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An analysis of space trajectories for the Earth-Apophis-Earth mission

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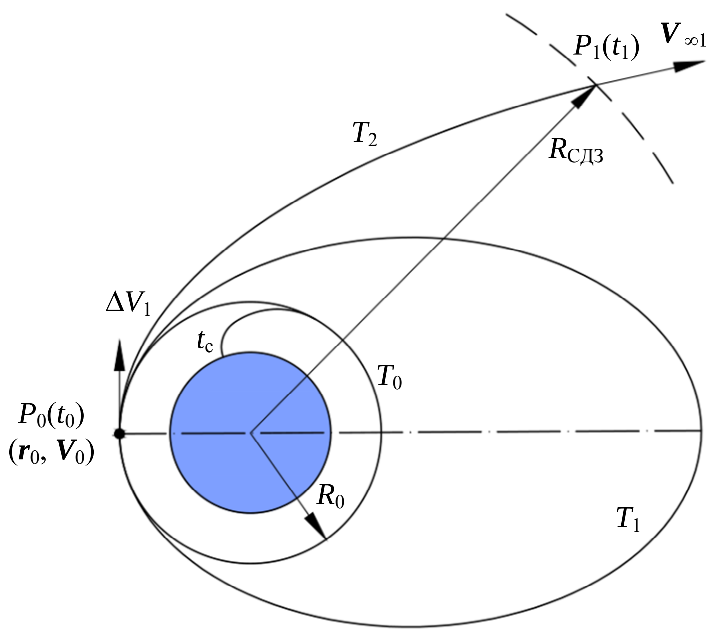
Introduction

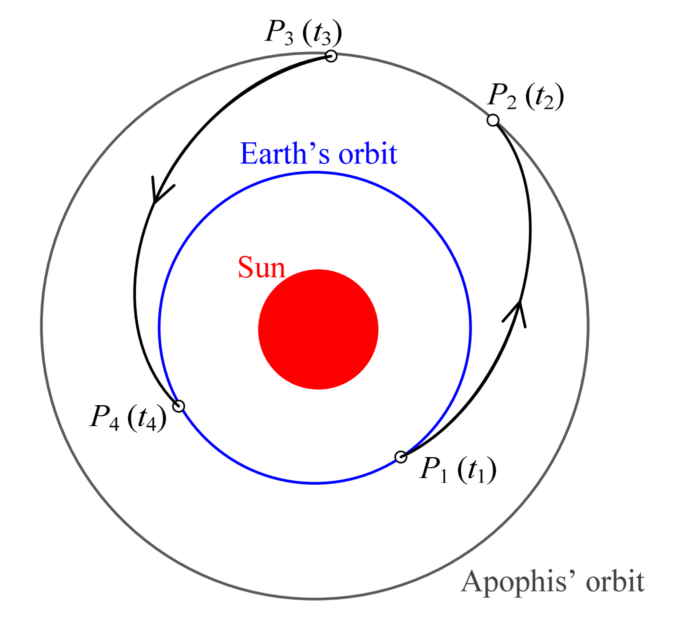
- The trajectories of spacecraft flight from Earth to Apophis with return to Earth, including the flight of orbiting around Apophis for sometime (for the main spacecraft and a special mini-satellite with a beacon (to refine the orbit of Apophis by processing the signals from it during a long-term movement around the asteroid)), are investigated.

- The optimal trajectories with maximum spacecraft payload mass are determined for the flight Earth-Apophis-Earth.

- The characteristics of the movement of the main spacecraft and the mini-satellite (probe) around the asteroid are studied, taking into account three types of perturbations: the gravitational effects of far celestial bodies (Sun, Earth, Moon, Venus, and Jupiter), non-spherical structure of Apophis and solar radiation pressure (SRP).

The flight scheme





$\Delta t_\Sigma = t_4 - t_1$ ={390,420,450,510,540,570,600,630,660,690,730} days.

$t_1 \in$[2019.05.01; 2022.12.31]; $\Delta t_A = t_3 - t_2$ = 7 days

More precise calculation of the trajectories

1) The correction of the trajectories, taking into account the real gravity field and SPR.

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{\mu_E}{|\mathbf{r}|^3}\mathbf{r} - \sum_i \mu_i \left(\frac{\mathbf{r}_i}{|\mathbf{r}_i|^3} + \frac{\mathbf{r} - \mathbf{r}_i}{|\mathbf{r} - \mathbf{r}_i|^3} \right) + \mathbf{\Delta};$$

2) The correction of the trajectories' energy characteristics (Velocity, mass)

- Non-pulsed accelerations are considered by taking into account the gravity losses - $\Delta V_1' = \Delta V_1 - + \sum \delta V_{grk}$ (Using 2 or 3 burns for the transfer from a LEO to an interplanetary orbit);
- The characteristics of the upper stage Fregat have been specified (the mass of the structure, propellants and so on);
- Taken into account the cost of the spacecraft trajectory correction and of the spacecraft motion control around asteroid $V_{К1}= 50$ m/s, $\Delta V_{К2}= 10$ m/s, $\Delta V_{К2}= 25$ m/s ;
- Given the separated mass of the mini-satellite of Apophis and the landing device – 10 kg и 20 kg (according to the Lavochkin Association recommendation).

Optimal trajectories

Table.1 Optimal trajectories for the case Δu<2π

	Trajectory 1
Δu	$\Delta u<2\pi$
Δt_{Σ} (days)	450
t_1 (data)	2021,01,23
Δt_{12} (days)	120
Δt_{34} (days)	323
t_4 (data)	2022,04,28
ΔV_1 (km/s)	3.888
ΔV_2 (km/s)	2.329
ΔV_3 (km/s)	0.912
V_{charact} (km/s)	7.129
m_f (kg)	379
m_p (kg)	149

Figure 1 (a)

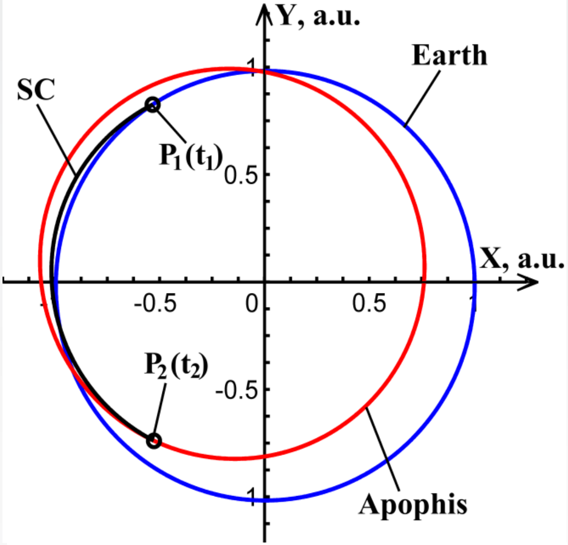
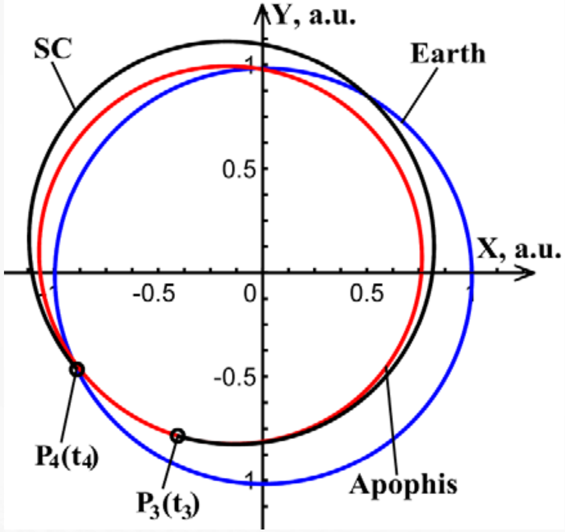


Figure 1 (b)



Optimal trajectories

Table.2 Optimal trajectories for the case $\Delta u_i > 2\pi$ ($i = 1,2$)

	Trajectory 2
Δu	$\Delta u_i > 2\pi$ ($i = 1,2$)
Δt_Σ (days)	690
t_1 (data)	2019,05,24
Δt_{12} (days)	335
Δt_{34} (days)	348
t_4 (data)	2021,04,13
ΔV_1 (km/s)	3.422
ΔV_2 (km/s)	2.851
ΔV_3 (km/s)	0.370
V_{charact} (km/s)	6.643
m_f (kg)	488
m_p (kg)	222

Figure 2 (a)

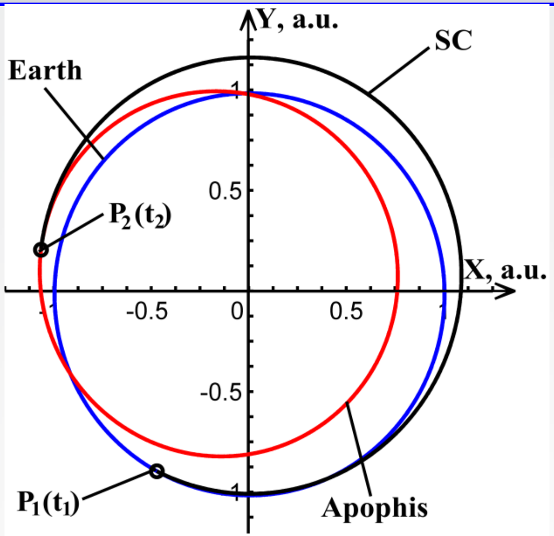
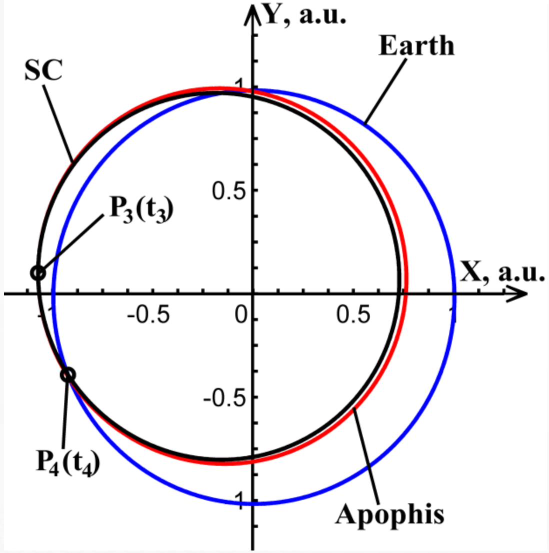


Figure 2 (b)



Payload mass m_p

Table.3 The value of payload mass m_p when using different rockets

	Trajectory 1			Trajectory 2		
	Soyuz-FG	Soyuz-2	Zenith	Soyuz-FG	Soyuz-2	Zenith
Initial mass m_0 (kg)	7130	8250	14000	7130	8250	14000
Final mass m_f (kg)	379	449	971	488	599	1183
Payload mass m_p (kg)	149	196	548	222	296	691

The equations of spacecraft motion around the asteroid (in a none-rotating Cartesian coordinate system centered at the asteroid)

$$\begin{cases} \dfrac{d\mathbf{r}}{dt} = \mathbf{v}; \\ \dfrac{d\mathbf{v}}{dt} = \mathbf{a_0} + k_1 \cdot \mathbf{a_1} + k_2 \cdot \mathbf{a_2} + k_3 \cdot \mathbf{a_3}; \\ k_1 = (0\,;1), k_2 = (0\,;1), k_3 = (0\,;1). \end{cases}$$

$$\mathbf{a_0} = -\frac{\mu_A}{r^3}\mathbf{r} \qquad \mu_A = 1.8\text{~}2.86\ \mathrm{m^3/s^2}$$

a_0 - central acceleration of gravity

a_1 – gravitational perturbation of Solar system major bodies

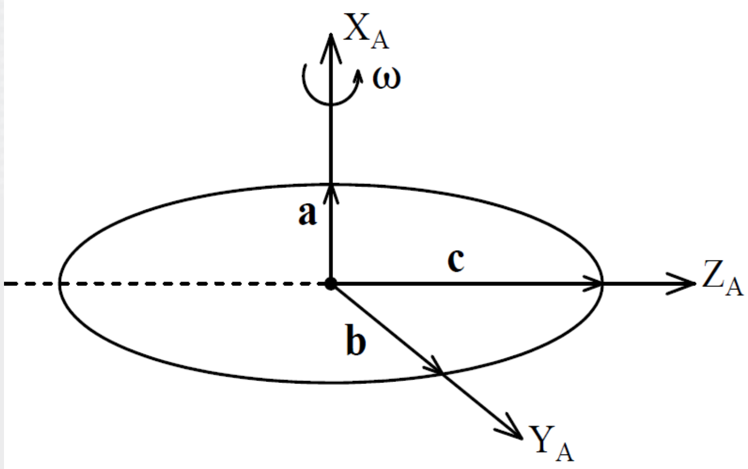
a_2 – perturbation acceleration from asteroid nonsphericity

a_3 – SRP acceleration

Numerical analysis (taking into account Sun, Earth, Moon, Venus, and Jupiter) are performed based on trajectory 2. The initial date is set on 23 April 2020, when SC approaches to the asteroid. The initial spacecraft orbit is circular, with the radius r_0 within the range of 0.5-2 km.

Model of Apophis

Figure 3. Model of Apophis



Parameters	
μ_A (m^3/s^2)	1.8-2.86
R_A (m)	160
b_A/a_A	1.06 (±0.02)
c_A/a_A (α)	1.5 (±0.2)
λ_L (deg)	250
β_L (deg)	-75
P_A (hours)	30.56

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Table.4 Parameters of asteroid Apophis

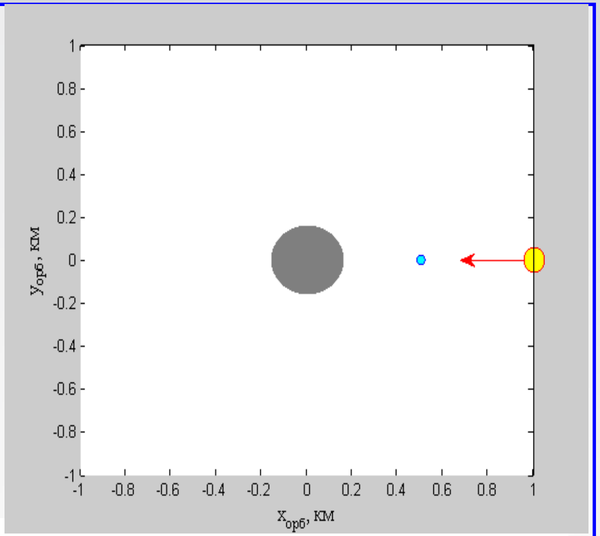
We assume:

1. $a_A=b_A<c_A$, elongation $\alpha=c_A/a_A$=(1.3; 1,5; 1.7).

2. ω~**a**~*L* , $\omega_{ZA}=\omega_{YA}=0, \quad \omega_{XA}=\omega.$

Calculation results and analysis

1. Gravitational effects of solar system major bodies.
2. Effects of asteroid’s nonsphericity.
3. Effects of solar radiation pressure (β_0).



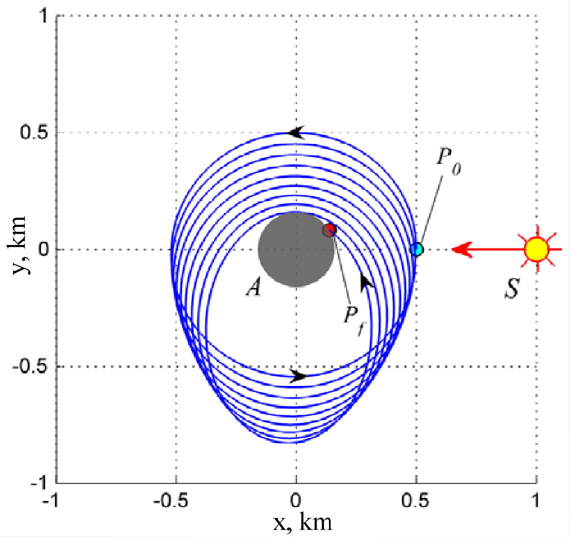


Figure 4. Main SC orbit about Apophis with only a_3 (T~5days) for the case t_0 = 2020/04/23, Ω_0=0, i_0=90°, r_0=0.5 km, μ_A=2.86 m^3/s^2 (β_0 ~80°)

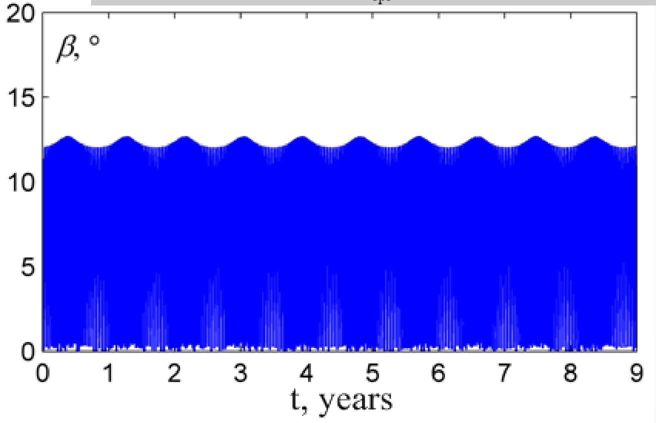


Figure 5. Evolution of angle β for the case t_0 = 2020/04/23, Ω_0=i_0=90°, r_0=0.5 km, μ_A=2.86 m^3/s^2 (β_0 ~10°)

Joint effects of all perturbations

Attention! The Non-linear correlation between the influence of the asteroid’s nonsphericity and the influence of SRP.

Table 5: Lifetime of the main spacecraft motion about Apophis (r_0= 0.5 km)

μ_A(m^3/s^2)	α	T (day)
1.8	1.3	136
	1.5	88
	1.7	38 (A)
2.86	1.3	71
	1.5	310
	1.7	60

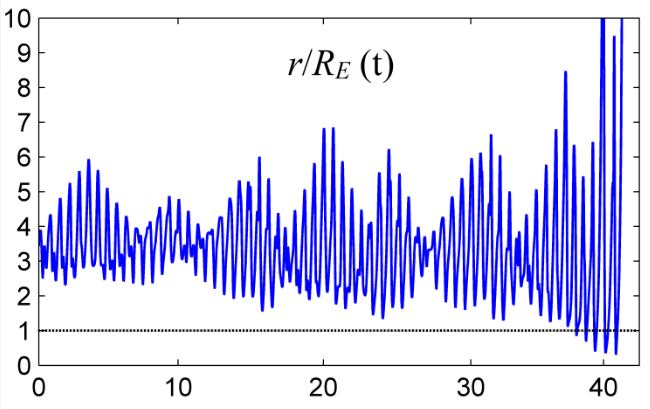


Figure 6. Evolution of the relative distance for example A : μ=1.8 m^3/s^2, α =1.7, r_0=0.5 km, e_0=0, $\Omega_0 = i_0 = 90^\circ$

Joint effects of all perturbations

Table 6: Lifetime of the mini-satellite motion about Apophis

μ_A (m^3/s^2)	α	r_0 (km)	T
1.8	1.3-1.5	1.5	~ 9 years
	1.7	0.9	~ 1.2 years
		1.5	~ 9 years (B, 2020-2029)
		2.0	~ 80 days
2.86	1.7	1.0	~ 2 years
	1.3-1.7	1.5	~ 9 years
		2.0	~ 9 years
		2.5	~ 90 days

Due to Apophis' close encounter with Earth on April 13th, 2029, an increase of the Earth's gravitational effects results in the mini-satellite escape from the vicinity of the Apophis.

Joint effects of all perturbations

Example B: μ_A=1.8 m^3/s^2, α=1.7, r_0= 1.5 km, $\Omega_0=i_0$=90°.

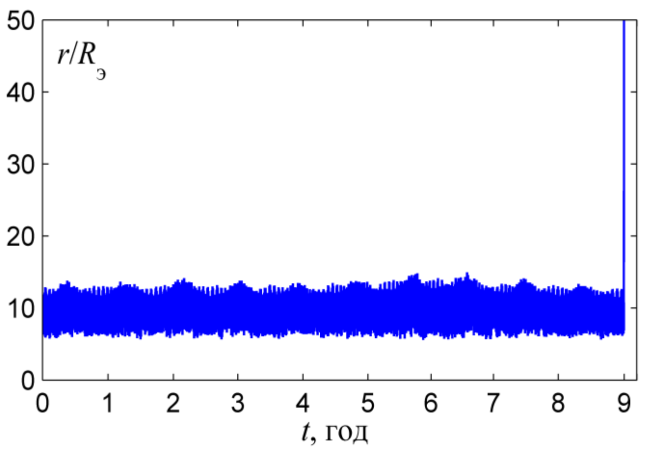


Figure 7. Evolution of the relative distance for example B.

P_0 - position of mini-satellite on April 13th 2029, Min(distance) ~38000 km.

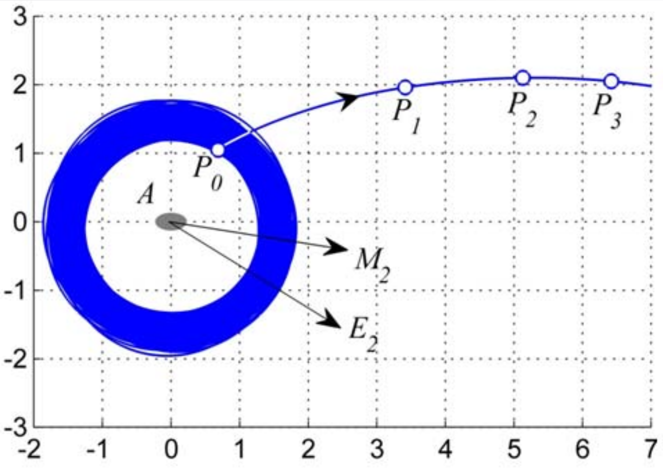


Figure 8. Mini-satellite trajectory during about 9 years (2020-2029) for example B with all perturbations. Units are in kilometers.

Joint effects of all perturbations

A number of main parameters are changed for more comprehensive analyses, in particular:

- The radius of the initial orbit r_0
- The orbital eccentricity e
- Gravitational parameter of the asteroid μ_A
- The asteroid's elongation α
- The rotation parameters of the asteroid,
- The mass and orbit parameters for SC (its plane, size, eccentricity),
- The start time of spacecraft motion
- The initial position of the satellite in orbit

Main results of the analysis presented in the paper are preserved in these cases.

Table 7: Some bounds on initial radius r_0 under which the mini-satellite can orbit the Apophis for about 9 years in the presence of all perturbations

μ_A (m^3/s^2)	α	r_0 (km)
1.8	1.5-1.7	1.3 - 1.6
2.86	1.7	1.4 - 2

Conclusions

- The optimal trajectories with maximum spacecraft payload mass are determined for the flight Earth-Apophis-Earth in the course of 2019-2022. Two cases are investigated:1) interplanetary paths have no complete revolutions; 2) one of the interplanetary paths has 1 complete revolution. Energy characteristics are estimated using different launch vehicles (Soyuz-FG, Soyuz-2, Zenith) and the upper stage Fregat, taking into account gravity losses, the perturbations of the celestial bodies and SRP.

- The orbital motion of the main spacecraft and the mini-satellite with a beacon around the asteroid are studied, taking into account three types of perturbations: the gravitational effects of far celestial bodies (Sun, Earth, Moon, Venus, and Jupiter), the non-spherical structure of Apophis and solar radiation pressure (SRP). The asteroid is modeled as an ellipsoid of revolution rotating around its own minor axis.

- In the case of joint influence of all perturbations special attention should be paid to the interaction between the influence of the asteroid’s nonsphericity and SRP.

Conclusions

- To improve the stability of SC motion and SC lifetime near asteroid Apophis, the optimal initial orientation of the SC orbit plane has to be normal to the asteroid-Sun direction.

- There is an optimal (in terms of "lifetime") of the initial orbital radius for the mini-satellite, ~ 1.5km.

- It is shown that the timing requirements for the satellite orbit of Apophis can be satisfied, "lifetime" of the main satellite (with an initial radius r0 ~ 0.5 km) is about a few weeks, "lifetime" of the mini-satellite (with r0 ~ 1.5 km) can be a few years, from 2020 to 2029.

Thank You for Your Attention !