# TAKING INTO ACCOUNT NON-CATALOGED SATELLITES IN LEO COLLISION RISK ANALYSIS

Zakhari N. Khutorovsky
"Vympel" International Corporation, 8-ii Marta 4-ul. 3, 125319 Moscow, Russia

## ABSTRACT

Technique is based on the use of archive of dangerous approaches of cataloged satellites, stored for long temporal interval. For risk characteristics evaluations distributions of non-cataloged objects in altitude and size, obtained using the Russian model of Space Debris Prediction and Analysis (SDPA) are employed.

## 1. INTRODUCTION

Analysis of space environment must take into account not only known (cataloged) satellites, but the orbiting objects, not catalogaed due to various causes, as well.

Not all orbiting objects are currently cataloged. The reasons are as follows. **First**, territorial limitations of Russian sensors (Ref.1). Some satellites do not pass through the fields of view of the radars and thus, are not observed. **Second**, small sizes of satellites. Small objects may regularly pass through radars fields of view, but they can not be observed due to weak reflected signals. **Third**, limitations of the used in Russian Space Surveillance Center (SSC) algorithms for primary orbits' detemination and tracking. Satellites, rarely observed, may not be properly determined due to limitations for the rate of measurements acquisition and their accuracy.

Break-ups are the major source of non-cataloged objects. Experiments and studies, fulfilled in eighties in the US and other countries revealed that the blasts and hypervelocity impacts produce a lot of fragments. The number of produced particles increases with the decrease of their size. Thus the fragments, observed by radars apparently comprise only a small part of orbiting particles. But the increase of satellite's ballistic coefficient with the decrease of its size is a positive factor, since small objects descend more rapidly and thus their orbital life terminates. But significant amount of these objects, invisible to detection radars are still in orbit.

The total mass of non-tracked satellites is rather small and comprises not more than 1% of the total mass of tracked satellites. Thus they are not capable of producing catastrophic affects of global scale. But even a 0.3-1 cm fragment may disable operational spacecraft, or inflict serious damage. The number of these objects in altitudes up to 1500 km exceeds the number of cataloged satellites almost in two orders of magnitude (Ref.2). Thus assessments of real collision risk are to take them into account.

Taking into account non-cataloged satellites in space situations analysis assumes the knowledge of their current **spatial distribution**. Now the only means is available to acquire this distribution - **modelling of non-cataloged populations**. In this paper we use for collision risk analysis the distributions of non-cataloged objects, obtained exercizing the model SDPA (Ref.3).

Technique of calculating collision probability is based on the use of the **archive of dangerous approaches** (Refs. 4,5), containing the data on all the approaches for all satellites cataloged by the Russian SSS, for which collision is possible. For each approach event the archive comprise rather ample data regarding approaching satellites and parameters of the approach and evaluation of collision probability as well. The archive is maintained since July 1992 and by the end of 1994 the data on two million of dangerous approaches was recorded.

This paper presents technique of rick characteristics evaluations and the results of performed calculations.

## 2. CALCULATIONS TECHNIQUE

All space objects (either cataloged by the Russian SSC or not) can be devided into two groups: launch elements and break-up fragments. We will consider that the non-cataloged objects can be only the break-up fragments. This assumption has the following rationale. **First**, all low-perigee launch elements not present in the Russian catalog are in orbits with great eccentricities, thus residing within the most "dangerous" altitudes (300-2000 km) for rather short time ($\approx$5 $-$10% of their orbital life). **Second**, there are only several hundred of low-perigee launch elements absent in the Russian catalog and present in the US one (Ref.6). Thus follows that the input of non cataloged launch elements to collision risk in altitudes 300-2000 km is not significant.

To take into account non-cataloged break-up fragments in calculations of collision probability using the archive of dangerous approaches we are to transform collision probabilities, stored in this archive only for the events, participated by the break-up fragments.

If approach of the launch element to the break-up fragment occured, taking into account of non-cataloged satellites with size $d$ is done using the formula:

$$\tilde{p}_c = p_c \left(1 + \frac{(d_l + d)^2}{(d_l + d_{db})^2} \cdot \frac{F_{ucdb}(h, \varphi | d)}{F_{cdb}(h, \varphi)}\right), \qquad (1)$$

Proceedings of the Second European Conference on Space Debris, ESOC, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997)

where $p_c$ and $\tilde{p}_c$ - are the initial and the transformed collision probabilities, stored in the archive for this approach; $d_l$ and $d_{db}$ - the sizes of approaching launch element and break-up fragment; $F_{cdb}(h,\varphi)$ - the density of cataloged break-up fragments in altitude $h$ and latitude $\varphi$; $F_{ucdb}(h,\varphi|d)$ - the density of non-cataloged fragments of size $d$.

If the approach of two break-up fragments with sizes $d_1$ and $d_2$ occured, then, to take into account non-cataloged objects of size $d$ we are to transform the collision probability for this event:

$$\tilde{p}_c = p_c\left(1+\left(\frac{(d_1+d)^2}{(d_1+d_2)^2}+\frac{(d+d_2)^2}{(d_1+d_2)^2}\right)\frac{F_{ucdb}}{F_{cdb}}+ + \frac{(d+d)^2}{(d_1+d_2)^2}\cdot\frac{F^2_{ucdb}}{F^2_{cdb}}\right). \quad (2)$$

Thus, to take into account non-cataloged satellites we are to know $F_{cdb}(h,\varphi)$ and $F_{ucdb}(h,\varphi|d)$.

The density $F_{cdb}(h,\varphi)$ is obtained directly from the catalog (Ref. 5). However, acquisition of $F_{ucdb}(h,\varphi|d)$ density is a serious issue. Currently the efforts to measure this density using radars, optical tools and space-based sensors are extended in several countries. Some of the results are presented, for example, in Ref. 2,7. Acccording to these data, variations of density $F_{ucdb}(h,\varphi|d)$ in altitude for certain sizes $d$ in general are similar to the functions for the density of cataloged satellites.

Solving practical tasks using the archive of dangerous approaches one must pay attention to the following:

- Presented above Eqs. 1,2 allow to take into account arbitrary distribution $F_{ucdb}(h,\varphi|d)$ for arbitrary $d$ without any limitations.
- In case the densities are given for various $d$, generalizations of Eqs. 1,2 relationships are obvious, though more bulky.
- The calculations may be performed either for individual satellite or for arbitrary group of them, including the catalog as a whole.
- If the level of uncertainty in $F_{ucdb}$ is known, i.e. known right $F^{(+)}_{utdb}$ and left $F^{(-)}_{utdb}$ limits for $F_{ucdb}$, the Eqs. 1,2 can be used to calculate upper and lower limits for the probability of collision, i.e. to evaluate the uncertainty in risk assessment.

In case the distribution of non-cataloged satellites in spatial coordinates for the size $d$ is completely similar to the distribution of tracked break-up fragments, i.e.

$$F_{ucdb}(h,\varphi|d) = k(d)\cdot F_{cdb}(h,\varphi), \quad (3)$$

we have

$$\frac{F_{ucdb}(h,\varphi|d)}{F_{cdb}(h,\varphi)} = k(d) = \frac{n_{ucdb}(d)}{n_{cdb}}, \quad (4)$$

where $n_{cdb}$ - total amount of cataloged fragments, $n_{ucdb}(d)$ - total amount of non-cataloged orbiting fragments of size $d$.

The function $k(d)$ is obtained experimentally, measuring the fluxes of objects of various sizes with ground and space based sensors. Table 1 presents the results of transforming intensivity of the flux of all orbiting objects (cataloged and non-cataloged), from Ref.2, to the ratio $k(d)$ of the number of orbiting objects with given range of sizes to the number of cataloged by the Russian SSC break-up fragments.

| sizes range, cm | 10-14 | 4-10 | 2-4 | 1-2 | 0.4-1 | 0.2-0.4 | 0.1-0.2 | 0.07-0.1 |
|---|---|---|---|---|---|---|---|---|
| $k(d)$ | 2.6 | 4.2 | 22 | 65 | 370 | 2600 | 19000 | 23000 |

**Table 1.** Experimental data on the ratio $k(d)$ of the number of all orbiting objects to the number of break-up fragments, cataloged by the Russian SSC for various sizes

For the case of Eq. 4, the formulas, taking into account non-cataloged satellites are essentially simplified.

The assumption of coincidence between normalized densities of cataloged and non-cataloged break-up fragments may be used for rough evaluations. More accurate results can be obtained, taking into account altitude dependence of $k(d)$. Available experimental data are insufficient to have this function for the whole range of interesting $h$ and $d$. Currently this function for $d > 0.1$ cm and 300 km $< h <$ 2000 km can be obtained only using the model accounting for the process of arrival and evolution of non-cataloged objects in the course of the 35 years, passed since the first break-up in space was registered. Professor A. Nazarenko kindly supplied us with these data.

This model gives the ratios $\tilde{k}(d,h)$ of the number of orbiting objects within given range of sizes $d\in(d_{i-1},d_i)$ and altitudes $h\in(h_{i-1},h_i)$ to the number of cataloged objects within these ranges. The values of $\tilde{k}(d,h)$ are presented in table 2. The values of $k(d,h)$ are obtained from $\tilde{k}(d,h)$ using the formula

$$\frac{F_{ucdb}(h,\varphi|d)}{F_{cdb}(h,\varphi)} = k(d,h) = \tilde{k}(d,h)\frac{n_{cs}(h)}{n_{cr}(h)}\cdot\frac{n_{cr}(h)}{n_{crdb}(h)}, \quad (5)$$

where $n_{cs}(h)$ - the total amount of cataloged satellites within the given altitude range[1]; $n_{cr}(h)$ - the number of cataloged objects present in Russian catalog for the same altitude range; $n_{crdb}(h)$ - the number of break-up fragments present in Russian catalog for the same range of $h$.

The functions $\frac{n_{cs}(h)}{n_{cr}(h)}$ and $\frac{n_{cr}(h)}{n_{crdb}(h)}$ are also given in table 2. In further calculations we will use the function $k(d,h)$, obtained according to Eq. 5.

## 3. RISK FOR INDIVIDUAL SATELLITES

Evaluation of collision probability for certain object (target) with regard to all (cataloged and non-cataloged) objects of the environment using the archive of dangerous approaches is fulfilled as follows:

- the dangerous approaches participated by cataloged satellites in orbits close to the orbit of the target are selected;
- all the probabilities for these approaches are transformed to the given size of the target $d_0$ and given environment;
- transformed probabilities are summed and matched to the given temporal interval.

[1] We mean the Joint US-Russian catalog

| altitude | sizes ranges, cm | | | | | | | | $\frac{n_{cs}(h)}{n_{cr}(h)}$ | $\frac{n_{cr}(h)}{n_{cr\,db}(h)}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ranges, km | 0.07-0.15 | 0.15-0.25 | 0.25-0.5 | 0.5-1 | 1-2 | 2-3.5 | 3.5-7 | 7-14 | | |
| 300-400 | 3500 | 1000 | 200 | 50 | 10 | 4.5 | 2.4 | 1.2 | 2.00 | 2.45 |
| 400-500 | 4400 | 1200 | 260 | 50 | 9 | 4.2 | 2.2 | 1.1 | 1.50 | 4.07 |
| 500-600 | 3500 | 700 | 190 | 48 | 10 | 4.7 | 2.5 | 1.3 | 1.26 | 3.57 |
| 600-700 | 6600 | 1500 | 390 | 97 | 18 | 8.3 | 3.7 | 1.6 | 1.17 | 3.75 |
| 700-800 | 11000 | 2600 | 640 | 150 | 26 | 11 | 4.6 | 1.9 | 1.16 | 2.62 |
| 800-900 | 16000 | 3600 | 850 | 190 | 32 | 13 | 5.3 | 2.1 | 1.18 | 2.36 |
| 900-1000 | 18000 | 4300 | 980 | 210 | 35 | 14 | 5.5 | 2.2 | 1.16 | 2.26 |
| 1000-1100 | 23000 | 5100 | 1100 | 230 | 36 | 14 | 5.5 | 2.2 | 1.12 | 1.96 |
| 1100-1200 | 44000 | 7600 | 1400 | 260 | 38 | 14 | 5.3 | 2.0 | 1.16 | 1.77 |
| 1200-1300 | 51000 | 8600 | 1500 | 280 | 40 | 15 | 5.4 | 2.0 | 1.23 | 1.69 |
| 1300-1400 | 40000 | 7200 | 1300 | 260 | 38 | 14 | 5.3 | 2.0 | 1.21 | 1.93 |
| 1400-1500 | 31000 | 6000 | 1200 | 240 | 36 | 14 | 5.2 | 2.0 | 1.06 | 4.42 |
| 1500-1600 | 55000 | 10000 | 2000 | 400 | 60 | 22 | 8.5 | 3.2 | 1.17 | 1.70 |
| 1600-1700 | 36000 | 6700 | 1300 | 250 | 37 | 14 | 5.2 | 2.0 | 1.26 | 1.46 |
| 1700-1800 | 37000 | 6800 | 1300 | 250 | 37 | 14 | 5.2 | 2.0 | 1.37 | 1.31 |
| 1800-1900 | 37000 | 6800 | 1300 | 250 | 37 | 14 | 5.2 | 2.0 | 1.43 | 1.35 |
| 1900-2000 | 35000 | 6500 | 1300 | 240 | 36 | 14 | 5.2 | 2.0 | 1.41 | 1.44 |

**Table 2.** The ratios $\tilde{k}(d,h)$ of the number of orbiting objects to the number of cataloged satellites for various sizes and altitudes

We will assume that the satellite is in near-circular orbit and has the size $d_0$.

Let us consider altitude dependencies of collision probability for different sizes of the target.

Fig. 1 presents collision probability as function of altitude for the target in circular or near-circular orbit, with regard to cataloged in the Russian SSC objects for various sizes of target $d_0$ ($d_0 = 1, 2, 3, 4, 5, 7,$ 10 m). Clustering interval in $h$ is 50 km. Collision probability is transformed to annual.

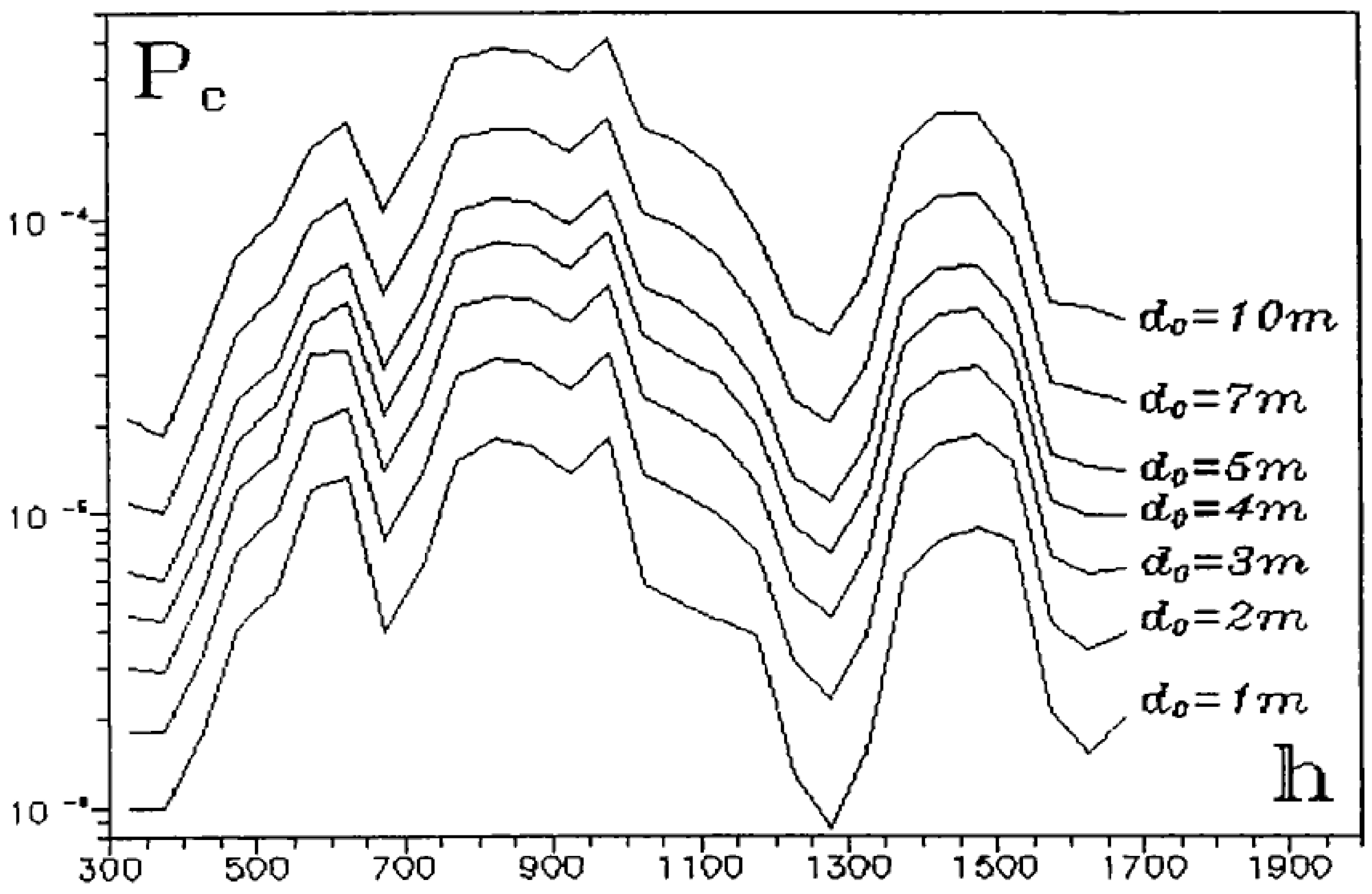


*Fig. 1* Annual probability of collision with Russian SSC cataloged objects for satellite with size $d_0$ in circular orbit with altitude $h$.

Similar functions can be obtained taking into account non-cataloged objects of the environment and those cataloged ones that are absent in Russian catalog. We are to use the same algorithm with the only one modification: all the collision probabilities for approaches involved in the calculations are to be corrected using Eqs. 1,5.

The results are presented in figs. 2-5. Fig. 2 takes into account all orbiting objects with sizes exceeding 3.5-7 cm, fig. 3 - all objects exceeding 1-2 cm, fig. 4 - all objects exceeding 0.25-0.5 cm, fig. 5 - 0.07-0.15 cm. The size of the target was variated from 1 m to 10 m.

Comparison of these charts demonstrate the following:

- In general all collision probabilities as functions of altitude are similar and have major maxima and minima corresponding to similar points. But they are not similar geometrically. With the decrease of size of taken into account objects of the environment the shape of the function changes. In particular the minimum, corresponding to $h \approx 1300$ km becomes less sharp, and the ratio between the two major maxima turns to inverse. For cataloged objects the first maximum (in altitudes ≈800-1000 km) exceeds the second one, and in case when all objects with sizes more than 0.1 cm are taken into account,the situation is the inverse.
- Taking into account non-cataloged satellites results in the increase of collision probability. If the size of the target is $d_0 = 1$ m, than taking into account all objects with sizes exceeding 5 cm increases collision probability in various altitudes from 1.7 to 6.5 times, all objects greater than 1.5 cm - from 3.5 to 45 times, all objects greater than 0.4 cm - from 32 to 1200 times, all objects greater than 0.1 cm from 550 to 40000 times. For $d_0 = 10$ m these values are 4-12, 18-85, 220-2500 and 4000-70000 times respectively. Maximal relative increase of collision risk corresponds to the altitudes ≈1250-1350 km, since relatively small amount of cataloged objects reside in these altitudes and the non-cataloged satellites enter these region as result of break-ups, occured in other altitudes. Minimal value is reached in altitudes lower than 600 km, that can be explained by greater influence of the atmospheric drag for small objects.
- The smaller objects of the environment are taken into account, the greater is the influence of target's size $d_0$ on collision probability. If only cataloged objects are taken into account the increase of $d_0$ from 1m to 10m results in the increase of collision probability depending on altitude from 15 to 45 times (and not 100 times, corresponding to quadratic function). If all the objects with sizes exceeding 5 cm are taken into account, the increase

of collision probability is from 40 to 80 times, all objects greater than 1.5 cm - from 70 to 95 times, all objects greater than 0.4 cm - 100 times.

- Maximal collision risk corresponds to altitudes 800-1000 km. Annual probability (frequency, if the value exceeds 1) of collision for them is given in table 3.

| target | space environment | | | | |
|---|---|---|---|---|---|
| size $d_0$ | cataloged | > 5.5 cm | > 1.5 cm | > 0.4 cm | > 0.1 cm |
| 1 m | 0.000022 | 0.000055 | 0.00027 | 0.0052 | 0.09 |
| 3 m | 0.000065 | 0.00038 | 0.0023 | 0.046 | 0.8 |
| 5 m | 0.00014 | 0.0010 | 0.0060 | 0.13 | 2.3 |
| 7 m | 0.00024 | 0.0019 | 0.012 | 0.25 | 4.6 |
| 10 m | 0.00040 | 0.0035 | 0.025 | 0.50 | 9.4 |

**Table 3.** Annual probability (frequency) of collisions for target in circular orbit with altitude 800-1000 km as function of its size $d_0$ and taken into account environment objects.

- In altitudes 400-450km, where currently "Mir" space station operates, annual collision probability is significantly less (approximately of the order of magnitude, if non-cataloged objects are taken into account). Corresponding figures are presented in table 4.

| target | space environment | | | | |
|---|---|---|---|---|---|
| size $d_0$ | cataloged | > 5.5 cm | > 1.5 cm | > 0.4 cm | > 0.1 cm |
| 1 m | 0.0000035 | 0.000005 | 0.000018 | 0.00031 | 0.0055 |
| 3 m | 0.000011 | 0.000035 | 0.00014 | 0.0027 | 0.050 |
| 5 m | 0.000023 | 0.00009 | 0.00040 | 0.0075 | 0.14 |
| 7 m | 0.000040 | 0.00017 | 0.00075 | 0.015 | 0.27 |
| 10 m | 0.000075 | 0.00035 | 0.0015 | 0.030 | 0.55 |

**Table 4.** Annual collision probability for target in circular orbit with altitude 400-450 km depending on its size $d_0$ and taken into account environment objects.

- Annual collision probability for "Mir" space station (cross-section $\approx 160\,m^2$) for various compositiona of space environment is presented in table 5. The second line presents the data obtained using the model of Prof. Nazarenko. Calculated by this model fluxes of environment objects of various sizes for "Mir" are from Ref.8.

| assessment | space environment | | | | |
|---|---|---|---|---|---|
| technique | cataloged | >5.5 cm | >1.5 cm | > 0.4 cm | > 0.1 cm |
| basic | 0.00015 | 0.00070 | 0.0030 | 0.060 | 1.2 |
| Nazarenko | 0.00019 | 0.00055 | 0.0025 | 0.050 | 1.5 |

**Table 5.** Annual probability (frequency) of collision for "Mir" space station depending on taken into account environment objects.

One can see from these data that the characteristics of risk, evaluated using different techniques are close.

For 10 years of space station operation collision frequencies, presented in table 5 are 10 times greater. Thus we can almost for sure say that collisions of "Mir" with objects with millimeter size or greater took place.

Thus, for large objects, similar to "Mir" space station or "Space Shuttle" in altitudes $\approx$400 km collisions with debris particles with sizes greater than 0.4 cm currently occure every 15-20 years. For long mission durations reliable protection means are required. In altitudes $\approx$800-1000 km collision frequency is a magnitude of a value greater and design of long duration missions of large objects in these altitudes poses very serious tasks.

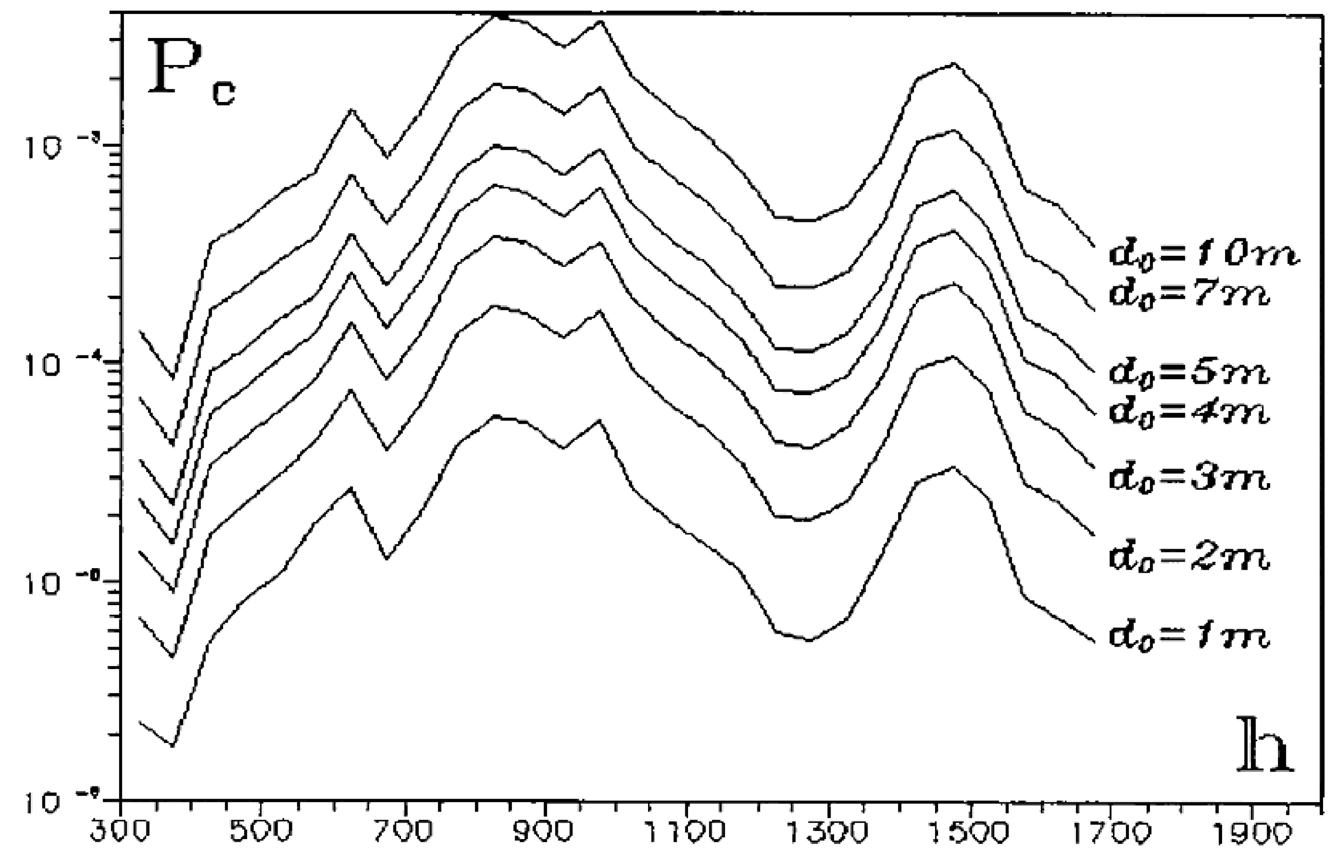


*Fig.2* Annual probability of collision with space environment sized more than 5cm for satellite with size $d_0$ in circular orbit with altitude $h$.

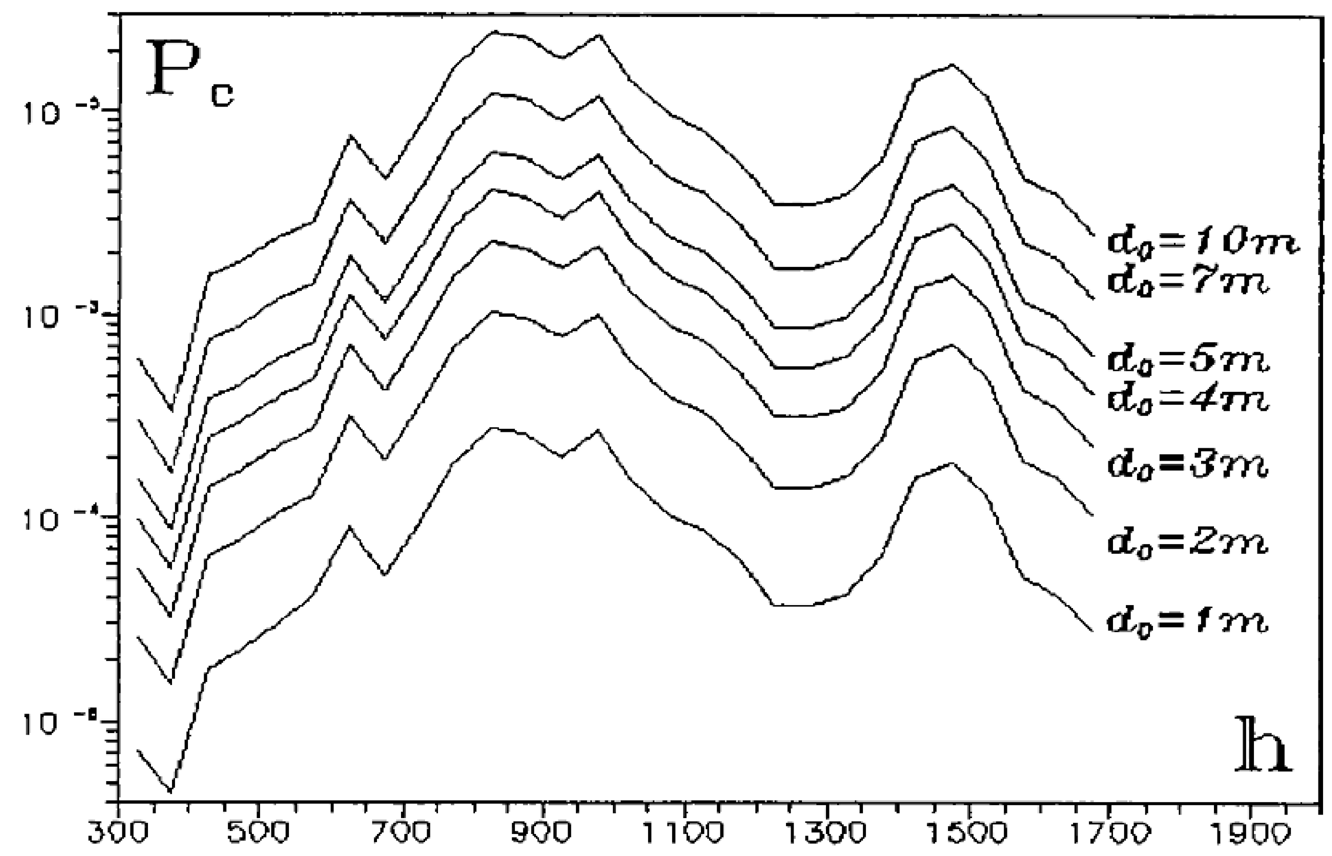


*Fig.3* Annual probability of collision with space environment sized more than 1.5cm for satellite with size $d_0$ in circular orbit with altitude $h$.

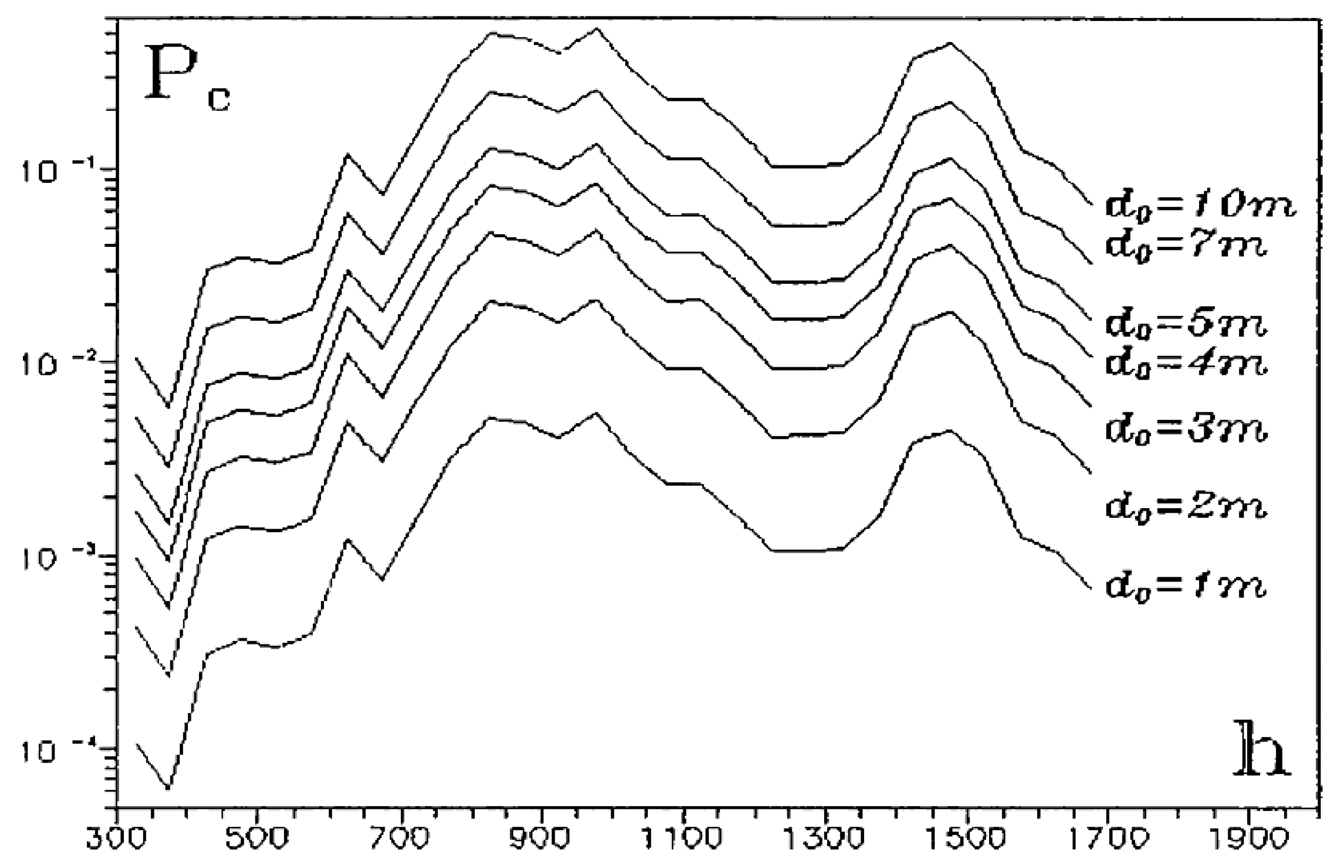


*Fig.4* Annual probability of collision with space environment with more than 0.4cm for satellite with size $d_0$ in circular orbit with altitude $h$.

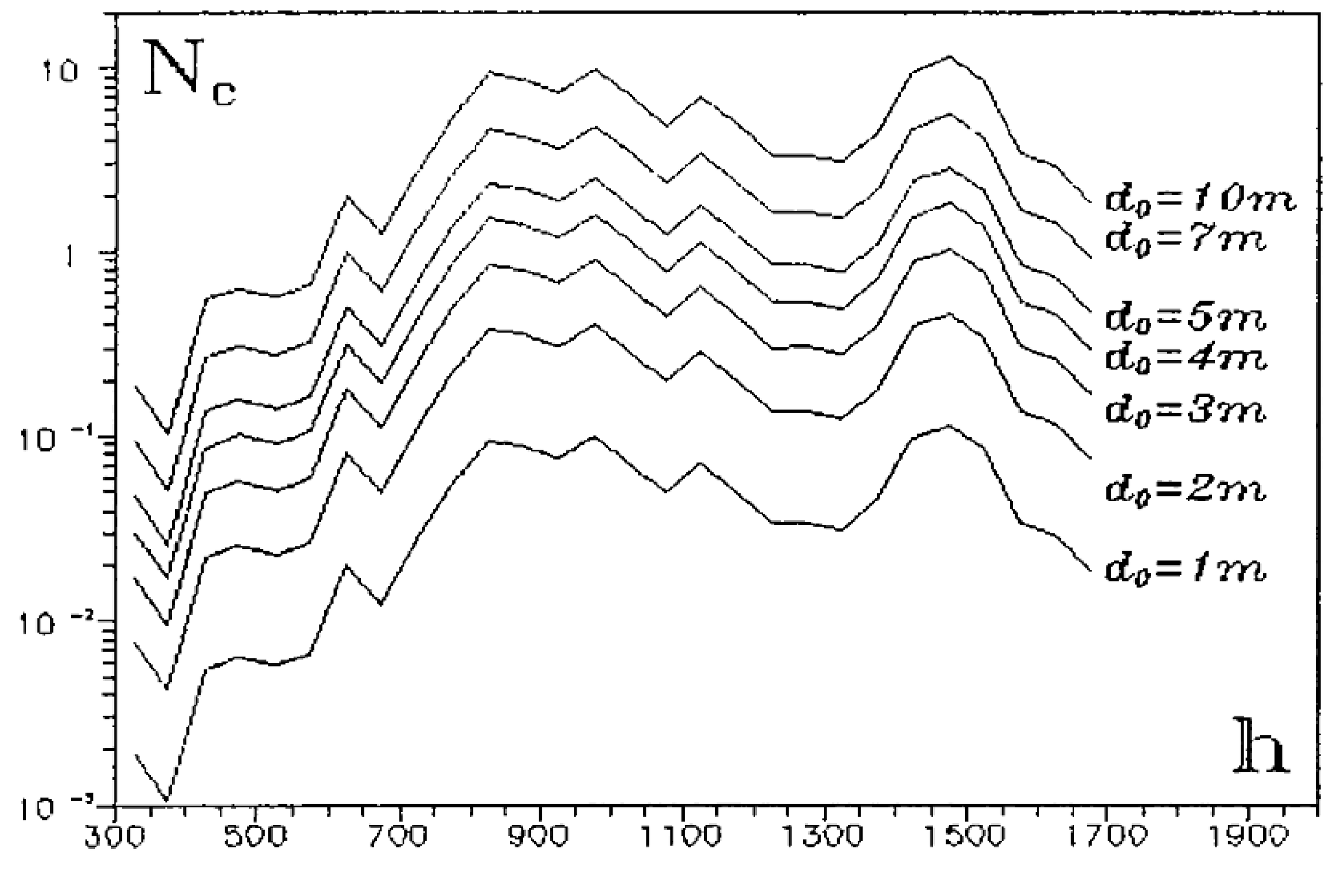


*Fig.5* Annual frequency of collision with space environment sized more than 0.1cm for satellite with sized $d_0$ in circular orbit with altitude $h$.

## 4. INTEGRAL RISK

Let us evaluate collision probability $P_{cs}$ for given temporal interval for all cataloged and non-cataloged satellites.

For evaluations of collision probability for a target in certain orbit with regard to environment objects, including small sized non-cataloged ones taking into account of dependence of $k$ on $h$ is necessary. Disregard of this function in low altitudes results in overestimation of collision risk and in high altitudes (especially for 1400 km< $h$ <1500 km) - in its underestimation. However, the influence of dependence of $k$ on $h$ on the probability $P_{cs}$ of collision between all orbiting object is less significant. Calculations, fulfilled on the basis of the archive of dangerous approaches proved this idea. It was demonstrated, that in calculations of $P_{cs}$ we may disregard $k(d, h)$ as function of $h$. Thus to simplify further calculations and to obtain more explicit final result we will assume that $k$ depends only on $d$.

Assume, that tere are $r$ groups of non-cataloged satellites with sizes $d_1, d_2, ...d_r$. The groups contain $n_{d1}, n_{d2}, ....n_{dr}$ objects respectively. Then from Eqs. 1,2 follows the relationship for calculating $P_{cs}$:

$$P_{cs} = P_c + \sum_i k_i P_i + P_{11} \cdot \sum_{i,j} k_i k_j d_i d_j, \qquad (6)$$

where $P_c$ - probability of collision between any of the cataloged objects; $P_i$ - probability of collision between any of the cataloged objects with cataloged break-up fragments under the condition that these fragments have the size $d_i$; $P_{11}$ - probability of collision between any pair of cataloged break-up fragments under the condition that they have the size 1 (for example, 1cm, in case $d$ is measured in centimeters); $k_i = k(d_i) = n_{di}/n_{db}$, where $n_{db}$ - the number of break-up fragments, tracked in Russian catalog, $n_{db} \approx 2600$ (all further figures from the Russian catalog correspond to the end of 1994).

Probability $P_c$ can be obtained by summing of all collision probabilities $p_c$, stored in the archive and transforming to needed temporal interval. For the interval of a year we have $P_c \approx 0.030$.

Probabilities $P_i$ are calculated similarly on the basis of collision probabilities from the archive $p_c$ for approaches, participated by break-up fragments. The summed collision probabilities $p_c$ are transformed using the formula:

$$\tilde{p}_c = p_c \cdot \frac{(d + d_i)^2}{(d + d_{db})^2}, \qquad (7)$$

where $d_{db}$ - the size of approaching break-up fragment, $d$ - the size of the object, approached by this fragment.

Each fragment, participating the approach brings its input to $P_i$. If two fragments are approaching there are two such inputs.

Probability $P_i$ slightly depends on $d_i$. If $d_i = 10\,$cm, the annual probability is $P_i \approx 0.0096$. With the decrease of $d_i$ probability $P_i$ decreases and tends to 0.0089. Thus the value of annual $P_i$ varies within the limits 0.0089-0.0096.

Probability $P_{11}$ is calculated using all the approaches, participated by the break-up fragments only. For each of these approaches before the summing of collision probabilities $p_c$ transformation is done according to the formula:

$$\tilde{p}_c = \frac{4 \cdot p_c}{(d_1 + d_2)^2}, \qquad (8)$$

where $d_1$ and $d_2$ - the sizes of approaching objects. The annual value of $P_{11} \approx 0.40 \cdot 10^{-6}$.

Let us analyze Eq. 6.

The main parameters, influencing $P_{cs}$, are the ratios $k(d_i) = k_i$ between the numbers of cataloged and non-cataloged break-up fragments. Eq. 6 contains the terms linearly and quadratically depending on $k_i$. Let us reveal the major ones.

It follows from Eq. 6 that the ratio $\eta_i$ of the linear term to quadratic one is:

$$\eta_i = \frac{2.25 \cdot 10^4}{k_i \cdot d_i^2}, \qquad (9)$$

For concrete evaluations we will use experimental data. Table 6 gives the values of $\eta_i$, corresponding to objects of various size ranges.

| sizes range, cm | 10-14 | 4-10 | 2-4 | 1-2 |
|---|---|---|---|---|
| $\alpha$ | 2.6 | 4.2 | 22 | 65 |
| $\eta$ | 160-300 | 50-300 | 65-250 | 75-300 |

| sizes range, cm | 0.4-1 | 0.2-0.4 | 0.1-0.2 | 0.07-0.1 |
|---|---|---|---|---|
| $\alpha$ | 370 | 2600 | 19000 | 23000 |
| $\eta$ | 55-350 | 45-180 | 30-120 | 80-160 |

**Table 6.** The values of $\eta_i$, corresponding to objects of various ranges of size

As follows from these data, for all sizes of non-cataloged objects quadratic term in Eq. 6 is essentially less than the linear one. It means, that in evaluations of integral collision probability $P_{cs}$ we can neglect the approaches between non-cataloged satellites, i.e. between small-sized objects. Thus, in case the collision would occure it will be participated by the cataloged (rather large) object with probability close to unity.

Neglecting quadratic terms in Eq. 6 and taking into account slight dependence of probabilities $P_i$ on size $d_i$ for $d_i < 10\,$cm, we can obtain the following very simple formula to calculate annual probability $P_{cs}$ of collision between all cataloged and non-cataloged objects:

$$P_{cs} \approx 0.030 + 0.009 \cdot \frac{n_s}{n_p}, \qquad (10)$$

where $n_s$ - the total amount of non-cataloged objects of various sizes taken into account in calculation of collision probability; $n_{db}$ - the number of cataloged break-up fragments in Russian catalog.

It follows from Eq. 10 that the integral collision probability $P_{cs}$ practically does not depend on the distribution of non-cataloged satellites in sizes and is determined only by their total amount.

Calculated according to Eq. 6,10 values of collision probability may turn to exceed 1. In this case they have the meaning of annually expected number $N_{cs}$ of collisions between all orbiting objects of given size. For the model of non-cataloged objects, corresponding to the data of table 1, the values of $N_{cs}(d^*)$, obtained taking into account all orbiting objects larger than $d^*$ (including the satellites, present in the US catalog and absent in Russian one), are collected in table 7.

| $d^*$, cm | 10-14 | 4-10 | 2-4 | 1-2 |
|---|---|---|---|---|
| $N_{cs}(d^*)$ | 0.040 | 0.084 | 0.28 | 0.92 |
| $d^*$, cm | 0.4-1 | 0.2-0.4 | 0.1-0.2 | 0.07-0.1 |
| $N_{cs}(d^*)$ | 4.5 | 32 | 200 | 450 |

**Table 7.** Average annual number of collisions depending on the limiting size $d^*$ of objects, taken into account.

One can see from the table, that the smaller is the size of included in collision risk evaluation objects, the greater is the value of the risk. Collisions between satellites with sizes greater than 10-14 cm are rare (approximately one per 25 years), for objects, sized more than 1-2 cm one collision in the average occures annually, and for objects sized more than 0.1-0.2 cm - about 200!

Thus, almost for sure collisions of orbiting objects with sizes greater than 1cm do already occure. But none of these collisions was registered and their results are unknown. It only means that the level of the control over pollution of space is insufficient. It is necessary to solve the task of small objects catalogization and provide reliable predictions for their future collisions. Both these tasks are extremely difficult and they (especially, the second one) are not likely to be solved in nearest future.

Data of table 7 rise great concern. But the current level of hazard should not be overestimated. It does not seem to produce the cascading collisions' effect right now. This effect can not remain unobserved, since it will result in destruction of large objects and these events are registerd by the radars of the US and Russian space surveillance systems, performing permanent observations. But the measures are to be taken to exclude cascading effect in future, since in case it commence the measures will be late and the mankind will remain passive observer of the consequences of its past spacefaring activities.

## 5. ACKNOWLEDGMENTS

Vasily Smelov helped the author in performing calculations using Elbrus-2 computer. He also developed computer codes for maintenance of the archive of dangerous approaches and analysis of data stored there.

## 6. REFERENCES

1. G.Batyr, V.Dicky, Z.Khutorovsky, A. Menshicov, S.Veniaminov, V.Yuracov, The Current State of Russian Space Surveillance System and its Capability in Surveying Space Debris, *Proceedings of the First European Conference on Space Debris*, Darmstadt, Germany, April 1993,pp.43-47.

2. D.J.Kessler, Orbital debris environment, *Proceedings of the First European Conference on Space Debris*, Darmstadt, Germany, 5-7 April 1993, pp. 251-262.

3. Г.М. Чернявский, А.И. Назаренко, Моделирование загрязнения околоземного пространства, *Столкновения в космическом пространстве (космический мусор)*, Москва, Космоинформ, 1995, стр. 104-130.

4. Z.N.Khutorovsky, V.F.Boikov, S.Yu. Kamensky, Direct Method for the Analysis of Collision Probabilities of Artifisial Space Objects in LEO: Techniques, Results and Application, *Proceedings of the First European Conference on Space Debris*, Darmstadt, Germany, April 1993, pp.491-509.

5. З.Н. Хуторовский, С.Ю. Каменский, В.Ф. Бойков, В.Л. Смелов, Риск столкновения космических объектов на низких высотах, *Столкновения в космическом пространстве (космический мусор)*, Москва, Космоинформ, 1995, стр. 19-91.

6. А.В. Меньшиков, Г.С. Батырь, З.Н. Хуторовский, С.С. Вениаминов, Г.Н. Махонин, В.И. Дикий, В.Л. Смелов, В.С. Юрасов, Идентификация американских и российских каталогов космических объектов, *Столкновения в космическом пространстве (космический мусор)*, Москва, Космоинформ, 1995, стр.104-130.

7. E.G. Stansbery, T.E. Tracy, D.J. Kessler, M. Mathey, J.F.Stanley, *Haystack Radar Measurements of the Orbital Debris Environment*, JSC-26655, May 1994.

8. A.I. Nazarenko, Z.N. Khutorovsky, *Modelling of Space Debris Population*, Technical Report, Contract N 10754/94/F/BM, 1994.