The forecast of near-Earth space contamination for 200 years and the Kessler Syndrome

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Abstract. The paper presents the results of application of the last version of the SDPA (Space Debris Prediction and Analysis) model for forecasting the human-produced contamination of the low Earth orbit area with accounting for mutual collisions of catalogued objects. The forecasting term is 200 years. It is shown that this source of formation of small-sized space debris is essential already now. The conclusion is drawn that the *irreversible growth of human-produced contamination of space has turned from a hypothesis (the Kessler syndrome) to reality: it already began.*

Previous works. At the end of 90-ties the SDPA model [1] was updated in the interests of performing the long-term forecast of the LEO contamination level. The feature of these studies consists in the fact that the main attention here was given to development of the technique of accounting for the consequences of mutual collisions. The results of these investigations were published in a series of papers [2 - 13] and in the monograph [11]. They have also been submitted at the Science and Technological Subcommittee of the UN Committee on Peaceful Use of Space [4].

Consider the principles of the technique *of accounting for mutual collisions of space objects (SOs).* The correct solution of this problem is an extremely difficult task. The main difficulties are caused by the probabilistic character of the problem, by the dependence of collisions' probability and conditions on a great number of factors, whose characteristics vary in time, as well as by the absence of an authentic model of estimating the collision consequences.

To estimate the number of collisions *(N)* of a spherical-shaped spacecraft, having the cross section area *F*, with small-sized space debris particles, the following differential equation is used:

$$\frac{dN}{dt} = F \cdot \rho(t) \cdot \overline{V}_{rel}(t). \tag{1}$$

Here $\rho(t)$- is the density of particles, $\overline{V}_{rel}(t)$ is the average collision velocity. Functions $\rho(t)$ and $\overline{V}_{rel}(t)$ in the right-hand part can greatly vary within the limits of one revolution (depending on the latitude and altitude of a point). But, usually, they only slightly differ on different revolutions, because the total level of human-produced contamination varies rather slowly (by some percents) within a year. So, equation (1) is expedient to be integrated firstly over the interval of one revolution *(T)*. As a result, we obtain the following estimate of a number of collisions per unit of time:

$$\frac{N(t_0, t_0+T)}{T} = F \cdot \frac{1}{T} \cdot \int_{t_0}^{t_0+T} \rho(t) \cdot \overline{V}_{rel}(t) \cdot dt = F \cdot Q(t_0). \tag{2}$$

This is a total flux of particles through the surface of the given spacecraft having the cross section area *F*. Widely applied in the known literature is the notion of the cross-sectional area flux *Q*, which has a meaning of flux through the spacecraft surface with a unit cross section area. In Eq. (2) this value is designated as $Q(t_0)$.

This technique takes into account the possibility of mutual collisions of objects related to groups of various size – the large (catalogued), average (from 1 to 20 cm), smaller-sized (for example, from 0.1 to 1 cm) etc. The density of particles, having size of more arbitrary value *d*, is expressed as a product of some dimensionless coefficient *k(d)* by the density of particles having size greater than the given value d_0:

$$\rho(d,t) = k(d) \cdot \rho(d_0, t). \tag{3}$$

We designate the derivative of coefficient *k (d)* as $f(d) = dk(d)/dd$. All SOs larger than 0.1 cm in size are sub-divided into 10 groups according to sizes. The minimum sizes of objects in each of groups are equal to:

i	1	2	3	4	5	6	7	8	9	10
d_i, m	0.001	0.0025	0.005	0.010	0.025	0.050	0.100	0.200	2.5	10

The following formulae is derived to the estimate of the average number of collisions of a group of objects having size in the range of (D_1, D_2), which lie in some altitude region (*h,h+Δh*), with all SOs having size (d_1, d_2) (this estimate is designated below as $N(h, h+\Delta h)_{Dd}$)

$$\frac{dN(h, h+\Delta h)_{Dd}}{dt} = F_{Dd} \cdot n(h, h+\Delta h)_{cat} \cdot Q(d_0, t). \tag{4}$$

Here $n(h,h+\Delta h)_{cat}$ is the number of catalogued objects in the altitude range *(h,h+Δh),*

$$F_{Dd} = \left[\frac{\pi}{4}\int_{D_1}^{D_2}\int_{d_1}^{d_2}(D+d)^2 \cdot f(d)\cdot dd \cdot f(D)\cdot dD\right]. \quad (5)$$

The results of calculations of the area F_{Dd} are given in Table 1.

Table 1. Matrix of values of F_{Dd} for SOs of various sizes, (sq. m)

i/i	1	2	3	4	5	6	7	8	9
1	275.2	109.7	55.43	29.25	43.68	67.95	58.6	3092	12363
2	109.7	32.69	12.84	5.64	7.67	11.38	9.59	496.8	1982
3	55.43	12.84	3.80	1.27	1.47	2.00	1.60	80.06	318.2
4	29.25	5.64	1.27	0.30	0.27	0.30	0.22	9.97	39.26
5	43.68	7.67	1.47	0.27	0.18	0.16	0.09	3.66	14.16
6	67.95	11.38	2.00	0.30	0.16	0.10	0.05	1.39	5.16
7	58.60	9.59	1.60	0.22	0.09	0.05	0.02	0.30	1.03
8	3092	496.8	80.06	9.97	3.66	1.39	0.30	1.11	2.08
9	12363	1982	318.2	39.26	14.16	5.16	1.03	2.08	1.72

The given results seem to be rather interesting and important.

First, expression (4) *characterizes the spatial distribution of the probability (the average number) of collisions*.

Second, it is seen from the data of Table 1 that, as the considered size of SOs decreases, the number of collisions increases some orders of magnitude – both inside the given group and between the groups.

Summing values (4) leads to the following formulae for the summary number of collisions of objects having the given size

$$\frac{dN_{Dd}^{sum}}{dt} = F_{Dd} \cdot \sum_j n\left(h_j, h_j + \Delta h\right)_{cat} \cdot Q(d_0,t)_j \,. \quad (6)$$

When assessing the total number of collisions objects larger than a specified value ($d > d_i$) in the formula (6) instead of F_{Dd} you must substitute sum

$$\overline{F}_i = \frac{1}{2}\sum_{D>d_i}\sum_{d>d_i} F_{Dd} \,. \quad (7)$$

Table 2 below presents the values of $\overline{Fi}$ from various ranges of sizes.

Table 2. Estimates of $\overline{Fi}$ for SOs from various ranges

i	1	2	3	4	5	6	7	8	9
$\overline{Fi}$,m^2	18988	3029	486.6	79.79	29.63	11.47	4.83	**3.49**	0.86

Table 3 gives the average number of expected collisions per 1 year in 2000 for SOs of various sizes.

Table 3. Estimates of the average number of expected collisions per 1 year

I	1	2	3	4	5	6	7	8	9
N_{sum}	203	324	5.20	0.854	0.317	0.123	0.052	**0.038**	0.009

These data testify once again, that the number (probability) of mutual collisions greatly depends on SO sizes. In particular, as the size decreases from 10 cm (j=7) down to 0.1 cm (j=1), i.e. by 2 orders of magnitude, the number of mutual collisions increases by a factor of 4000. For particles sizing greater than 0.1 cm the estimate of 200 collisions per year was obtained. It is also seen from these data, that at the end of 90-ties the probability of collision of catalogued SOs was 0.038 per 1 year. That is, one collision occurred for 27.5 years, on the average.

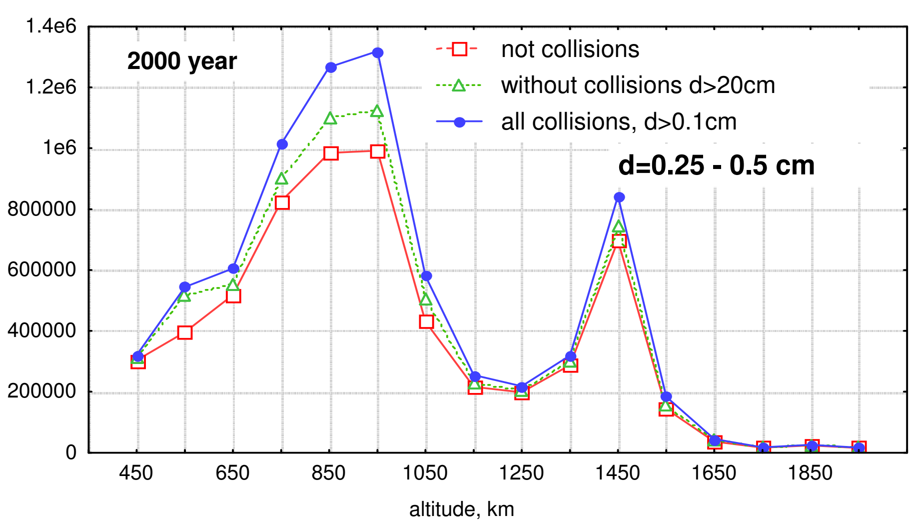

Figure 1. Comparison of the altitude distribution of SO number for different prediction strategies

Figure 1 gives the comparison of altitude distributions of a number of SOs in the 100-km altitude layer in 2000, obtained using the model with and without collisions of SOs of different sizes, as well as in the intermediate case (without collisions of objects sizing larger than 20 cm). These data indicate that the maximum contribution of collision consequences is achieved in the altitude range of 800 – 1000 km with allowance for all mutual collisions and is equal now to 33 % of the total level of the altitude layer contamination with particles of the regarded size. The growth accounts 16% as compared to the intermediate case. This shows that the contribution of mutual collisions of catalogued objects is slightly greater, than the contribution of all other collisions under consideration. Nevertheless, the contribution of collisions of smaller SOs between each other and with large-sized objects is rather significant – it is equal to 14 %.

More than 10 years have passed after obtaining the stated results. During this time the level of human-produced contamination of space has essentially increased [14, 15]. Therefore, new forecasts of environment are required with accounting for both the changed environment and mutual collisions of SOs of various sizes.

Accounting for the random character of collisions. When the consequences of collisions are taken into account, of importance is the technique of accounting for their random character. In solving the problems of such a kind the Monte Carlo technique (the random choice of parameters) is widely applied.

Comment. In Russia, the founder of the scientific school on using the Monte Carlo technique [16] for solution of various applied problems was Nikolay Pantelejmonovich Buslenko (1922-1977). The author of this paper has got acquainted with him 50 years back. Nikolay Pantelejmonovich has trained the author in applying the Monte Carlo technique for solution of one of applied production tasks. The results of this work gave rise to preparation and publishing of a large paper in the collection of "Problems of cybernetics", No. 9, 1963.

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In choosing the number of realizations it is necessary to take into account the random factors which influence the consequences of collisions. The analysis has shown that the number of such factors is not less than 6. We shall list the basic ones:

1. Size of colliding SOs.

2. Specific weights of colliding objects.
3. Variety of shapes of objects.
4. Altitude of a point of collision.
5. Angle between the velocity vectors of SOs.
6. Directions of fragments scattering.

In the case, if each of listed factors has 10 essentially different values, the necessary number of realizations occurs to be not less than 10^6. The direct application of the Monte Carlo technique for random choice of collision conditions in the process of forecasting the human-produced space contamination does not allow one to obtain a great enough number of realizations. Recurrence of forecasts makes such an approach extremely laborious.

In the SDPA model the Monte Carlo technique is applied in some unusual way. *Before performing forecasts*, on the basis of application of the special independent program ("Frag2010.pas") *the averaged characteristics of consequences of one collision are determined*. The efficiency of such an approach is stipulated by stability of characteristics of listed factors in time. For each of possible combinations of values of these factors, one should address to the standard procedure of fragmentation model and determine the orbital parameters of fragments of various sizes. The total number of combinations of listed factors equals $260 \cdot 10^6$. The results are averaged with regard to a priori statistical characteristics of each of factors. It is obvious that application of such a number of realizations allows one to obtain more authentic results as compared to application of a random choice in the process of forecasting human-produced space contamination. Computer time expenses for obtaining the averaged characteristics of consequences of the 1-st collision equal ≈ 30 minutes. With using this result, the environment forecasting for 100 years takes not more than 1-2 minutes.

Figure 2 presents the obtained altitude distribution of a number of SOs of various sizes, formed as a result of one collision of SO larger than 20 cm in size. This altitude distribution of collision fragments is taken into account in the right-hand parts of evolutionary equations during their integration as an additional source of space debris (SD) formation. Such technology does not require repeated forecasts. In addition, it allows for taking into account the small-sized fragments.

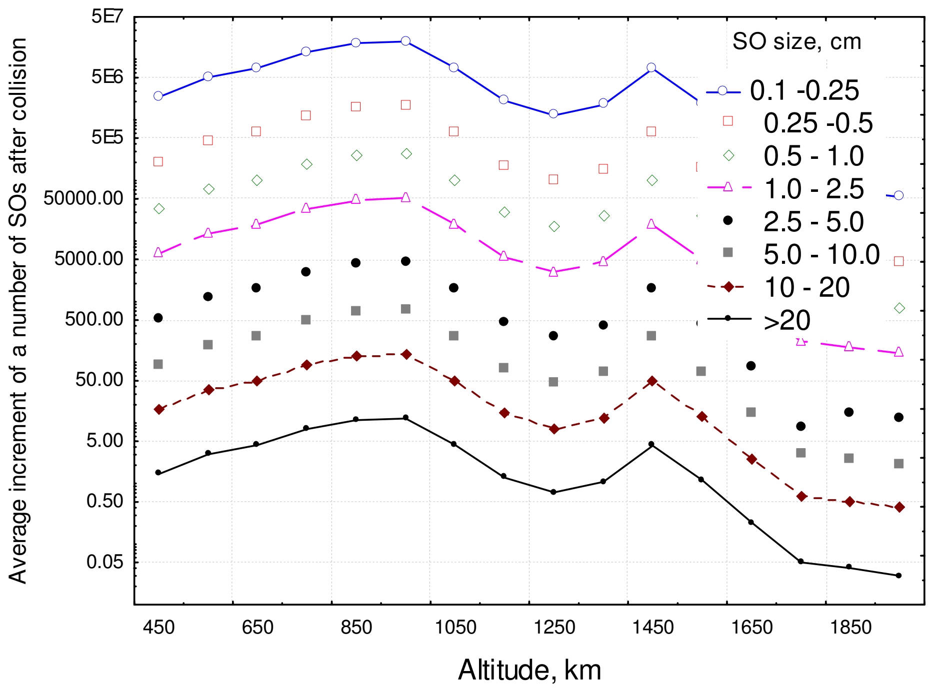

Figure2. Altitude distribution of a number of fragments of the1-st collision

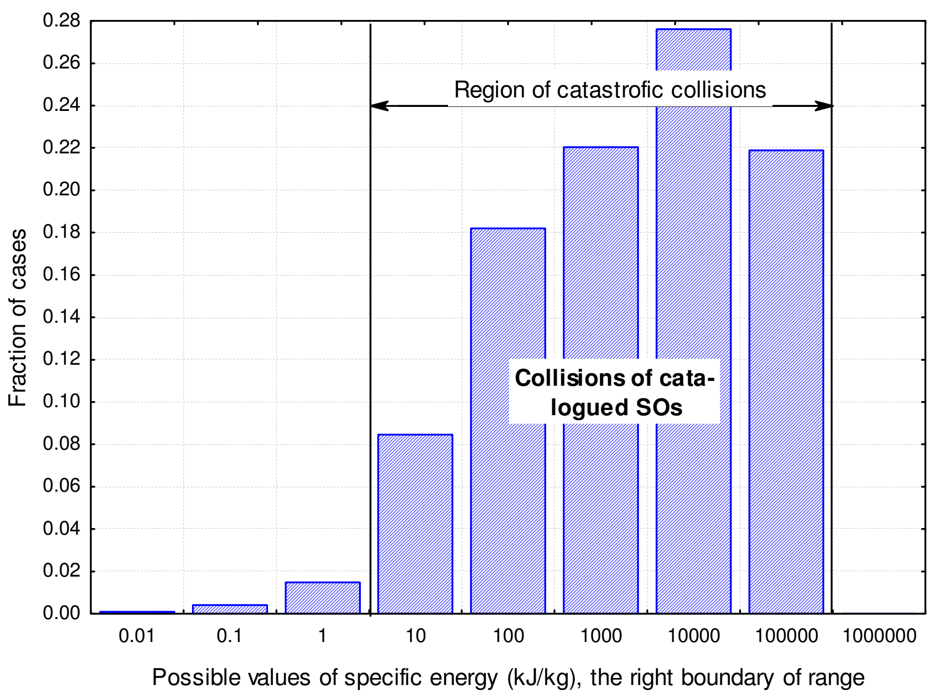

Figure 3. Possible values of specific energy of collisions

Figure 3 presents the histogram of estimates of so-called specific energy of collisions.

This quantity is calculated by formula [11]

$$u = \frac{1}{2} \cdot \frac{m_1 \cdot m_2}{(m_1 + m_2)^2} \cdot V_{col}^2 , \qquad (8)$$

where m_1, m_2 are masses of objects, V_{col} is the relative velocity at collision.

In the known publications one usually considers that collisions, in which the specific energy exceeds the value of 1000 J/kg =1 kJ/kg, are catastrophic. It is seen from the given histogram, that at collisions of catalogued SOs (larger than ≈ 20 cm in size) the overwhelming majority of collisions are catastrophic. They result in destroying both objects.

Comment. The technique of long-term forecast of human-produced space contamination, used in the SDPA model, is not free from some simplifying assumptions. In particular, this concerns the "rarefaction" of addresses to the program for determining the averaged characteristics of consequences of one collision, the introduction of restriction on the lower boundary of sizes of both colliding SOs and the fragments, as well as some other simplifications. Nevertheless, the results of SDPA model application for environment forecasting do not concede in accuracy to foreign analogues and are much more complete, since they take into account formation of small- sized fragments.

The problem of further perfection of the technique of accounting for consequences of collisions, as a basic source of space contamination in the future, is topical.

<u>Possible future scenarios of </u>human-produced space <u>contamination.</u> In developing possible future scenarios of human-produced space contamination it is expedient to take into account the following circumstances:

- Availability of documents, including normative ones, which state the measures directed at mitigation of space contamination [17 - 25]. These measures are based on the results of numerous investigations. They are approved by the international community.
- There are the results of long-term forecasts of human-produced space

contamination carried out by foreign experts.

- The author of this paper has gained certain experience in studies on the environment forecasting problem.

With regard to above considerations, two *scenarios* were applied here for performing long-term forecasts on the basis of SDPA model application:

Scenario 1. Total termination of all launches over the forecasting interval with excluding the possibility of explosions of spacecraft and launch vehicles (the "ideal" scenario).

Scenario 2. Continuation of launches at a medium rate with excluding the possibility of explosions of spacecraft and launch vehicles and without applying deflections of spacecraft and launch vehicles (the pessimistic scenario).

These scenarios take into account, to a maximum extent, such measures on mitigation of human-produced space contamination, as prevention of space debris formation during a regular operation of a space system (SS) and prevention of possible SS destruction as a result of explosions. In all scenarios the consequences of mutual collisions of catalogued SOs (larger than ≈ 20 cm in size) were taken into account.

The space contamination forecast for the period till 2210. In performing the given study, the model of satellite fragmentation at collision [26], used earlier, was modified. The model parameters were updated to provide acceptable consent with the known data on the consequences of collision of Iridium 33 and Cosmos 2251 spacecraft on February 10, 2009. This information provides a unique opportunity to update the fragmentation model parameters based on the experimental data.

Comment. To adjust the fragmentation model parameters on the experimental data basis, one usually applies the results of ground tests (shooting with fine particles over test structures). Obviously, the conditions and consequences of collisions of large-sized objects essentially differ from those of ground experiments. It is impossible to simulate them on the Earth. Just for this reason the data on collision of mentioned satellites are unique.

For the 1-st scenario the basic forecasting results are presented in Figure 4.

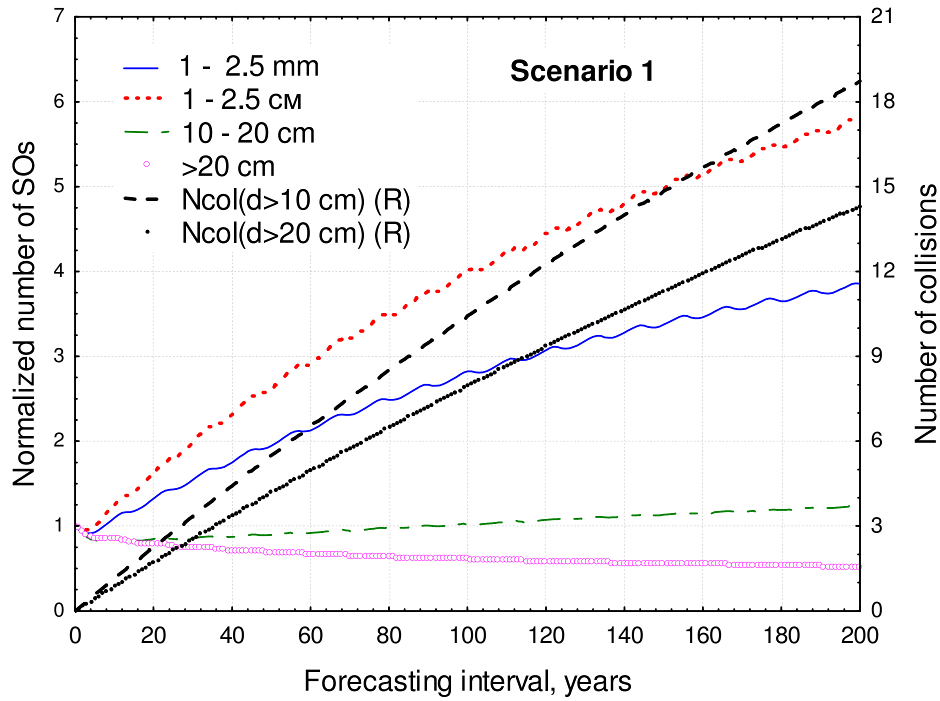

Figure 4. Change of a number of SOs in scenario 1

For 4 ranges of sizes this figure presents the estimates of a number of SOs, which will exist in the space over the forecasting interval, as well as the estimates of a number of collisions of SOs larger than ≈ 20 cm (catalogued objects) and larger than 10 cm in size. It is seen from these data, that on the forecasting interval the number of SOs larger than ≈ 20 cm in size will decrease 2-fold. This effect is explained by the dissipative effect of SO drag in the atmosphere, as a result of which the altitude of SOs drops so low, that they stop orbital flight. This effect results in gradual decreasing of annual increment of a number of collisions. Nevertheless, the number of collisions will grow monotonously, and in 200 years it will reach the value of 14. These collisions will result in growing the number of SOs of smaller size. Whereas for SOs sizing from 10 to 20 cm this growth will be insignificant (by 24 %), the growth of a number of smaller-sized fragments will be essential: *their quantity will increase 4 - 6 times!*

The result stated here, namely, the significant growth of a number of small-sized SOs over the forecasting interval, as a result of collisions, seems to be quite important. Over the considered time interval it is *inevitable*. Even complete termination of launches of new SOs and exclusion of other sources of space debris formation cannot stop, in the foreseeable future, this process of growing a number of small-sized SOs as a result of collisions. Nevertheless, the results stated above demonstrate a possibility of preventing the exponential growth of a number of small-sized fragments – the tendency to stabilizing a number of collisions' fragments is observed. This is achieved on the basis of complete termination of launches of spacecraft and launch vehicles.

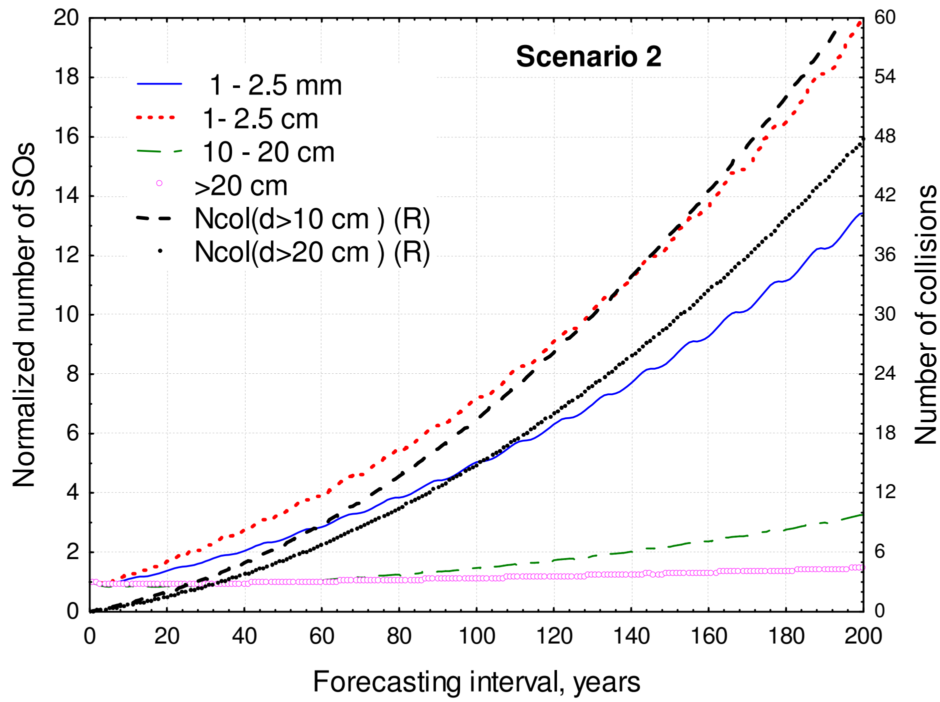

Figure 5. Change of a number of SOs in scenario 2

The basic forecasting results for the 2-nd scenario are presented in Figure 5. As one should expect, in this scenario the growth of a number of catalogued of SOs (larger than ≈ 20 cm in size) will continue. In 200 years their quantity will increase about 1.5 times. As a consequence, the annual increment of a number of collisions will grow, and in 200 years the total number of collisions of catalogued SOs will reach the value of 48, that is 3.4 times greater, than the corresponding estimate for scenario 1. The number of SOs sizing from 10 to 20 cm will increase 3.2 times, and the increase of a number of smaller-sized fragments will be very essential: *their quantity will increase*

13 - 20 times! A prominent feature of the data of Figure 5 is the exponential growth of both a number of collisions and a number of small-sized space debris fragments over the forecasting interval. This result confirms once again the necessity of taking cardinal measures on preventing the formation of new space debris.

Thus, with keeping the intensity of increment of a number of catalogued SOs at the existing level, the number of small-sized, non-catalogued objects will grow exponentially. This implies that the *avalanche growth of human-produced space contamination has turned from a hypothesis (the Kessler syndrome) to reality: it already began.* The possibility of preventing the exponential growth of a number of small-sized fragments can be achieved by zeroing the increment of a number of new SOs of large size. However, under real conditions this measure can occur to be insufficient, since the technique of estimating the consequences of collisions, applied at the given stage of studies, does not take into account the "contribution" of collisions of objects smaller than 20 cm in size.

The results of forecasting the human-produced space contamination stated above *should be taken into account at designing new spacecraft and planning their launches.* The study of possibilities of preventing the growth of human-produced space contamination should be continued.

Conclusion.

The theses of the report [27] “The Kessler Syndrome: Implications to Future Space Operations” were published in the ODQN Journal for April, 2010. The authors have drawn the following conclusion: « … the result of all research to date confirms that we are now entering a time when the orbital debris environment will increasingly be controlled by random collisions. Without adequate collision avoidance capabilities, control of the future environment requires that we fully implement current mitigation guidelines by not leaving future payloads and rocket bodies in orbit after their useful life. In addition, we will likely be required to return some objects already in orbit”.

The above materials on environment forecasting for 200 years correlate, basically, with aforementioned paper's conclusions. Namely, the complete termination of new catalogued SOs formation (scenario 1) results in preventing the exponential growth of space debris. In this case the growth of a number of large-sized (catalogued) objects stops. However, in the mentioned paper (as well as in the other recent publications on this problem) the data on smaller-sized space debris fragments were not considered. In addition, under real conditions the given measure can occur to be insufficient, since the technique of estimating the consequences of collisions, applied at the given stage of studies, does not take into account the "contribution" of collisions of objects smaller than 20 cm in size. Therefore, as shown above, *even in this case the uncontrollable growth of a number of small-sized fragments of collisions will still proceed for a very long time*. Thus, the conclusion of the authors of paper on the Kessler syndrome, that «the orbital debris environment will increasingly be controlled by random collisions» is not convincing. The studies on this problem are expedient to be continued.

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