SPACE DEBRIS EVOLUTION MODELING WITH ALLOWANCE FOR MUTUAL COLLISIONS OF OBJECTS LARGER THAN 1 CM IN SIZE

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ABSTRACT

To estimate the contribution of consequences of collision of small-size space objects (SOs) into the current near-Earth space (NES) contamination level, the situation forecasting since 1990 to 2012 was carried out. The forecasting has been fulfilled in two stages. At the first stage on the mentioned time interval the evolution of altitude distributions of various-size objects has been constructed without allowance for mutual collisions. At the second modeling stage these results were used as initial data for determining characteristics of objects larger than 1 mm in size taking into account mutual collisions of SOs larger than 1 cm in size.

During situation forecasting the fragmentation model was used, whose parameters were updated based on available experimental data. For catalogued objects the forecasted and real data agree well enough. For smaller-size objects the results occurred to be unexpected. They testify to very strong effect of mutual collisions on NES contamination by particles of size from 1 mm to 5.0 cm. As compared to the SDPA model data for 2010 (without allowance for mutual collisions), the estimates of a number of objects of mentioned size occurred to be greater an order of magnitude. The conclusion was drawn from modeling materials that the so-called cascade effect transmuted from a hypothesis to reality.

Keywords: the mutual collisions, situation forecasting, model.

1. INTRODUCTION

The estimates of the effect of catalogued objects' collisions on the near-Earth space contamination [1, 2] were presented at recent IADC sessions. These materials stated: «*Space activity continuation and space debris (SD) population growth will inevitably initiate the cascade effect in the near-Earth space. This effect (Kessler's syndrome) was predicted by Kessler and Cour-Palais more than 30 years ago. The current SD modeling in the near space (at altitudes up to 2000 km) confirmed that the NES contamination has already reached the instability level. The NES contamination mitigation measures, approved by the international space community including the Interagency Debris Committee (IADC) and the United Nations Organization (UN), may be insufficient to stop the future growth of SD. If the NES contamination instability is confirmed, it would be necessary to consider additional measures to save the NES for future generations*».

The mutual collisions effect on NES contamination was considered in reports [3, 4]. The results stated in them not fully agree with IADC publications [1, 2]. Possible reasoning of this consists, apparently, in the fact that the situation forecasting technique applied in the Russian SDPA model [5, 6, 7] essentially differs from the methodology of preparing the materials of the mentioned IADC report.

The Space Debris Prediction and Analysis (SDPA) model is a semi-analytical stochastic model for mid-term and long-term forecasting of man-made SD larger than 1 mm in size in the LEO and GEO regions, which is used for constructing spatial distributions of density and velocity characteristics, as well as for estimating the risk of collisions. The model began to be developed in ≈ 1990. It has been permanently updated and renewed for the past 23 years. The summary data on various-size SD (without their "attribution" to particular contamination sources) are considered. The current state of NES contamination is characterized by: a) SD density dependence on the altitude and latitude of a point, and b) statistical distributions of magnitude and direction of particles velocity in the inertial coordinate system. These characteristics were constructed on the basis of complex utilization of accessible measurement information and various a priori data.

Prominent features of the technique applied in the SDPA model are as follows:

- The original technique of accounting for mutual collisions of various-size SOs is developed. Its fundamentals are stated in the monograph [6].
- Collisions of non-catalogued objects (smaller than 10 - 20 cm in size) are taken into account.

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- Parameters of the model of fragmentation at collisions are updated based on accessible experimental data. Here, the minimum size of fragments is determined with using the estimate of specific energy of collision.

- Instead of conventional application of the Monte Karlo method in the situation forecasting process, the averaged matrix of collision consequences is used, which is calculated by the original technique before performing forecasts. Its using is equivalent to application of ≈100000 conventional implementations of the Monte Karlo method.

- The assumption is used that the lower boundary of catalogued SO sizes is "blurred". This means, that not all objects larger than 10 cm in size are catalogued.

The listed features of SDPA model allow one to extend the region of estimates of the effect of mutual collisions consequences as compared to the IADC materials; namely, they allow taking into account mutual collisions of smaller-size objects and to estimate the consequences of these collisions into NES contamination by fragments larger than 1 mm in size. Corresponding results are stated below.

2. MODELING OF THE EVOLUTION OF A NUMBER OF CATALOGUED SOS WITHOUT ALLOWANCE FOR COLLISIONS

The contamination process modeling on the time interval from 1960 to 2012 was performed in two stages. At the first stage modeling was carried out over the interval from 1960 to 2012 without allowance for collisions. For performing forecasts the modified situation-forecasting unit of SDPA model (the “update.pas” software) was used. The feature of this software consists in the fact that, on the basis of altitude distribution of catalogued SOs in various years, the altitude distributions of an annual growth of a number of SOs were updated. On the interval up to 2000 the parameters of the earlier model version were used, and after 2000 the catalogs in the TLE form for the years 2005, 2009 and 2012 were utilized. In the modeling process the altitude distributions of an annual number of SOs have been updated in such a manner, that the consent of modeled and real altitude distributions of a number of catalogued SOs in 2005, 2009 and 2012 be ensured. The change of a number of launches in time was taken into account by using the formula

$$dph(h,t_i) = dph(h)_0 \cdot k(t_i)\,. \tag{1}$$

As a result, the following estimates were constructed: a) the nominal altitude distribution of the annual growth $dph(h)_0$, and b) the estimates of coefficients $k(t_i)$, which were used in calculating the annual growth distributions in various years.

Figure 1 presents the normalized altitude distributions of: a) the number of SOs in the catalog at various altitudes (at the end of 2012), and b) the nominal annual growth of a number of SOs. The estimate of a nominal annual growth constituted 413 objects.

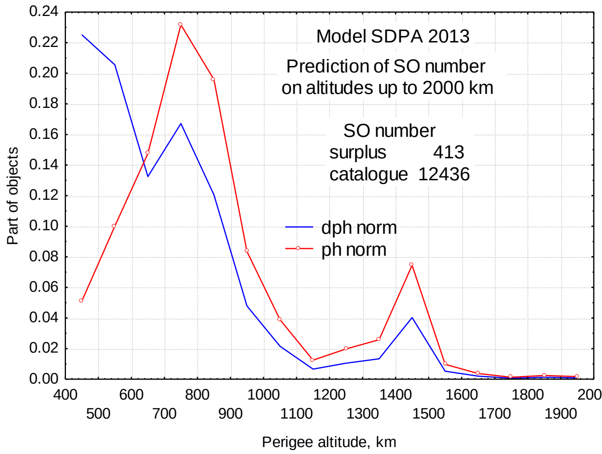


Figure 1. Normalized altitude distributions

For each curve the sum of presented estimates is equal to 1. It is seen from the data of this figure that at altitudes up to 1000 km the character of distributions is different. Here the fraction of an annual growth is essentially greater than SOs fraction at the same altitudes in the catalog. This effect is explained by the influence of SO drag in the atmosphere. At low altitudes many SOs have dropped so deeply, that ceased their lifetime.

Values of coefficient $k(t_i)$ are presented in table 1.

	Data for various years							
Years	1960-1990	1990-2006	2007	2008	2009	2010	2011	2012
$k(t_i)$	1.0	0.8	5.0	1.5	3.0	2.0	0.8	1.5

Table 1. Values of coefficient $k(t_i)$

High values of coefficient $k(t_i)$ in 2007 and 2009 years are explained by unique events of SO fragmentation in these years.

Figure 2 presents the results of modeling the number of catalogued SOs over the time interval since 1960 to the end 2012. Periodic variations of SOs number in forecasting results are explained by the solar activity effect on their atmospheric drag. The growth of a number of objects in 2007 and 2009 is caused by unique events of fragmentation, as mentioned above. Figure 3 presents corresponding NASA’s data [4].

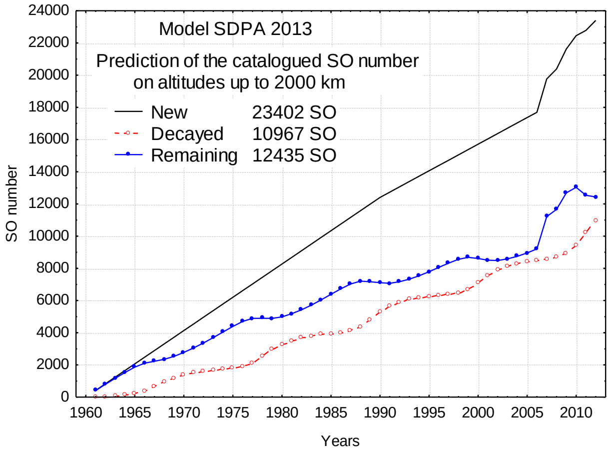
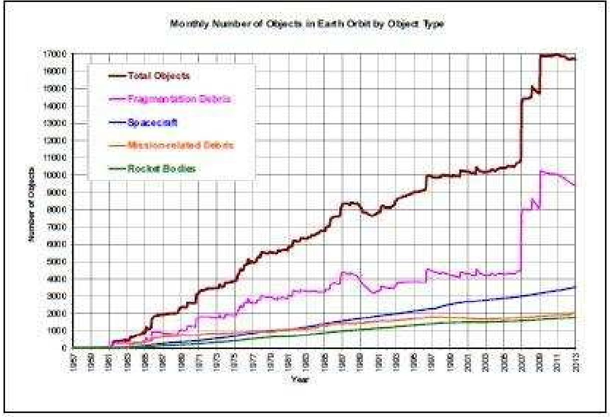


Figure 2. Modeling of the number of catalogued objects



Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Figure 3. NASA's data on the growth of a number of SOs in the catalog

The data of this figure agree in an acceptable manner with forecasting results. Here the number of SOs in the catalog is slightly greater, because it includes the objects at various altitudes – up to the GEO region.

3. MODELING OF A NUMBER OF NON-CATALOGUED SOS WITHOUT ALLOWANCE FOR COLLISIONS OVER THE TIME INTERVAL UP TO 2012

In the SDPA model SO sizes are sub-divided into 8 ranges which are presented in table 2.

№ of range *jd*	1	2	3	4	5	6	7	8
SO size, cm	0.1-0.25	0.25-0.5	0.5-1.0	1.0-2.5	2.5-5.0	5.0-10	10-20	>20

Table 2. SO sizes sub-division into ranges

In situation modeling without allowance for collisions over the time interval since 1960 to 2012 we did not take into account the altitude distribution of annual growth $dph(h, jd)$ for the objects smaller than 1 cm in size, but we constructed this distribution for the objects of larger size (*jd*=4, 5, 6 and 7) only. As a result of situation forecasting with allowance for these initial data and without allowance for collisions, we obtained the estimates of a number of various-size objects of the entire time interval since 1960 to 2012. It is these estimates, which were used subsequently for situation forecasting with allowance for collisions of objects larger than 1 cm in size. This approach makes it possible to obtain the lower (guaranteed) estimates of a number of SD fragments smaller than 1 cm in size.

For constructing the distributions $dph(h, jd)$, *jd*=1,…, 8 the assumption was used that the number of annually formed fragments of size d_j is $k(d_j)$ times larger than the corresponding number of catalogued objects (figure 1). The values of coefficient $k(d_j)$ were determined in the process of tuning the SDPA model parameters on the previous interval [6], as well as with allowance for their correction at the given stage (table 3).

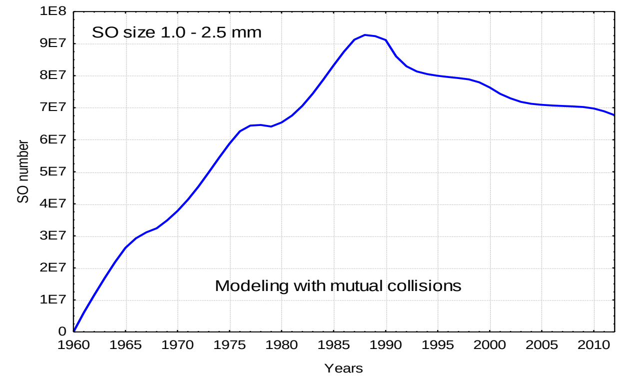
Range No.	1	2	3	4	5	6	7	8
$k(d_j)$	1830	1426	230	44	10	3.6	1.4	1.0

Table 3. Values of coefficient $k(d_j)$

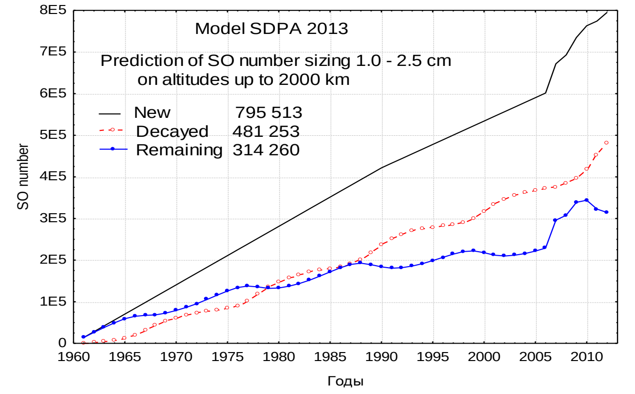
In this sub-division the value of sizes ">20 cm" relates to catalogued objects. It's natural to expect that the lower boundary of sizes of catalogued SOs is "blurred". The average value of minimum SO size in the catalog lies in the interval of values from 10 to 20 cm. So, the application of the ">20 cm" boundary is conditional (symbolic). The catalog data analysis [9] has shown that in recent years the objects were detected, which could not be catalogued earlier. This means that the lower size boundary for the *jd*=8 range has decreased. Some part of objects "passed" from the *jd*=7 size range into the section of *jd*=8. By this reason the value of coefficient $k(jd = 7)$=1.6 was replaced by 1.4.

In situation forecasting without allowance for collisions we have used the fragmentation model, whose description was given in publications [6. 10, 11]. It is based on application of $k(d_j)$ coefficient values (table 3).

For performing forecasts we have used the results presented in the previous Section, namely, the estimates of a nominal annual growth of a number of catalogued SOs (figure 1).



a) SO size: 1.0 – 2.5 mm



b) SO size: 1.0 – 2.5 cm

Figure 4. Examples of evolution of a number of objects of various sizes, 1960 – 2012

Figure 4 gives some results of forecasting of a number of various-size objects over the time interval since 1960 to 2012 inclusively. The top of these figures distinctly indicates the time instant (1990), when the estimates of an annual growth for SOs smaller than 1 cm in size were zeroed, and the number of objects began to monotonously decrease as a result of atmospheric drag. The shape of curves in the lower figure is similar to the data of figure 2.

Table 4 presents the estimates of a number of various-size SOs in 1990 and 2012, obtained in situation modeling over the preceding interval without allowance for mutual collisions.

The comparison of data for 2012 and 1990 indicates that the calculated number of objects smaller than 1 cm in size decreased by 20-30%, and the number of objects larger than 1 cm in size increased by 75%. We pay attention to the fact that the mentioned decrease of a number of objects smaller than 1 cm in size is not real. In the considered modeling technique it is applied in order to more strongly (assuredly) separate the contribution of collision consequences into the NES contamination by objects smaller than 1 cm in size. Under real conditions the level of contamination by objects of this size will be higher than calculated one.

Year	Size range, *jd*							
	1	2	3	4	5	6	7	8
2012	67673975	5035806	878288	314260	63050	22116	4233	12435
1990	91130255	6812990	1153231	183845	35927	12576	2397	7108
Ratio	0.74	0.74	0.76	1.74	1.75	1.76	1.76	1.78

Table 4. Number of various-size objects in 2012 and 1990 at altitudes up to 2000 km

4. SITUATION EVOLUTION OVER THE TIME INTERVAL SINCE 1990 TO 2012 WITH ALLOWANCE FOR COLLISION CONSEQUENCES

Situation forecasting was performed on the basis of the data on changing the number of various-size objects over the time interval since 1990 to 2012 presented in Sections 2 and 3. We remind that, here, the collisions of objects larger than 1 cm in size have been taken into account. In this case the assumption was used that collisions are the only source of formation of fragments smaller than 1 cm in size. The obtained estimates of changing of a number of various-size objects are presented in figure 5.

Table 5 summarizes the data on a number of objects in the altitude region up to 2000 km at the end of 2012, obtained with and without allowance for mutual collisions.

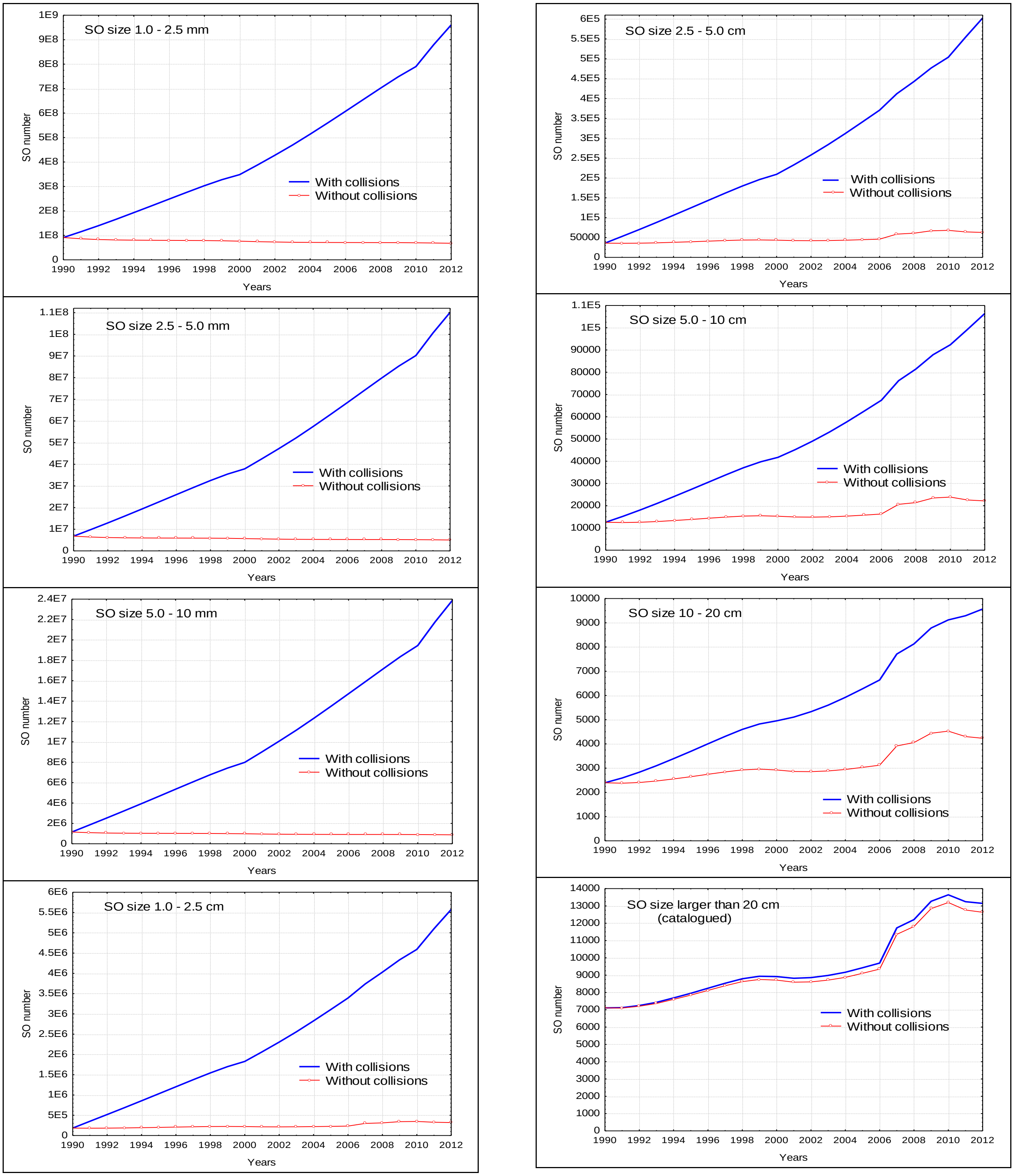


Figure 5. Situation modeling with allowance for mutual collisions of various-size objects

Range No.	1	2	3	4	5	6	7	8
With allowance	**960E+6**	**110E+6**	**23.8E+6**	**5.576E+6**	**604E+3**	**106E+3**	**9568**	**13146**
Without allowance	67.6E+6	5.03E+6	0.878E+6	0.314E+6	63.0E+3	22.1E+3	4233	12634
Ratio	14.2	21.8	27.1	17.5	9.6	4.8	2.26	1.04

Table 5. Number of various-size objects at the end of 2012

The above estimates indicate that:

- The mutual collisions have the greatest effect on a number of objects of size from 1 mm to 2.5 cm. As compared to estimates without allowance for collisions, the number of objects increased 14 – 27 times.

- For objects larger than 2.5 cm in size the effect of collision consequences monotonously decreases from 10-fold down to 1.

- The consequences of mutual collisions have insignificant effect on a number of catalogued objects.

As it was stated in reports [3, 4], the feature of the applied technique of allowance for collisions consequences is an essential expansion of the range of sizes of colliding objects. In this connection, and also for convenience of comparison with previous results, all possible collisions were sub-divided into 3 types (groups):

Group 1. Mutual collisions of space objects (SOs) in the size range from 1 cm to 20 cm.

Group 2. Mutual collisions of catalogued SOs larger than 20 in size.

Group 3. Collisions of SOs in the size range from 1 cm to 20 cm with catalogued SOs larger than 20 cm in size.

As a result of modeling of collision consequences for all three aforementioned types of SOs, the probabilities of collisions were determined in each group. They are presented in table 6.

Group No., *i*	1	2	3
Probability *Pi*	0.96727	0.00027	0.03226

Table 6. Probabilities of collisions of various types

The sum of these probabilities is equal to 1.0. An important feature of these estimates is the fact, that *the probability of mutual collisions of non-catalogued objects of size from 1 to 20 cm is ≈3600 times greater, than the probability of mutual collisions of catalogued SOs*.

Figure 6 summarizes the estimates of an average number of mutual collisions of catalogued SOs (group 2) on the time interval since 1990 to 2012. For objects from the 2nd group the total number of mutual collisions (mathematical expectation) reached the value of 2.7. For objects from other groups it was found to be equal to 9660 (group 1) and 323 (group 3).

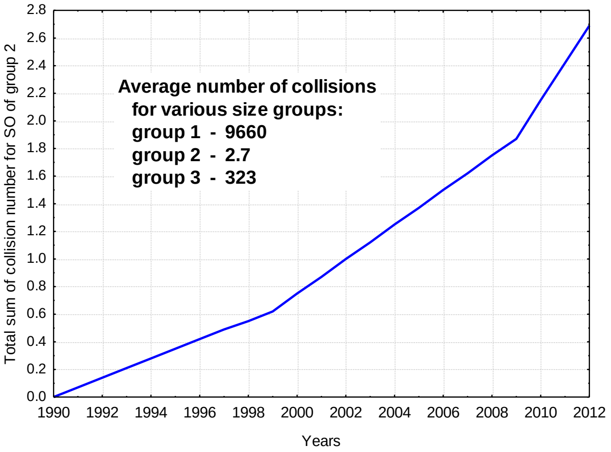


Fig. 6. Growth of a number of collisions in time for the objects of 2nd group

Figure 7 presents the distributions of various-size objects in the perigee altitude at the end of 2012.

Figure’s data allow one to draw the following conclusions:

- Relative characteristics of altitude distributions, obtained with and without allowance for collisions, agree with the conclusions, which were drawn based on the data of figure 5.

- For objects smaller than 20 cm in size the maximum of altitude distributions with allowance for collisions lies in the altitude interval from 800 to 1000 km.

- For catalogued objects (larger than 20 cm in size) the maximum of altitude distributions with allowance for collisions is slightly displaced to the left side and lies in the altitude interval from 700 to 900 km.

Comment. The displacement of altitude distributions’ maxima, mentioned above, is explained by stronger atmospheric drag effect on small-size objects as compared to catalogued ones, because their ballistic coefficients are greater.

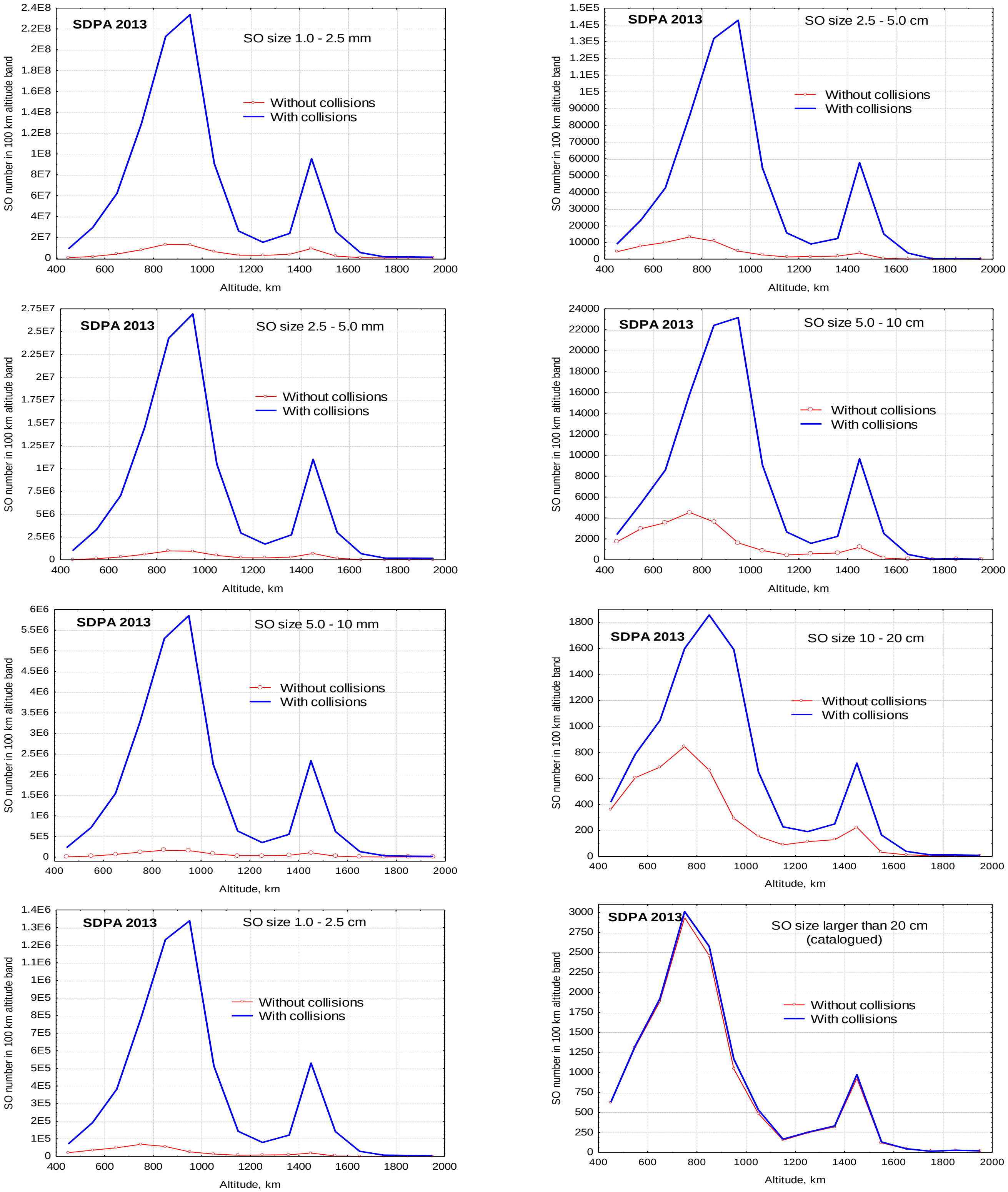


Figure 7. Distribution of various-size objects in the perigee altitude at the end of 2012 with and without allowance for mutual collisions

Range No.	1	2	3	4	5	6	7	8
SDPA2013	6.36E-3	8.33E-4	1.99E-4	5.31E-5	6.14E-6	1.13E-6	9.30E-8	1.36E-7
SDPA2010	1.08E-3	9.11E-5	1.67E-5	2.81E-6	5.68E-7	1.89E-7	6.14E-8	1.27E-7
Ratio	5.89	9.14	11.87	18.82	10.51	5.95	1.51	1.07

Table 7. Comparison of estimates of maximum densities in 2012 and 2010

Table 7 presents the results of comparison of maximum density estimates for various-size objects, calculated by the SDPA2013 model (with allowance for mutual collisions) and by the SDPA2010 model (without allowance for collisions).

The estimates of mutual collisions' contribution into NES contamination by objects larger than 1 cm in size (jd> =4), presented above, well agree with the data of table 5. Here, the greatest (almost 20 times) increase of density relates to object sizes from 1.0 to 2.5 cm. We remind that in modeling we took into account collisions of SOs larger than 1 cm in size. Apparently, such a coincidence of size ranges in taking into account collisions and in estimating their consequences is not casual. One can suppose that, when taking into account the collisions of smaller-size objects, their contribution into NES contamination by objects smaller than 1 cm in size will also increase.

CONCLUSIONS

1. Modeling results have shown that in recent time, as a result of mutual collisions of objects larger than 1 cm in size, the great number of smaller-size fragments was generated. For the objects of size 1.0 - 2.5 cm the growth of a number of objects occurred to be almost 20-fold.

2. The greatest number of collisions occurs in the altitude range of 800 – 1000 km. In the same range the greatest number of fragments is generated. Thus, the so-called cascade effect has transmuted from a hypothesis into reality; namely, in the mentioned altitude region the avalanche process of space debris self-multiplication is already in progress.

3. The cascade effect initiation on a preceding time interval testifies to instability of NES contamination by small-size objects. It is impossible to stop this avalanche process.

4. At present there are no measurement data, which would confirm the existence (initiation) of the irreversible process of space debris self-multiplication. Organizing of such kind of measurements is a topical task.

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