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**NEAR EARTH ASTEROIDS ANALYSIS AS THE OBJECTS FOR MOTION  
CONTROL USING GRAVITY ASSIST MANEUVERS**

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Among possible tools to prevent collision of hazardous asteroid with the Earth is kinetic impact of some controlled body targeted to it. This function may be fulfilled by spacecraft and it was really done in Deep Impact mission when Tempel 1 comet was hit by controllable impactor. But mass of spacecraft which can be used for this purpose is constrained by technical launcher capabilities and can not exceed 5-6 tons for contemporary technologies. To overcome this obstacle it was proposed to use comparatively small near Earth asteroid to target it to hazardous one using gravity assist maneuver near Earth or other Solar System planet, Venus or Mars for example. Estimations of required delta-V necessary to direct small asteroid to vicinity of the Earth in order to execute such maneuver have been done by authors in previous studies for the Apophis asteroid as the body to be prevented collision with the Earth. In the paper the results of systematic explorations aimed to determine the necessary delta-V to transfer the asteroid to near planet orbit for gravity assist maneuvers are presented. The asteroids which satisfy the different levels of constraints on delta-V are identified for Earth, Venus and Mars for supposed dates of possible missions. The possible target asteroids which are reachable applying proposed concept are found and classified depending on required delta-V. The examples of possible mission scenarios and impact trajectories are presented and required mass of the upper stage on low Earth orbit for chemical and electric propulsion engines are given.

As another goal of gravity assist maneuvers, the asteroid transfer on resonant with planet orbital motion orbits was considered. Possible candidate asteroids for this were found as the families of trajectories achievable by subsequent multiple gravity assist maneuvers. Some examples of such trajectories are presented.

**Estimations of the cost of gravity assist maneuvers**

First step in construction of the mission to intercept the hazardous sky object with the use of asteroid or some fragment of it is estimation of required delta-V in order to transfer asteroid onto the trajectory passing in the close vicinity of the planet to be used as attracting body for gravity assist maneuver. In the paper [1] it was shown that for Apophis as a target at least five asteroids do exist which are possible to direct to it by applying delta-V not exceeding 20m/s. Further studies have shown that the same approach may be used to deviate the other asteroids from the trajectory hitting the Earth and the list of projectile asteroids can be significantly broaden. In the

Table1 parameters of the gravity assist maneuvers near Earth, which include the target body (Apophis, Bennu, and Mars moon Phobos, which is added to the table just as example of other than asteroid body) and list of candidate projectile asteroids (consisting from 27 ones) is presented. For each case of maneuver the required delta-V is given as the dates of its applying, Earth flyby and the target hit. Obviously not every asteroid which is possible to direct to the Earth vicinity by small enough delta-V has acceptable orbital parameters in order to target it by gravity assist maneuver to the chosen hazardous object. But it is shown in the table for each target one can find at least 13-14 projectile asteroids. In addition the other task of the Earth flyby was explored: the possibility to transfer asteroid onto trajectory resonant with the Earth orbit, i.e. onto trajectory having the period with relation to the Earth orbital period as even figures. If this ratio is 1:1 then asteroid will return to the Earth each year.

Table 1. Near Earth gravity assist asteroid interception trajectories

using the Earth for gravity assist maneuver					Date of collision of the asteroid projectile with ...		
No	Asteroid	$\Delta V$ , m/s	Maneuver date	Date of perigee	Apophis (asteroid)	Bennu (asteroid)	Phobos (moon)
1	2015 AZ43	11.91	2035-12-14	2038-02-26		2040-07-27	
2	2014 GQ17	10.09	2043-11-12	2044-06-11	2045-01-22	2044-12-23	
3	2014 QN266	18.77	2040-05-16	2041-03-15	2042-02-13	2041-08-01	
4	2014 KW76	16.54	2036-12-21	2038-05-27	2040-04-02		
5	2014 HB177	13.53	2033-12-10	2034-05-06			2034-10-06
6	2013 VX4	18.22	2022-05-26	2023-12-15			2026-02-17
7	2012 PB20	18.82	2024-06-14	2025-02-11		2025-06-04	2025-07-02
8	2012 SY49	9.96	2027-12-27	2029-09-29		2030-01-27	
9	2012 AP10	11.85	2042-07-11	2043-01-01			2043-08-30
10	2012 UE34	12.04	2040-07-20	2041-04-08	2041-08-25		
11	2012_HB25	10.96	2023-11-23	2027-07-10			2030-11-21
12	2011 TO	15.33	2044-04-16	2044-09-27	2045-05-09		2045-03-23
13	2011 CF22	10.80	2038-08-16	2041-02-06	2043-08-03		
14	2011 AM37	18.89	2025-02-11	2026-01-11	2026-12-25	2026-09-13	2026-11-18
15	2011 CF22	10.80	2038-08-16	2041-02-06	2043-08-03		
16	2011 AG5	4.44	2038-07-07	2040-02-05	2041-09-24	2040-05-15	
17	2010 TN55	16.35	2035-12-21	2038-10-10	2042-01-14	2042-01-04	2041-12-19
18	2010 VN1	10.95	2033-12-08	2035-11-03		2037-07-25	
19	2008 WK96	10.03	2037-02-17	2038-11-29			2040-10-21
20	2007 TL16	19.69	2036-06-21	2037-10-06			2038-01-24
21	2007 DX40	3.61	2042-04-01	2043-08-18	2045-03-16		2045-02-02
22	2006 SR131	15.60	2016-08-15	2017-09-23	2019-02-08	2019-01-31	2019-01-08
23	2006 SU49	8.01	2027-06-15	2029-01-23		2029-06-04	2030-08-09
24	2004 MN4	3.88	2028-08-03	2029-04-14		2029-10-13	
25	2000 QK130	11.13	2035-03-05	2036-03-14			2036-07-10
26	1997 XF11	10.23	2027-05-16	2028-10-26	2030-04-03	2030-03-06	
27	1995 CS	2.64	2039-09-25	2041-02-03		2043-07-02	
					13/27	14/27	14/27

Connected with proposed technologies some objections of their implementation may be formulated. Most often objection is presumption that gravity assist maneuvers intended to deviate hazardous objects from collision with the Earth may carry the danger their self. The answer for this is estimation of the mass of the asteroids or their fragments planned to be used for hitting the hazardous object is estimated to be less than 2000 tons. It is supposed that in case if such asteroid would enter the Earth

atmosphere it will be burned before reaching the surface of the Earth. In order to reach full safety Mars or Venus as centers for gravity assist maneuvers may be explored.

For the case of Mars and Venus as a gravity center of such maneuvers the results of studies are given in the Table 2.

Table 2. Near Mars and Venus gravity assist asteroid interception trajectories

using the Mars for gravity assist maneuver					
No	Asteroid	$\Delta V$ , m/s	Maneuver date	Date of perigee	Date of collision of the asteroid projectile with asteroid Bennu
1	2003 LX5	14.13	2018-12-14	2022-01-17	2026-06-12
using the Venus for gravity assist maneuver					
No	Asteroid	$\Delta V$ , m/s	Maneuver date	Date of perigee	Date of collision of the asteroid projectile with asteroid Apophis
1	2009 CE	23.10	2042-08-19	2043-04-27	2043-10-20
2	2010 DG1	21.05	2037-08-11	2039-11-03	2042-05-21

As one can see one asteroid may be intercepted using Mars flyby by applying delta – V equal 14.3 m/s, and two asteroids with delta – V less than 23.1 m/s if Venus is used for gravity assist.

It should be mentioned that motion control of asteroids may be considered not only as a tool in resolving the planetary defense problem, but also as an instrument for Solar system exploration. Here we mean the method used in Deep Impact project [2] where impactor spacecraft was directed to Temple-1 comet in order to generate gases by impacting the surface of the comet nucleus. In this project the mass of impactor did not exceed 370 kg, and to observe the ejected gases the special flyby spacecraft was used. With asteroid – projectile the effect of such hitting may be much more powerful and the use of ground based instruments for observation the consequences of such collision are expected to be promising. So in the Table 1. the Phobos chosen as to be hit target, is presented among examples of asteroids considered as hazardous. It should be mentioned that these sky bodies may be used as some intermediate targets in the development of the technology of interception hazardous object by controllable asteroids to prevent their collision with the Earth.

### Resonant orbits

Resonant orbits are very convenient for further modification. For resonant ratio 1:1 we have equal values of velocities in Sun reference system for the Earth and asteroid in the common point in space. And the family of the possible asteroid resonant orbits is determined by the vector of relative velocity of the asteroid with respect to the Earth. Geometrically this family is presented by two cones with the common base and axis. These cones are generated by rotation of the triangle from three velocities: Earth's (axis of the cones), asteroid's (in Sun reference system), and asteroid relative to the Earth velocity, as it is shown by Fig.1. Choosing the position of the vector of asteroid relative velocity one chooses the resonant orbit.

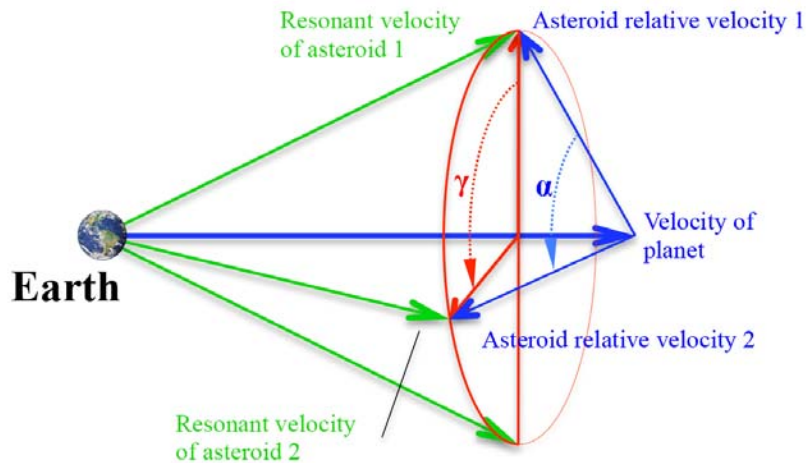


Fig. 1. Cones generated by rotation of the triangle from three velocities: Earth's, asteroid's, and asteroid relative to the Earth velocity.

Transfer between any from these orbits is possible by gravity assist maneuvers and the required number of maneuvers is determined by the value of asteroid relative velocity and consequently by maximum achievable rotation angle of velocity vector. Estimations of the required number of such maneuvers are given in [3]. To illustrate such maneuvers Fig. 2. is presented for 2012 VE77 asteroid where trajectories projections on ecliptic plane are given for six directions of asteroid relative velocity.

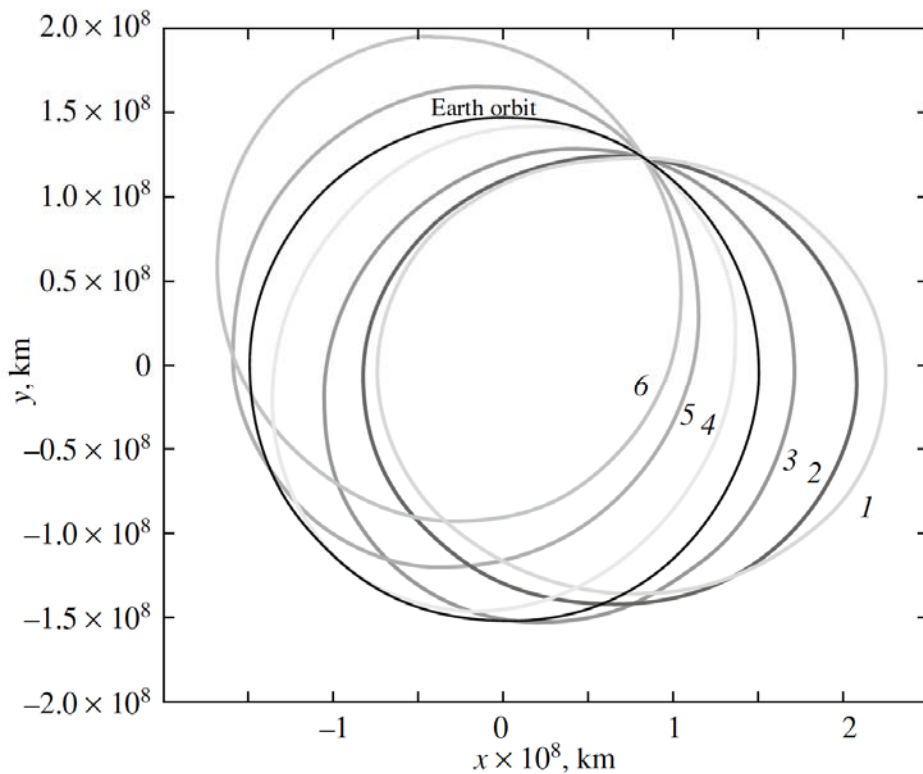


Fig. 2. Projection of resonant orbits onto the ecliptic plane with a period of one year for the asteroid 2012 VE2007 for various eccentricities  $e$  and inclinations  $i$ .

Table 3. Parameters for the resonant orbits

Orbit no.	e	i, deg
1	0.5	0
2	0.44	16
3	0.26	26
4	0.015	29.6
5	0.24	26
6	0.41	15.8

These positions are received from initial one by rotation around Earth velocity vector by maximum allowed value equal here 23.3 degrees, what determines maximum duration of gravity assist maneuvers required to reach any demanded position of vector of relative asteroid velocity from any initial one, as equal 8 years.

The corresponding values of eccentricity and inclination with respect to ecliptic plane are given in Table 3. Relative value of the asteroid velocity at infinity with respect to Earth is equal 15.4 km/s and this figure is maximum for the list of asteroids presented in [3] as the ones which are possible to transfer on the resonant with Earth orbit by gravity assist maneuver applying delta-V not exceeding 20 m/s. For comparison the characteristics of the other 2012 PB20 asteroid from the mentioned list which have the minimum relative to the Earth velocity, equal 4 km/s, may be given. For it maximum rotation angle is 103.7 degrees what mean that duration of transfer to any position does not exceed 2 years.

Purpose of such maneuvers is to broaden the area of space reachable for asteroid when it is sent to hazardous object from resonant orbit. By such a way it is possible to bypass to some extent the constraints due to limits of relative velocity vector rotation angle. From the other side using such maneuvers one can transfer the asteroid onto orbit with maximum inclination with respect to ecliptic. In this case the orbit becomes almost the same as the Earth's one. It means that resonant asteroid on this orbit comes to the close vicinity with the Earth two times per year what makes missions to the asteroid more convenient because it allows to return payload (or crew) each 6 months.

Table 4. Mars resonant orbits

	Asteroid	$\Delta V$ , m/s	Maneuver date	Date of percenter	Mars velocity	Asteroid relative velocity	Resonant velocity	Vsmin	Vsmax	Rotation angle
1	2008 KD6	7.30	2041-12-18	2042-10-26	24.89	13.27	24.51	21.22	24.55	7.25
2	2013 GD34	17.78	2019-11-04	2021-01-12	24.12	8.76	24.13	22.47	26.99	15.41
3	2009 WX6	13.33	2036-10-14	2038-02-12	23.04	11.59	23.59	22.89	26.39	9.34
4	2004 UR	16.80	2030-04-04	2031-12-03	26.46	11.09	25.32	24.78	28.58	10.12
5	2002 EW	16.57	2016-07-20	2017-12-11	22.27	20.66	23.22	21.61	23.58	3.11

Table 5. Venus resonant orbits

	Asteroid	$\Delta V$ , m/s	Maneuver date	Date of percenter	Venus velocity	Asteroid relative velocity	Resonant velocity	Vsmin	Vsmax	Rotation angle
1	2009 CE	23.10	2042-08-19	2043-04-27	34.80	5.43	34.91	31.06	39.87	79.57

### Missions optimization

Criteria of mission optimization consist from two constituents. The first one is delta-V required to send the asteroid onto gravity assist trajectory near planet in order to intercept hazardous sky object or to transfer asteroid onto resonant orbit. This problem is resolved by choosing two parameters giving minimum to delta-V: the time of applying velocity impulse to the asteroid and time of arrival to the Earth with tuning

Earth flyby trajectory parameters in order to intercept target object or reach resonant orbit required parameters. The second one is final mass of the spacecraft delivered to the surface of asteroid. To maximize this mass the time of spacecraft start from low near Earth orbit and its arrival to asteroid surface and the best ratio between delta-V for start and delta-V for deceleration are chosen. For our calculations it was supposed that Russian Proton-M launcher is used with Breeze-M upper stage, which give 1.5 km/s velocity at infinity to the spacecraft having 6185 kg mass [4]. Further operations are fulfilled by solar electric propulsion low thrust engine with specific impulse equal 32373 m/s. Some characteristics of spacecraft transfer trajectory including maximum mass delivered to the surface of asteroid are given in the Table...One can see that from the list of the asteroids chosen as candidates for gravity assist maneuvers, the maximum mass spacecraft (5672 kg) can be landed on 2004 MN4 (Apophis) asteroid and minimum mass (4592 kg) –on 2010 CA asteroid.

Table 6. Earth resonant orbits

Asteroid	Flight duration, days	$C_{3,2}(V_\infty)$ km <sup>2</sup> /s <sup>2</sup> (km/s)	Near Earth impulse at start, km s <sup>-1</sup>	Spacecraft mass after start, kg	Braking impulse near asteroid, km/s	Spacecraft mass after braking, kg
2004 MN4	307	2.4 (1.549)	3.335	6168	2.8	5672.5
2006 SU49	518	17.2(4.147)	3.981	4700	0.6	5594.2
2011 AG5	532	27.9(5.282)	4.428	3690	1.5	5254.2
1997 XF11	793	38.3(6.189)	4.846	2950	3.2	4847.2
2011 ES4	217	5.1(2.258)	3.456	5870	3.2	5472.9
2012 VE77	883	57.1(7.556)	5.569	5123	3.4	4612.0
2010 VQ	225	0.4(0.632)	3.245	6420	2.9	5869
2012 KP24	401.1	6.8(2.608)	3.531	5680	10.1	4376.1
2011 UK10	422.3	47.2(6.870)	5.194	5518	0.5	5433
2012 PB20	324	1(1)	3.272	6355	4	5616
2010 CA	669	42.0(6.481)	4.992	2750	4.6	4600

## Conclusion

According to the studies fulfilled the use of gravity assist maneuvers near Earth allows to intercept hazardous sky objects which threaten to Earth. For this rather modest delta-V impulses are sufficient in order to direct small near Earth asteroids to vicinity of the Earth in such a way which transfer them on to trajectory of collision with threatening object and thus deviating it from Earth hit. At least 13 asteroids were found which is possible to direct to Apophis asteroid and 14 ones for Bennu by applying delta-V impulse to them less than 18.82 m/s with minimum impulse equal 2.64 m/s. S

It was shown that the approach can be realized by gravity assist maneuver near Mars and Venus with the cost of delta-V required: 14.13 m/s for Mars and less than 23.10 m/s for Venus.

Resonant orbits construction using gravity assist near Earth, Mars and Venus is confirmed to be possible with the same rather low limits on delta-V.

Estimations of the mass of spacecraft to be delivered onto surface of asteroids planned be transferred on resonant with the orbit are presented for the case of Proton-M launcher with Breeze-M upper stage. These estimations under assumption of solar electric propulsion is used, confirm that the proposed technology of asteroid control is doable.

## References

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