Evolution of Apophis Orbit for 1000 Years and New Space Targets

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Abstract. As a result of the analysis of publications it is established that uncertainty of trajectories of Apophis are caused by imperfection of methods of its determination. The differential equations of motion of Apophis, planets, the Moon and the Sun are integrated by new numerical method and the evolution of the asteroid orbit is investigated. The Apophis will pass by the Earth at a distance of 6.1 its radii on April 13th, 2029. It will be its closest approach with the Earth during next 1000 years. A possibility of transformation of Apophis orbit to an orbit of the Earth's satellite, which can be used for various tasks, is considered.

It is known from the publications (see for example [1]) that the asteroid Apophis will pass on April 13, 2029 by the Earth at a distance, which can vary in a range from 5.62 to 6.3 its radii. Because of essential change of the Apophis orbit the further prediction of its motion becomes impossible. However there is some probability of its encounter with the Earth in 2036.

We have analyzed papers [1- 4] and have established that uncertainties of the Apophis trajectory are caused by imperfection of methods of its computing. We have developed [5] a new method for integration of the not simplified differential equations of interaction of asteroid, Sun, planets and Moon under the Newton law of gravitation, which are:

$$\frac{d^2\vec{r}_i}{dt^2} = -G\sum_{k\neq i}^{n}\frac{m_k\vec{r}_{ik}}{r_{ik}^{\ 3}}, \quad i = 1,2,\ldots,n, \tag{1}$$

where $\vec{r}_i$ is radius-vector of a body with mass m_i relatively Solar System barycenter; G is gravitational constant; $\vec{r}_{ik}$ is vector $\vec{r}_i - \vec{r}_k$ and r_{ik} is its module; $n = 12$.

As a result of numerical experiments and their analysis we came to a conclusion, that finite-difference methods of integration do not provide necessary accuracy. For the integration of equations (1) we have developed algorithm and program "Galactica". The meaning of function at the following moment of time $t=t_0 + \Delta t$ is determined with the help of Tailor series, which, for example, for coordinate x looks like:

$$x = x_0 + \sum_{k=1}^{K}\frac{1}{k!}x_0^{(k)}(\Delta t)^k , \tag{2}$$

where $x_0^{(k)}$ is derivative of k order at the initial moment t_0.

The meaning of velocity x' is defined by the similar formula, and acceleration x_0'' by the formula (1). Higher derivatives $x_0^{(k)}$ are determined analytically as a result of differentiation of the equations (1). The calculation algorithm of the sixth order is now used, i.e. with K=6. The mass of bodies, and also their initial coordinates and velocities on the epoch of November 30.0, 2008 are given on a site: http://www.ikz.ru/~smulski/Data/OrbtData/ in a folder AsApophs, and their description is in a file ReadMeOREn.pdf.

By this numerical method we have integrated the differential equations (1) of motion of Apophis, the major planets, the Moon and the Sun and investigated evolution of the asteroid orbit. On April 13, 2029 Apophis will pass at a distance R_{min} = 38907 km from the Earth centre and during the next 1000 years there will not be so close approaches of the asteroid with planets.

The minimum distances R_{min} of the asteroid from planets and the Moon were determined for a number of successive intervals of time of ΔT duration each. The researches have been executed over three time spans: 0 ÷ 100 years (Fig. 1a), 0 ÷ –100 years (Fig. 1b) and 0 ÷ +1000 years (Fig. 1c).

On Fig. 1 the points, connected by a broken line, give the minimal distances R_{min} of asteroid from bodies, which are marked by points united by a horizontal line. That is, the ordinate of a point in the broken line is equal to the minimum distance attained by the asteroid during time interval ΔT = 1 year from a body which is noted by a point in a horizontal line at the same moment.

As the Fig. 1*a* shows, since November 30.0, 2008 during 100 years there will be only one very close approach with the Earth (point A) at the instance T_A = 0.203693547133403 centuries (on April 13, 2029, $21^h45^m47^s$ of

Greenwich time) up to a distance R_{minA} = 38906.9 km. The following close approach (point B) will be also with the Earth, but at the instance T_B = 0.583679164042455 centuries (on April 13, 2067) up to a distance R_{minB} = 622231 km, which is 16 times greater as compared with the distance of the first approach. As to the other bodies, the closest approach will be only with the Moon (point D) (see Fig. 1*b*) at the instance T_D = -0.106280550824626 centuries up to a distance R_{minD} =3545163 km.

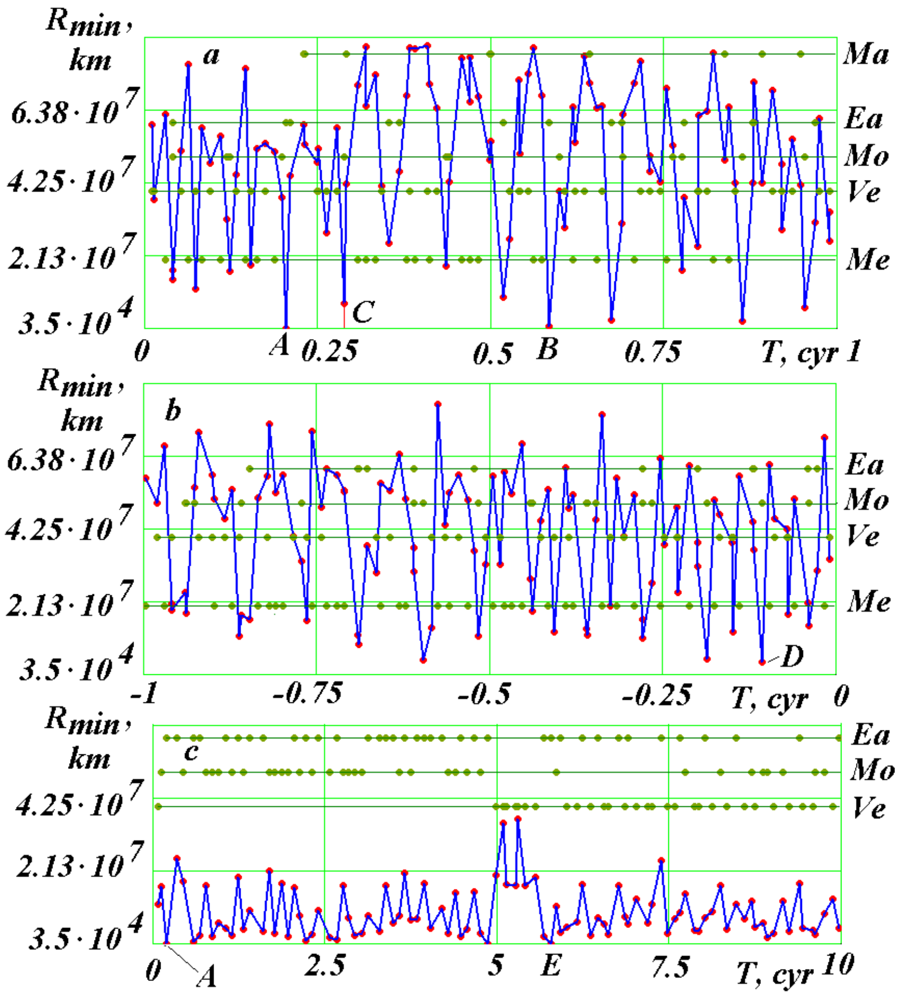

Fig. 1. Apophis' minimum distance R_{min} (in kilometers) for successive intervals of time of ΔT duration with celestial bodies: Mars (Ma), the Earth (Ea), the Moon (Mo), Venus (Ve) and Mercury (Me); *a* and *b* – ΔT = 1 year; *c* – ΔT = 10 years. *T*, cyr – time in Julian centuries from epoch JD0 = 2454800.5 = November 30.0, 2008.

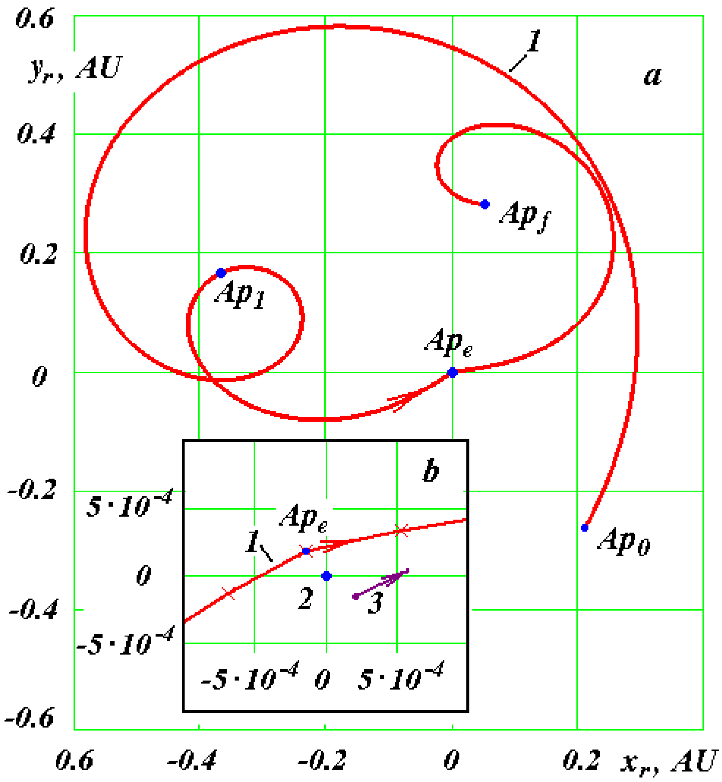

Fig. 2. Trajectory of Apophis (1) in a geocentric equatorial frame $x_r y_r$; Ap_0 and Ap_f – initial and final points of the Apophis trajectory; Ap_e – the point of Apophis minimum distance to the Earth: *a* – in usual scale, *b* - in the enlarged scale at the moment of Apophis approach with the Earth (2); 3 – position of Apophis at the moment of its approach with the Earth after correction of its trajectory with coefficient of reduction of velocity k = 0.9992; coordinates x_r and y_r are given in AU.

When the equations of motion (1) were integrated during 1000 years interval (see Fig. 1*c*), the minimum approach distances of the asteroid with bodies were counted every 10 years. In so doing we do not show the approaches with Mercury and Mars as approaches to other bodies are more close. There is an approach with the Earth at the instance T_A which can be seen as well on Fig. 1*a*. The second close approach also occurs with the Earth (point E) at the instance T_E = 5.778503 centuries (on October 10, 2586) up to a distance R_{minE} = 74002.9 km, i.e. at the distance from the Earth, which is almost twice more than at the moment T_A.

So, on April 13, 2029 Apophis will pass by the Earth 38907 km apart from its centre and in the nearest one thousand years such close approaches to the Earth will not happen anymore. Therefore thanks to a happy opportunity, the possibility to transmute Apophis into a satellite of the Earth and then into a manned station represents the considerable interest. Other applications of such satellite are also possible. It can form a base for a space lift. It can be used as "shuttle" for delivery of loads to the Moon. In this case the satellite should have the elongate orbit with perigee distance close to radius of a geostationary orbit and the apogee distance which is coming near to distance of the perigee of the Moon orbit. Then loads from a geostationary orbit would be shifted to an Apophis-satellite in perigee and then, in apogee, these loads could be delivered to the Moon. The last two applications are possible, if the satellite motion coincides in the direction with Earth rotation and the Moon motion.

On Fig. 2*a* the trajectory of Apophis relatively to the Earth for two years is shown. Apophis moves on the trajectory *1* from point Ap_0 to point Ap_1. At point Ap_e it approaches to the Earth, and the point Ap_f is final point of its trajectory. The loops of Apophis trajectory represent its returnable motions relatively the Earth. The fracture of the Apophis trajectory nearly point Ap_e is shown in a large scale on Fig. 2*b*. The origin of coordinates (point 2) coincides with the Earth. The Sun is located in the upper right quadrant. Velocity of the asteroid relatively to the Earth in point Ap_e is equal v_{AE} = 7.39 km/s. Velocity of the Earth's satellite in a circular orbit with radius R_{min} is equal v_{cE} = 3.2 km/s. To transmute the asteroid into a satellite it is necessary to slow down its velocity v_{AE} to v_{cE}. At reduction of Apophis velocity in point Ap_e it would be transformed into the Earth's satellite, however into a satellite with retrograde motion.

If Apophis (see Fig. 2*b)* will pass by the Earth the other side (see point *3*), then at reduction of its velocity it would be transmuted into a satellite with prograde motion. For the purpose of numerical experiment the equations (1) have been integrated at variation of the asteroid velocity in point Ap_1. In the experiment the velocity components were proportionally changed by the same factor, i.e. they were multiplied by coefficient *k.* As a result it has been established that at reduction of velocity the asteroid starts to approach more closely to the Earth and at k = 0.9999564 Apophis encounters with the Earth. On farther reduction of velocity of the asteroid it approaches the Earth from the other side of the globe and at k =0.9992 asteroid pass by the Earth at almost the same distance R_{min}.

In this case the asteroid velocity relative to the Earth also is equal v_{AE} =7.39 km/s. With its reduction by 1.9 times the Apophis is transmuted into the Earth's satellite with the steady orbit and with revolution period of 2.436 days.

So, to transform Apophis into a satellite with direct revolution it is necessary to reduce its velocity by 2.54 m/s 0.443 years prior to approach of Apophis with the Earth, and at approach with the Earth it is necessary to reduce it by 3.5 km/s.

The reduction of velocity by 3.5 km/s of a body of mass 30 million tones represents now a serious scientific and technical problem. But ahead is 20 years and experience of creation of the first Earth artificial satellite testifies that if society is confronted with such aim, it will be successfully accomplished.

References

1. *Georgini J.D., Benner L.A.M., Ostro S.I., Nolan H.C., Busch M.W.* Predicting the Earth encounters of (99942) Apophis // Icarus. 2008 V. 193, P. 1-19.
2. *Sokolov L. L. , Bashakov A. A. , Pit'ev N. P.* O vozmozhnykh sblizhenijakh ACZ 99942 Apofis s Zemlej // Okolozemnaja astronomija 2007. Materialy mezhdunarodnoj konferentsii 3-7 sentjabrja 2007 g., Terskol. Mezhdunarodnyj centr Astronomicheskikh i mediko-ekologicheskikh issledovanij Nacional'noj akademii nauk Ukrainy i Institut astronomii RAN. Nal'chik, 2008 g, P. 33 - 38. (On the possible approaches of NEA 99942 Apophis with the Earths). (in Russian).
3. *Smirnov E. A.* Sovremennye chislennye metody integrirovanija uravnenij dvizhenija asteroidov, sblizhajushchihsja s Zemlej // Ibidem, P. 54-59. (Modern numerical methods of integration of equations of motion of the asteroids approaching with the Earth). (in Russian)
4. *Bykova L.E. Galushina T.Ju.* Evoljucija verojatnoj oblasti dvizhenija asteroida 99942 Apofis // Ibidem., P. 48 - 54. (Evolution of probable areas of a motion of the asteroid of 99942 Apophis). (in Russian).
5. *Smulsky J.J.* Optimisation of a passive orbit with the help gravity-assist maneuver // Kosmicheskie Issledovaniya, 2008, V. 46, № 5. P. 484-492. (In Russian) http://www.ikz.ru/~smulski/Papers/KOS0484.pdf. Smulsky J.J. Optimization of Passive Orbit with the Use of Gravity Maneuver // Cosmic Research, 2008, Vol. 46, № 55, P. 456–464. (In English) http://www.ikz.ru/~smulski/Papers/COSR456.PDF.