Calculation methods for estimating the prospects of a space experiment by means of impact by asteroid Apophis on the Moon surface

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Abstract. The problem of principal change of asteroid 99952 (Apophis) orbit is formulated. Aim of this change is the termination of asteroid motion in Solar system. Instead of the passive rescue tactics from asteroid threat, an option is proposed for using the asteroid for setting up a large-scale space experiment on the impact interaction of the asteroid with the Moon. The scientific and methodical apparatus for calculating the possibility of realization, searching and justification the scientific uses of this space experiment is considered.

1. Introduction
The asteroid 99942 (Apophis) has an irregular elongated shape of $150 \times 420$ m$^2$ and mass about $50 \times 10^6$ t. According to our estimates, the energy of explosion at entrance of Apophis into the atmosphere of our planet will be 800 Mt of trinitrotoluol (TNT), and in case of impact on the Moon–250 Mt TNT. According to astronomical observations and computational research, the asteroid Apophis will fly in 2029 at a distance of about 40000 km from the center of the Earth. However, there is a certain risk of collision of this asteroid with our planet in 2036. As a rule, the aim of correction of the asteroid orbit is to prevent this collision only. However, it is not possible to predict the consequences of such correction for a long period of time after 2036. As a result, the final solution to the problem of asteroid Apophis through its deviation from the trajectory of collision with the Earth will not be achieved.

The goal [1, 2] is to qualitatively change the orbit of the asteroid with the cessation of its motion in the Solar system. Instead of a passive rescue tactic, the use of asteroid Apophis is considered for setting up a large-scale space experiment on the impact of an asteroid on the Moon. The organization of a collision of a cosmic scale will solve a number of physical problems concerning the Moon [2]. Note that a high-speed impact along the lunar surface has already been used to conduct physical experiments [3]. The purpose of this article is to consider the available scientific and methodological apparatus for calculating the feasibility of realizing, searching and substantiating the directions for the scientific use of a large-scale space experiment on the high-speed impact of asteroid Apophis over the lunar surface. Such an apparatus should represent a complex of computer programs that allow performing mathematical modeling of the following physical processes:
(i) perturbed by the actions of artificial origin (AAO), the movement of an asteroid to the surface of the Moon (for the formulation of requirements for devices capable to provide an asteroid exit to an orbit of a meeting with the Moon);

(ii) the mechanical action at high-speed impact and in the case of conventional or nuclear explosions near or inside the asteroid, as well as fluxes of radiation and particles of different physical nature (to justify the parameters of the devices for AAO production);

(iii) the mechanical effect of an asteroid impact on the surface of the Moon (for predicting the parameters of this action in the near impact zone and for calculating the characteristics of the ground release cloud);

(iv) the seismic action.

As a result, computational research with the help of the scientific and methodological apparatus will make it possible to substantiate the principal possibility of carrying out the proposed space experiment and to formulate requirements for space systems for the collection and analysis of soil emissions, as well as for the accuracy of measurements of seismic characteristics, and the number and location of seismic stations on the lunar surface.

2. Space dynamics of an asteroid (modeling of an orbit is disturbed by AAO)

Numerical integration of orbits is performed by the method and computer program described in [4]. The method makes it possible to integrate only perturbations, and the influence of the sun is calculated from the formulas of unperturbed motion, and is especially effective when integrating orbits with small perihelion distances. The calculation takes into account the perturbations from all eight planets of the Solar System, Pluto and the three largest asteroids. Relativistic effects in the displacement of perihelion bodies are also taken into account. Perturbations from the Earth and the Moon are considered separately. The integration step changes depending on the proximity of the asteroid to the perturbing bodies. In this case, the coordinates of the Moon are determined independently by program DE 406/LE406 and introduced into the main program in the form of polynomials.

The minimum geocentric distance of Apophis in 2029, according to calculations by the method of [4], is 37,790 km. This differs slightly from the data in [5], but it fits perfectly into the range of permissible spreads of this characteristic. The values scatter of 690 km calculated by us due to possible errors in the initial elements of the asteroid orbit completely coincides with the results of [5]. Therefore, the accuracy of our calculations is sufficient to solve the problem under consideration.

We will assume that the artificial correction (AC) of the Apophis orbit as a result of the AAO is to be carried out with a one-time explosion or impact. This will change the components of its heliocentric velocity. It can be assumed that since the explosion or impact occurs very quickly, the heliocentric coordinates of the asteroid during this time of the AAO do not change. So the impulse action is characterized only by the velocity increment vector.

The search for rational parameters of AAO for the perturbed orbit of Apophis implies the choice of four independent parameters: correction moment $t_c$ and three components of the heliocentric velocity increment vector. In our calculations, we looked for the magnitude modulus of the velocity increment $\Delta V$ and the two angles defining the direction of this vector $\varphi_1$ and $\varphi_2$ ($\varphi_1$ is the angle between the velocity increment vector and the ecliptic plane, $\varphi_2$ is the angle between the projection of the velocity increment vector on the ecliptic plane and axis OX, lying in the plane of the ecliptic and pointing at the point of the vernal equinox). Setting different values of $t_c$, $\Delta V$, $\varphi_1$ and $\varphi_2$, leads to the corresponding perturbations of the parameters of the asteroid orbit. It is clear that after the perturbation, the asteroid orbit will change under the influence of various factors, first of all, the gravitational effects of the planets.
Table 1. Dates and AC parameters of Apophis orbit in order to redirect it to the surface of the Moon ($V$ is impact velocity; $\Psi$ is the angle of impact counted from a normal).

| Date UT (h) | $m$ ($^\circ$) | $\Delta V$ (m/s) | $\Delta R$ (km) | $V$ (km/s) | $\Psi$ ($^\circ$) |
|-------------|----------------|-----------------|-----------------|------------|-----------------|
| 11.06.2017 7 | 121.65         | 7.33            | 900             | 3.2        | 31              |
| 30.04.2018 21 | 121.57         | 7.33            | 900             | 3.2        | 31              |
| 20.03.2019 7 | 121.29         | 7.33            | 300             | 4.7        | 10              |
| 26.12.2020 12 | 121.20         | 7.30            | 200             | 4.9        | 7               |
| 15.11.2021 2 | 121.26         | 7.30            | 300             | 4.3        | 10              |
| 04.10.2022 16 | 121.12         | 7.30            | 700             | 3.4        | 24              |
| 24.08.2023 0 | 120.62         | 7.30            | 90              | 5.6        | 3               |
| 11.07.2024 4 | 118.95         | 7.30            | 300             | 4.5        | 10              |
| 29.05.2025 21 | 117.98         | 7.34            | 450             | 4.0        | 16              |
| 17.04.2026 2 | 116.47         | 7.34            | 750             | 3.2        | 26              |
| 04.03.2027 12 | 114.09         | 7.50            | 480             | 3.8        | 16              |
| 18.01.2028 0 | 109.57         | 7.72            | 450             | 3.9        | 15              |

Until 2029 the minimum geocentric distance of Apophis will be much larger than the radius of the Moon orbit. Consequently, in the same year, it will pass at the minimum selenocentric distance $r_{\text{min}}$. In April 2029, the minimum value of $r_{\text{min}}$ is reached after close proximity to the Earth. For the unperturbed orbit of Apophis this $r_{\text{min}}$ value should be about 104 thousand km. It is obvious that the perturbation of orbits of Apophis for redirecting it to the Moon should be performed earlier than the moment when the minimum distance $r_{\text{min}}$ is reached when moving along the unperturbed orbit. The required values of the AC parameters $t_c$, $\Delta V$, $\varphi_1$ and $\varphi_2$ should be such that in April 2029 the $r_{\text{min}}$ value will be less than the radius of the Moon and the value of $\Delta V$ will be the minimum possible. The search for the required values of $t_c$, $\Delta V$, $\varphi_1$, $\varphi_2$ is performed by an overcharge method. First, an arbitrary time $t_c$ is chosen for which different sets of quantities $\Delta V$, $\varphi_1$, $\varphi_2$ are already set, and at the end of integration we get the value $r_{\text{min}}$ on April 14, 2029. Note that the solution of the problem does not exist for every value of the correction moment $t_c$. The first suitable correction time was at 7 h (UT) on June 11, 2017 and 21 h (UT) on April 30, 2018 (UT—Universal Time). To redirect Apophis to the Moon, it should have been given an increment of heliocentric speed of about 7.33 m/s. The time interval of the correction moments was about 17 hours. As further studies have shown, solutions for the values of $t_c$ exist at various dates until 2028 (table 1, where $\Delta R$ is distances of a point of falling of an asteroid from the center of the Moon disk that it is visible from an asteroid). It is important that the average anomaly $m$ of the asteroid in the orbit at the time of the AC should not significantly differ from 118$^\circ$.

Note that the formal moment of correction may be the moment just after the close approach of the asteroid to the Earth in April 2029 (until the moment of minimal rapprochement with the Moon). However, the magnitude of rate increment $\Delta V$ in this case is more than 2 km/s. Obviously, such a correction option is not applicable in practice, due to the large mass of the asteroid and, correspondingly, excessive impulses and energy costs for their creation. For asteroids with a mass close to the mass of Apophis, it is of practical interest to increase the velocity $\Delta V$ not more than several tens of meters per second.

The results of computational studies show that the successful redirection of the Apophis asteroid to the Moon is realized in rather narrow ranges of all four correction parameters ($t_c$, $\Delta V$, $\varphi_1$, $\varphi_2$). This indicates the extreme complexity of the practical implementation of such
an AC. However, the correction task is simplified if we allow the possibility of a reusable AC. As can be seen from table 1, the moments of successful correction exist every year until the moment Apophis approaches closely to the Earth in 2029. And in each case the values of the average anomaly of the asteroid do not differ much from each other. This makes it possible in principle to perform correction in several stages, in each of which the velocity increment module can already be less than 7 m/s. In addition, at each subsequent stage of correction it will be possible to take into account and eliminate inaccuracies made at the previous stages.

3. Mechanical action of explosion or high-speed impact
The calculation of the mechanical action [6] is required both in the problems of ensuring the required parameters of the AAO [7, 8], and in predicting the parameters of near zone, the interaction of the asteroid (or other body) and the Moon [9], and also in determining the characteristics of the ground release cloud [10], which forms with this interaction. Calculations of the parameters of near zone of impacts and explosions are carried out using multidimensional computer codes [7,11–14], which makes it possible to numerically simulate big deformations and large formings.

Deviation of the asteroid from the trajectory of collision with the Earth with a small time reserve (late detection and awareness of the threat) at the current level of technology can be realized only through the mechanical action of a nuclear explosion near the surface. As calculations show [6,8], the magnitude of the impulse transmitted to the asteroid has a maximum at a distance from the asteroid of the order of 1/10 of its radius. For the explosion power $Q = 10 \text{ Mt}$, dimensions and masses close to the Apophis characteristics, the increment in the velocity of the asteroid will be $\Delta V = 30–40 \text{ m/s}$, which is much larger than required for its escape to the Moon surface (see table 1). Note that this solution to Apophis problem should hardly be considered optimal, since for the time being we have sufficient time available until 2029. The mechanical action of the nuclear explosion will not only lead to the deflection of the asteroid, but also its destruction and dispersion into a swarm of fragments with different velocity vectors. Therefore, part of this swarm can also appear in the Earth atmosphere with hardly predictable consequences. Therefore, if the AAO is to be realized through a nuclear explosion, then it should be done far away from the Earth (at least outside the Moon orbit), so that the fragments are scattered over long distances and most of them do not reach our planet. The AC requirement of the distance from the Earth planned by us does not satisfy and the use of the mechanical action of a nuclear explosion to move to the Moon does not seem appropriate in this case.

Calculations of the perturbed AC trajectory according to the method of [4] show the velocity of impact along the surface of the Moon varies in the interval $V = 3.2–5.6 \text{ km/s}$ (see table 1). Numerical simulation of the mechanical action of the Apophis impact at the velocity $V = 5 \text{ km/s}$ using the finite-size particle method [14] leads to the formation of a crater with a radius of 0.95 km and a depth of 1.25 km. The maximum temperatures and pressures for impact are $T = 8000 \text{ K}$, $P = 250 \text{ kbar}$.

Calculation of development of the soil cloud which is formed as a result of impact in the field of the Moon gravity is difficult on the basis of gasdynamic model until times which are of practical interest. Therefore the data obtained in a near impact zone by numerical methods of gas dynamics are used as initial data for the offered approximate model of soil cloud dynamics. In this model the cloud consists from two independent subsystems. These subsystems are the gas and condensed medium. Scattering is accepted as axisymmetric (a case of perpendicular impact) and is considered in cylindrical system of coordinates. Particles of the medium are presented in the form of noninteracting ringlets (torus) of the known initial density and mass depending on $r, z$. The mass center of ringlet section is considered moving like a material point in the field of acceleration of the Moon gravity and having the known initial speed. Expansion
of a ringlet along the radius of cross section \( R \) is considered analytically. Expansion on \( R \) is neglected when calculating evolution of the condensed cloud subsystem (expansion remains as a result of the movement and change of radial coordinate of ringlet \( r \)).

Calculations of parameters of a explosion cloud were carried out at perpendicular impact of Apophis on the Moon surface with a speed of 5 km/s. It is obtained that the external contour of a cloud rises up to the heights of 500 km at time 550 s and soil cloud density changes with height from 1 g/cm\(^3\) to practical zero.

4. Mechanical effect of radiation and particle fluxes
As already noted, surface and near-surface nuclear explosions lead to fragmentation of the asteroid, which is undesirable for a number of reasons. More preferable is the variant of the explosion remote from asteroid surface. In addition, this option is less sensitive to the topography and structure of the asteroid.

Quasione-dimensional approach [15] is used for calculation of mechanical action of high-intensity radiations and particles fluxes from powerful explosion [16] near 3D-asteroid. In this approach pressure impulse in each point of the irradiated object is determined by a one-dimensional gasdynamic code because thicknesses of sublimated material and the scattering cloud are small in comparison with sizes of the Apophis (cloud thickness is small for those times at which pressure impulse accumulates). Calculation of energy density located in each point of the asteroid and definition of an impulse force acting on Apophis is carried out in 3D-geometry. For convenience Apophis form is approximated by a rotation ellipsoid. The force impulse of mechanical action is integration of distribution of the pressure impulse on the asteroid surface. The speed increment is defined by the force impulse and asteroid mass.

Thus the task is split on one-dimensional gasdynamic calculation of dependence of the pressure impulse from surface density of the energy (these calculations are made previously) and two-dimensional integration in system of the curvilinear coordinates connected with an asteroid surface. This splitting allows considering the physical processes forming mechanical action of radiation as much as possible in a one-dimensional problem of interaction of radiation with substance. It is essentially important because AAO energy density reached to Apophis surfaces is very big and the physics of the phenomenon is very diverse respectively.

Calculation of energy release from fluxes of the x-ray radiation (XRR) and neutrons of powerful explosion is required for determination of parameters of mechanical action (pressure impulse depending on energy density). Calculation of energy release from streams of neutrons is carried out by the Monte Carlo method [17]. Transfer of XRR in material of the asteroid is modelled by method of densities of collisions [18].

Generally the pressure impulse is defined as the sum of vaporizing part and spall part. The vaporizing impulse much more exceeds spall part for the considered case of very high energy density (hundreds of megajoules on square centimeter) and the spall impulse can be neglected. Energy of sublimation is also small in comparison with specific energy release. Calculation of the pressure impulse at the known profile of the energy release localized in a barrier was carried out by means of a one-dimensional gasdynamic code [19]. Formation and increase in transparency of plasma are considered in this code.

The variant of x-ray radiation action on Apophis surface was considered for Planck spectrum. Settlement increments of asteroid speed as a result from mechanical action of radiations and particles depending on rigidity of XRR spectrum are presented in table 2 for various powers of explosion and its distance from Apophis (\( \Delta V_\gamma \) is without neutrons, \( \Delta V_{\gamma+n} \) is with neutrons). Wide-range equations of a condition for aluminum was used for the description of behavior of material of an asteroid [20]. As appears from table 2 powers of explosion in several tens of megatons are required for redirection of an asteroid Apophis to the Moon surface (it is necessary speed increments near 7 m/s for this purpose according to table 1).
Table 2. Asteroid speed increment at various AAO parameters ($L$ is the distance between a source of radiation and the Moon surface; $T_{\text{eff}}$ is effective temperature of the Planck spectrum).

| $Q$ (Mt) | $L$ (m) | $T_{\text{eff}}$ (keV) | $\Delta V_\gamma$ (m/s) | $\Delta V_{\gamma+n}$ (m/s) |
|----------|---------|------------------------|------------------------|------------------------|
| 10       | 35      | 3                      | 2.2                    | 5.7                    |
| 10       | 35      | 6                      | 4.2                    | 7.9                    |
| 10       | 35      | 9                      | 7.0                    | 10.5                   |
| 10       | 35      | 12                     | 8.9                    | 12.2                   |
| 10       | 100     | 3                      | 0.7                    | 1.6                    |
| 10       | 100     | 6                      | 1.3                    | 2.3                    |
| 10       | 100     | 9                      | 2.1                    | 3.2                    |
| 10       | 100     | 12                     | 2.7                    | 3.8                    |
| 40       | 100     | 3                      | 1.5                    | 2.5                    |
| 40       | 100     | 6                      | 2.7                    | 5.1                    |
| 40       | 100     | 9                      | 4.5                    | 6.6                    |
| 40       | 100     | 12                     | 5.5                    | 7.6                    |

Table 3. Characteristics of the Moon layers.

| Layer   | $\rho$ (g/cm$^3$) | $V_p$ (km/s) | $V_{sh}$ (km/s) | $E$ ($10^{11}$ Pa) | $G$ ($10^{11}$ Pa) | $\nu$ | $R_{\text{min}}/R_{\text{max}}$ (km) |
|---------|-------------------|--------------|-----------------|-------------------|-------------------|-------|-------------------------------|
| bark    | 3.000             | 6            | 4.7             | 1.715             | 0.660             | 0.294 | 1690.0/1737.5                 |
| mantle  | 3.348             | 8.0          | 4.0             | 1.428             | 0.536             | 0.333 | 308.8/1690.0                 |
| core    | 7.866             | 4.5          | —               | $K = 1.593$       | 0                 | —     | 0/308.8                      |

5. Seismic waves
Parameters of the near zone are used as initial data for the calculation of seismic waves within the Moon. These data are formulated on a hemispherical surface far enough from the point of impact. The calculations show that the radius of the hemisphere is 40 km or more.

The calculation of seismic waves is possible only in the presence of data for the structure, density and elastic properties of the Moon layers. At present, these data are very incomplete. In particular, the problem of the size and composition (iron, iron–sulfide or iron–nickel) of the liquid core of the Moon is still not solved. Therefore, for the calculations it is proposed to use the simplest three-layer model of the Moon with the data presented in table 3 ($V_p$ and $V_{sh}$ are the longitudinal and shift speeds of elastic waves; $E$ is the Young’s modulus; $G$ is the shear modulus; $\nu$ is the Poisson’s constant; $K$ is the bulk modulus). This model corresponds to astronomical data of the Moon radius $R = 1737.5$ km, mass of the Moon $M = 7.35 \times 10^{22}$ kg, inertia moment $I/(MR^2) = 0.395$ and the Latem and Toksotsu speed model [21]. Using the parameters from table 3, we calculated that the pressure in the center of the Moon is $P = 56.9$ kbar, and the temperature (calculated from the equations of state of iron $T = T_{\text{iron}}(P, \rho)$ [20]) is 2170 K.

6. Conclusions
Thus the main results of this work are the following:

(i) The principal possibility of redirection of an asteroid of Apophis to the surface of the Moon is proved.
(ii) Parameters of a near zone of high-speed impact of an asteroid to the surface of the Moon are determined.

(iii) The problem about calculation of the seismic waves which are formed at impact by an asteroid Apophis on the Moon surface is formulated.

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