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The algorithms and programs for investigations of near-Earth asteroids

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The investigation of motion of near-Earth asteroids is a complicated problem of celestial mechanics. The problem solving leads to the necessity of development of special algorithms and programs. In this paper the algorithms and program system meant for the study of asteroids dynamics are described. This system allows us to predict the motion of asteroids with high accuracy.

Keywords: Near-Earth asteroids; Dynamics; Algorithms; Programs

1 Introduction

This system allows us to solve the following problems:

- numerical integration of differential equations of motion by Everhart method;
- revelation of close encounters of the asteroid with planets;
- revelation of resonances caused by commensurability of mean motions of the asteroid and the planet, from condition $|k_0 n_0 - k_j n_j| < \alpha$, where n_0, n_j are mean motions of asteroid and planet correspondingly, k_0, k_j are integers, α is a small quantity;
- determination of discrepancies (O−C) of observed and calculated positions of the asteroid;
- improvement of the asteroid orbit by least-squares method;
- construction of the initial domain of the probability motions and its evolution in time;
- construction of the ephemeris for the observation of the asteroid;
- searching of collisional orbits in the probability motion domain by conditional minimization;
- demonstration of the motion of asteroids and planets on computer screen.

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2 The structure of the program system

The applied program system consists of several subsystems.

1. Subsystem "Observations" is intended for a work with observations. With the help of this subsystem we can determinate discrepancies (O−C) of observed and calculated positions of the asteroid and improve initial parameters of the orbit.
2. Subsystem "Ensemble of particles" allows us to construct initial probability domains of asteroids.
3. Subsystem "AsSol" produces the numerical model of the asteroid motion and allows us to investigate the evolution of the ensemble.
4. Subsystem "Ellipsoid" produces the projection of a probability domain to the celestial sphere.
5. Subsystem "Closest orbits" is intended for the searching of collisional orbits in the probability motion domain.

The system is created by using developing tool Delphi.

3 The numerical model

We have used differential equations of perturbed two-body problem in the program system. But as known, these equations are singular in vicinities of coordinate origin and close encounters with perturbing bodies. In addition, the solution of equations is unstable in the sense of Lyapunov. Therefore, we have used different regularizing and stabilizing transformations of differential equations (Stiefel, Scheifele, 1971). The perturbations from the major planets, Pluto, the Moon, Earth oblateness, light pressure and the greatest 3 asteroids (Ceres, Pallas, Vesta) are taken into account in the process of numerical integrating. There is a possibility of choice of perturbing factors. The positions of the Moon, the Sun and the planets are taken from DE405 or DE406. Initial parameters of asteroid orbit are taken from catalogue of Bowell (ftp://ftp.lowell.edu/pub/elgb/astorb.dat). There is a possibility to add new objects to catalogue in our program system. The numerical model has been realized by the subsystem "AsSol". This subsystem also allows us to reveal orbital resonances and close encounters of the asteroid with planets and to demonstrate the motion of the asteroid and planets on a computer screen. For example, one of the dialog boxes of subsystem "AsSol" is presented on Figure 1.

4 The algorithm of the construction of possible motion domains

The possible motion domain $\Theta(t)$ of an asteroid is constructed as the ensemble of trajectories $\left\{\Theta^i\,(t) \in \Theta\right\}_{i=\overline{1,s}}$ of some set of test particles from the initial probability domain Θ_0 (here s is a number of test particles, subscript "0" corresponds to the initial

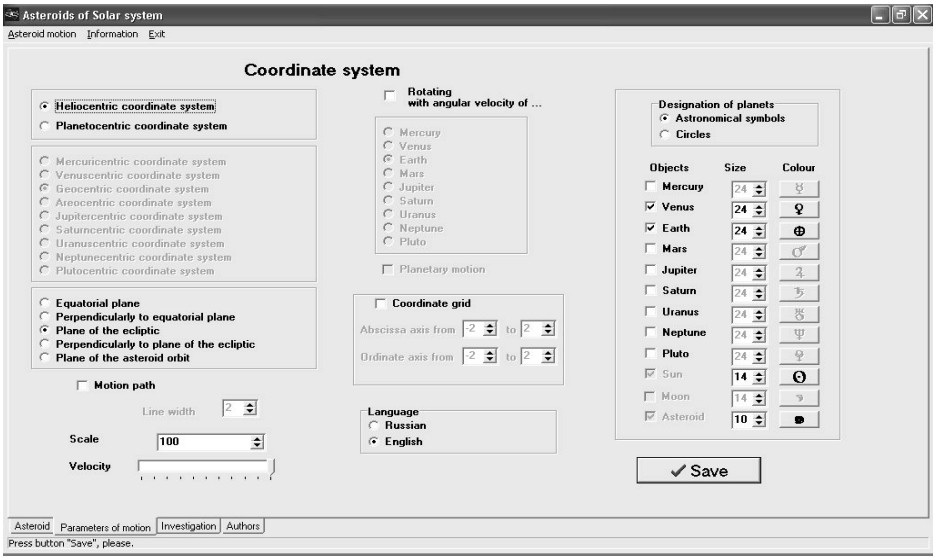


Figure 1 The dialog box "Parameters of the motion".

epoch t_0). The initial domain Θ_0 is given by the error ellipsoid which is received by least-square method (LSM) from observations. The set of test particles is generated by the random number generator in relation to the selected center $\left(t_0, X_0, \dot{X}\right)$ on the basis of the normal law of dispersing and the corresponding covariance matrix D_0,

$$\Theta_0 = \Theta_0\left(\widehat{X_0},\, \dot{\widehat{X}}_0,\, k^2 D_0\right).$$

Here $\widehat{X_0}$, $\dot{\widehat{X}}_0$ are LSM-estimations of asteroid vectors of the position X_0 and the velocity $\dot{X}_0$in an epoch t_0; k is the gain factor of the matrix D_0. This algorithm has been realized by subsystems "Observations" (Figure 2) and "Ensemble of particles". The prediction of the motion of test particles on time interval $(t - t_0)$ is fulfilled by high-precision numerical model, described above.

5 The algorithm of the construction of searching ephemeris

The visible boundary of the possible position domain $\Theta(t)$ of an asteroid in current time t is constructed in the special cylindrical coordinate space. The osculating orbit of the reference point of the domain lies in the base of the cylinder. In this space the covariance matrix $D(t)$ is found and its eigenvalues and eigenvectors are determined. The received error ellipsoid is projected to the celestial sphere by corresponding transformation to visible spherical coordinates $\alpha(t)$ and $\delta(t)$. It allows us

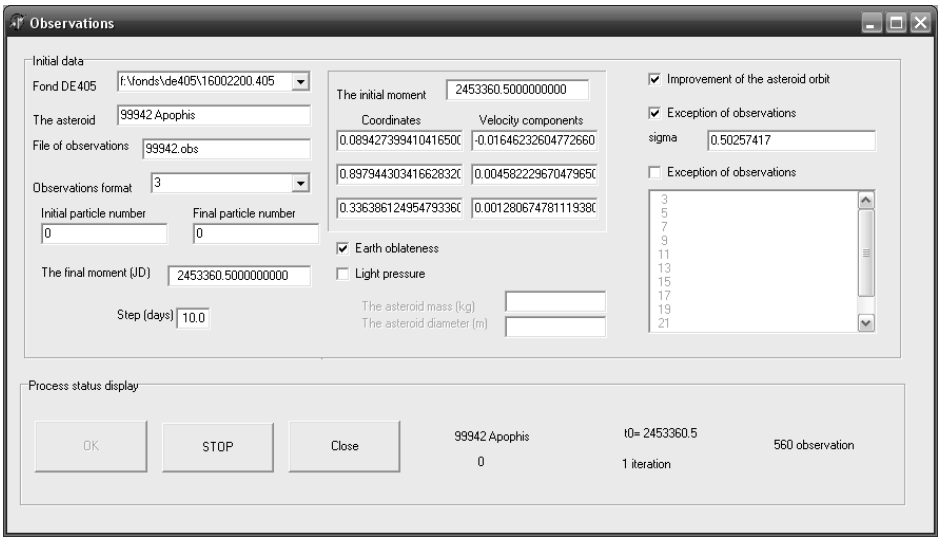


Figure 2 Subsystem "Observations".

to find the extreme values of coordinates which give the limits of variations α and δ (Bykova et al., 2007). This algorithm has been realized by the subsystem "Ellipsoid".

6 The algorithm of the searching of collisional orbits in the probability motion domain

For the revelation of collisional trajectories we have used the known Lagrange method of conditional minimization (Mudrov, Kushko, 1983). With the help of this method we have minimized the distance to the Earth on conditions that mean square error received in the time of orbit improvement is preserving constant. Such an approach allows us to find collisional trajectories in the initial probability motion domain. This algorithm has been realized by the subsystem "Closest orbits".

7 The exploitation of the system

With the help of this program system we have addressed the following problems: all Near-Earth asteroids (NEAs) in the vicinity of near mean motion resonances with planets have been revealed (Bykova, Galushina, 2002); the probability motion domains of NEAs in the vicinity of resonances with Jupiter and resonance 1/1 with terrestrial planets have been constructed and investigated; asteroids coming in gravitation sphere of the Earth in the next 120 years have been revealed and its probability motion domains have been investigated; searching ephemeris for several NEAs have been constructed; collisional orbits for 99942 Apophis have been found (Bykova, Galushina, 2008).

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