NEAR MOON GRAVITY ASSIST MANEUVERS AS A TOOL FOR ASTEROID CAPTURE ONTO EARTH SATELLITE ORBIT

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Abstract: *Gravity assist maneuvers have become broadly applied technology for contemporary spacecraft missions allowing sufficiently to decrease demanded amount of propellant. Efficiency of such approach looks even more impressive for the cases when it is used for small near Earth asteroid motion control when the latter are targeted to hazardous sky objects in order to deviate them from Earth collision using kinetic impact by controlled small asteroid [1]. In the paper the similar methods are proposed for solution of the problem to capture asteroid onto Earth satellite orbit by the method different from the one proposed for Keck project [2]. After delivering spacecraft on the surface of the asteroid and its anchoring, some small delta –V is applied which transfers asteroid to trajectory of gravity assist maneuver near Earth. The goal of this maneuver is to put asteroid onto the orbit resonant with the Earth orbital motion. The latter orbits are considered as those which are among most convenient for the further operations aimed to capture asteroids onto Earth satellite orbits. This procedure consists from multiple near Earth gravity assist maneuvers executed under condition that after each maneuver the orbit is kept to be resonant. It should be mentioned use of only single near Moon gravity assist maneuver to capture asteroid on Earth satellite orbit demands rather low relative velocity with respect to Earth what drastically reduces the possibilities to realize this approach. To overcome this obstacle one needs to execute proposed multiple near Moon gravity assist maneuvers. The results of applying such conception are demonstrated by presenting several asteroid capture onto Earth satellite orbit.*

Keywords: near-Earth asteroids, asteroid hazard, asteroid capture, flight dynamics.

1.Introduction

The application of rocket engines is known to be a standard method of changing the orbits of spacecraft, including the capture of a flyby spacecraft into a planet's (for example, the Earth) satellite orbit. However, this method cannot be used in pure form for asteroids, because the mass of even small asteroids exceeds the mass of present-day spacecraft by several orders of magnitude. Therefore, the American Keck project [2], whose task is to deliver a small asteroid to an Earth satellite orbit for a subsequent study, envisages using a gravity-assist maneuver near the Moon, in other words, a fairly close flyby of the Moon, in addition to a rocket engine. As a result of such a maneuver, the asteroid passes from a hyperbolic orbit relative to the Earth to an Earth satellite orbit. In this case, however, the hyperbolic velocity is expected to be reduced dramatically almost to the parabolic one by the engine before the gravity-assist maneuver. This requires high fuel consumption, because this reduction in the Keck project reaches values exceeding many hundreds of meters per second even in the best cases. Otherwise, the gravity-assist maneuver is not enough to capture the asteroid, and the latter will leave forever the Earth's sphere influence after this maneuver.

In the concept presented below, this difficulty is overcome by performing a specially planned sequence of operations to capture the asteroid into an Earth satellite orbit whose main part are multiple gravity assist maneuvers near the Moon and the Earth, so that the necessary total change in the asteroid velocity through the switch-on of the rocket engine is kept within 20 meters per second.

2. Asteroid Transfer to the Orbits Resonant with the Motion of the Earth

It should be noted that the gravity-assist maneuvers of an asteroid only near the Earth cannot change the magnitude of the asteroid velocity relative to the Earth after their execution but can change only its direction, in contrast to the velocity in the reference frame associated with the Sun. Nevertheless, even such maneuvers extend the possibilities of asteroid research, because they can change the magnitude of the asteroid velocity relative to the Sun. Previously [1,5], we analyzed the gravity-assist maneuvers near the Earth aimed at transferring asteroids to orbits resonant with the Earth's motion, i.e., with orbital periods relating to the Earth's period as integers. In particular, we gave a list of asteroids that could be transferred by gravity assist maneuvers near the Earth to orbits with a period of one Earth year provided that the necessary impulse imparted to the asteroid for its transfer to the maneuver trajectory did not exceed $20ms^{-1}$. We then showed that once the asteroid had been placed in a resonant orbit, it became possible to change its orbital parameters, such as the inclination and eccentricity, in a fairly wide range while its orbit remained resonant. In this way, conditions are achieved when one can send spacecraft to an asteroid and return them every year and, in the case where the asteroid has been transferred to the orbit with a maximum inclination to the ecliptic plane, every six months. Figure 1 presents a scheme of operations to transfer an asteroid to an orbit resonant with the Earth's motion using a gravity-assist maneuver near the Earth.

Below, we describe a method of using another advantage of resonant orbits: the possibility of multiple gravity-assist maneuvers near the Moon under conditions when the asteroid orbit in its motion relative to the Earth remains hyperbolic, i.e., the asteroid leaves the Earth's sphere of influence after each maneuver near the Moon, but the asteroid period in its motion around the Sun remains constant, equal to one year.

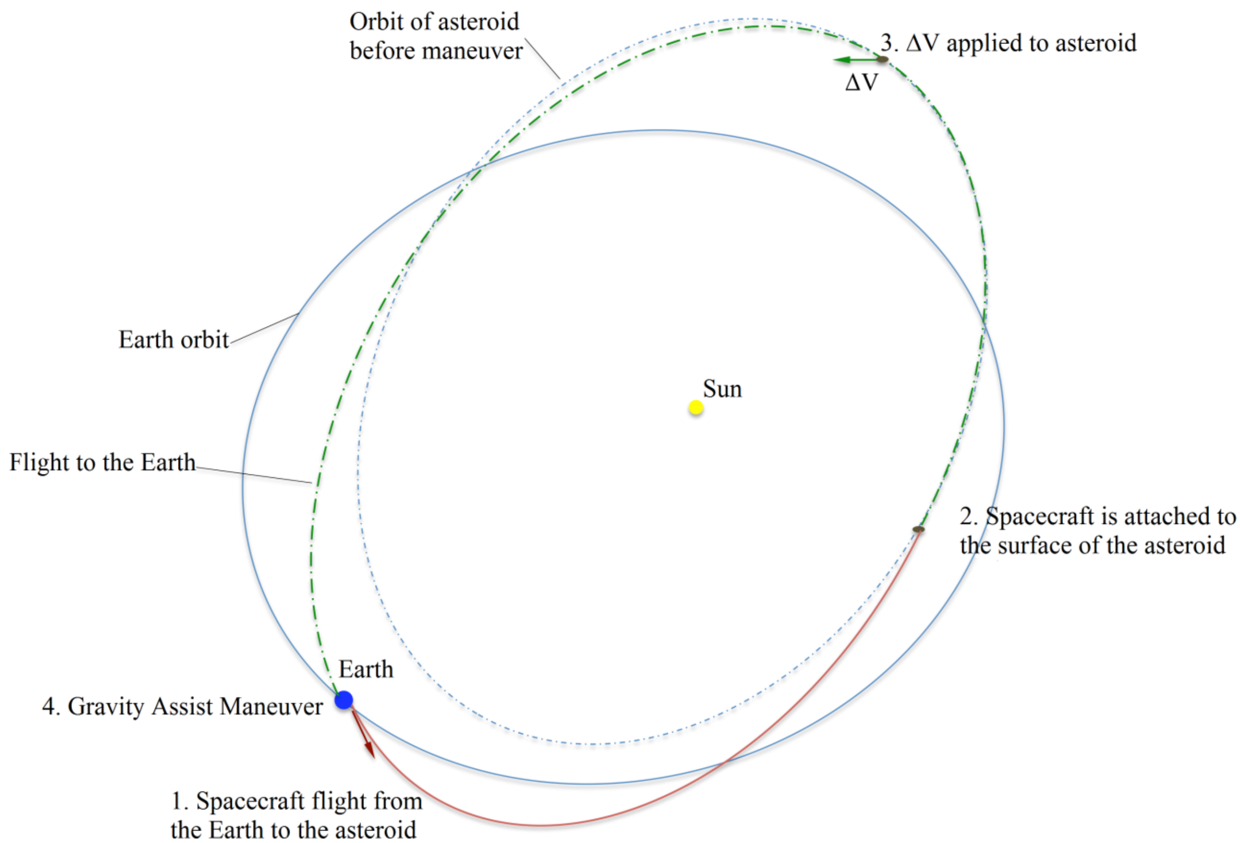

Figure 1. The first four steps of the mission to capture the asteroid 2014 QN66 into an Earth satellite orbit. After the fourth step, the asteroid is in an orbit resonant with the Earth's orbit

3. Gravity Assist Maneuver Near Moon

The availability of yearly flights to asteroids after their transfer to resonant orbits gives noticeable advantages for unmanned missions, but the impossibility of a sufficiently fast return of the crew to the Earth in case of emergency remains a serious disadvantage for manned missions. It is this circumstance that prompted the developers of the Keck project to choose an orbit close to the lunar one to place the asteroid being captured. In this variant of an orbit, the crew can be returned to the Earth in one or two weeks in case of emergency. This gives grounds for seeking efficient methods of capturing an asteroid into an Earth satellite orbit. As has been mentioned above, in the case where the periods are equal, the asteroid returns to the Earth yearly. The parameters of its flyby near the Earth are achieved by small corrective velocity impulses imparted to the asteroid by the rocket engine. Basically, a gravity-assist maneuver is performed during each such flyby. One can keep the orbit resonant and, at the same time, change the declination of the relative Earth flyby velocity vector relative to the ecliptic plane by choosing and realizing the control parameters. In addition, the Moon's flyby parameters can be changed. Thus, a double gravity-assist maneuver can be realized: in the Earth's sphere of influence in the Sun–Earth system and in the Moon's sphere of influence in the Earth–Moon system. The term "sphere of influence" is used here for methodological purposes to describe the procedure of choosing the parameters of an orbit passing in a close vicinity of the Moon in such a way that the magnitude of the asteroid velocity vector relative to the Earth decreases, while the magnitude of its velocity in the reference frame associated with the Sun remains equal to the Earth's one due to the influence of the Moon's gravitational field in combination with the Earth's gravitational influence. As a result, the orbital period of the asteroid about the Sun is kept equal to (or a multiple of) the Earth's orbital period. Therefore, the asteroid again returns to the Earth in a year (or a whole number of years) if its velocity relative to the Earth after the first flyby remained greater than the parabolic one, i.e., the asteroid left the Earth's sphere of influence. The new flyby of the Earth–Moon system is planned similarly to the preceding one. In this case, the main condition for each flyby is to keep the orbit of our controlled asteroid resonant (with the Earth's one) in its motion relative to the Sun when performing the task of decreasing (at least not increasing) the asteroid velocity relative to the Earth until this velocity becomes less than the parabolic one. Thus, the asteroid will be captured into an Earth satellite orbit at a sufficient number of lunar flybys.

In other words, the key feature of the proposed method is the multiplicity of gravity-assist maneuvers near the Moon achieved here, during each of which
the asteroid velocity decreases relative to the Earth and remains constant relative to the Sun.

4. Examples of Capturing an Asteroid into an Earth Satellite Orbit

As an example, the last seven rows in Tab.1 give the sequence of operations and their characteristics for the missions to capture the asteroids 2014 QN266 and 2012 AP10 into Earth satellite orbits.

Table 1. Operations characteristics for asteroids capture

Asteroid	2014 QN266	2012 AP10
Magnitude	26.3	26.4
Asteroid size	15 ≈ 30 m	15 ≈ 30 m
Spacecraft start date from Earth	2028-04-27	2038-01-20
Boosting impulse at start from low circular orbit	3.3 km/s	3.48 km/s
Spacecraft landing date on asteroid	2029-02-21	2038-05-14
ΔV of braking for spacecraft landing on asteroid	590 m/s	870 m/s

Execution date of maneuver for transfer to resonant orbit	2040-05-16	2042-07-11
ΔV of maneuver for spacecraft transfer to orbit resonant with Earth	18.77 м/с	11.85 м/с
Date of perigee passage	2041-03-15	2043-01-01
Maneuver number near Moon	Maneuver date near Moon and decrease in velocity relative to Earth km/s	
1	2043-03-15 3.19 – > 2.77	2050-12-30 3.77– > 3.63
2	2044-03-15 2.77 – > 2.19	2054-12-29 3.63 – > 3.41
3	2047-03-15 2.19 – > 1.96	2056-12-28 3.41– > 3.11
4	2048-03-15 1.96 – > 1.05	2059-12-28 3.11 – > 3.02
5		2062-12-27 3.02 – > 2.57
6		2063-12-27 2.57 – > 2.11
7		2064-12-26 2.11 – > 1.38

It can be seen from Table 1 that the entire mission to capture the asteroid 2014 QN266 takes 20 years, from the start of the spacecraft from a low circular orbit to the execution of the last gravity-assist maneuver near the Moon that transfers the asteroid to an Earth satellite orbit. A total of four maneuvers near the Moon are required. Figure 2 presents the velocity vectors of the asteroid and the Moon before and after the execution of capture operations near the Moon as an illustration of the gravity-assist maneuvers for the asteroid 2014 QN266 performed in the vicinity of the Moon.

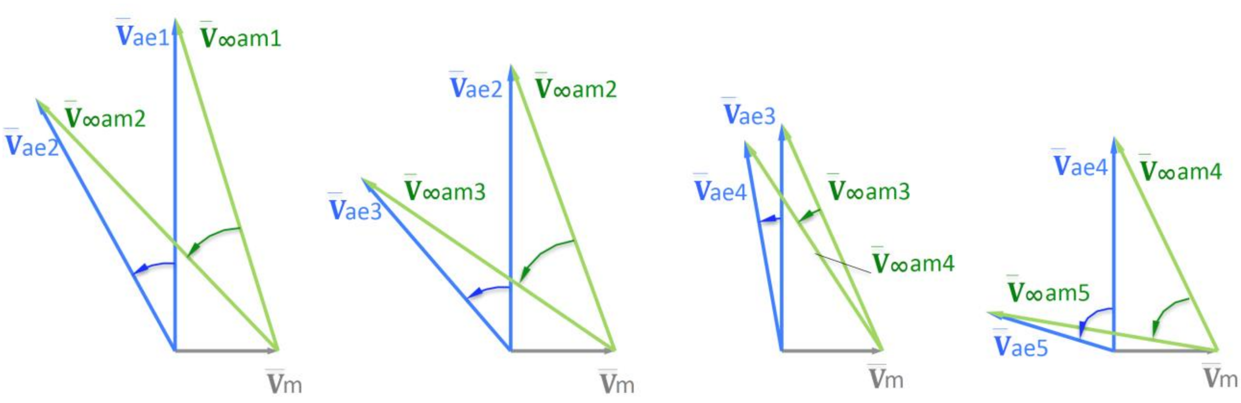

Figure 2. Gravity assist maneuvers near the Moon to capture the asteroid 2014 QN266.

The following notation is used here: V_m is the Moon's velocity relative to the Earth, $V\infty_{am}$ is the asteroid velocity at infinity relative to the Moon (before the Moon's flyby and . $V_{am(i+1)}$ after its flyby), . V_{ae} is the asteroid velocity relative to the Earth (before the Moon's flyby and . $V_{am(i+1)}$ after its flyby). The last, fourth maneuver near the Moon reduces the asteroid velocity relative to the Earth from 2.08 to 1.05 kms^{-1}, i.e., to a value smaller than the parabolic velocity at the distance of the lunar orbit. Thus, the asteroid is captured by the Earth's gravitational field, and it subsequently moves in a highly elliptical near Earth orbit.

The change of the velocity at infinity relative to the Earth is illustrated by the Fig.3.

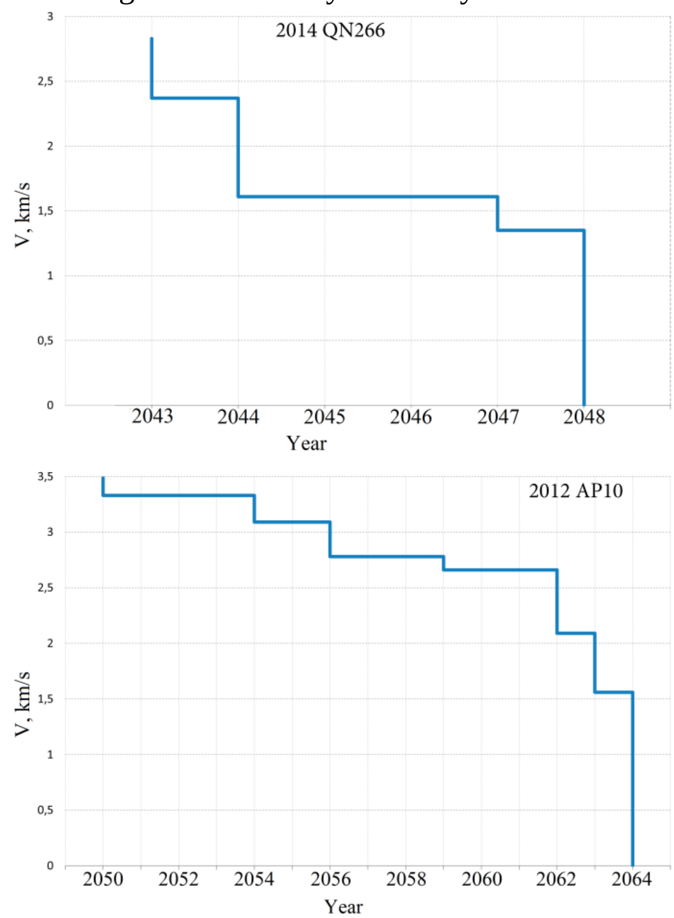

Figure 3. Change of the velocity at infinity with respect to Earth for the asteroids 2014 QN266 and 2012 AP10

The osculating orbital elements of the captured asteroid 2014 QN266 in the geocentric equatorial coordinate system at epoch J2000 are presented in Tab. 2.

Table 2. Osculating elements for the asteroid 2014 QN266.

Asteroid	2014 QN266
Time, UTC	2048-03-15 06:00:00
Eccentricity	0.7877
Semimajor axis, km	426295.29417
Inclination, deg.	153.7
Longitude of ascending node, deg	168.9
Argument of perigee latitude, deg	29.30

The Earth satellite orbit to which the asteroid 2014 QN66 is transferred is shown in Figs. 4 and 5. The scheme at large of the mission to transfer the asteroid 2014 QN266 to an Earth satellite orbit is presented in Fig.6.

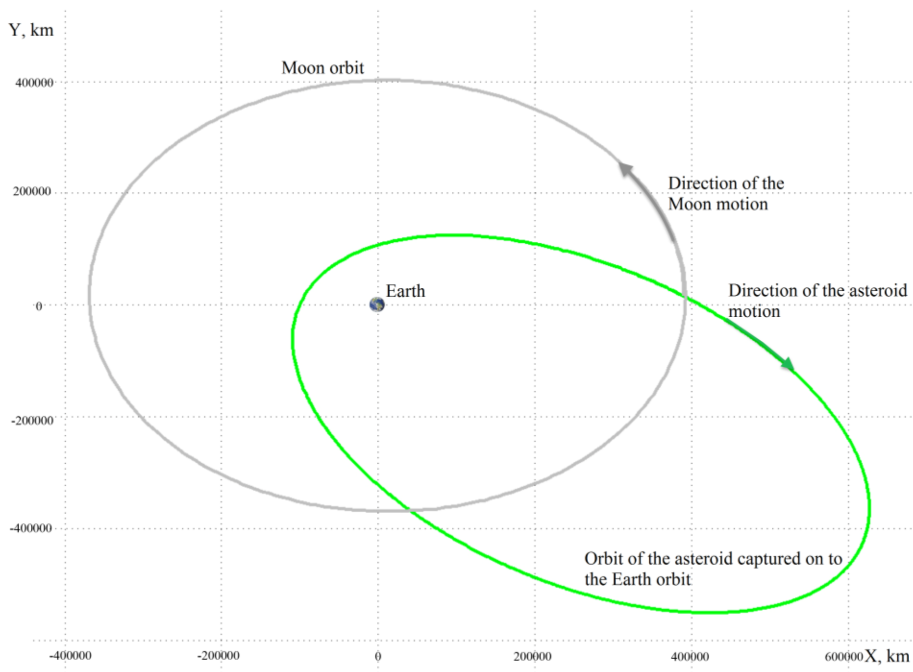

Figure 4. Projection of the asteroid orbit onto the XY plane of the ecliptic geocentric coordinate system.

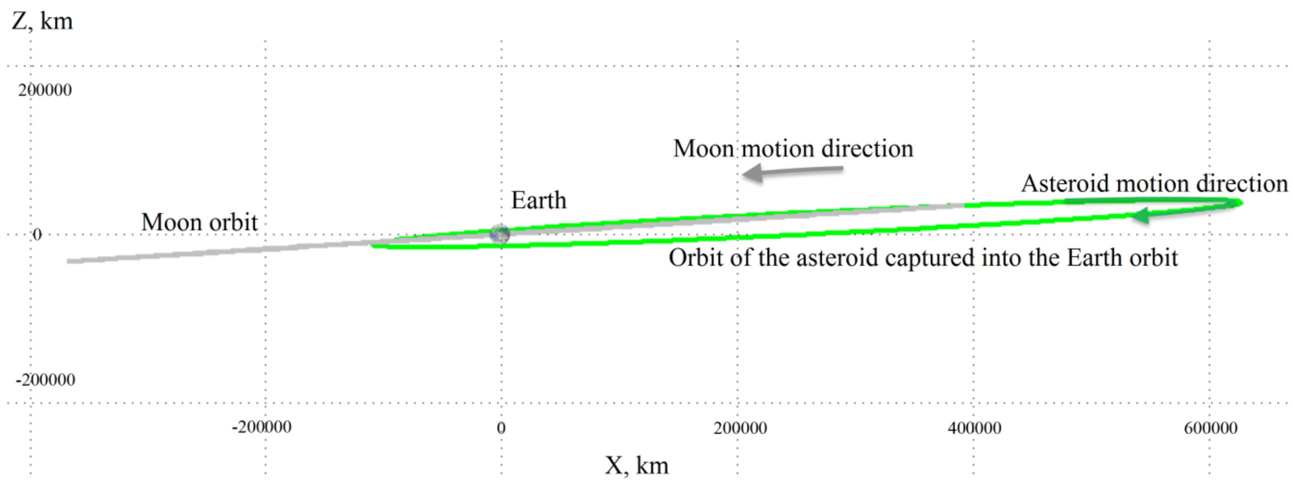

Figure 5. Projection of the asteroid orbit onto the XZ plane of the ecliptic geocentric coordinate system.

As a second example, Table 1 provides the capture characteristics for the asteroid 2012 AP10. In this case, seven gravity-assist maneuvers near the Moon are required, and the total duration of the mission is 26 years. These asteroids do not enter into the list of objects provided in our previous papers [1,5], because they were discovered after this publication. Here, it can be noted that the rate of discovery of new near-Earth celestial objects is fairly high (more than 1300 per one year), as one can see in [6].

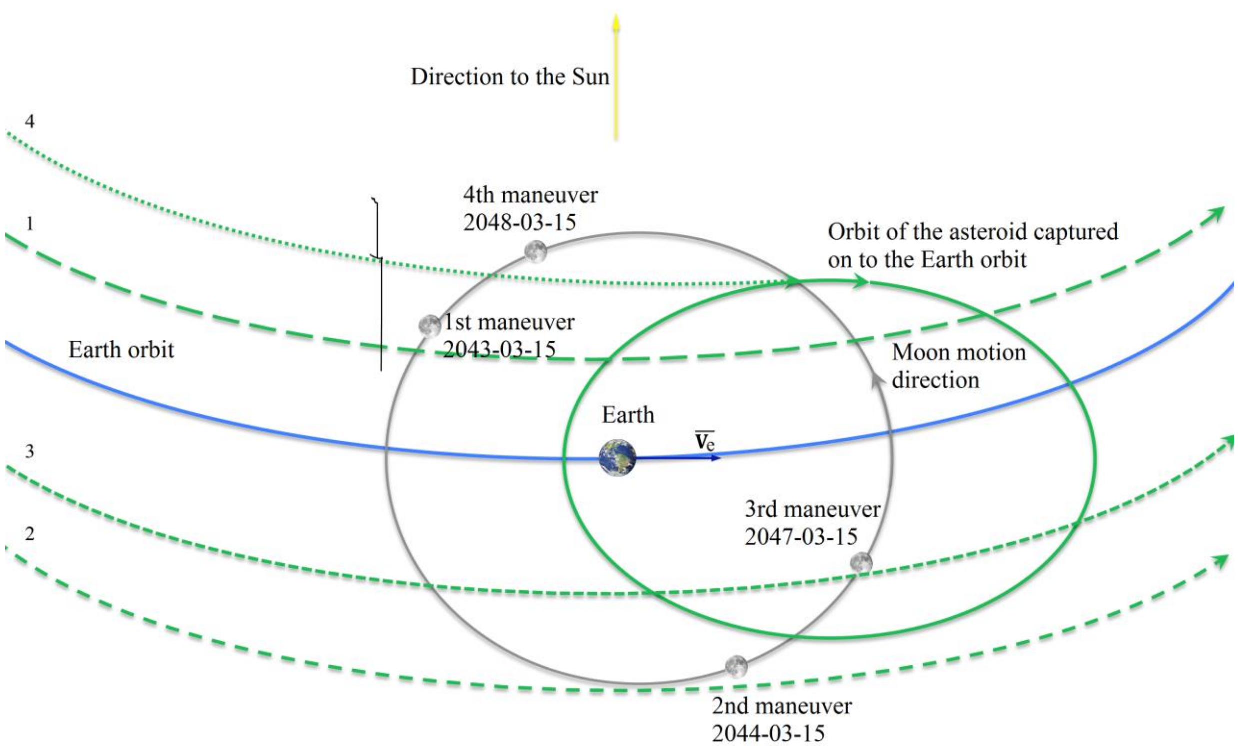

Figure 6. Scheme for the asteroid transfer to an Earth satellite orbit.

5. Achievable Parameters of the Satellite Orbit after the Asteroid Capture

The asteroid capture operations are performed with a sufficient number of free parameters, which allows the entire sequence of gravity-assist maneuvers to be optimized. The total duration of the sequence of operations can be taken as an optimization criterion, but the necessary propellant consumption to execute the corrective maneuvers should be taken into account under real conditions. An important requirement imposed on the parameters of the satellite orbit in which the asteroid is placed is the possibility of further control using the gravity-assist maneuvers near the Moon. This is achievable if the period of the near-Earth orbit ensures encounters with the Moon. The availability of free parameters allows one to count on achieving
the periods of the asteroid orbit after its capture that are resonant with the period of the lunar orbit, which makes further maneuvers possible. The possibility of reverse operations, i.e., a sequence of gravity-assist maneuvers near the Moon that return the asteroid again to the trajectory of its escape from the Earth's sphere of influence to an orbit resonant with the Earth's one, also seems fairly obvious in this connection. This opens up new possibilities for pointing the captured asteroid toward hazardous near-Earth objects in an effort to deflect them from the collision trajectory with the Earth. Here, we have in mind a comparison with the use of resonant orbits, but this approach is limited by the dates of possible gravity-assist maneuvers near the Earth for the purposes of interception, as we showed previously [1,5]. In the case of an asteroid capture into an Earth satellite orbit, we actually transfer the asteroid to a waiting orbit if our final goal is to point it toward a hazardous object, i.e., we can choose the start date to the interception trajectory of the object threatening the Earth with a collision. We do not consider the optimization problem in this paper, because our main goal here is to show the very possibility of capturing near-Earth asteroids into Earth satellite orbits through a combination of gravity-assist maneuvers near the Earth and the Moon.

6. Methods and Algorithms for Designing the Asteroids Capture Operations

Previously [5] we described the methods for designing the gravity-assist maneuvers near the Earth to transfer near-Earth asteroids to orbits resonant with the Earth's one. We also presented the methods for choosing an optimal pointing of such asteroids toward hazardous near-Earth objects. An optimization criterion in this case were the velocity impulses that should be imparted to the asteroid for its transfer to the trajectory of the gravity-assist maneuver that provided the obtainment of the necessary parameters of the asteroid orbit after its execution, being hitting a hazardous object [1] or achieving a resonance of the orbit with the Earth's one. An approach known as the Lambert problem [3] was used as a basis for the solution. The choice of a suitable asteroid was determined by the maximum admissible values of the velocity impulse needed for the solution of the problem. In the case of hitting the object, the problem of the trip from the asteroid's initial position to the Earth and the problem of the trip from the Earth to the target asteroid were solved. The parameters of the gravity assist maneuver were chosen so as to provide the transition from the trajectory of arrival at the Earth to the trajectory of hitting the hazardous object without applying a rocket dynamical impulse [4]. For the capture problem, we initially solved the problem of transfer to a resonant orbit [5]. Next, as the initial variant the initial resonant orbit was transferred to the position with a maximum declination of the asteroid velocity vector relative to the Earth to the ecliptic. Then, the problem of the lunar flyby in the sphere of influence of the lunar gravitational field was solved for the Earth–Moon system. The perilune radius and the position of the lunar flyby plane in the relative motion were chosen as the parameters of the lunar flyby trajectory. We have in mind the plane formed by the asteroid motion vector relative to the Moon and the lunar center. We chose the angle between this plane and the Moon–Earth line. These parameters turned out to be sufficient to ensure a reduction in the asteroid velocity relative to the Earth, while its velocity relative to the Sun was kept constant during the lunar flybys. The latter restriction is important, because the time of arrivals at the Moon was essentially fixed after the transfer to a resonant orbit, and, consequently, the Moon's position was also fixed. In this case, however, the impulse of the Moon's gravitational influence in view of its position may turn out to be insufficient to compensate for the Earth's gravitational influence, which gives a projection onto the asteroid velocity in the reference frame associated with the Sun. As a result, the asteroid velocity cannot be reduced at some flybys of the Earth–Moon system.

The described methods give the first approximation for the trajectories obtained by numerically integrating the equations of motion for celestial bodies. As our comparison of the integration results with the approximate solution [4] shows, the latter is quite satisfactory for the design evaluations and analysis of space missions.

7. Conclusions

The results obtained give grounds to assert that the use of gravity-assist maneuvers near the Earth to transfer near-Earth asteroids to orbits resonant with the Earth's one open up the possibility of performing further operations to capture the asteroids into Earth satellite orbits. If an asteroid can be transferred to a resonant orbit, then the succeeding gravity-assist maneuvers near the Moon provide a solution of this problem. For this purpose, it will suffice to keep the orbit resonant during the successive lunar flybys, which, as we showed, is achievable for an appropriate choice of flyby parameters when using the present day space rocket technology, which allows a characteristic velocity within 20 m s^{-1} to be imparted to the asteroid or its fragments.

8. References

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