# NEAR EARTH ASTEROIDS TRANSFER ONTO EARTH RESONANCE ORBITS WITH THE USE OF GRAVITY ASSIST MANEUVERS

**A. Ledkov(1), N. Eismont(1) , R. Nazirov(1), K. Fedyaev(1) and David Dunham(2)**
(1)*Space Research Institute of Russian Academy of Space, 117997, 84/32 Profsoyuznaya Str, Moscow, Russia ,+7(495)333-12-66, aledkov@rssi.ru*
(2) *KinetX, Inc., 7913 Kara Ct, Greenbelt, MD 20770, USA, +1-301-526-5590, david.dunham@kinetx.com*

***Abstract:*** *Discovery of Apophis asteroid which initially considered as potential hazardous sky object with some meaningful probability to hit Earth in year 2036 has increased the interest for exploration of asteroids and comets. As one of consequences of this interest the studies have been fulfilled in framework of so called "Keck Project"[1]. The Project has the aim to deliver some small enough asteroid onto Earth satellite orbit similar to the Lunar orbit. After that the manned missions are supposed to be started to this asteroid in order to explore it and to deliver its soil samples to the Earth. In the paper the alternative approach is proposed and analyzed. The principal idea of getting the asteroid onto more convenient for explorations trajectory is to capture it on the orbit which is in resonance with the orbit of the Earth. As a tool to reach it the gravity assist maneuver near Earth is considered. It is supposed that spacecraft is to be sent to of the chosen asteroid. After landing it is to be mounted on the surface of the asteroid in such a way which would allow using the propellant in its tanks for further maneuvering together with asteroid considered as payload. The first maneuver is intended to put asteroid onto trajectory of the Earth flyby in order to fulfill gravity assist maneuver resulting in reaching the orbit with respect to Sun having resonance period with the Earth orbital motion. It was accepted that the most interesting is period equal Earth orbital period. From the catalogue of JPL near Earth asteroids, the ones were chosen satisfying supposed constraints on the velocity impulse which is necessary to transfer them on gravity assist maneuver resulting in reaching one year period. For technically feasible maneuver it is necessary to take into account the size (mass) of the asteroids – candidates for transfer onto resonance orbit. These constraints were not considered as absolute ones following the assumption that if asteroid is too big in order to apply to it velocity impulse then some part of it may be separated for transfer onto resonance orbit. After putting the asteroid onto resonance orbit the another problem arises: have to control the further motion of the asteroid in order to keep it on this orbit or to change this orbit to do it more convenient for further exploration of the asteroid. It was shown the possibility to change the initial resonance orbit by further successive gravity assist maneuvers without losing the resonance. For example it is possible to put asteroid onto orbit which is practically similar to the Earth orbit but having some inclination to the ecliptic. For resonance orbit some station keeping maneuvers are necessary. Studies are fulfilled in order to understand the possibilities to fulfill manned expeditions to the captured asteroid and how to adjust the orbits of them for such missions. In framework of this analysis the estimations were received which demonstrate achievable minimum duration of such missions taking in account the contingency cases, depending on available propellant mass onboard spacecraft. More sophisticated task connected with transfer on Earth satellite orbit of the asteroid captured on resonance orbit, with the use of several Moon flybys is explored. The conditions for solving such problem are described in terms of required propellant mass and duration of needed operations.*

***Keywords:*** *Near-Earth asteroids, planetary protection.*

## 1. Manned spaceflight and space resources

International Space Station presents an impressive example of the constant man presence in space to deliver uninterrupted flow of scientific products to the Earth. But to build it several dozen of spacecraft launches have been fulfilled so hundreds of ton of instruments and constructions constituents were put onto near Earth orbit. To expand space explorations beyond near Earth orbit much more payload mass is expected to be necessary to get in space. So the idea was proposed to find the demanded material in space. Keck project proposes as a first step to implement such idea to capture some small near Earth asteroid onto orbit similar to the Lunar orbit. The mass of such asteroid was proposed to be inside limits of approximately 500 ton. To capture this sky object the use of solar electric propulsion is planned as the gravity assist maneuver near Moon. About 12 ton xenon as propellant estimated to be used to fulfill all necessary maneuvers to capture asteroid onto demanded orbit. To satisfy such constraints the total delta-V is to be not higher than 300-400 m/s. Concrete asteroid for such mission is not chosen still but there are several candidates. The difficulties to choose appropriate candidate are caused beside the sizes of the body also by acceptable relative to Earth velocity vector value which is not be too high in order to reach the conditions to seize it onto Earth satellite orbit by gravity assist maneuver near Moon.

After asteroid is captured onto Earth satellite orbit some maneuvers are to be done in order to transform this orbit into one analogous the Moon retrograde orbit. The purpose of this is to reach stable enough orbit not demanded some additional control of its parameters to keep them practically constant during further operations.

After this the series of manned missions to the captured asteroid are planned. It is planned that after reaching the captured asteroid and docking astronauts will start their extravehicular operations including asteroid material samples collecting exploration. One of the goals of such studies is the development of technologies of the asteroid resources utilization.

As principal advantage of described scenario, the possibility of fast enough return of the crew to the Earth in case of contingency is considered. With the planned 15 days of the mission the duration of the return flight from the any point of the trajectory does not exceed 3.5 days.

Simultaneously the described approach how to extend manned spaceflight beyond low Earth orbit is proposed as some important step for more distant destinations in solar system. The final goal in this progress is the manned mission to the Mars. Minimum duration for the travel to the Mars with landing to its surface and for back trip to the Earth is estimated to be 1000 days. So some intermediate missions between those to asteroid on Moon orbit and to Mars surface seem to be more than desirable. As the candidate for such step in the progress towards Mars the asteroid on the Earth resonant orbit may be proposed.

## 2. Asteroids redirections on Earth resonant orbits using gravity assist maneuvers

In the papers [2, 3, 4] it was proposed to use small near Earth asteroids to deflect hazardous sky objects from the trajectories hitting Earth. It was shown that it is possible by applying to these asteroids velocity impulses not exceeding 10 – 20 m/s which lead to transfer the ones onto trajectory gravity assist maneuvers near Earth which lead to collision of controlled asteroid with hazardous object deflecting it from trajectory going through Earth surface. As the target, considered dangerous at that time Apophis asteroid has been chosen. The studies have shown that such method is doable in framework of contemporary astronautics technology under conditions that some problems of orbital guidance accuracy would be solved. Thus one of the possible uses of asteroid resources was proposed: supposing that kinetic impulse of asteroid is the natural resource in planetary defense.

Further exploring of the technologies based on motion control of asteroids with gravity assist maneuvers led to the idea to apply this concept for transfer of near Earth asteroids onto resonant orbits i.e. on the heliocentric orbits having the orbital periods with their ratio to the Earth period equal the ratio of integer numbers. As the most preferred ratio 1:1 was considered. In this case the asteroid transferred onto resonant orbit would return to the Earth each year. It allows organizing regular operations with this sky body analogous the ones planned in Keck project. Besides some additional possibilities as compared with the ones of Keck project are given by such orbits, for example the asteroids flying on resonant orbits may be used also as projectiles for deflecting hazardous sky objects in the way described in previous paragraph.

## 3. Possible technologies of the use of asteroids on heliocentric resonant orbits

Key orbital parameters of the asteroids transferred on resonant with Earth heliocentric trajectories are presented in Tab. 1, as the values of delta-V necessary for transfer from initial orbit onto one including gravity assist maneuver resulting by resonant orbit.

The list of asteroids included in table presents the ones which demanded delta-V necessary for transfer through gravity assist maneuver is less than 10 m/s.

**Table 1.** Characteristics of some asteroids that can be transferred to the orbits resonant with the Earth orbit. In the table we denote: $\Delta V_3$ is the velocity impulse magnitude necessary for transferring the asteroid to the resonant orbit, $V_{smin}$, $V_{smax}$ and $V_{st}$ are the minimal, the maximal and the targetting values of the asteroid velocity after the maneuver in the reference frame associated with the Sun, $T_3$ and $T_4$ are dates of the asteroid velocity correction and the gravitational maneuver.

| Asteroid ID | $\Delta V_3$, m/sec | V, km/sec | $V_p$, km/sec | $V_a$, km/sec | φ, deg. | α, deg. | $V_{smin}$, km/sec | $V_{smax}$, km/sec | $V_{st}$, km/sec | $T_3$ | $T_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 MN4 | 2.2 | 5.8 | 29.7 | 28.4 | 71.6 | 78.8 | 23.9 | 34.9 | 29.7 | 2028/11/13 | 2029/04/13 |
| 2012 TC4 | 5.6 | 6.6 | 29.8 | 33.9 | 123.0 | 71.0 | 26.3 | 36.2 | 29.8 | 2016/12/12 | 2017/10/12 |
| 2006 SU49 | 7.9 | 5.0 | 30.3 | 34.3 | 140.0 | 89.1 | 27.4 | 33.8 | 30.3 | 2027/06/11 | 2029/01/23 |
| 2011 AG5 | 9.9 | 9.5 | 30.2 | 34.4 | 108.0 | 46.6 | 27.0 | 39.0 | 30.2 | 2021/08/14 | 2023/02/04 |
| 1997 XF11 | 10.0 | 14.1 | 30.0 | 34.2 | 95.1 | 26.7 | 28.0 | 39.2 | 30.0 | 2027/04/27 | 2028/10/26 |
| 2011 ES4 | 11.0 | 7.7 | 29.5 | 30.8 | 92.0 | 59.8 | 23.3 | 36.5 | 29.5 | 2027/10/27 | 2028/09/01 |
| 2012 VE77 | 12.6 | 15.4 | 30.1 | 35.4 | 97.0 | 23.3 | 29.7 | 40.1 | 30.1 | 2030/01/05 | 2031/11/18 |
| 2010 VQ | 14.0 | 4.6 | 29.8 | 27.3 | 53.4 | 95.5 | 26.6 | 33.8 | 29.8 | 2034/03/04 | 2034/10/08 |
| 2012 KP24 | 14.6 | 12.7 | 29.4 | 34.0 | 100.2 | 31.1 | 27.5 | 39.0 | 29.4 | 2021/08/12 | 2023/05/29 |
| 2011 UK10 | 15.9 | 7.5 | 29.8 | 32.5 | 104.3 | 62.2 | 24.8 | 37.1 | 29.8 | 2025/09/13 | 2026/10/10 |
| 2006 SR131 | 16.8 | 8.4 | 29.7 | 33.3 | 108.5 | 54.1 | 25.7 | 37.8 | 29.7 | 2016/08/06 | 2017/09/23 |
| 2012 PB20 | 18.8 | 4.0 | 30.2 | 30.9 | 97.4 | 103 | 26.2 | 33.9 | 30.2 | 2024/06/11 | 2025/02/11 |
| 2010 CA | 19.3 | 14.6 | 29.4 | 32.8 | 90.2 | 25.2 | 26.7 | 38.0 | 29.4 | 2027/03/07 | 2028/08/06 |

The quantities, $V_p$, $V$ and $V_a$ given in the table are the lengths of the vectors $\boldsymbol{V}$, $\boldsymbol{V_p}$, and $\boldsymbol{V_a}$ (forming the corresponding triangle) of asteroid velocity relative to the Earth (at infinity), the velocity of the Earth and heliocentric asteroid's velocity at the time immediately before Earth flyby, respectively. The $\alpha$ angle is the angle of rotation of asteroid relative velocity vector $\boldsymbol{V}$ needed to transfer the asteroid into heliocentric orbit with period of one year. Calculation results in the table were obtained by assuming that the minimum distance of the Earth flyby (perigee radius) is 6700 km. The angle $\varphi$ between the sides of the triangle $V_p$, $V$ before Earth flyby can take values within $\varphi$-$\alpha_{max}$ and $\varphi$+$\alpha_{max}$ after flyby. As a result we can get the maximum $V_{amax}$ and minimum $V_{amin}$ heliocentric velocities of asteroid after the Earth flyby. They are listed in the table. For a given orbital period (one year) after flyby the corresponding heliocentric velocity $V_{at}$ of the asteroid can be easily calculated and for our resonance case with the Earth orbit it is to be equal the Earth velocity. If it falls into the possible range of velocities determined by limit values of $\varphi$ angle, than transfer of the asteroid to the resonant orbit is doable and satisfying this requirement asteroids are included in the table.

In addition to the table the results are illustrated by the Fig.1 where the points of gravity assist maneuvers for the list of the asteroids given in table are shown along Earth trajectory. One may see that these points are distributed almost uniformly in covering Earth orbit. It means that in case if such asteroid system is constructed for planetary defense then the launch of its constituent as projectile may be done almost each month.

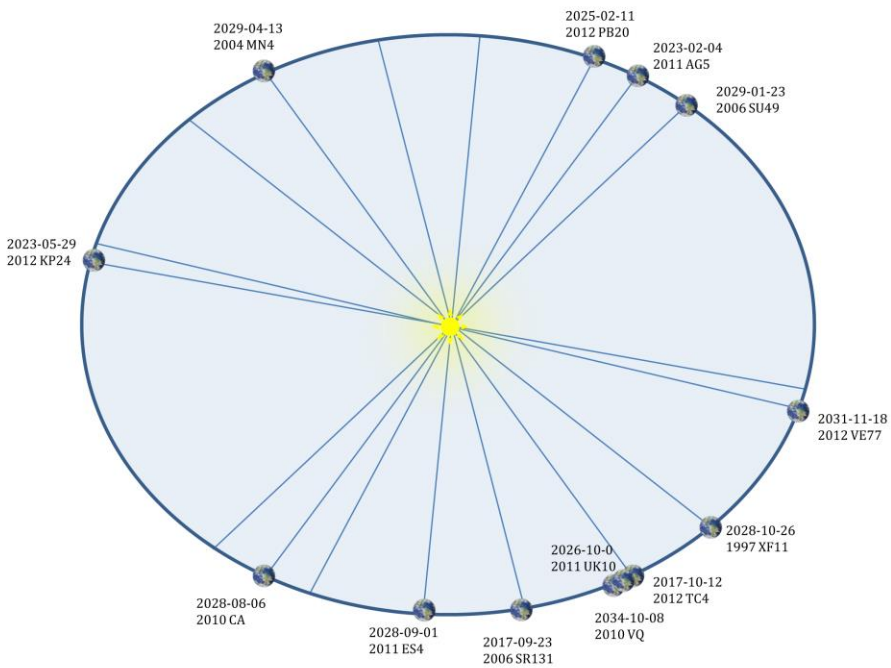


**Figure 1. The points of gravity assist maneuvers for the list of the asteroids given in table are shown along Earth trajectory**

Besides there are the possibilities modifying resonant orbit of each asteroid to make it more convenient for further use. To do this one need to take into account that after asteroid is transferred onto resonant orbit then such orbit presents some family of resonant orbits. This family can be described by two cones with the common base and common axis. This axis goes along Earth velocity vector (in the point of gravity assist maneuver). The surface of one cone is generated by the asteroid heliocentric velocity vector received after gravity assist maneuver i.e. this vector is generating line of the cone. The second is generated by asteroid relative to the Earth velocity vector. In other words both cones one receives by rotation of the mentioned above triangle as it is shown in Fig. 2. Each chosen position of the triangle corresponds some resonant orbit. To transfer from one resonant orbit to the other one it is enough to fulfill rotation of the relative velocity vector from its one position on the cone to another one. It is possible if the angle between these positions does not exceed earlier mentioned $\alpha=\alpha_{max}$ angle determined by minimum allowed flyby perigee distance $R_\pi = R_{\pi min}$ according to formula:

$$\sin\frac{a}{2}=\frac{1}{1+R_pV^2/m} \qquad (1)$$

where μ is gravity constant of the Earth.

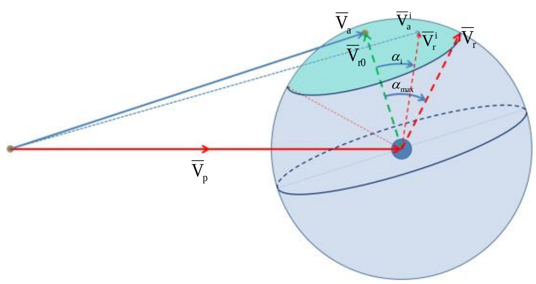


**Figure 2. The geometry of the gravity maneuver in the reference frame associated with the Sun**

In case if necessary rotation angle of relative velocity vector of asteroid exceed $\alpha_{max}$, then the demanded rotation may be reached by several sequence gravity assist maneuvers done in such a way that after each maneuver the asteroid orbit continues to be kept resonant. What means that intermediate positions of relative vector (and hence the heliocentric vector) lies on the mentioned above cones. Thus full circle of rotation is possible and the fastest multiple rotation circle is reached by each individual rotation with maximum allowed angle $\alpha_{max}$. Procedure of such sequence maneuvers is illustrated by Fig. 3 where two pyramids are shown with their edges lying on the surface of the mentioned above cones.

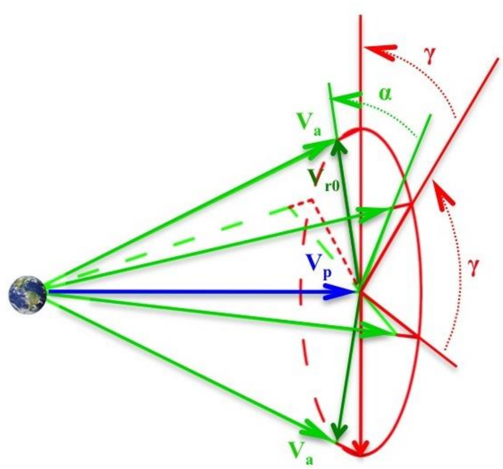


**Figure 3. Gravity assist maneuvers around the Earth**

How parameters of the resonant orbit are changed depending on γ angle between triangle plane and ecliptic is shown on the following Fig. 4a for 2010 VQ asteroid. Fig. 4b gives the asteroid distance from the Earth, Fig. 5a - eccentricity of the orbit. Fig. 5b presents the eccentricity as the function of the inclination. In is obvious that for zero inclination the eccentricity reaches its maximum values, and maximum value of inclination is reached in vicinity of zero value of eccentricity. These values are not exact because Earth orbit is not exactly circular.

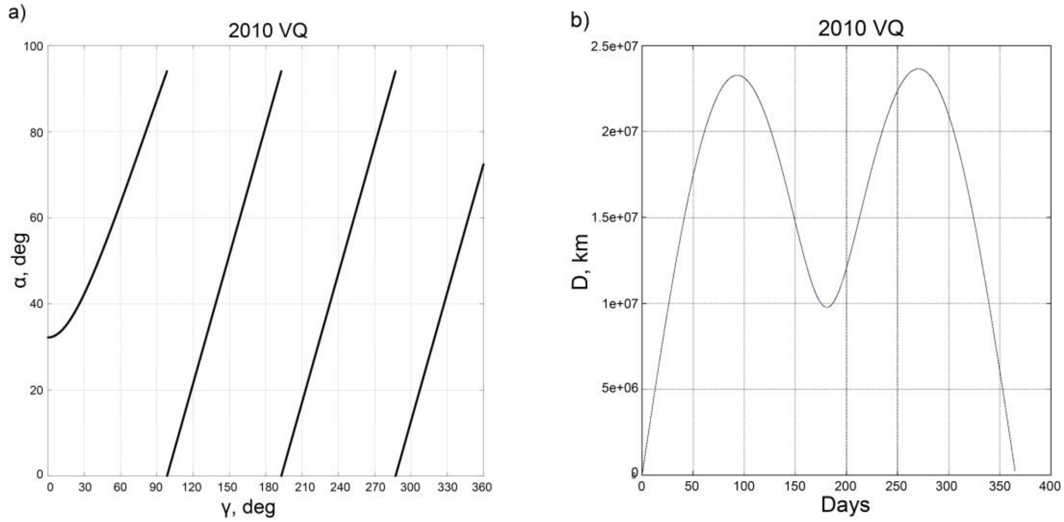


**Figure 4. a - $\gamma$ - $\alpha$ relationship, b - the asteroid distance from the Earth**

As practically interesting case the one may be considered when during one orbit the asteroid reaches ideally zero distance from the Earth two times, i.e. approaches close to the Earth each half an year. This situation may be realized when inclination is close to maximum value and the orbit of asteroid become exactly as the Earth orbit but lying in inclined with respect to ecliptic plane. If asteroid is chosen with comparatively small relative velocity, for example 4 km/s (such asteroid 2012 PB20 is presented in the Table 1), then maximum inclination which may reach 7.6 degrees and asteroid will have two close approaches to the Earth per one year. To reach this asteroid by spacecraft only 4 km/s hyperbolic excessive velocity is needed, for return back to the Earth after 6 months practically no delta-V is needed.

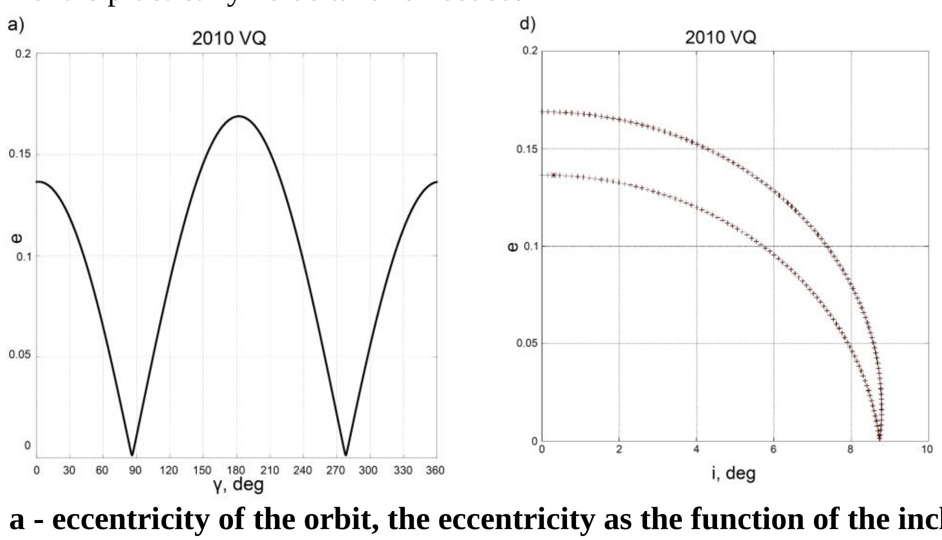


**Figure 5. a - eccentricity of the orbit, the eccentricity as the function of the inclination**

For asteroids with high relative velocity like in case of 2012 VE77 asteroid version with zero inclination may be used in order to reach distant regions with respect to Earth. Fig. 6 illustrates this advantage of such orbit presented in ecliptic plane. One can see that this orbit reaches Mars orbit and intersects the Venus orbit.

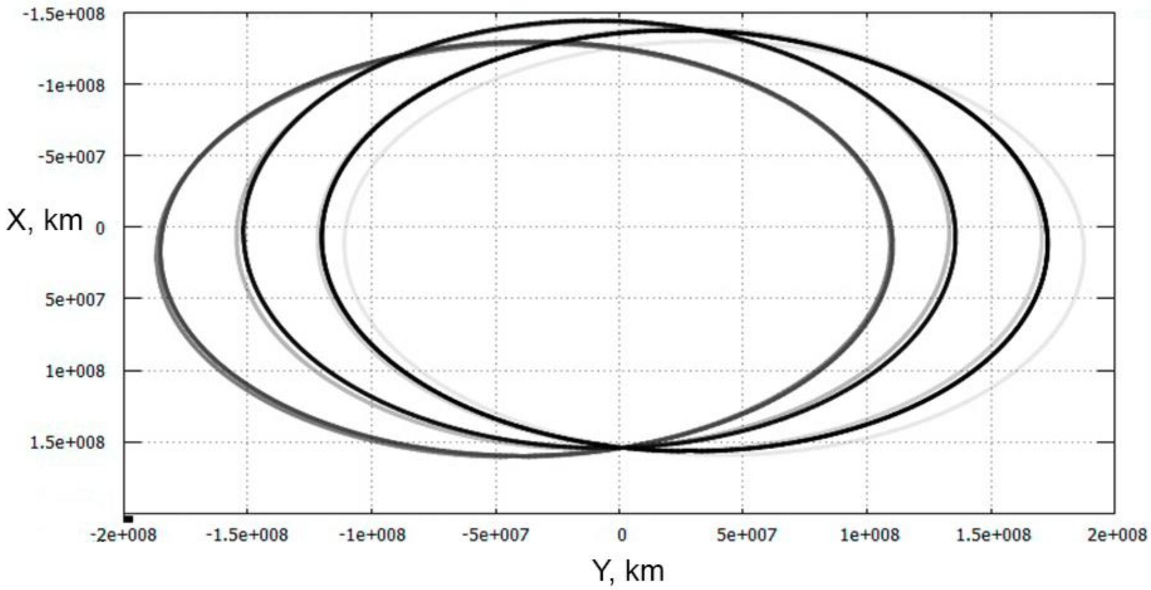


**Figure 6. Projections of resonant trajectories to the ecliptic plane.**

## 4. Methods of capture asteroid from the heliocentric resonant orbit onto Earth satellite orbit

In order to capture asteroid moving along heliocentric Earth resonant orbit onto Earth satellite orbit it is necessary to decrease its relative with respect to Earth velocity to the value less than parabolic. It is obvious that it is impossible to do by the use Earth gravity assist maneuver. Moon gravity assist maneuver may be applied for this but it demands low enough relative to Earth velocity. Its maximum value is determined by the achievable level of its decreasing by Moon gravity field. In case if moon gravity is too weak for this and after this near Moon maneuver asteroid leaves resonant orbit then we miss our goal. But if we manage to construct the required relative geometry of four body motion (Sun, Earth, Moon and asteroid) then we succeed because it gives the chance to repeat the operations one year later. As analysis shows that good enough case for asteroid velocity vector direction relative towards the Earth is the one when it is close to be orthogonal to the ecliptic. As our description above demonstrates it is possible when the resonant orbit has the maximum inclination towards ecliptic.

Figure 7 illustrates Lunar gravity assist maneuver. Asteroid velocity vector relative to the Earth calculated taking into influence of the Earth gravity field $\boldsymbol{V_{ae}}$ is shown before Lunar flyby as vertical. Moon relative to Earth velocity vector $\boldsymbol{V_{me}}$ is shown as horizontal. Asteroid velocity vector with respect to Moon is designated as $\boldsymbol{V_{am}}$ for the moment before Moon flyby. Asteroid velocity vector with respect to Earth after flyby is designated as $\boldsymbol{V_{aef}}$ and with respect to Moon $\boldsymbol{V_{amf}}$.

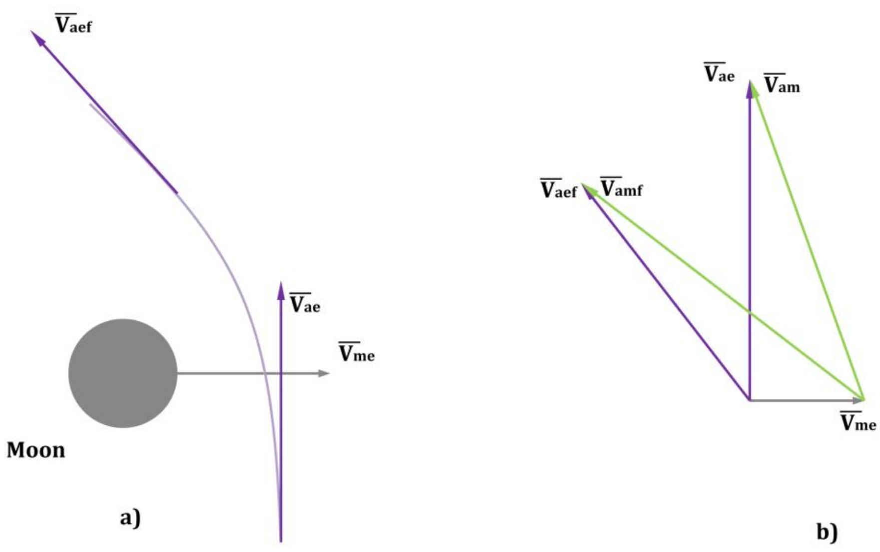


**Figure 7. Lunar gravity assist maneuver**

Fig. 8 shows the positions of the Earth and Moon and direction to the Sun along line of the Earth and asteroid planes of intersection. On this figure the vectors of the velocity impulse caused by gravity of the Earth and the Moon are shown.

The task of maneuver is to decrease the length $\boldsymbol{V_{aef}}$, ultimately to the value less than parabolic. But during preceding maneuvers the asteroid heliocentric velocity is to be kept equal to the one corresponding resonant orbit. It means that the sum of mentioned above impulses in projection to the asteroid heliocentric vector is to be equal zero. From the Fig. 8 it is possible to see that by choosing the position of the Moon and the distance from the Moon of asteroid during flyby it is possible to solve the problem. Roughly it is enough to flyby the Moon when it is in the Earth sector marked on Fig. 8.

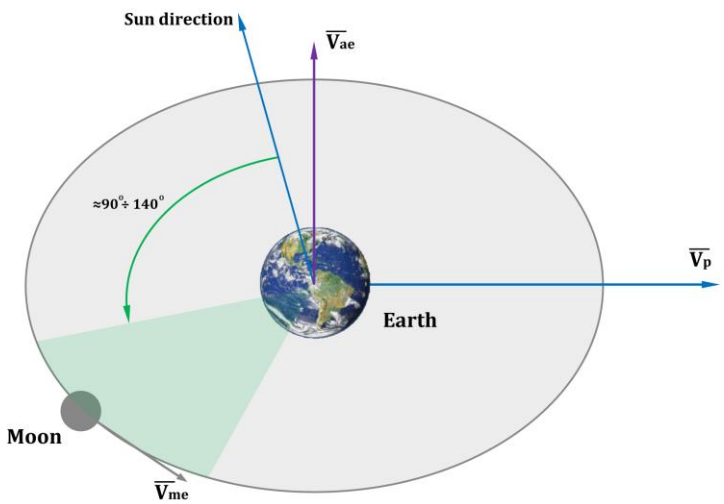


**Figure 8. The positions of the Earth, Moon and Sun direction along line of the Earth and asteroid planes of intersection.**

## 5. Conclusion

Gravity assist maneuvers near Earth may used as a tool to transfer near Earth asteroids onto resonant with Earth orbit

It is possible to modify the parameters of such orbits still keeping them resonant despite of varying their inclination and eccentricities in broad limits.

The asteroids resonant orbits may be used as convenient destinations for manned spaceflights especially for the possible version of return these asteroids to the Earth each half of year.

It is possible with the use of combined gravity assist maneuvers near Earth and Moon to capture the asteroids onto Earth satellite orbit if on begins the operations from resonant orbit.

## 6. References

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