 100. Over the past 60 years, the main transfer trajectories are elliptical and hyperbolic

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heliocentric trajectories. In order to optimize flights for changing the heliocentric velocity of motion of the spacecraft on the migratory path used gravity assist in the major planets gravitational fields (Siddiqi and Launius, 2002).

Interest in sending a spacecraft to an asteroid appeared in the late XX century, when it allowed the technological level of development of astronautics. The American space agency NASA became an innovator in 1996, which equipped the "NEAR" spacecraft to study the surface of the asteroid (433) Eros. After leaving the sphere of action of the Earth, the spacecraft was launched onto a heliocentric trajectory close to 1.5 astronomical units. This required an increase in the heliocentric velocity of the spacecraft by 4.5 km/s compared with the speed of the Earth. Before approaching the asteroid, the trajectories of the probe were corrected. The total change in speed was 1.2 km/s. Thus, after moving away from the Earth, it was necessary to change the speed of the probe by 5.7 km/s. Landing on its surface took place in 2001 (Dunham et al. 2002).

It was followed in 2003 by the Japanese aerospace research agency JAXA with the "Hayabusa" probe, designed to study the composition of the soil of the asteroid (25143) Itokawa. In 2006, a close rapprochement with this asteroid took place and the "Minerva" probe was landed on its surface (Fujiwara et al. 2006).

After the break, the JAXA agency launched the "Hayabusa-2" spacecraft in 2014 to study the surface of the asteroid (162173) Ryugu. The spacecraft approached the asteroid and landed on its surface in June 2018 (Sarli and Tsuda 2017).

In 2016, NASA sent the "OSIRIS-REx" interplanetary station to the asteroid (101955) Bennu. Rapprochement with this asteroid was planned for 2019 (Williams et al. 2018).

In addition to the listed space missions to asteroids, in 2004 the European Space Agency, in collaboration with NASA, launched the "Rosetta" probe to the comet 67P/ChuryumovGerasimenko. In 2014, for the first time, the descent vehicle was soft-landed on the surface of a small celestial body (Jurado et al. 2016).

Thus, over the past 10 years, the relevance of space missions to the Near Earth Asteroids (NEA) has grown significantly. It is important to note that in all these space missions to asteroids and comets, the approach of spacecraft with targets occurred at significant geocentric distances. In the process of constructing transfer orbits in these missions, it was necessary to plan multipulse maneuvers using the Earth's gravitational field. This increased flight time, but reduced fuel consumption (Dunham et al. 2002). The advantage of such flights can be considered as the possibility of multiple corrections and the possibility of approaching various asteroids, near which the transfer trajectory lies. For example: asteroids (21) Lutetium and (2867) Steins (Jurado et al. 2016). Such space missions are accompanied by additional difficulties arising from the small size of the targets. The diameters of all asteroids are less than 1000 km and almost all of them are irregular in shape and look like rocky fragments (Binzel et al. 2002).

The object of our research is the possible transfer trajectories to asteroids approaching the Earth (NEA). NEAs are called asteroids whose orbits intersect the Earth's orbit and have a perihelion distance of less than 1.3 AU (Center for Near-Earth Object Studies (CNEOS)).

The purpose of the work is to build a transfer trajectory of a spacecraft that flies from a near-Earth parking orbit to a target asteroid, while moving inside the Earth's

sphere of action and its optimization.

We offer a new approach to the construction of transfer trajectories to asteroids from the NEA group, which cross the Earth's sphere of action in the coming decades. The flight is performed near the moment of approach of the asteroid to the Earth. In this case, the length of the transfer trajectory is minimal and all of it is located in near-Earth space. This ensures a short-term flight, although the spacecraft experiences significant disturbances from the side of the Earth. Even small errors in the initial part of the trajectory quickly increase, and the time for correction is limited. This significantly increases the requirements for the accuracy of calculations and implementation of transfer trajectories.

2 Main part

The subject of our research is the orbits of asteroids in the sphere of action of the Earth and the transfer trajectories of the spacecraft toward them.

According to the classification of the International Astronomical Union, asteroids approaching the Earth are divided into 4 groups: Atira, Aten, Apollo and Amor. This classification is based on the values of the perihelion and aphelion orbital distances of asteroids (Center for Near-Earth Object Studies (CNEOS)). Potentially hazardous asteroids (PHA) are distinguished from the group of asteroids that approach the Earth. The main sign of the PHA orbit is its distance to the Earth's orbit; it is not more than 0.05 AU (Center for Near-Earth Object Studies (CNEOS)). The large number of objects of this type poses an urgent problem of asteroid-comet hazard. PHA can penetrate the Earth's sphere of action, the radius of which exceeds 900 thousand kilometers (Ovchinnikov 2016).

We propose to take advantage of the close proximity of the PHA with the Earth for the flight of an automatic probe to one of these asteroids. Previously, the probe should be placed in a near-Earth parking orbit. The position of the plane of this orbit depends on the position of the plane of the orbit of the target asteroid. In this orbit, the probe makes several turns and at a strictly defined point turns on the engines to enter the transfer orbit to the target asteroid. We picked several asteroids according to the criteria proposed by us below, set the parking orbits of the spacecraft in near-Earth space for each selected asteroid, and calculated the approximate Kepler elements of the transfer orbits to the target asteroids.

2.1 Primary definition of transfer orbit

To fly to the asteroid, it is necessary to build a trajectory of the spacecraft that has common points with the parking orbit and the orbit of the asteroid. We used the method of searching for an orbit by two positions and a parameter (Subbotin M.F., 1968). The first position is chosen in the near-Earth parking orbit of the spacecraft, this is the starting point, the second is in the asteroids orbit, this is the meeting point of the spacecraft with the target asteroid. To apply this method, it is necessary that the geocentric angle between these points is less than 90°.

To search for the starting point, a search was performed for the positions of the spacecraft in the parking orbit with a step of 30 minutes. We searched for the meeting

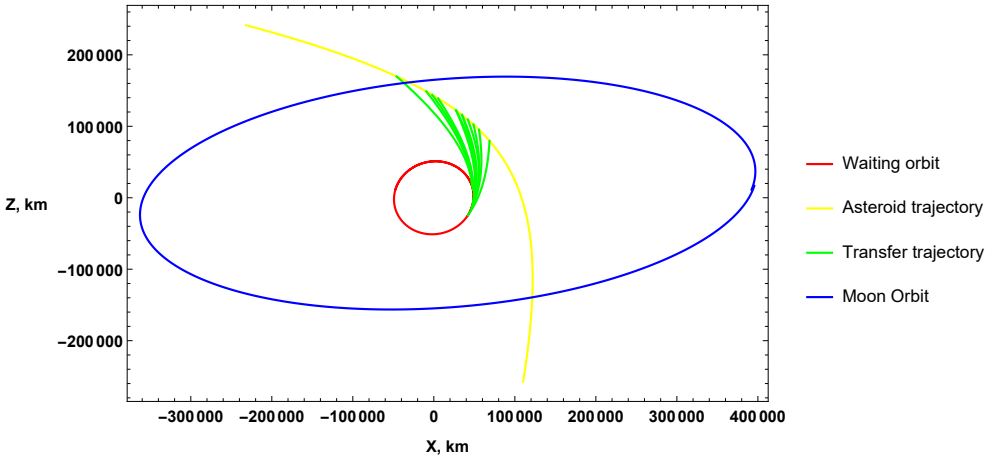


Figure 1 Variants of transfer trajectories from one of the parking orbit 2 to the asteroid 2016RD34.

point by sorting through the positions of the target asteroid in its orbit inside the Earth's sphere of action in 1 hour increments. An example of the obtained flight paths is shown in Figure 1 for the asteroid 2016RD34. The corresponding state vectors of the PHA are borrowed from the JPL NASA web resource. We opted for flight orbits for which the value of the velocity increments at the starting point from the parking orbit and at the meeting point of the spacecraft with the asteroid is minimal. In addition, we selected orbits for which the angles between the speeds of the spacecraft in all orbits (parking orbit, transfer orbit and asteroid trajectory) would be as small as possible (Wakker 2015). To construct all the orbits, we used the Cartesian geocentric ecliptic coordinate system.

2.2 Target asteroid selection

Many years of experience in searching and cataloging PHA orbits has been accumulated at the NASA Jet Propulsion Laboratory. The web resource "Center for Near-Earth Object Studies (CNEOS)" provides access to information about the close proximity of small celestial bodies and the Earth. The information is presented in the form of tables indicating the date and time of approaching the Earth, the distance between the asteroid and the center of the Earth at that moment, the values of the geocentric speed of the asteroid, the absolute magnitude and the estimated value of the asteroids diameter. According to these data, it can be concluded that everyday the Earth is approaching several asteroids. It follows that in the coming years, the Earth will be approaching thousands of asteroids. This opens up the possibility of choosing the path of the PHA, in accordance with the criteria we set.

By δV consumption one of the most expensive maneuvers is changing the orbital plane (Ilin and Kuzmak 1976). We demanded that the PHA orbit should have a slight inclination to the ecliptic plane of not more than 5°. The second requirement is that the minimum PHA distance at the moment of close approach to the Earth is less than the radius of the Earth's sphere of action. The third requirement is the geocentric

velocity of the asteroid in near-Earth space should differ as little as possible from the geocentric velocity of the spacecraft.

In accordance with the set requirements, we selected the orbits of the three PHAs shown in Table 1.

Table 1 Potentially hazardous asteroids with the lowest geocentric speed, entering into the orbit of the Moon.

Asteroid	Inclination of the orbital plane to the ecliptic ±0.1 deg	Time closest approach	The minimum distance ±100 km	Asteroid speed in geocentric reference system ±0.01 km/s
2016$RD34$	4.1	2047–09–05 11±6 (hour)	103 200	3.01
2018NX	4.2	2086-07–05 21±5 (hour)	267 100	3.70
2001$AV43$	0.1	2029–11–11 15±1 (hour)	313 100	3.99

2.3 Refinement of the transfer orbit

The orbits of the transfer trajectories to these asteroids lie in near-Earth space. The approximation of the two-body problem is poorly suited to describe the motion of the spacecraft due to significant disturbances from the side of the Moon and the Sun. Therefore, we moved on to the model of the geocentric problem of five bodies: The Earth, the Sun, the asteroid, the Moon, and the spacecraft (Merritt 2006). We neglected the masses of the spacecraft and the disturbing acceleration caused by the pressure of sunlight on the surface of the spacecraft with a characteristic mid-section of 4 m^2 - 2.7 $\cdot$ 10^{-10} m/s^2 (El-Saftawy et al. 1998). We consider this acceleration to be small in comparison with the acceleration of the spacecraft toward the Earth, the magnitude of which varies from 0.44 to 0.01 m/s^2 (Merritt 2006).

Given these limitations, we formulated the following system of equations of motion for a spacecraft in a Cartesian geocentric ecliptic coordinate system:

$$\begin{cases} \dfrac{d^2x_\kappa}{dt^2} = -GM_0\dfrac{x_\kappa}{r_\kappa^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{x_\kappa - x_i}{r_{\kappa i}^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{x_i}{r_{i0}^3}, \\ \dfrac{d^2y_\kappa}{dt^2} = -GM_0\dfrac{y_\kappa}{r_\kappa^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{y_\kappa - y_i}{r_{\kappa i}^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{y_i}{r_{i0}^3}, \\ \dfrac{d^2z_\kappa}{dt^2} = -GM_0\dfrac{z_\kappa}{r_\kappa^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{z_\kappa - z_i}{r_{\kappa i}^3} - G\sum\limits_{i=1}^{4} M_i\dfrac{z_i}{r_{i0}^3}, \\ i \neq \kappa, \end{cases} \quad (1)$$

where indices κ – spacecraft, 0 – Earth, i – Sun, asteroid and Moon; G – gravitational constant, M_0 – mass of the Earth and M_i – masses of the Sun, asteroid and Moon, $r_\kappa = \sqrt{x_\kappa^2 + y_\kappa^2 + z_\kappa^2}$,

$r_{\kappa\, i} = \sqrt{(x_\kappa - x_i)^2 + (y_\kappa - y_i)^2 + (z_\kappa - z_i)^2}$ and
$r_{i\, 0} = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$ corresponding distances. The numerical integration of this system of equations was carried out by the 15th order Everhart method (Everhart, 1974).

2.4 Parking orbit search

The spacecraft is placed in advance in a geocentric parking orbit. The plane of the parking orbit is chosen close to the plane of the orbit of the PHA. As a parking orbit, we used a high circular geocentric orbit. We examined two parking orbits.

In the first case (orbit 1), its radius was chosen equal to the smallest distance between the asteroid and the Earth, that is, the orbits are in contact. The position of the spacecraft in this orbit is set so that it comes to the point of contact simultaneously with the asteroid. Due to the tangency of their orbits, at the meeting point the velocity vectors of both bodies are parallel up to the inclination of the heliocentric orbit of the asteroid – 4.1, 4.2 and 0.1 degrees (Table 1). Approximately the speed of the spacecraft we got from the energy integral:

$$V = \sqrt{\frac{GM_0}{r}}, \tag{2}$$

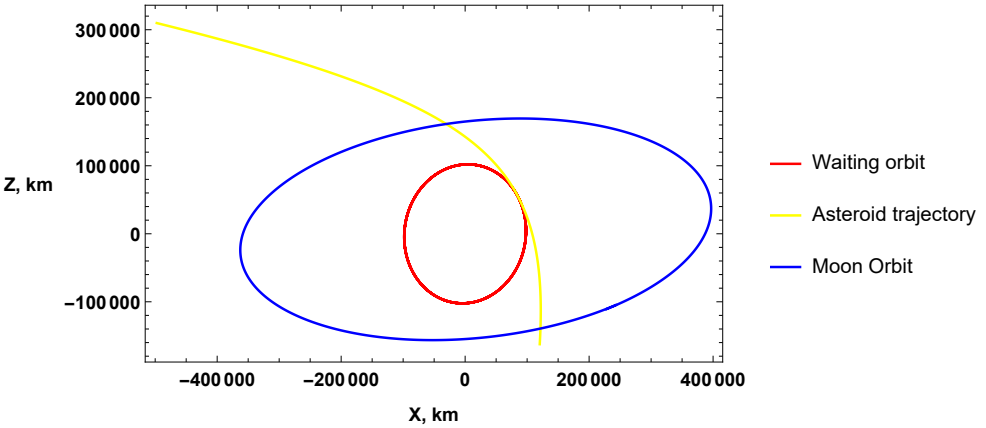
where GM_0 Earth's gravitational parameter and r – the radius of the parking orbit.

To equalize the speed of the spacecraft and the asteroid, it is necessary to perform a short-term increment of speed. The values of the velocity increments for the corresponding asteroids are shown in Table 2. In this case, as such, there is no transfer trajectory, but this maneuver requires high precision. If you need to correct the deviations from the set values, then this will have to be done within an extremely limited time interval.

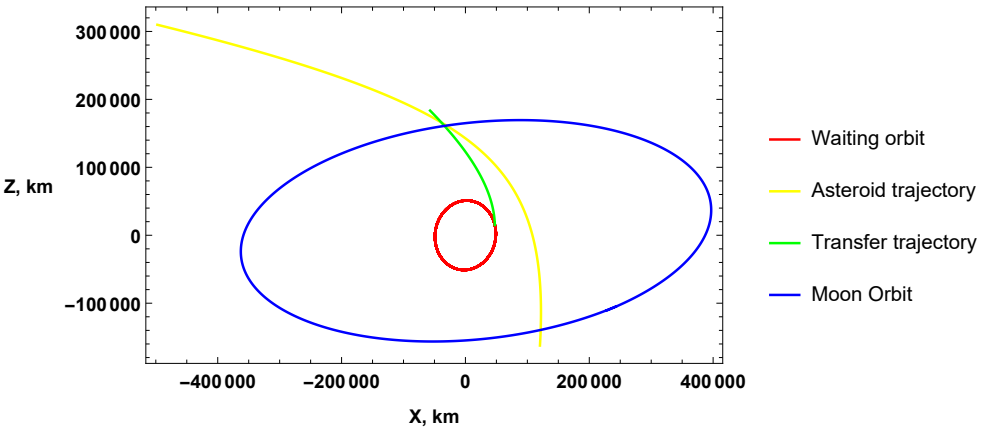
Table 2 Some parameters of flights to potentially hazardous asteroids inside the Earth's sphere of action.

Asteroid	Orbit 1	Orbit 2				
	Speed increase at the point of contact ±0.01 km/s	Speed increase at the starting point ±0.01 km/s	Speed increase at the meeting point ±0.01 km/s	Starting angle ±0.1 deg	Meeting angle ±0.1 deg	Time of flight ±10 min
2016RD34	1.05	1.17	0.24	13.2	15.6	1 070
2018NX	2.48	0.81	1.91	8.8	19.3	2 720
2001AV43	2.86	1.23	1.67	21.1	20.9	1 650

To obtain less stringent requirements for speed equalization, we considered the second version of the parking orbit (orbit 2). In this case, the radius of the parking orbit was chosen equal to half the smallest distance between the asteroid and the Earth. The calculation results for the asteroid 2016RD34 are shown in Figure 2. In Figure 2a, the parking orbit 1 and a maneuver at the point of contact with the



a. Orbit 1



b. Orbit 2

Figure 2 The location of the orbits when flying to the asteroid 2016RD34.

asteroid trajectory are shown. In Figure 2b, the parking orbit 2 and the transfer trajectory of the spacecraft are presented. The results of calculations of similar flight options to the asteroids 2018NX and 2001AV43 have a similar appearance.

This made it possible to obtain an estimate of the characteristic time of flight from the parking orbit to the orbit of the asteroid. The duration of all flights is from 1 to 2 days. The values of the obtained increments of speed and angles between the trajectories at the starting and meeting points, and the flight time for the corresponding asteroids are also shown in Table 2.

Since the parking orbit 1 and orbit 2 belong to high orbits (significantly higher than the geostationary one), the difference in the speeds required to enter these orbits after launching from the Earth's surface does not exceed 150 m/s. Such a slight difference cannot affect the choice of a parking orbit.

For some improvement in the flight paths, we performed the variation of the parking orbit 2 along the radius. We randomly selected the variation value equal to

1/8 of the minimum distance when approaching the Earth for each target asteroid. As a result of sorting the corresponding transfer trajectories, we received a significant decrease in the increment of the velocity of the spacecraft at the meeting point with the target asteroid 2016RD34. For example, if, prior to optimizing the parking orbit, speed increments at the starting point of 1.17 km/s and the meeting point of 0.24 km/s were required, then after it at the starting point of 1.07 km/s and the meeting point of only 0.03 km/s (the first and third lines of Tables 2 and 3, respectively). In this case, the angles between the velocity vectors decreased by more than ten times. The values of the obtained increments of speed and angles between the trajectories at the starting and meeting points, and the flight time for the corresponding asteroids from some geocentric transfer orbits are also shown in Tables 3, 4 and 5.

Table 3 Minimum flight parameters to the asteroid 2016RD34. Approach 2047–09–05.

Trajectory variant	Speed increase at the starting point ±0.01 km/s	Speed increase at the meeting point ±0.01 km/s	Starting angle ±0.1 degrees	Meeting angle ±0.1 degrees	Time of flight ±10 min
1	0.95	0.19	1.0	2.0	1 100
2	0.91	0.26	2.4	3.4	740
3	1.07	0.03	0.5	0.2	850
4	0.80	0.38	3.0	6.2	1 670
5	0.96	0.30	4.9	3.0	1 430

Table 4 Minimum flight parameters to the asteroid 2018NX. Approach 2086–07–05.

Trajectory variant	Speed increase at the starting point ±0.01 km/s	Speed increase at the meeting point ±0.01 km/s	Starting angle ±0.1 degrees	Meeting angle ±0.1 degrees	Time of flight ±10 min
1	1.29	1.56	26.9	9.0	830
2	1.25	1.59	26.1	8.6	860
3	1.55	1.21	17.8	11.2	980
4	1.35	1.34	15.0	9.6	1 130
5	1.60	1.16	8.3	13.1	1 370
6	1.48	1.21	5.5	11.6	1 590

Table 5 Minimum flight parameters to the asteroid 2001AV43. Approach 2029–11–11.

Trajectory variant	Speed increase at the starting point ±0.01 km/s	Speed increase at the meeting point ±0.01 km/s	Starting angle ±0.1 degrees	Meeting angle ±0.1 degrees	Time of fight ±10 min
1	1.55	1.53	8.8	11.9	1 010
2	1.54	1.51	16.9	7.0	1 730
3	1.30	1.69	4.5	6.6	2 780
4	1.45	1.58	10.8	9.2	1 880
5	1.57	1.60	8.0	15.7	2 060

3 Conclusions

Until now, spacecraft flights to asteroids from the NEA group have been carried out in complex heliocentric orbits. Their duration exceeded one year. We propose to perform a flight inside the Earth's sphere of action to some asteroids from the PHA group.

To reduce the cost of putting the spacecraft into orbit of the flight to the asteroid, we formulated three requirements for the orbits of the PHA: the plane of the asteroid's orbit should be close to the ecliptic plane, the minimum distance at the moment of closest approach to the Earth should be less than the radius of its sphere of action, and the geocentric speed of movement of the asteroid should be as close as possible to the speed of the spacecraft. From our point of view, the asteroids $2016RD34$, $2018NX$ and $2001AV43$ satisfy the set requirements.

Initially, the spacecraft is launched into a circular geocentric parking orbit. We examined two parking orbits: with a radius equal to the smallest distance of the asteroid from the Earth and also eight variants of orbits of other radii.

To search for the transfer trajectory from the parking orbit to the asteroid, we used the model of the geocentric problem of five bodies: The Earth, the Sun, the asteroid, the Moon and the spacecraft. The numerical simulation of the motion was carried out in a Cartesian rectangular coordinate system by the 15th-order Everhart method.

As a result of modeling, we received a set of possible transfer trajectories to asteroids inside the Earth's sphere of action. The most successful is the transfer trajectory to the asteroid $2016RD34$. For the transition from the parking orbit to it, a velocity increment from 0.80 to 1.07 km/s is required, and for the transition from it to the asteroids orbit, a velocity increment from 0.03 to 0.38 km/s is required. For the flight to the asteroids $2018NX$ and $2001AV43$, large increments of the speed increment were obtained. According to the authors, it is possible to search for transfer trajectories with lower values of the increment of speeds.

The flight paths we proposed require significantly lower velocity increments than, for example, the flight to the asteroid (433) Eros. Then, after reaching a parabolic geocentric trajectory (11.2 km/s), it was necessary to change the speed of the probe by 5.7 km/s. The flight lasted for years. When flying to PHA, after reaching a high circular orbit (speed less than 11.0 km/s), it will be necessary to change the speed of the spacecraft by 1–3 km/s. The flight will take no more than two days.

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