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•On prevention of possible collision of asteroid Apophis with Earth

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Session 3.1. Counteraction systems against hazardous objects
•June 28, Saturday; 11:30

1. INTRODUCTION

A problem connected with the asteroid Apophis is discussed in our paper. Now there is any probability for the Apophis-Earth collision. So, it is important to analyze possibilities to prevent this collision.

An analysis of the orbit correction for the asteroid Apophis is performed in the study.

This correction has to prevent the asteroid-Earth collision in 2036.

1. Nominal Trajectory of Asteroid Apophis

a) **A Model and the Equations of the Asteroid Motion**

$$\ddot{\mathbf{r}} = -\frac{\mu_S}{|\mathbf{r}|^3}\mathbf{r} - \sum_i \mu_i \left(\frac{\mathbf{r}_i}{|\mathbf{r}_i|^3} + \frac{\mathbf{r} - \mathbf{r}_i}{|\mathbf{r} - \mathbf{r}_i|^3} \right) + \Delta_1 + \Delta_2 \qquad \textbf{(1)}$$

r, $\mathbf{r_i}$ – asteroid's and celestial bodies' radius-vectors (planets and the Moon – from DE-405);

μ_S – Gravitational parameter of the Sun;

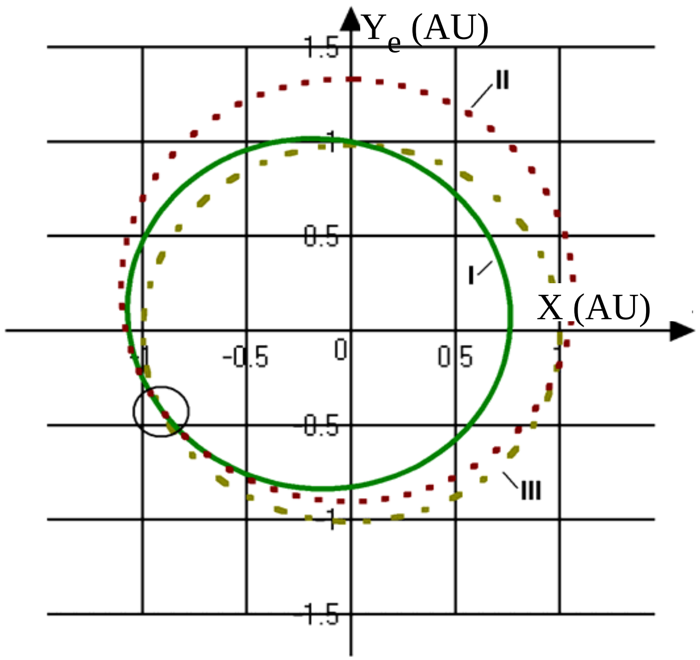
μ_i – Gravitational parameters of celestial bodies;

Δ_1 – takes into account the Earth oblateness;

Δ_2 – takes into account the solar-radiation pressure.

Set aside: small planets, relativistic effect and the Yarcovsky effect

2. Nominal Trajectory of Asteroid Apophis
b) Characteristics of *Apophis*



- **Fig. 1. Orbits of Apophis and Earth**
- **I** – Asteroid's orbit before its approaching to the Earth in 2029
- **II** – Nominal Trajectory of the *Apophis* after its approaching to the Earth in 2029
- **III** – Orbit of the Earth

Apophis' orbit **I** (Aten ast.):

- sidereal period T=0.89 y. (synodic one≈8 y.)
- aphelion distance R_α=1.10 AU
- perihelion distance R_π=0.75 AU
- semi-major axis a=0.92 AU; incl. I=3°.3

Apophis' nominal orbit **II** (Apollo ast.):

- sidereal period T=1.17 y. (synodic one ≈ 7 y.)
- aphelion distance R_α =1.33 AU
- perihelion distance R_π =0.90 AU
- semi-major axis a=1.11 AU; incl. I=2°.1

Geocentric Velocity "at infinity" ≈ 5.5 km/sec

Collision velocity ≈12.6 km/sec

Physical characteristics:

- Diameter D_A=250-390 m
- Density d_A=2.5-3 g/cm^3
- Mass (D_A=320 m, d_A=2.5 g/cm^3) m_A ≈ 4.3·10^{10} kg
- Energy of possible Collision with the Earth ~ 800 MT TNT
- Tunguska event, 1908: ~12 MT

2. Nominal Trajectory of Asteroid Apophis
b) Asteroid-Earth Distance

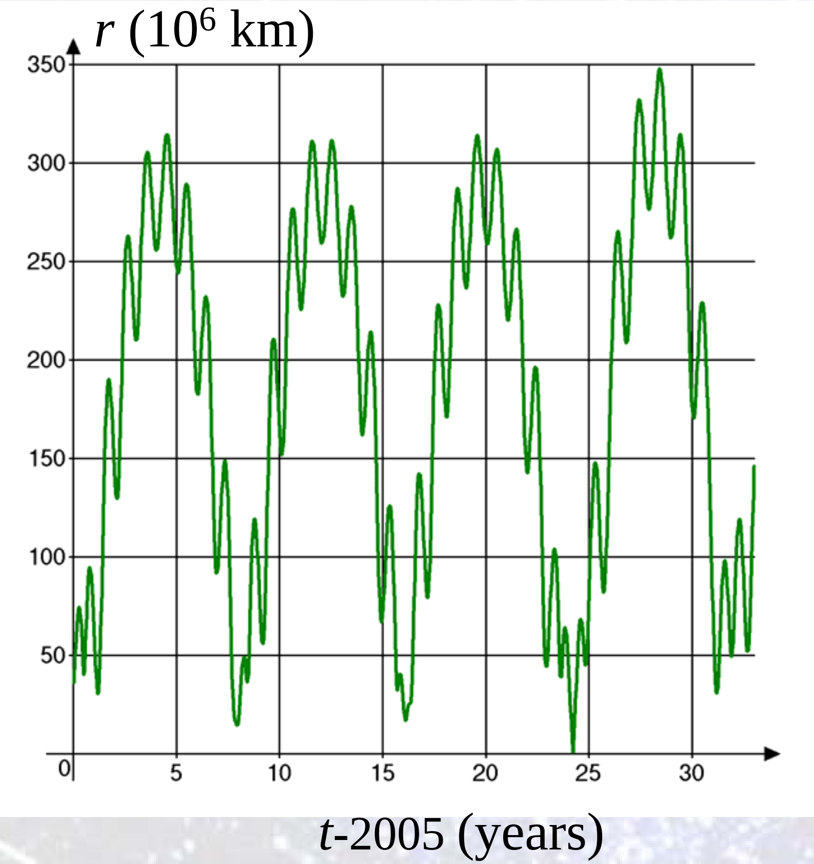


Fig. 2. Asteroid's nominal distance to Earth in 2005-2038

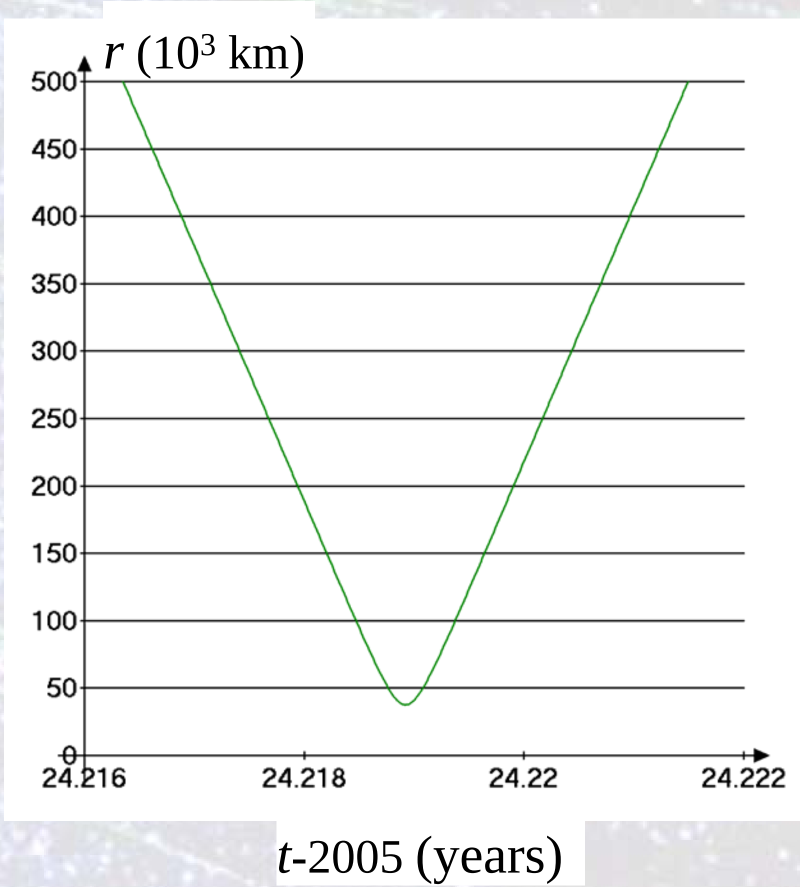


Fig. 3. Asteroid's distance to Earth for approaching in 2029

3. "Tube" of Asteroid's Trajectories

The following set of asteroid's possible kinematic parameters at initial moment t_0=2005 Jan. 30.0 is taken:

D={ $|\Delta r_0| \leq 3$ km; $|\Delta V_0| \leq 0.002$ m/sec } [1: Yagudina E.I., Shor V.A., 2005] (2)

This results in a set ("tube") of the Apophis orbits. Its map on the aim plane is a "Dispersion Ellipse" .

This aim plane is perpendicular to the asteroid geocentric velocity for the time of its closest approaching to the Earth in April 2029.

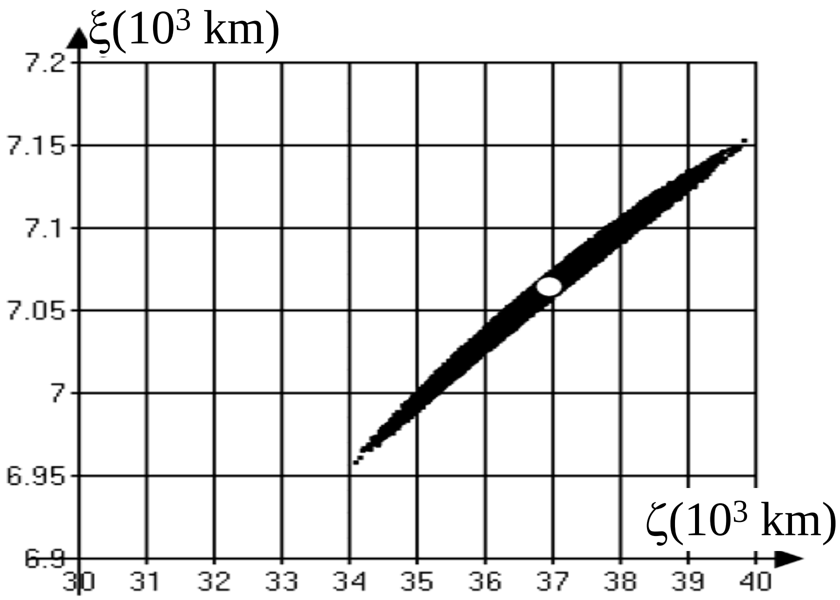


Fig. 4. "Dispersion ellipse" for Asteroid's trajectories in the aim plane near the Earth in April 2029
[2-5: Ivashkin V.V., Stikhno C.A., 2007**]:**
***a* ≈3000 km; *b*≈8 km;**
$\zeta_0 \approx$ 36 948 km, $\Delta\zeta \approx$3000 km;
$\xi_0 \approx$ 7 064 km, $\Delta\xi \approx$ 100 km

Parameters of Approaching in 2029:
$r_\pi \approx$ 37600 ± 3000 km; $t_f \approx t_{f\,n}$ ± 120 sec

4. A Set of Apophis' Trajectories with the Asteroid-Earth Collision in 2036

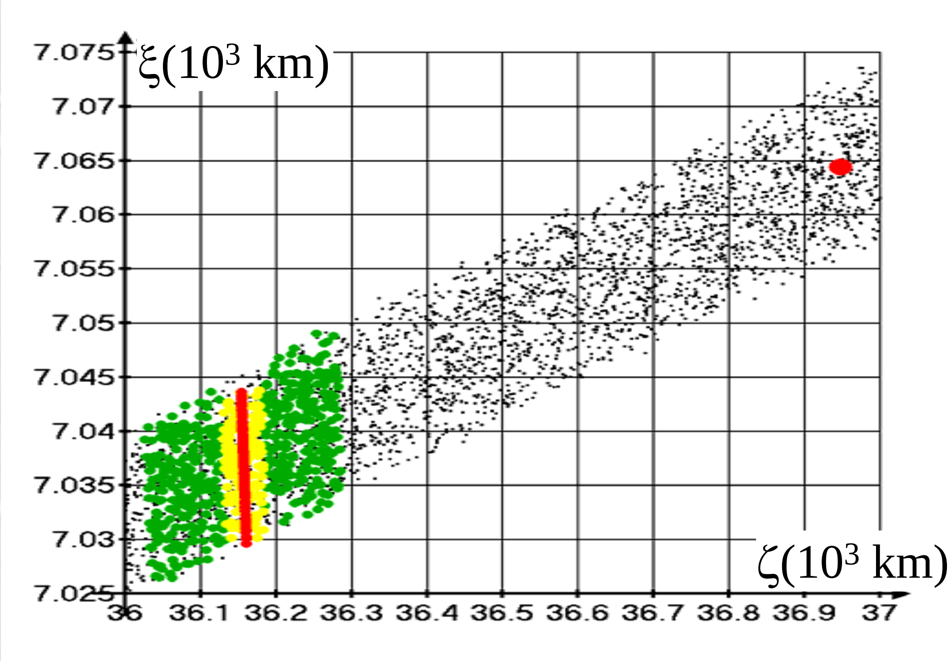


Fig. 5. Sets of the Apophis "dangerous" and collision trajectories (in April 2036) on the aim plane near Earth in 2029 [2-5] :

- ***narrow red strip*, r_π<6371 km, ζ ~36160 km**
- **surrounding *yellow band*, r_π<$1\cdot10^6$ km**
- ***green band*, r_π<$5\cdot10^6$ km, ζ~36000-36300 km**
- ***points* of "dispersion" ellipse**

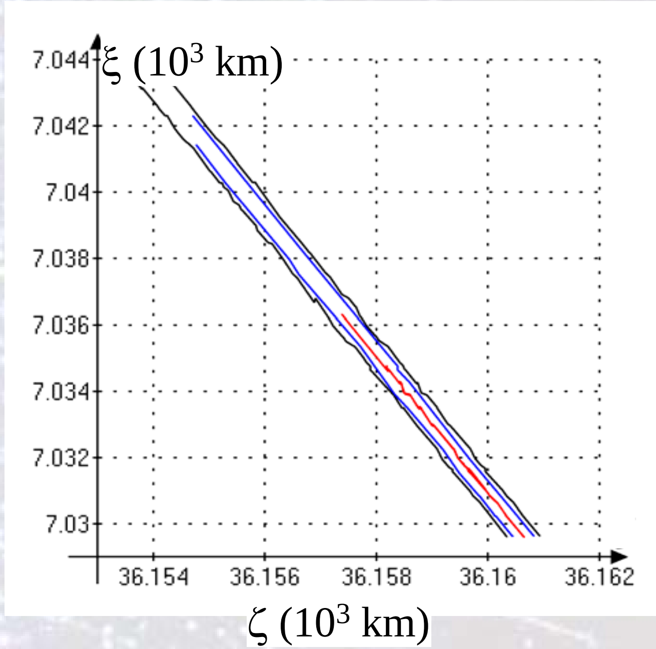


Fig. 6. Lines on the aim plane with constant perigee distance (2070 km; 4000 km; 6370 km) in 2036 for the asteroid Apophis orbit; a domain with ~600 m width. [3, 4]

5. Correction of Asteroid's Orbit - a

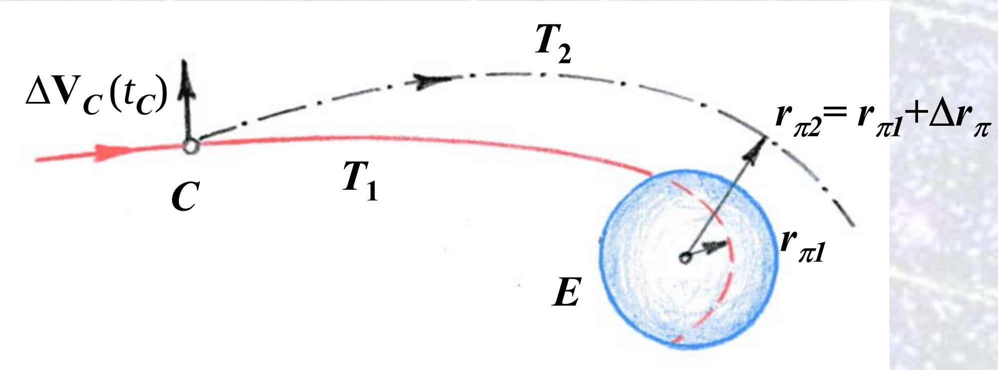


Fig. 7. Scheme of one-impulse correction for a collision trajectory

Schemes of Asteroid's Orbit Impulsive Correction

1. One-impulse correction

- **One-parameter correction of the perigee distance in 2036 and 2029;**
- **One-parameter correction of the flyby point distance to the origin on the aim plane near the Earth in 2029 and 2036;**
- **Two-parameter correction of the flyby point coordinates on the aim plane near the Earth;**
- **Three-parameter correction for arrival to a fixed position at a fixed time.**

2. Two-impulse correction

5. Correction of Asteroid's Orbit - b

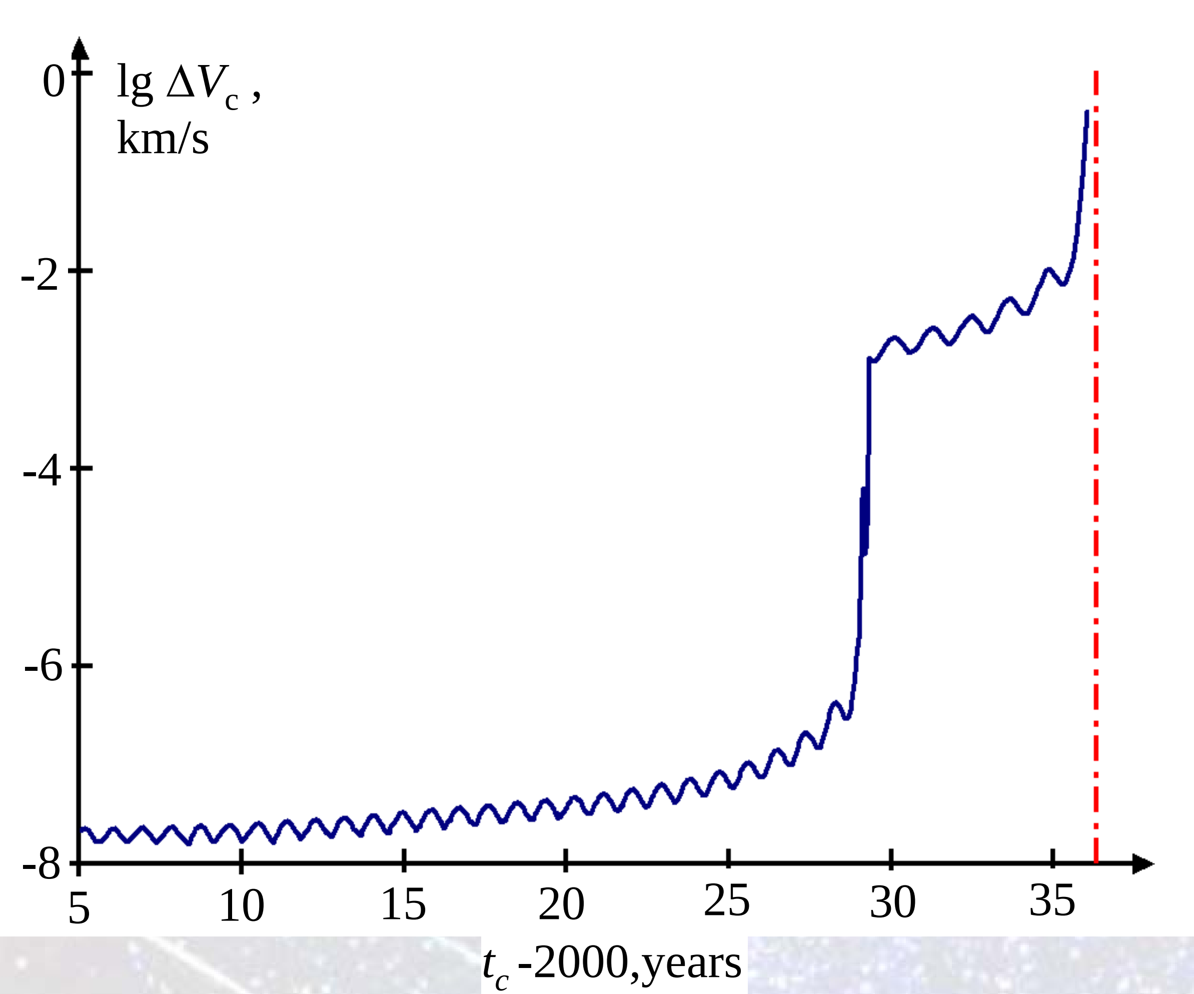


Fig. 8. Value of Correction Velocity Impulse for Apophis' deflection from the Earth at the distance $\Delta r_{\pi}=10^6$ km in April 2036 [2-5]: a right vertical line corresponds to the collision in 2036.

For the correction before the year 2029, the correction velocity impulse is less considerably than after 2029.

5. Correction of Asteroid's Orbit – c

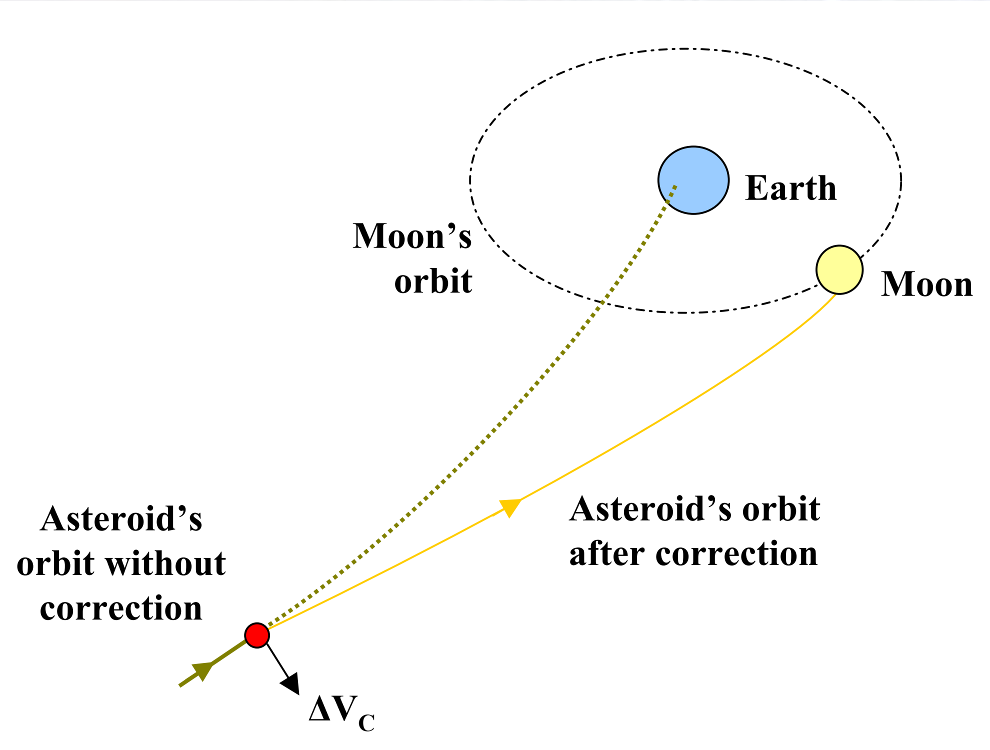
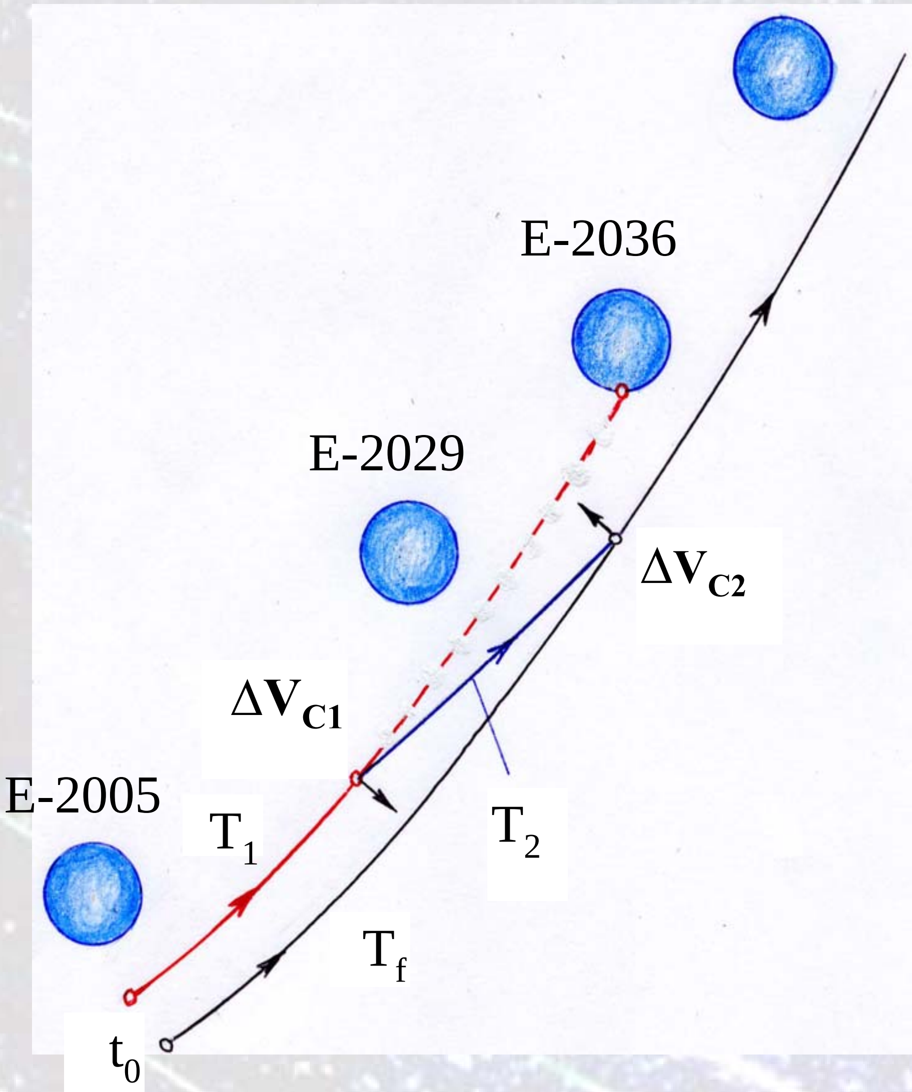


Fig. 9. Scheme of the one-impulse "Lunar" Correction for Apophis' deflection from the Earth and its sending to the Moon. [3-5]

For this correction, a change of the perigee distance for the Apophis orbit Δr_π is up to ~$0.4\cdot10^6$ km. Velocity impulse applied to the Moon is of ~ 10^{-11} km/s and a change of the semi-major axis of Moon's orbit to ~ 10^{-5} km.

5. Correction of Asteroid's Orbit - d



2. Two-impulse correction

- It is a transfer of asteroid from the collision trajectory (T_1) to a "good" enough one (T_f), which has no close approaching to the Earth for next hundred years
- the second impulse can revise the measurement and execution errors for the first impulse

Fig. 10. Scheme of two-impulse correction of the collision trajectory.[2-5]

5. Correction of Asteroid's Orbit – e

Table 1. Spacecraft mass m_{SC} (near Apophis) and m_0 (on LEO) for kinetic-impact effect of spacecraft on the Apophis to prevent its collision with the Earth in 2036 [2-5]

t_c, year	Δr_π, km	ΔV_c, m/s	m_{SC}, t A/B	m_0, t A/B
2020-2021	$1 \cdot 10^6$	0.6 10^{-4}	0,9/0,3	2,7/1,0
2028	$1 \cdot 10^6$	10^{-3}	14 / 5	45 / 16
2029-	$1 \cdot 10^6$	10^{-2}	140 / 50	450 / 160
2029+	$30 \cdot 10^3$	0.12	1700 /610	5400/2000

A)–Model for perfectly inelastic impact of spacecraft on the asteroid

B)–the Stanyukovich Model for high-speed explosive impact **[6-8]**

6. Baum F.A., Stanyukovich K.P., Shekhter B.I. *Physics of Explosion*, Moscow, 1959

5. Correction of Asteroid's Orbit – f

Table 2. Valuation of Energy for nuclear effect on the asteroid (by the surface explosion) [2-5]

t_C, years	2029 –	2029 +	2031	2033	2034	2035 (1)	2035 (2)
Δr_π, 10^6 km	1	1	1	1	1	1	1
ΔV_C, m/s	10^{-2}	4	6	8	11	21	54
E_N, MT TNT [9, 10]	0.004	1.6	2.4	3.2	4.5	8.3	22

9. Ahrens T.J., Harris A.W., 1992
10. Nechay V.Z., Nogin V.G., et al., 1997.

5. Correction of Asteroid's Orbit – f

Slow Gravity effect on the Asteroid - a

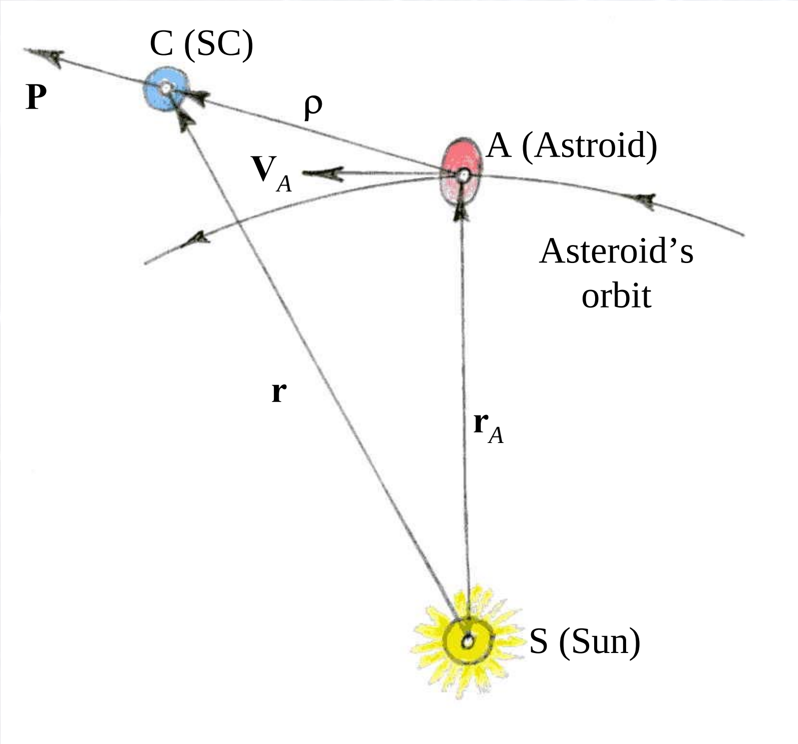


Fig. 10. Scheme of the spacecraft placing near the Asteroid to correct its orbit by the gravity effect [11: E.T. Lu, S.G. Love, 2005]

5. Correction of Asteroid's Orbit – g

Slow Gravity effect on the Asteroid - b

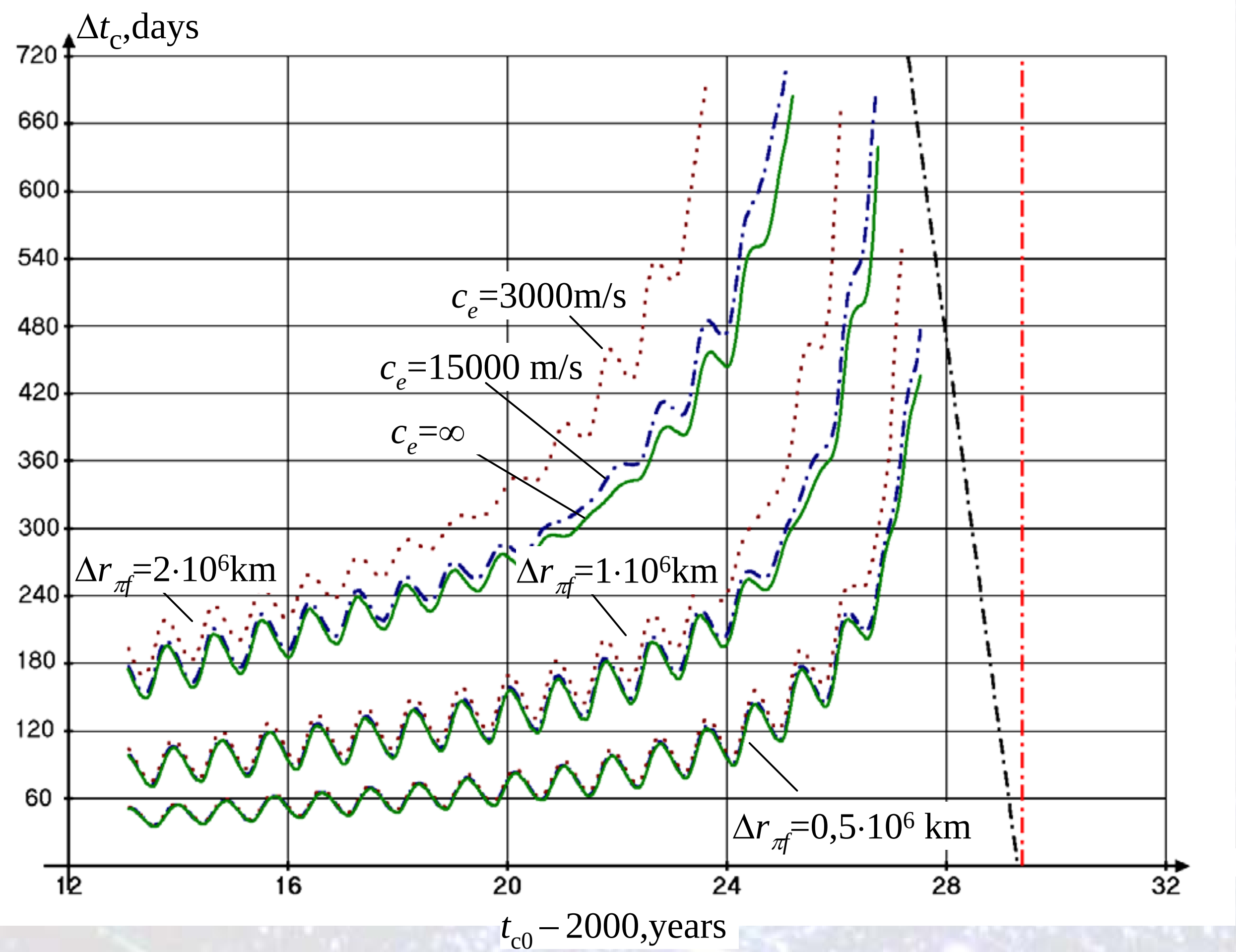


Fig. 11. Duration of gravity effect versus the initial time of correction, exhaust velocity (c_e=∞, 15000 m/s, 3000 m/s) and change of perigee distance in 2036 (initial SC mass m_0=5000 kg).
[12: **Ivashkin V.V., Stikhno C.A., 2008**]

5. Correction of Asteroid’s Orbit – h

Gravity effect - c

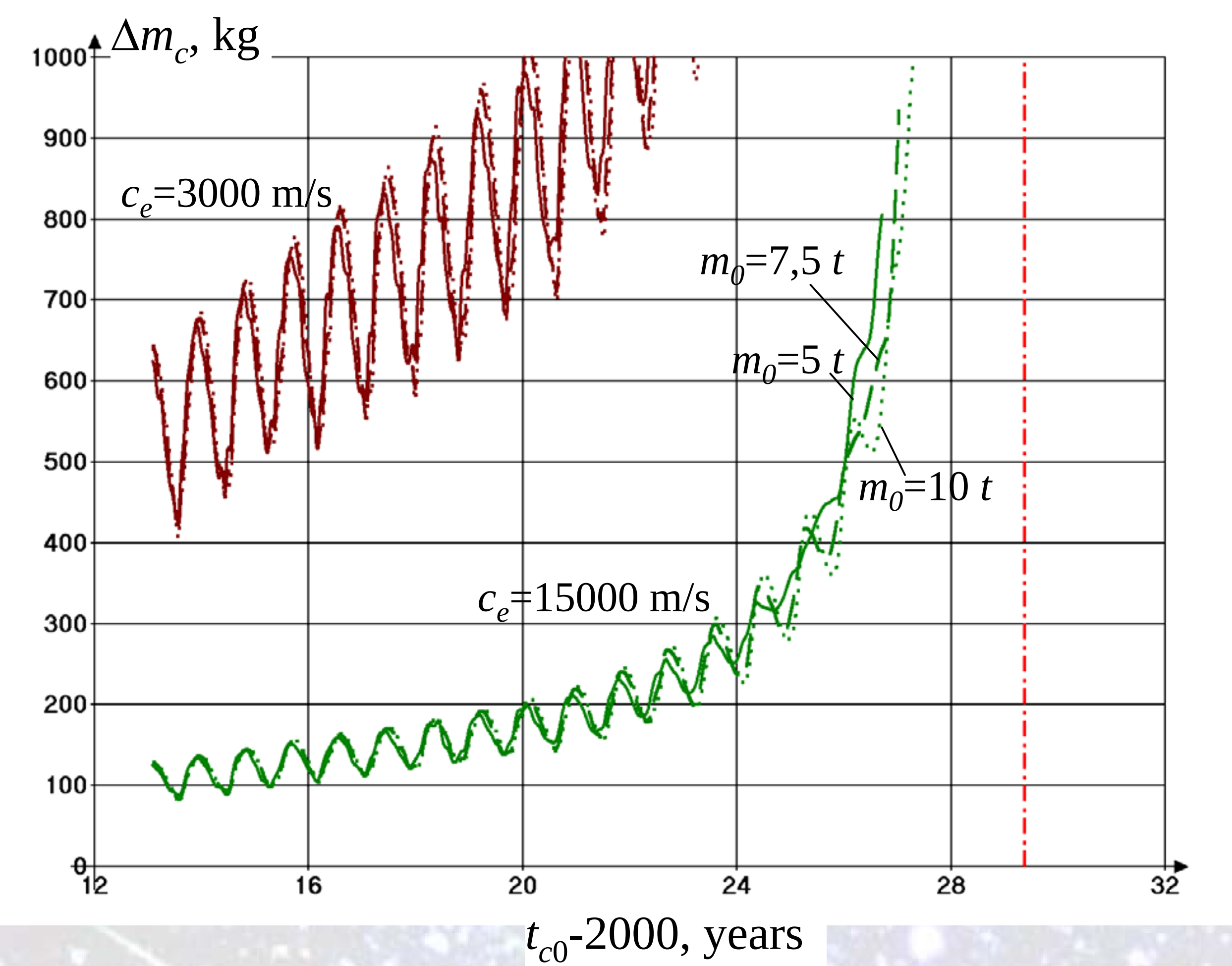


Fig. 12. Fuel mass consumption versus the initial time of correction, initial mass of SC and exhaust velocity (change of perigee distance in 2036 is 10^6 km). [12]

6. Conclusions

Because of the possible Apophis-Earth collision, it is important to analyze the problem how to prevent this collision if the hitting orbit of the asteroid is realized.

Some impulsive and slow effects can be used for this.

It is also very important to know better the asteroid orbit as well as its physical characteristics and to develop International Programs for both ground measurements especially during Apophis-Earth close approaching in 2013, 2021 and sending to the Apophis a special spacecraft.

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Thank you for attention!

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