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A VIRTUAL COCOON OF POSSIBLE TRAJECTORIES OF A PROJECTILE ASTEROID AS A TOOL FOR PLANETARY DEFENCE

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This paper describes methods using small asteroids targeted to dangerous sky objects in order to deflect them from collision with the Earth. This approach as a level of concept was proposed about ten years ago. As a tool for directing this asteroid to the approaching hazardous one, a gravity assist maneuver was proposed. Unanswered questions include the one related to the possibilities to use a minimum number of asteroids intended to be applied as projectiles for any incoming hazardous sky body from any direction. In an ideal case, one can expect only one projectile asteroid as a sufficient number required for the task solution. Also an important point is estimation of the minimum allowed time interval between detection and cataloging/characterizing the target asteroid, and then hitting it. In the earlier published papers, it was proposed to use as a parking trajectory for projectile asteroids, an Earth resonance orbit with 1:1 orbital periods ratio. With enough free parameters, that is our case, one can state that it is possible to reach any direction of hyperbolic velocity vector with respect to Earth. With the mentioned required duration of fulfillment of the commanded maneuver sequence, possible scenarios of events were explored on the basis that a celestial body coming from any direction is intercepted well before it might hit the Earth. The surface of interception points are positions that the projectile asteroid can reach after the last gravity assist maneuver sending it to the target. It changes with time, expanding till an inevitable meeting with the target. In the paper the results of modeling the scenario with real asteroids and virtual hazardous objects are presented. It is explained in the paper how to build the mentioned surface as a defense shield in such a way that avoids holes that would permit bypassing it to impact the Earth. In addition, it is estimated how, by increasing the number of asteroids in the defense shield, how that influences the characteristics of the surface of interception. Also possibilities were explored to increase the number of maneuvers versus the cost of decreasing the number of projectile asteroids or broadening the time interval needed for the defense operations.

1. Introduction

The impact of a small celestial body (asteroid or comet) on Earth can lead to global consequences. Since prehistoric times, the collision of celestial bodies with the Earth has repeatedly led to global and local catastrophes, in some cases even to mass extinctions. Thus, according to a theory, the Earth's collision with a large asteroid of about 10 kilometers in diameter about 252 million years ago may have been the

cause of the largest Permian mass extinction [1], [2]. Also, interaction with a celestial body about 10 km in size about 65 million years ago may have caused the Cretaceous-Paleogene extinction of non-bird dinosaurs [3]. In modern history there are known cases of collisions with smaller asteroids, such as the Arizona or Tunguska asteroids. Also, worth mentioning is the most famous one in the last decade, the Chelyabinsk meteorite impact, which led to economic and technogenic consequences for the region [4].
Since 1932, after the observed approach of asteroids of the Apollo near-Earth group, development began of an assessment of the asteroid and comet danger, namely, earlier detection of potentially dangerous objects and the search for methods and means of eliminating particularly dangerous asteroids. One of the most popular methods of eliminating a dangerous asteroid is to change its orbit so as to exclude its intersection with the Earth. At this point, there is a whole range of capabilities that allow for a similar change. These methods include directed nuclear explosion near the center of mass of the dangerous asteroid [5], changing the albedo by painting the asteroid with a special composition [6], the use of a spacecraft with low thrust engines and nuclear power plant to tow the dangerous asteroid [xx], the use of laser installations to evaporate the rocks from the asteroid surface and create a push in the right direction [7]–[9], the concept of asteroid billiards [10]–[14], and some others.

This paper considers the use of resonant orbits in the concept of asteroid billiards, namely placing an asteroid on a resonant 1:1 Earth orbit for subsequent use as a projectile to eliminate a potentially dangerous object for the Earth. As such, a small stone asteroid is selected for the projectile. As a dangerous object is selected, simulating the potentially dangerous asteroid PDC21, which is virtually approaching the Earth on October 20, 2021 and the asteroid (99942) Apophis, approaching to a distance of 31 thousand km. expected by April 14, 2029 [15].
The results show that the concept of protection with one or two asteroids on resonant 1:1 orbit to the Earth, justifies itself and in the case of early detection of a potentially dangerous object, allows carrying out its interception and deflection from its trajectory of approach to the Earth.

2. Gravity assist maneuver in the problem of transfering a projectile asteroid into a resonant orbit

The concept of making the Earth gravity assist in order to obtain a resonant orbit is described in detail in the works [10]–[14], [16].
The essence of such a maneuver is to rotate the vector of the relative velocity of the projectile asteroid during the flyby of the Earth. In this case there is a possibility to choose from a set of possible resonant 1:1 orbit to the Earth, which differ from each other by the value of inclination and eccentricity. The choice is made by rotating the relative velocity vector around the heliocentric velocity vector of the planet. The surface described by the rotation of the velocity vector is a cone. Thus, the vectors of heliocentric velocity of the spacecraft after the gravity assist lie on the surface of the cone, the length of the formative of which is equal to the heliocentric velocity of the planet.
The maximum achievable angle of rotation of the relative velocity vector due to the gravitational field of the planet can be determined as follows:

$$\sin\frac{\alpha^*}{2} = \frac{1}{1 + r_\pi V_\infty^2 / \mu}, \qquad (1)$$

where α^* – the achievable angle due to the gravitational maneuver, the angle of rotation of the relative velocity vector of the projectile asteroid, r_π – periapsis radii, V_∞ - relative velocity of projectile asteroid, μ - Earth gravitational constant.

The required resonant orbit from the available set of possible orbits is selected by rotating the velocity vector not only by angle α in the plane formed by the vector of incoming relative velocity, but also by rotating by angle γ, counted from the planet's north pole, in the plane perpendicular to the planet's heliocentric velocity vector and radius vector to the Sun (Fig. 1).

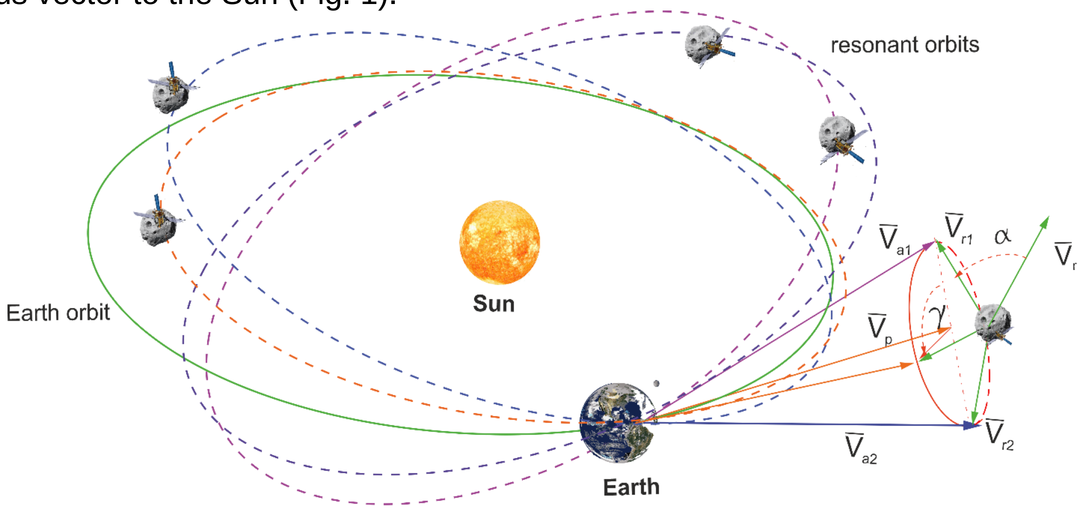

Fig. 1 Geometry of transfer to resonant 1:1 to Earth orbits

3. The concept of using an asteroid on resonant orbits to eliminate potentially dangerous objects

The basic idea behind the suggested approach is to put the projectile asteroid into a 1:1 resonant orbit with the Earth. The projectile asteroid moves passively along the resonant orbit, approaching the Earth every year or six months. In case of detection of a potentially dangerous object (fig. 2) this asteroid-snipe at the moment of the next passing of the Earth by means of gravity assist maneuver is directed to the dangerous object threatening the Earth and hits it not less than 10 days before approaching the Earth.

The general concept of using an projectile asteroid in a 1:1 resonant orbit to Earth is shown in Figure 2.

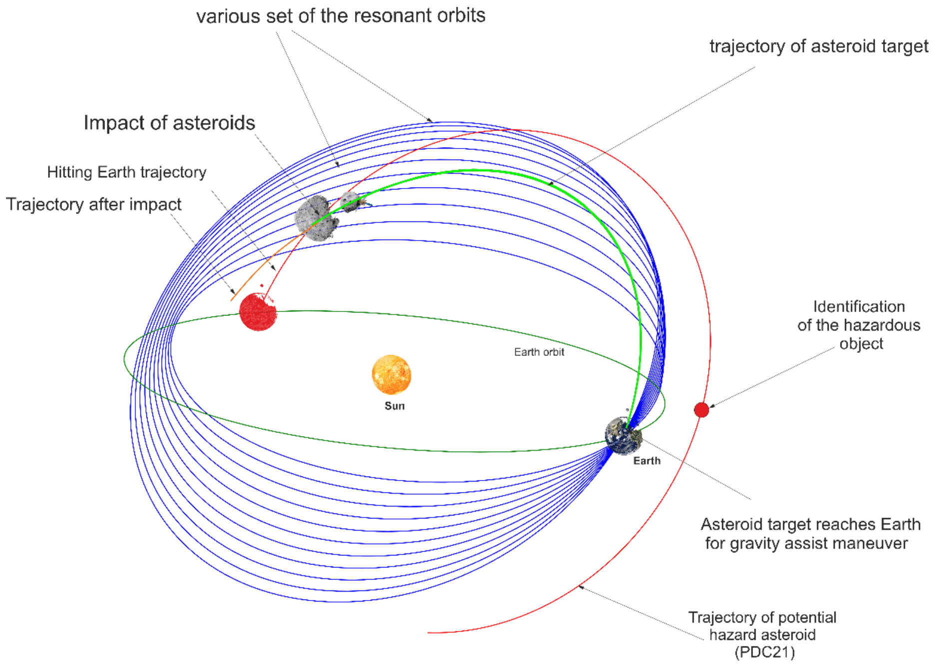

Fig. 2. The concept of using projectile asteroid to deflect a near-Earth hazardous object

It is assumed that the collision of an projectile asteroid with a potentially dangerous object is an inelastic impact, after which both asteroids move together along a new trajectory (Fig. 2). The velocity after the impact is estimated as follows:

$$\mathbf{V} = \frac{m_1\mathbf{V_1} + m_2\mathbf{V_2}}{m_1 + m_2} \qquad (2)$$

Converting (2), the following will be written:

$$\Delta\mathbf{V} = \frac{m_1\mathbf{V_1} + m_2\mathbf{V_2}}{m_1 + m_2} - \mathbf{V_1} \qquad (3)$$

where **V** – velocity of asteroids after collision, $\mathbf{V}_1$ – velocity of hazardous object before collision, $\mathbf{V}_2$ – velocity of projectile asteroid before collision, m_1, m_2 – asteroids mass.

Restriction of the proposed concept occurs at the time of detection of a potentially dangerous object, as in the case of use of only one potential asteroid projectile, a potentially dangerous object must be discovered and not discovered again. This restriction can be eliminated by increasing the number of projectile asteroids in resonant orbits[16]. It should also be noted that a potentially dangerous object must cross the surface formed by the set of attainable resonant orbits of the projectile asteroid. Otherwise, at the moment of the next flight, the Earth may need additional costs of characteristic velocity.

4. The concept of operations for intercepting dangerous asteroids

As the principal idea it is proposed to capture some small asteroid onto orbit resonant with Earth orbit with 1:1 periods ratio. As a tool for this, Earth gravity assist was proposed in [10]–[14]. Instead of asteroid itself it is considered possible to use some builders taken from asteroid surface. Such approach may be illustrated if as candidates for builders supply we consider the ones similar to Bennu or Rugu asteroids. It was confirmed that dozens of asteroid are possible to be used for such scenario application if there mentioned types of builders on their surface.

It is first step in building shield consisting from asteroids (their fragments) for Earth defense from sky bodies moving on trajectories hitting the Earth.

After execution operations of capturing such asteroid we continue to keep it as controllable object, i.e. it has motion control system and some constrained mass of propellant required for further orbital control. We consider it as projectile asteroid. After capture it has the following key orbital characteristics: period equal Earth orbital period, point and time of gravity assist maneuver which transferred it onto resonance orbit. And these parameters we cannot change. Also we cannot change the value (module) of relative velocity vector during our further orbital control operations. Value of this vector is determined by requirement meaning that resulting after gravity assist maneuver projectile orbit in solar referenced system is to be resonant with the Earth. In terms of geometry it means that projectile velocity vector with respect to Sun is to be the sum of Earth velocity vector and projectile relative velocity with respect to Earth.

After capture we are allowed to do with this relative vector what we wish under condition that it keeps resonance condition demands. Besides rotation of this vector is constrained by maximum allowed angle determined from formulae () with minimum limit for perigee.

It means that any position of relative vector with keeping its resonance constraints may be reached by appropriate number of sequential rotations.

So, if relative velocity is not too high it is possible to rotate vector using one operation maneuver by say 95 degrees, then in two successful maneuver we can reach in these operations any position of relative vector. In other words, we can generate the sphere of doable relative velocities for the point where the Earth was during the first maneuver were asteroid was captured in order further fulfilling the role of projectile to hit dangerous sky object threatening Earth by hitting.

Presented above allows to state that with using captured onto resonant orbit projectile asteroid it is possible to intercept any target sky body moving to Earth along hitting trajectory if this hitting forecasted before enough time of reachable gravity assist maneuver moment.

It means that we have the possibilities to do this gravity assist maneuver in such a way that any target will be intercepted by proper controlled gravity assist maneuver. Because we have the possibilities to target our projectile in any point of the sphere around the Earth. It may be described as a expanding swarm virtual projectile around the Earth. And if some object is moving along reaching the Earth trajectory it unavoidably intersects the surface of this swarm at some moment. Our purpose is only to choose from the swarm the proper bee, i.e. the proper parameters of gravity assist maneuver. They are two and it is enough.

With the time initial sphere is expanding and it is experiencing some deformations as it is shown on the following Figures. These figures show the surface of virtual projectiles for sequential moments after maneuver. When expected dangerous body goes through this surface it is hit by projectile. And there no ways to reach the Earth, other than to go through these surfaces.

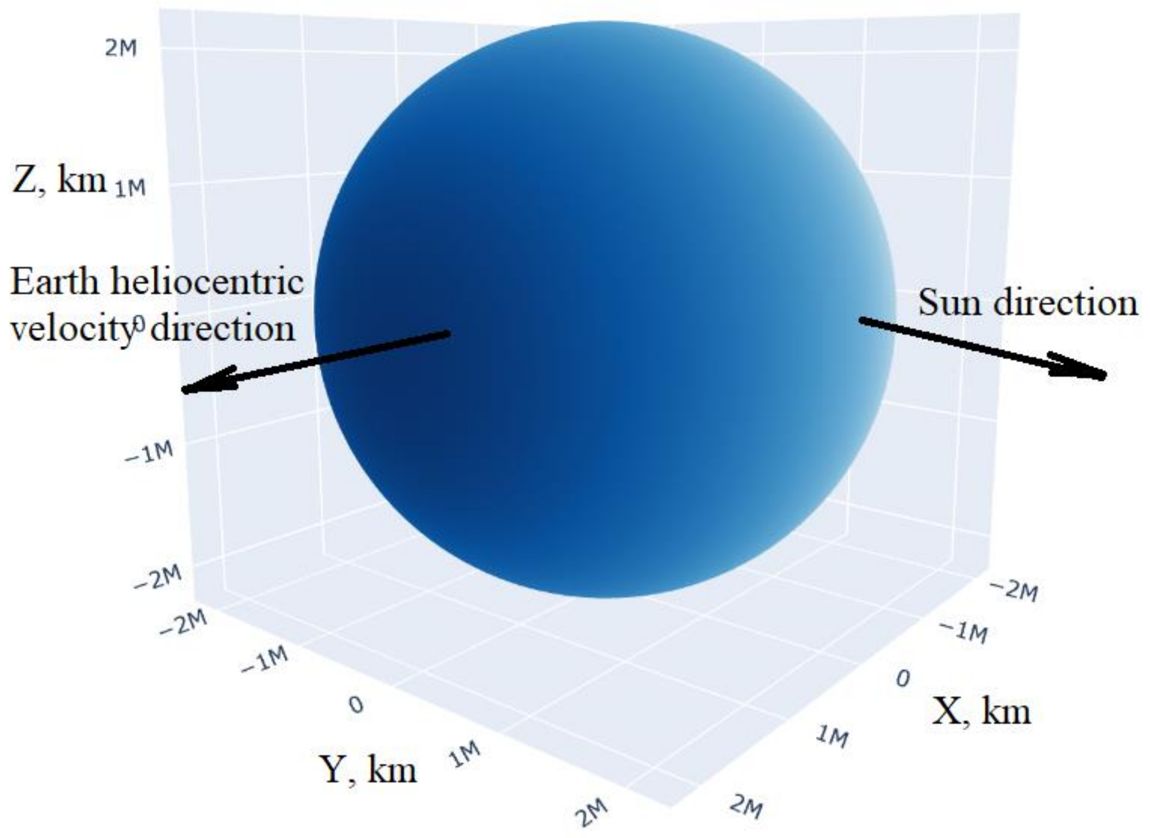

Fig. Sphere after 10 days from Earth gravity assist in Sun-Earth rotating frame

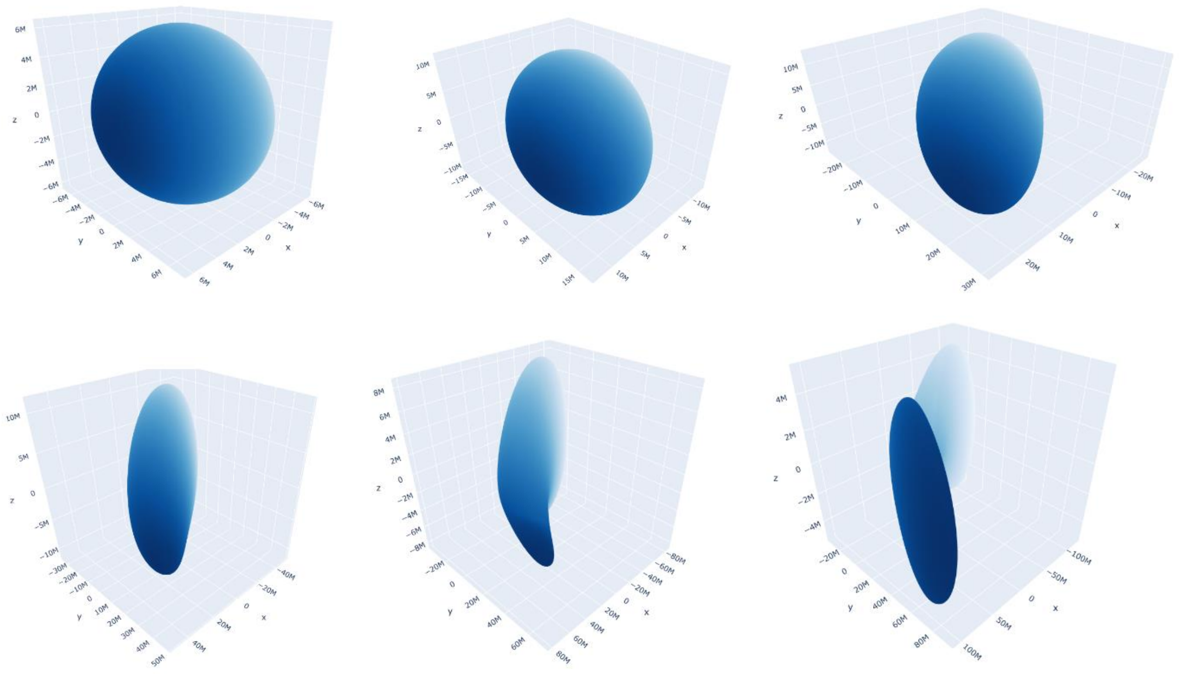

Fig. Deformation of sphere through 1 to 6 month from Earth gravity assist in Sun-Earth rotating frame

As presented Figures show at least for the time interval up to 6 months since gravity assist maneuver the Earth is situated inside this shield so threatening body cannot bypass the protecting projectiles.

Figures illustrating our statement, are constructed for the assumption that relative velocity of resonance asteroid is equal 3.5 km/s. For higher possible values of relative velocities, the dimensions of them will be obviously larger, but our conclusions about applicability propose conception seem to be still valid.

5. Results

5.1. Possible scenario of an projectile asteroid capture into a 1:1 resonant orbit with the Earth

As a demonstration of the approach described above, we present the results obtained for the asteroid 2012 TC4. The trajectory of the asteroid, as well as the characteristics of the flight to the asteroid with its subsequent transfer to the resonant orbit are shown in Fig. 3 and Table 1.

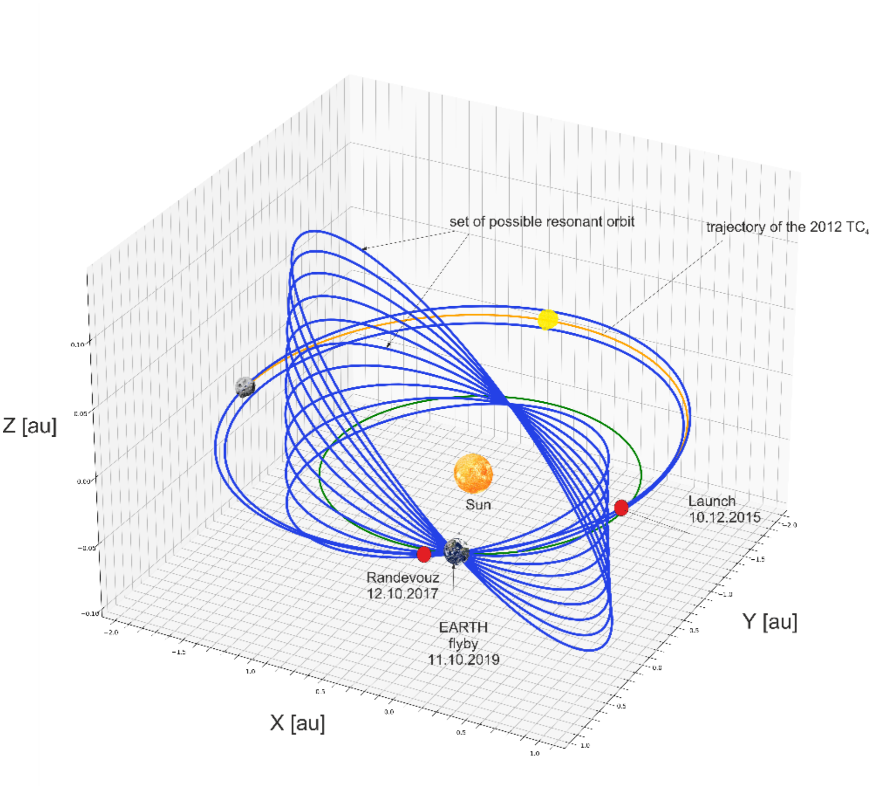

Fig. 3. Trajectory of the flight to the asteroid 2012 TC4 with its subsequent transfer to the resonant 1:1 orbit to the Earth.

Table 1. Parameters of the motion of the spacecraft to 2012 TC4 with a subsequent landing and transfer of the asteroid to a resonant orbit after a gravity assist maneuver near the Earth.

Date of launch/flyby	Celestial body	Height of flyby, $10^3\ km$	Relative velocity value, km/s	$\Delta V,\ km/s$
10.12.2015	Earth	0.2	6.7	5.11
12.10.2017	2012 TC4	-	0.34	0.34
11.11.2017	2012 TC4	-	0	0.17
20.10.2019	Earth	1.1	6.4	0

Possible resonant orbits of the projectile asteroid after the Earth gravity assist will vary between each other by the value of eccentricity (e) and inclination to the ecliptic plane (i). The mutual dependence of these parameters is shown in Fig. 4.

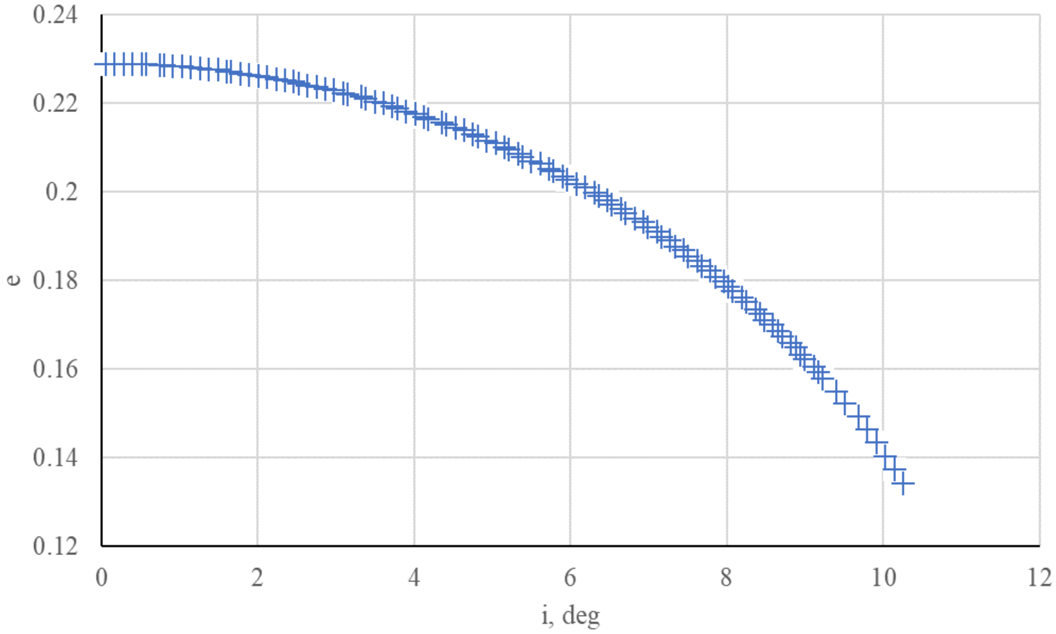

Fig. 4. Eccentricity of the resonant orbit versus the inclination

Fig. 4 shows that the maximum eccentricity is possible when the resonant orbit of a projectile asteroid lies in the plane of the Earth's orbit, and the maximum inclination is realized at the lowest possible value of eccentricity, which agrees with the results obtained in [xx].

5.2. Scenario of the interaction with the virtual asteroid PDC21

As an example, for the demonstration of the proposed concept was selected virtual asteroid PDC21, which is used as a model for participants in the PDC conference. The detection of this asteroid takes place on April 20, 2021. The degree of danger and the possibility of its collision with the Earth is estimated on April 26, 2021. Two possible cases of deflection of a dangerous object by a projectile asteroid are being considered:

- The projectile asteroid and a hazardous object converge in the vicinity of Earth's sphere of action, with the orbit of the projectile asteroid remaining resonant. This case is possible because the resonant orbit we have chosen assumes that the projectile asteroid approaches the Earth in October of each year.
- The projectile asteroid is on a rendezvous orbit with the Earth through a semicircle of the resonant 1:1 orbit. During realization of such a scenario, it is assumed that the sniper asteroid at the moment of the next passing the Earth (20.04.2021) passes on a trajectory of a collision with a dangerous object by means of a gravity assist maneuver near the Earth. In this case, the projectile asteroid after 20.04.2021 will be in a non-resonant orbit.

Let us consider in more detail, each of the possible cases.

5.2.1. The projectile asteroid is on a resonant orbit right until approaching a hazardous object

The trajectory of potentially dangerous object (PDC21) before possible collision with the Earth on October 20, 2021 is shown on the fig. 5. This figure shows that this asteroid cross the surface formed by the attainable resonant orbits of the 2012 TC4 projectile asteroid.

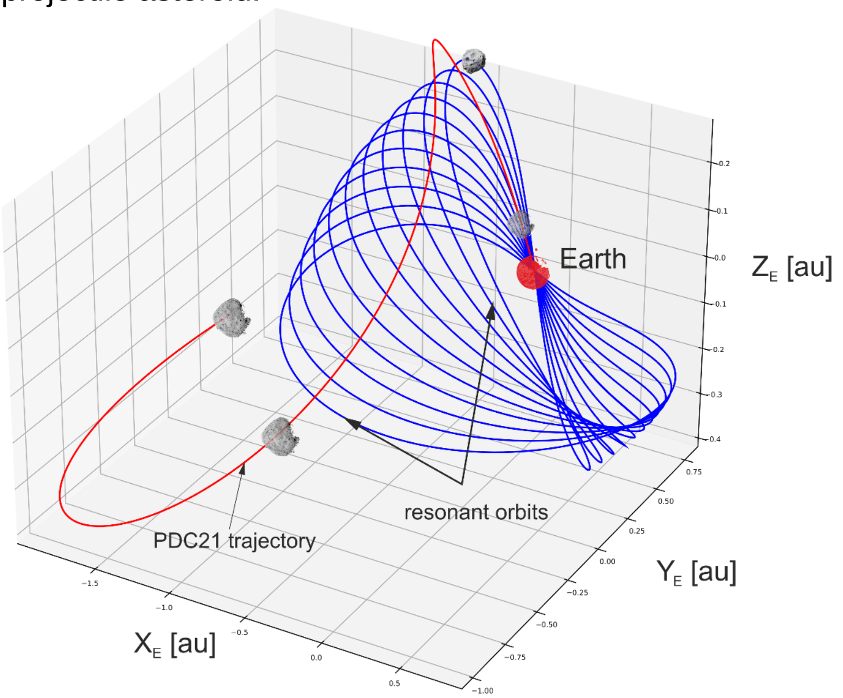

Fig. 5. Trajectory of potentially dangerous object (PDC21) before its possible collision with the Earth on October 20, 2021 in the geocentric (J2000) ecliptic coordinate system.

Let's show the main stages of the trajectory of the projectile asteroid during its movement along the resonant orbit from the moment of the dangerous object detection (20.04.2021) to its approaching in the Earth vicinity (01- 20.10.2021) in Fig. 6.

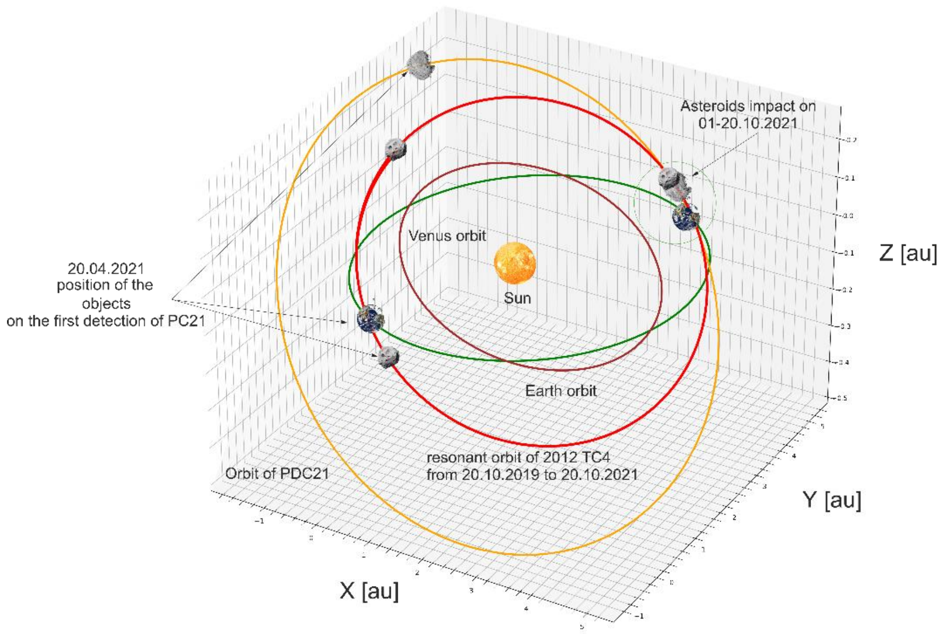

Fig. 6. Trajectory of the projectile asteroid before approaching PDC21 in the heliocentric (J2000) ecliptic coordinate system.

As can be seen from Fig. 6 the projectile asteroid chosen by ourselves catches up with a dangerous object in the vicinity of the Earth, which subsequently allows to use any of the methods described in the introduction for eliminating dangerous objects. For example, to use methods based on the exchange of energy between the asteroid projectile and the dangerous object, in particular, to use the projectile asteroid as a vehicle to deliver a nuclear charge for subsequent detonation of the dangerous object. However, in this article we limited ourselves to the stage that follows before approaching the dangerous object, while the above studies require separate and thorough research.

5.2.2. The projectile asteroid is directed by a gravity assist maneuver to a dangerous object (PDC21)

Let us consider the second case of a possible deflection of a dangerous object described above.

When implementing this scenario, it is assumed that the projectile asteroid is on a resonant 1:1 orbit with the Earth of maximum inclination, which allows us to implement the scenario of meeting with the Earth every half turn of the asteroid's orbit. As the date of the projectile asteroid to the resonant orbit is considered received earlier 20.10.2019. It is assumed that at the moment of detection of a dangerous object (PDC21), the asteroid projectile being in the pericenter of the flyby orbit with respect to the Earth passes from the resonant orbit to the orbit assuming the meeting with a dangerous object at a considerable distance from the Earth.

Fig. 7 shows the trajectory of the asteroid projectile as it travels in a resonant orbit before approaching the Earth, and a section of the trajectory hitting the PDC21 asteroid.

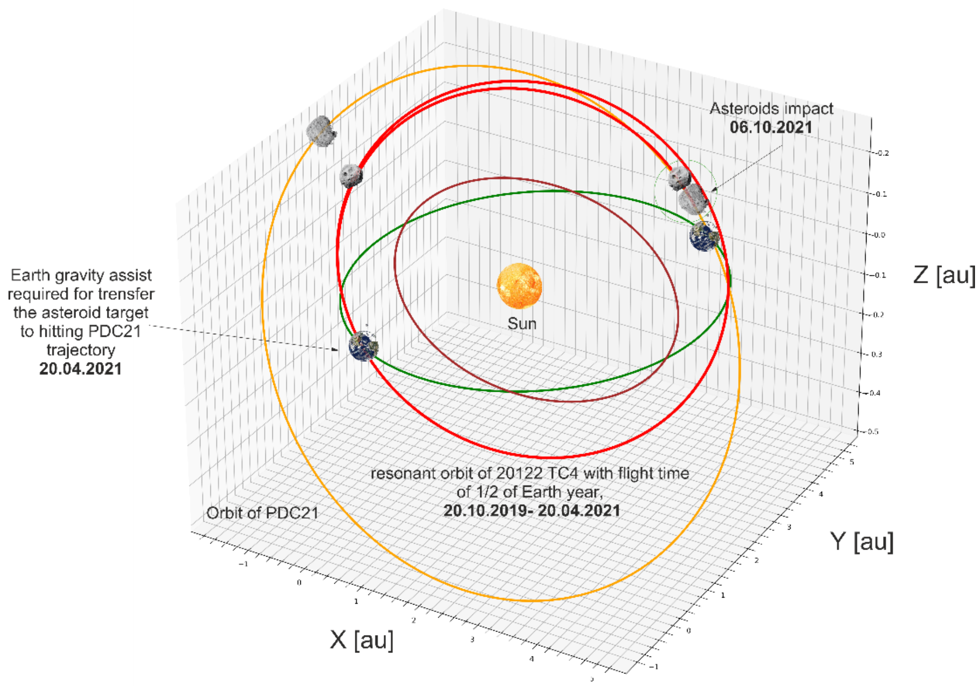

Fig. 7. Trajectory of the projectile asteroid before the collision with PDC21 in the heliocentric (J2000) ecliptic coordinate system.

We can calculate the impact on the hazardous object using eq. (3), taking the asteroid mass ratio m1/m2 = 30...40, thus the ΔV reported by the projectile asteroid will be about 100 m/s. After the interaction of the asteroid projectile with PDC21, the trajectory of the latter was integrated by the Runge-Kutta method of order 8(9)- taking into account the gravitational influences from other (besides the Sun) celestial bodies. The result of the integration shows that the asteroid impact completely eliminates the danger, taking PDC21 from the rendezvous trajectory with an approximate distance of at least 1.5 million km past the Earth.

5.3. Scenario of interaction with the asteroid Apophis

Let's consider the scenario of Apophis deflection from the collision trajectory with the Earth by the asteroid 2012 TC4, which is virtually in a resonant orbit from 20.10.2017. We assume that the asteroid projectile is in any of the possible 1:1 resonant orbit to Earth until 2028. At the moment of the next gravitational maneuver near the Earth on 20.10.2028, the asteroid-snipe is transferred to the trajectory of meeting with a potentially dangerous object (Apophis) and after its approach deflects it from the trajectory of meeting with the Earth.
The trajectory of the projectile asteroid up to the moment of meeting with Apophis is shown in Fig. 8.

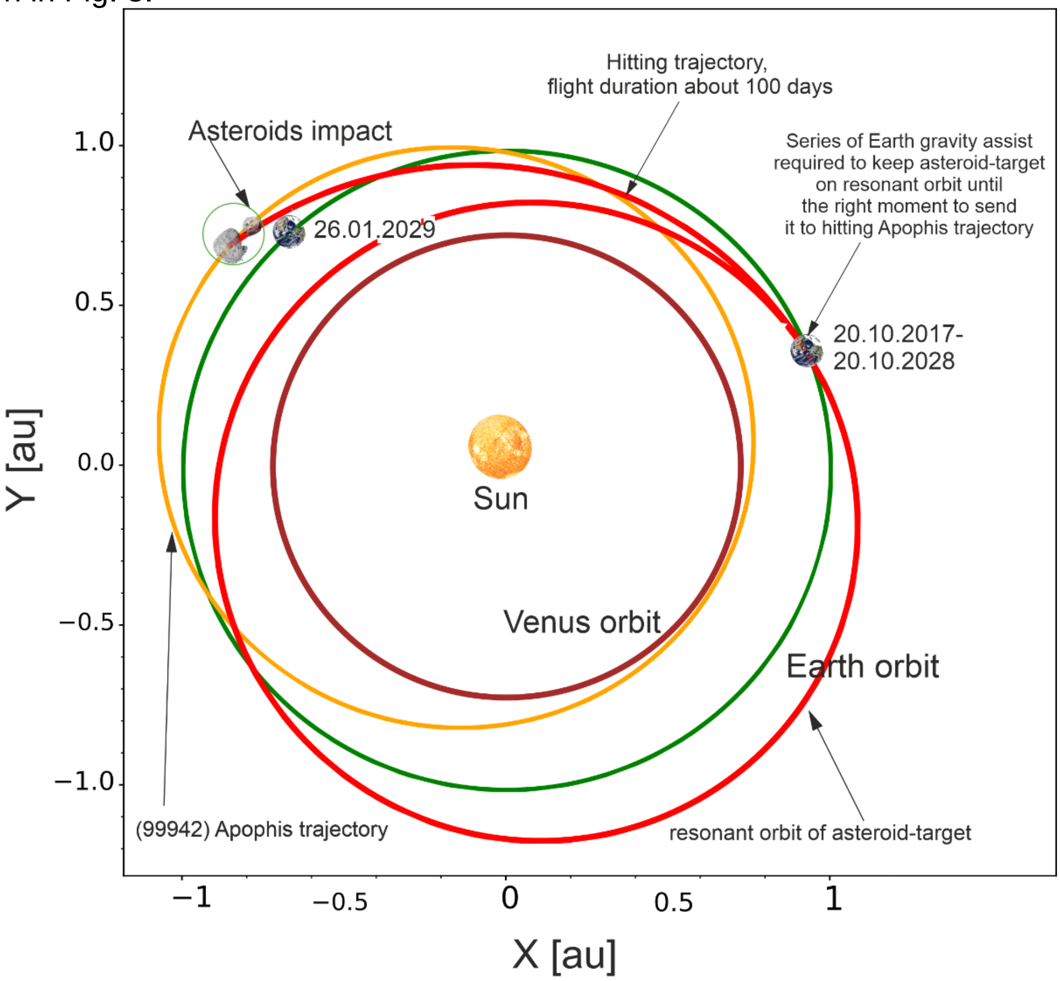

Fig. 8. Trajectory of the projectile asteroid before the collision with Apophis in the heliocentric (J2000) ecliptic coordinate system.

6. Applying the asteroid shield concept to assess the possibility of deflection of a hazardous object

According to the concept outlined earlier in section 4., for the ideal case when an random asteroid with a relative velocity near the Earth of 3.5 km/s is considered, we can formulate the assumption that any angle of rotation of the relative velocity of the projectile asteroid is instantly available, i.e. the angle from eq. (1) should be equal to 180 deg.
Let us show the application of this concept to the trajectories of dangerous objects: the virtual PDC21 and the asteroid Apophis.
Note that the date of the gravitational maneuver, the ideal asteroid projectile will not be tied to the previously described case with 2012 TC4.

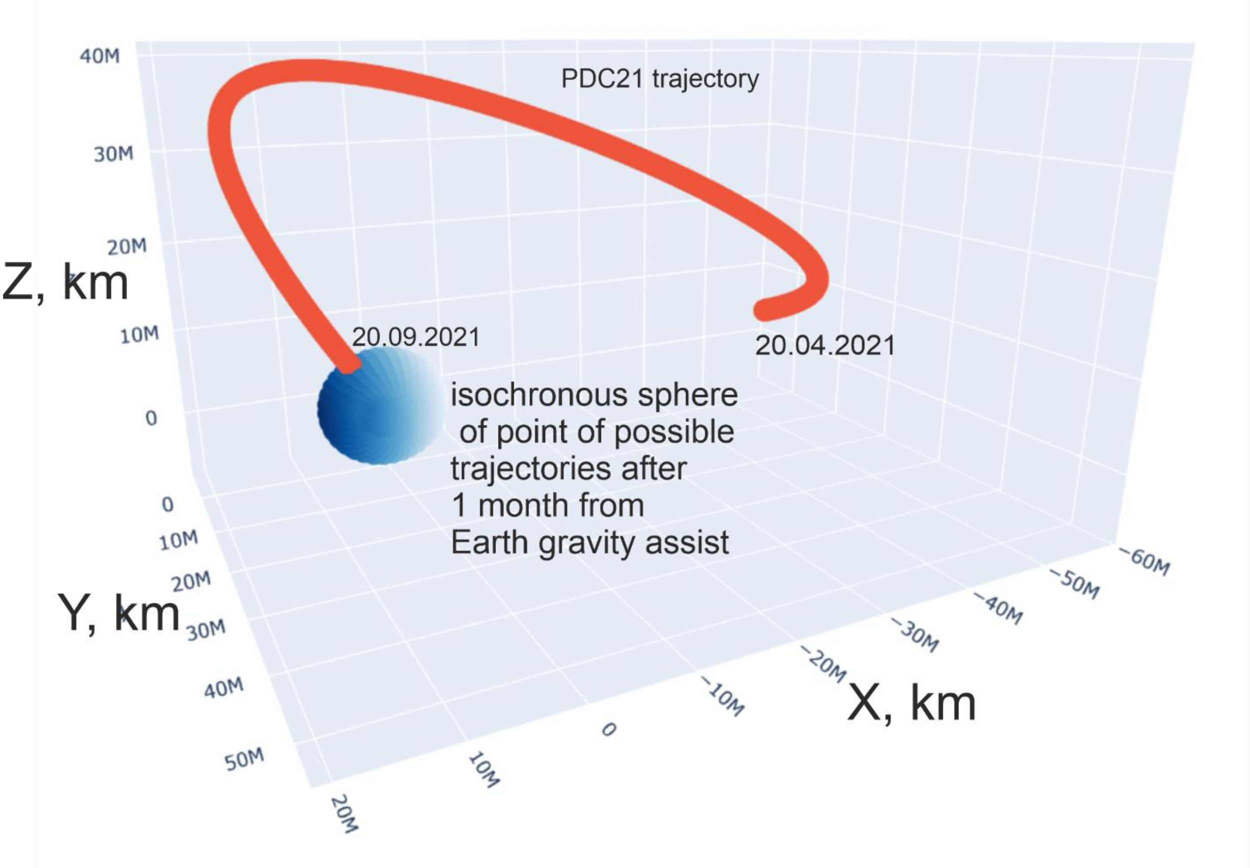

Fig. 9. Trajectory of the virtual asteroid PDC21 from 20.04.2021 to the moment of crossing the sphere on 20.09.2021.

Note that the gravity assist maneuver for the mentioned projectile asteroid should take place on 20.08.2021. In this case, when crossing the nominal trajectory of the PDC21 sphere, the projectile asteroid with use of Earth gravity assist is directed to the dangerous object and after a month strikes it at the moment of crossing the sphere.
Similar conclusions can be given for the case of Apophis (Fig. 10). Since the danger of approaching Apophis to the Earth is known for many years ahead, the assumption of instant availability of any angle of rotation of the vector of relative velocity of the projectile asteroid near the Earth can be neglected. Since for a relative velocity of 3.5 km/s and a pericenter radius of about 8000 km, according to eq. (1), the maximum achievable rotation angle would be 118 degrees instead of the accepted earlier 180 degrees for ideal case. In this way, it will take about two years for the asteroid to

stay in a resonant orbit to build a full shield around the Earth, providing the desired position of the projectile asteroid.

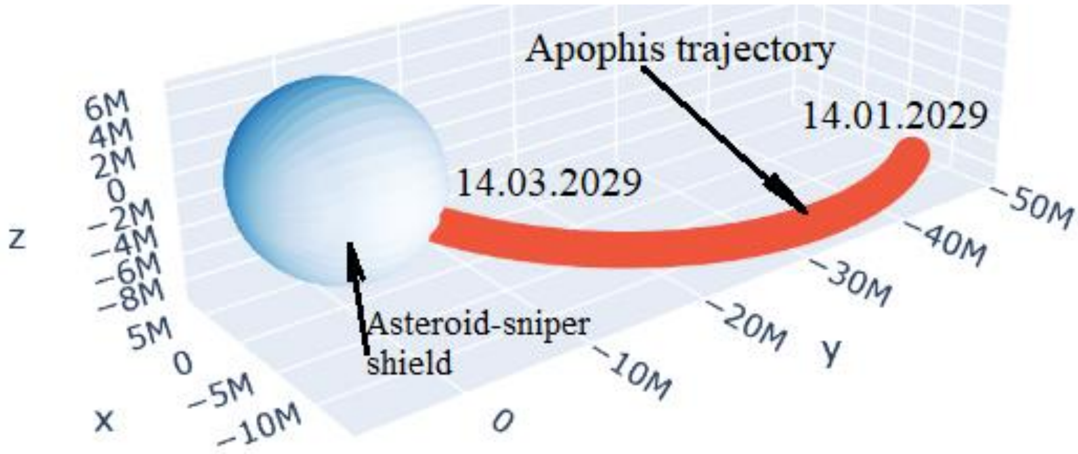

Fig. 10. The trajectory of the virtual asteroid PDC21 from 20.04.2021 to the moment of crossing the sphere on 20.09.2021.

Thus, the demonstrated examples clearly show that in the first approximation using only one asteroid in a resonant orbit can provide full protection of the Earth from hazardous objects.

7. Conclusions

The research conducted in this paper show that the use of resonant orbits can prevent the collision of a potentially dangerous object with the Earth or make such a collision less possible. The virtual dangerous asteroid PDC21 discovered on April 20, 2021 is considered as a potentially dangerous object. A realistic approach to the asteroid (99942) Apophis is being considered and is expected to occur on April 14, 2029. A virtual asteroid-snipe collision with PDC2021 is assumed to occur on October 20, 2021. Asteroid 2012 TC4 is assumed to be sniper.

The results of the calculations given in this paper have shown that the deflection of a dangerous object is possible if a dangerous asteroid is detected at least six months before the expected collision with the Earth. In the case of detection of the asteroid for a long time before the possible dangerous approach (for example, the detection of Apophis), the possibility of its deflection significantly expands, as well as expands the number of available asteroids, which in this case can be used as an asteroid projectile.

It is proposed to use a one asteroid on resonant orbit to form a shield that could prevent an asteroid impact. The preliminary calculations for ideal case when the projectile asteroid is random and has a relative velocity near Earth about 3.5 km/s, shows that this assumption provides full protection of the Earth by building a shell consisting of trajectories formed by Earth gravity assists.

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