The long-term evolution of geostationary satellite fragments after an explosion

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The model of the spherically symmetric explosion of the geostationary object is constructed. The evolution of the fragment's cloud is simulated by the Numerical Model of Artificial Satellite Motion. The densityand maximum and minimum initial velocities are determined for the fragments cloud. The collision velocities of the fragments with the satellites and the collision energies are calculated. The dynamical evolution of geostationary satellite fragments after low energy explosion is investigated. The numerical modelling of the fragments motion on time-scales 100 days and 10 years are made. It is the drawn conclusion on the considerable role of the libration resonance, due to the ellipticity of the Earth's equator on the fragments cloud evolution. The expansion of the cloud along to the explosion object orbit, and closing one to the torus, is the result of the fragments moving in circular modes only. The libration resonance leads to the fact that the inner structure of the cloud will stay heterogeneous on a long-term interval. Peculiarities of evolution of the node longitudes of the fragments' orbits evolve into regions where the particle flow is maximum. These regions are the best to search for the explosion fragments, and on the other hand, are regions of highest emergency for active geostationary objects.

Introdution

The ballistic life-timea of geostationary satellites are estimated as millions of years. Fast increases in the quantity of satellites in geostationary orbit lead to increases of space debris particles in the geostationary region. The number of geostationary objects increases not only due to the launch of new satellites, but also the destruction of objects in geostationary orbit. In this case, the number of small sized fragments is increasing considerably. It represents serious damage for satellites. However, most large fragments are observed only singly. One source of man-caused particles on geostationary orbit is the explosion of satellites. Several random explosions of satellites and upper stages in the geostationary ring are detected [4, 6, 7].

Investigation of the dynamical evolution of the fragment cloud can help to estimate the danger of the fragments to the geostationary satellites. The modelling results are where the density of flow is high, whereever the region of space is more dangerous, and where it is necessary seek the explosion fragments. Short-period evolution gives the description of the debris torus formation along the exploding object orbit. Long-period evolution gives the prediction of distant consequences of the explosion.

In the present work we investigate the kinematical and dynamical parameters of the fragment cloud due to a small power explosion. Dynamical evolution of the fragment cloud after an explosion of a geostationary satellite with masses of 1000 and 2000 kg is considered.

Model of explosion

The model of the spherically symmetric explosion of the geostationary object is based on the results of the works [2, 3, 5].

Model input parameters are the satellite orbital elements (the semi-major axis a, the eccentricity e, the inclination i, the longitude of ascending node Ω, the argument of pericentre g and the mean anomaly M_0), the satellite mass m_{sp}, the relation of the satellite middle section area A to the its mass $\gamma = A / m_{sp}$, and the maximum and minimum masses m_{min} and m_{max} of the fragments.

Model output parameters are the number of fragments N, the masses of the fragments m_n, the area-to-mass relations $\gamma_n = A_n / m_n$, the velocity vector $\mathbf{v}_n = (v_{xn}, v_{yn}, v_{zn})$ and the orbital elements a_n, e_n, i_n, Ω_n, g_n, M_{0n}.

The modelling of explosion is in following.

Geocentric coordinates x_0, y_0, z_0 and velocities w_{0x}, w_{0y}, w_{0z} of a satellite at the explosion moment are calculated from the orbital elements of a satellite.

Number $N(m)$ of fragments with masses less than m

$$N(m) = \begin{cases} 1.71 \cdot 10^{-4} m_{sp} e^{-0.02056\sqrt{m}}, & m \geq 1936g, \\ 8.69 \cdot 10^{-4} m_{sp} e^{-0.05756\sqrt{m}}, & m < 1936g. \end{cases}$$

Here, $m_{\min}$ is the minimum mass of a fragment, masses are in grams.

The distribution function of the fragment masses

$$F(m) = \frac{\eta^{1-s}}{\eta_{\max}^{1-s} - 1}, \qquad \eta = \frac{m}{m_{\min}}, \qquad s = 0.83.$$

Calculation of fragment masses for the limit mass m is made a few times. On the first step m=100 g, on the next m=10 g, and so on, while the total mass of fragments is equal to m_{sp}.

Diameters d of fragments are determined from

$$d = \begin{cases} \left(2.119 \cdot 10^{-2} m\right)^{1/2.26}, & m > m_0, \\ \left(7.076 \cdot 10^{-4} m\right)^{1/3}, & m \leq m_0, \end{cases}$$

$$m_0 = 1403.193 \left(\frac{2 c_1 \rho}{3} \right)^{\frac{3}{c_2 - 1}}, \quad \rho = 2699 \text{ kg/m}^3, \qquad c_1 = 0.01664, \quad c_2 = 0.26.$$

Here masses are in kg, diameters are in meters.

Middle area of fragments are found from the assumption of its spherical shape

$$A = \frac{\pi d^2}{4}, \qquad \gamma = \frac{A}{m}.$$

A mean value of the velocity increment $\overline{\Delta v}$ (km/s)is calculated from

$$\log \overline{\Delta v} = -0.676 \log^2 d - 0.804 \log d - 1.514.$$

The velocity increment Δv is founded from triangular distribution

$$G(x) = \begin{cases} \frac{5}{27}(5x^2 - x + 0.05), & 0.1 \leq x \leq 1, \\ \frac{5}{27}(-15x^2 + 39x - 19.95), & 1 < x \leq 1.3, \end{cases} \qquad x = \frac{\Delta v}{\overline{\Delta v}}.$$

Velocity vectors are isotropically distributed. Distribution functions for angles Φ and T are

$$F(\Phi)=\frac{\Phi}{2\pi}, \qquad F(T)=\frac{1-\cos T}{2}.$$

Components of relative velocity Δv_x, Δv_y, Δv_z are

$$\Delta v_x=\Delta v\cos T,$$
$$\Delta v_y=\Delta v\cos\Phi\sin T,$$
$$\Delta v_z=\Delta v\sin\Phi\sin T.$$

Components of geocentric velocity are

$$w_x=w_{0x}+\Delta v_x,\quad w_y=w_{0y}+\Delta v_y,\quad w_z=w_{0z}+\Delta v_z.$$

Orbital elements of fragments are calculated from the initial position x_0, y_0, z_0 and velocity w_x, w_y, w_z.

The kinematical and dynamical parameters of the fragment cloud

Using the model of the object explosion on a geostationary orbit the kinematical and dynamical parameters of the fragment cloud are investigated. The initial orbital elements of the explosive object are chosen as follows: semi-major axis is equal to 40 000 km, eccentricity is equal to 0, inclinations are equal to 0°, 10°, 20°. Input parameters of the model are used as following: the initial mass of object is equal to 1 000 and 2 000 kg, minimum mass of fragments is equal to 1 g.

Two types of explosions are considered. The first type explosion produces one fragment of a big mass, 0.2–0.3 $m_{sp,}$ and a few number of small mass fragments (from 9 to 26). The second type explosion produces greater fragments (from 230 to 310), and the mass of the biggest fragments are less than 0.02 m_{sp}. Table 1 gives some parameters of fragments for small power explosions.

Table 1. Parameters of fragments for two types of small power explosions.

Description	First type explosion	Second type explosion
Minimum mass of fragments, g	100–700	100–110
Diameters of fragments, m	0.07–9	0.007–3
Relation of middle area to mass, m^2/kg	0.13–0.33	0.17–0.33
Initial velocity, m/s	3–60	4–69

To simulate the evolution of the fragment's cloud the numerical model of artificial satellite motion [1] was used. Evolution of orbital elements of the fragments and 48 geostationary satellites (a=42165 km, e=0, 0.01, i=0°, 15°, Ω=0°, 250°, g=0°, 270°, M_0=0°, m_{sp}=500, 1 ,000, 1 500 kg) was made on a time interval of 100 days.

The results of modelling show that the impact velocities essentially depend on the mutual inclination, I, of orbits of the fragment and the geostationary satellite. Table 2 gives maximum impact velocities, V_{max}, and correspond to the masses of impactors, m_{lim}, depending on the angle of mutual orbit inclination, I, for the geostationary satellite of mass 1 500 kg. In this case the maximum increment of semi-major axis, Δa, of the geostationary satellite is equal to 400 km. The mass, m_{lim}, corresponds to the maximum mass of the impactor for non catastrophical impact. Impact is catastrophical if the energy density exceeds 45 kJ/kg [5]. Catastrophical impacts destroy the satellite.

Table 2. Maximum impact velocities V_{max} that correspond to masses of impactors m_{lim} depending on theangle of mutual orbit inclination, I, for geostationary satellite of mass 1 500 kg.

I	V_{max}, m/s	m_{lim}, kg
15°	800	200
25°	1330	70
35°	1850	30

Impacts of geostationary object with the fragments are generated by low power explosion and do not destroy objects generally. First type explosions can generate a few number of fragments that impact catastrophically.

Short-periodic evolution of the fragment cloud

To investigate short-periodic evolution of space debris particles after an explosion of the geostationary object, the modelling of the fragments motion is taken on 100 days interval. The Numerical Model of a Artificial Satellite Motion [1] is used. Main perturbations due to the Earth's gravity model EGM-96 (up to 20 order and degree), Moon and the Sun attraction, tides and solar radiation pressure are taken into account.

84 explosions are considered. Initial values of the orbital elements span the geostationary region completely: semi-major axis is equal to 42130, 42150, 42170, 42190 and 42210 km, eccentricity is equal to 0 and 0.01, inclination is equal to 0°, 10° and 20°.

Analysis of the results shows that the fragments' cloud resulting from small power explosions exceed along the semi-major axis the libration region (from 42130 to 42200 km), and close-fitting regions of rotation motion. It leads to a significantly different evolution of the subsatellite points longitudes of fragments, even on short-time intervals. The fragments move in the regions with different modes of motion: circulation on the east or west,and libration near one or two stable libration points. The longitudes drift relative to the parent object (exploded satellite) essentially depends on the semi-major axis of the fragment orbit. On 100 days intervals the range of subsatellite point longitude is changed from 5°, near stable libration point, to 1 600° for particles moving in circulation mode. The fragment cloud is propagated along the orbit due to the particles moving in circular mode, high and low of the libration motion region. Moving near one stable libration point, particles influence the formation of the inner regions of the debris torus in this libration region only.

Long-periodic evolution of the fragment cloud

The long-periodic evolution of the fragment cloud after an explosion of the geostaionary object was investigated numerically. The motion of the fragments on the 11 years time interval was studied for 12 small power explosions. Initial values of the orbital elements correspond to the geosynchronous satellite: semi-major axis is equal to 42165 km, eccentricity is equal to 0, inclination is equal to 0° and 10°. The satellite was situated near the stable libration point 255°.

Analysis of the modelling results shows that more than 95% of the particles arising after an explosion of the libration satellite are moved in a circular mode. If, at the moment of explosion, the satellite is situated near the stable libration point, then on the phase plane "subsatellite point longitude, semi-major axis" near the other stable libration point, the fragments will be absent. "Slow diffusion" of a small number of the fragments to the region near the other stable libration point is possible for fragments, which moved in libration mode near two stable points, due to the luni-solar and light pressure perturbations (in one particle for 4 explosions from 11 ones). In the physical space this effect is evinced more weakly due to nonzero inclinations and eccentricities of orbits of particles moving in the neighboring regions of circular motion. Libration resonance leads to the debris ring staying heterogeneous on long-term interval.

Fig. 1 gives the fragment cloud structure. Positions of all particles of the cloud are shown at the initial moment (vertical line on longitude 250°), 1 day after an explosion (slanting line for longitude range from 230° to 315°), and further with 40 days step on a time interval of 400 days. Size of the fragment cloud, with respect to semi-major axis, is larger than the size of the libration motion region.

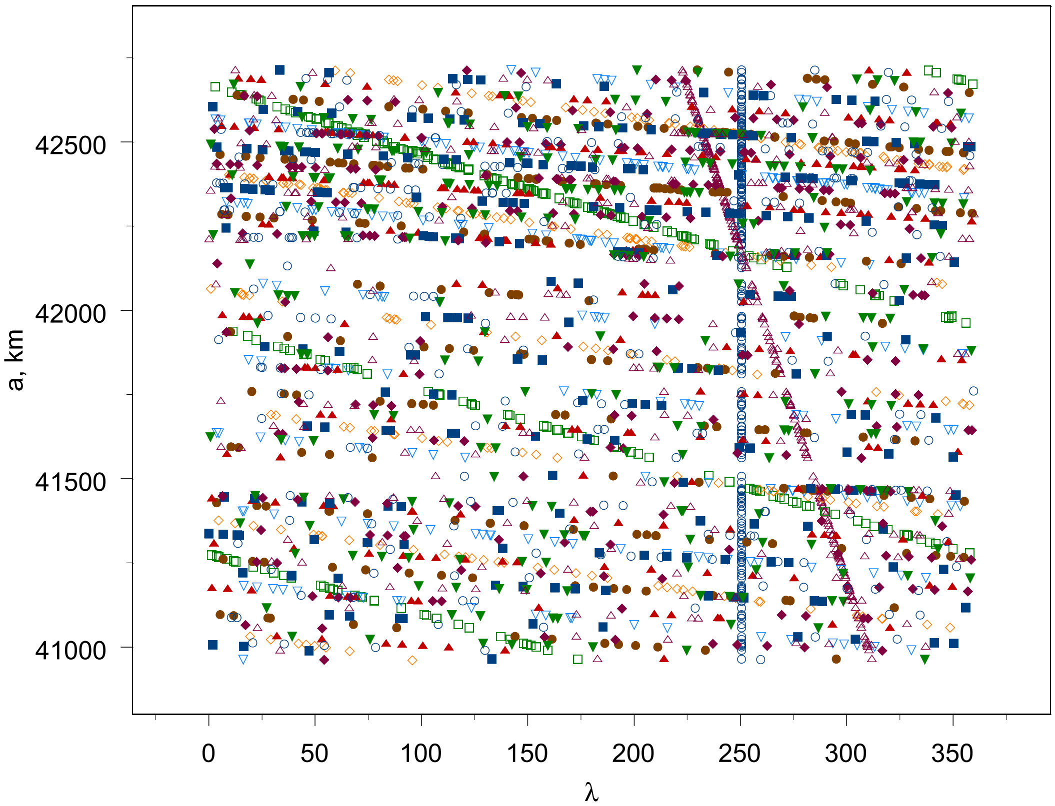

Fig. 1. The fragment cloud structure.

Fig. 2 shows the fragment cloud structure near the region of the libration resonance. In the present explosion model, several fragments, moving near the stable libration point 255°, and one particle, librating with respect to the two stable libration points, are generated. In the libration region near the stable point 75°, fragments of the explosion are absent.

Typical trajectories of the fragment cloud particles are given on fig. 3: circulation to the east or west, libration near the stable point 255°, and libration with respect to the two stable libration points.

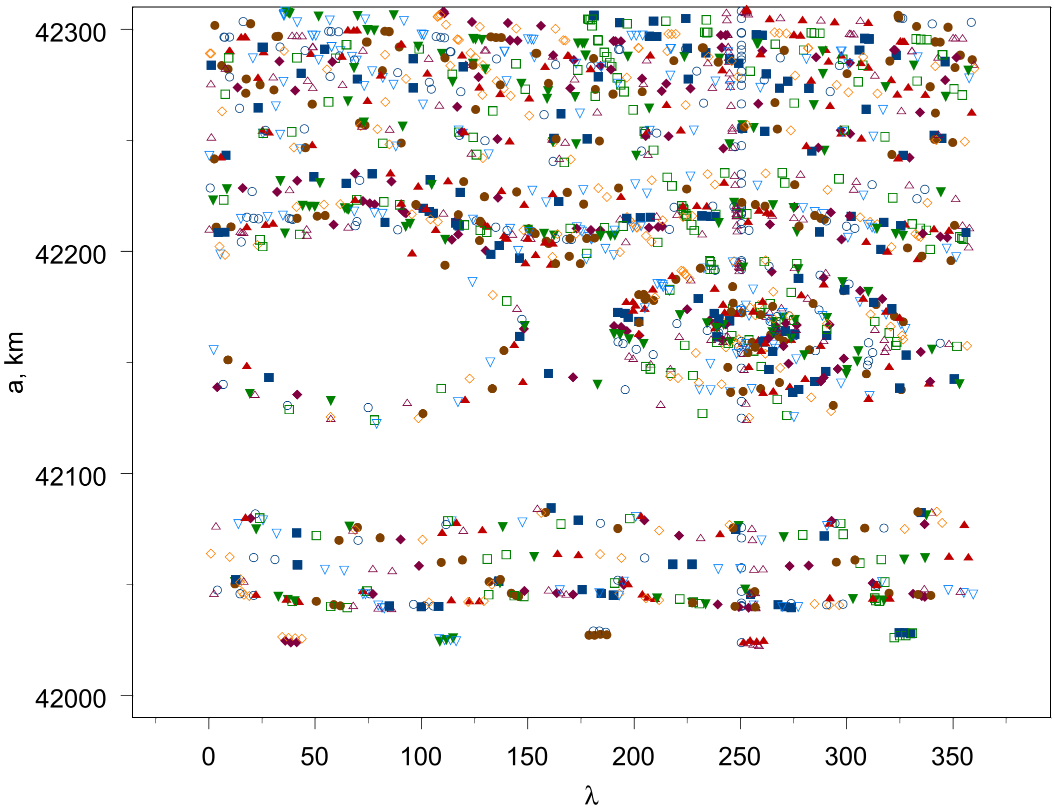

Fig. 2. The fragment cloud structure near the region of the libration resonance.

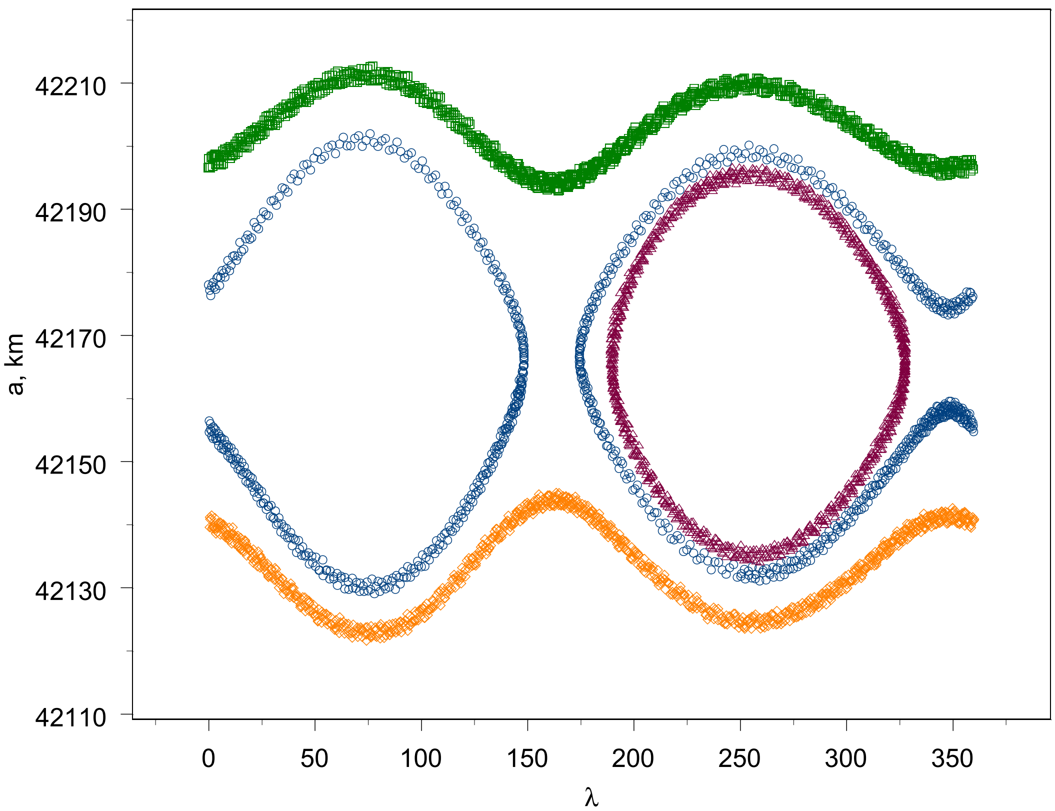

Fig. 3. Typical trajectories of the fragment cloud particles.

Dynamical evolution of the fragments' cloud leads to the formation of two regions with small cross-sections. These regions correspond to situations of the fragment orbits nodes with respect to the orbital plane of the exploded satellite. Position and shape of these regions are changed due to perturbations with time.

Immediately after an explosion the nodes of the particles' orbits are collected at the explosion point and along a line crossing the antipode line (fig. 4a). In the first time nodes of the fragments orbits are situated in a small neighborhood. After a short time period (less than 0.5 years), nodes of orbits are distributed along the orbit of the parent body (fig. 4b). Further evolution leads to closings in the node lines of the fragment orbits, and decreased distances between the orbital nodes (fig. 4c, d). The mean distance between nodes is a measure of nodes closeness. Initially the mean distance between the nodes amounted to approximately 600 km, then increased up to 30 000 km, and 11 years after an explosion decreased to 2 000 km. Several years after an explosion the neighborhood of the nodes of the fragments' orbits density of the particle flow is a maxima. ???The fragments of the explosion necessary to seek in neighborhood of nodes of the fragments orbits.???

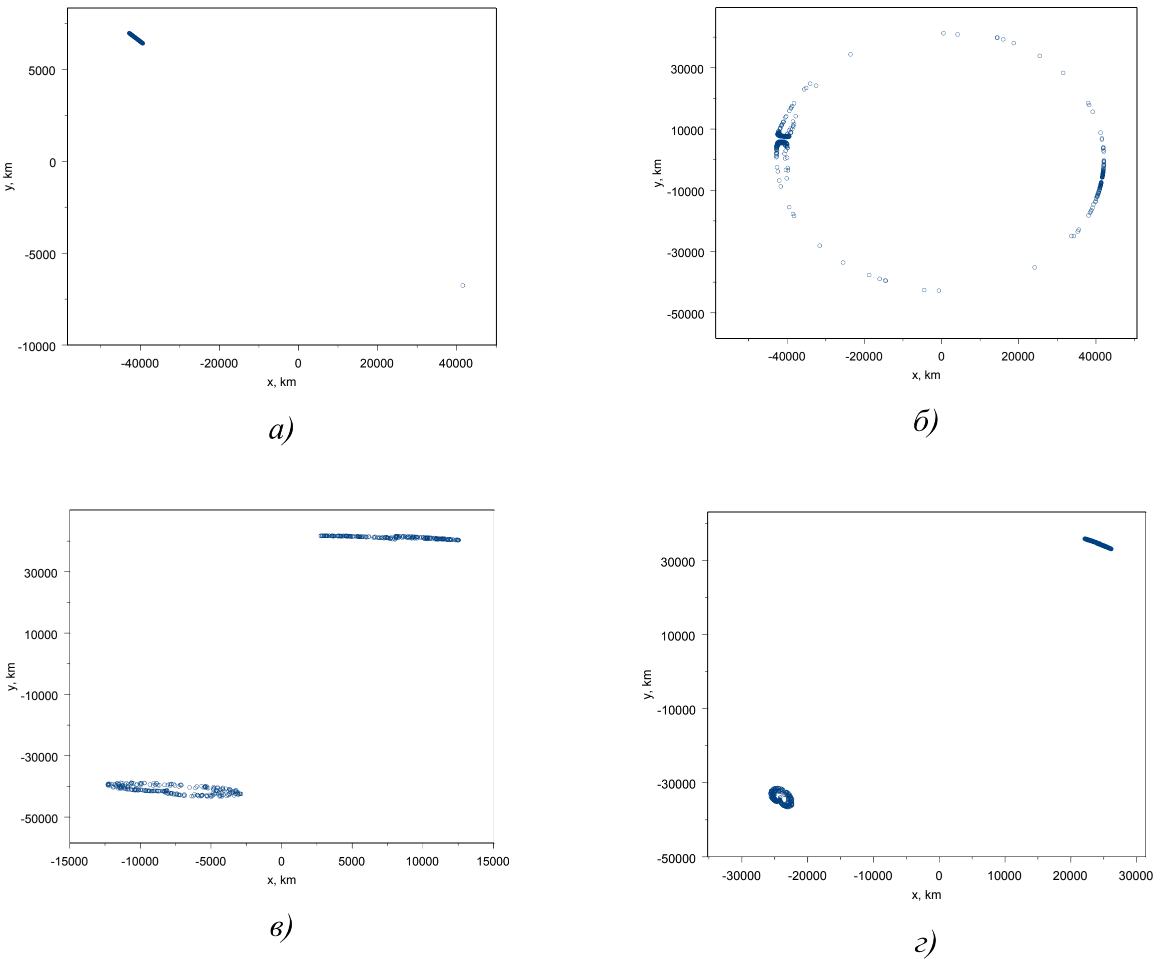

Fig. 4. Evolution of nodes.

Conclusion

Modelling of kinematical and dynamical properties of the fragment's cloud arising from an explosion of an object shows that the number of fragments andtheir velocity are changed in wide intervals. In spite of the fact that the initial increments of velocity are less than several tens of m/s for low energy explosions, impact velocity on orbits with big mutual inclinations can exceed 1 km/s. Impacts with massive fragments can be catastrophic sometimes.

Resonance due to ellipticity of Earth's equator influences significantly the dynamical evolution of the fragments cloud. The propagation along orbit and close in torusis the result of the motion of particles in circular mode. Libration resonance leads to the inner structure of the fragments cloud staying heterogeneous on long-term interval.

Features of the orbital nodes evolution eliminates regions where flow of particles is maxima. These regions are the most convenient to search for fragments of explosions. On the other hand, these are regions of higher danger for geostationary satellites.

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