RESULTS OF UPDATING THE PARAMETERS OF THE SPACE DEBRIS MODEL IN 2007 AND IN 2009

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ABSTRACT

The updating of parameters of the Space Debris Prediction and Analysis Model (SDPA) is performed on the basis of matching the results of environment forecasting in the time interval from 1960 through 2009 with the data of real catalogue of space objects (SO). In the SDPA model, the intensity of increasing the number of catalogued SOs at various altitudes is used for modeling the evolution of small-size space debris (SD).

It was found that the estimates of maximum density of SD of various sizes increased 2.3 - 2.6 times in 2009 as compared to 2003. This is a consequence of destruction of the Chinese Fegun-1C satellite in January, 2007.

1. UPDATING OF MODEL PARAMETERS

We apply the averaged approach to the description of SD sources [1 - 5]. Its characteristic feature is that we apply, instead of the data on specific launches and breakup cases, the following averaged data: (a) the altitude distribution $dp(t,h_p,d)$ of a number of annually formed objects sizing larger than d (here t is time, h_p is the perigee altitude), and (b) statistical distributions of their eccentricities $p(e,d)$ and inclinations $p(i, d)$. The dependencies of initial distributions on objects' sizes are constructed based on the natural assumption, that all small-size SD were formed as a result of large (catalogued) objects fragmentation. Such an approach is based on using: (a) Monte-Carlo method, (b) statistical distributions of annual surplus constructed from the real data on catalogued objects, and (c) a priori data about the dependence of SD fly-away velocity on their size. The less the size of a particle, the greater velocity increment it acquires at the formation time. In such a manner the initial distributions were updated by using the fragmentation modeling data [2].

In adjustment and calibration of the SDPA model, 4 catalogues of elements in the TLE form have been used: for January 2003, February 2005, October 2007 and March 2009. These catalogues were rewritten from the NORAD data [6]. The number of objects with perigee altitudes in the range from 400 to 2000 km in these catalogues was equal, respectively, 6566 (2003), 8828 (2005), 9152 (2007) and 12009 (2009). The histograms of objects distribution in perigee altitudes, eccentricities and inclinations were constructed from these data for SOs from the mentioned altitude range. The obtained distributions are presented in Fig's. 1, 2 and 3.

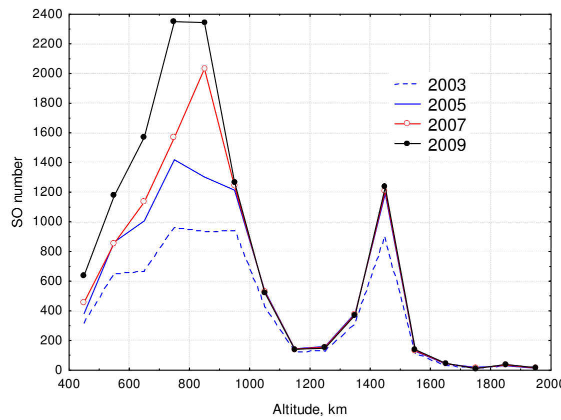

Figure 1. Distributions of objects in the perigee altitude in 2003, 2005, 2007 and 2009

It is seen from the perigee altitudes distribution that the number of SOs has increased most intensively in the altitude range of 600 - 900 km. Here, in the altitude layer from 700 to 900 km the number of catalogued SOs has grown 2.5 times for 6 years, having reached 2350. Obviously, the essential increase of the number of objects in the altitude interval from 600 to 900 km should be taken into account in updating SD characteristics.

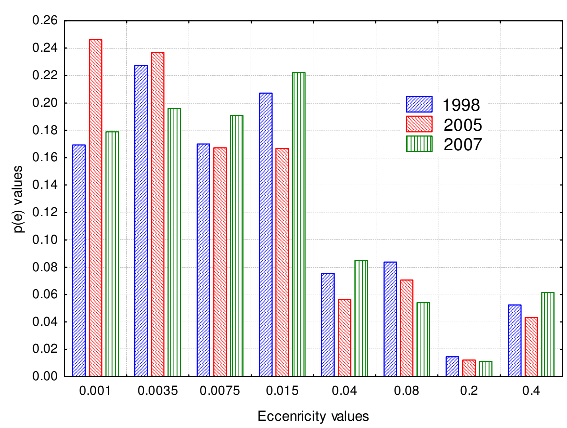

Figure 2. Distributions of objects' eccentricities in 1998, 2005 and 2007

As to the SO distribution in the eccentricity values (Fig. 2), these distributions have only slightly changed. In this case the fraction of objects with small eccentricities (< 0.002) first increased, and then decreased. This effect is explained by changes of SO drag in the atmosphere in connection with the 11-years cycle of solar activity. The relative stability of SO distribution in eccentricities confirms sufficient correctness of the assumption, applied in SDPA model, that this distribution can be assumed invariable over the forecasting interval.

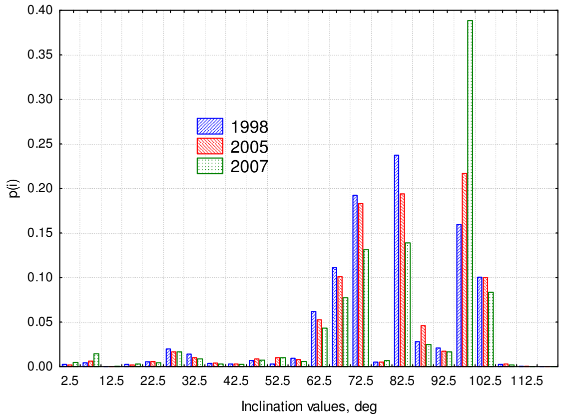

Figure 3. Distributions of objects' inclinations in 1998, 2005 and 2007.

The distributions of inclinations, presented in Fig. 3, reveal some interesting regularity. It consists in the fact, that the greatest changes have taken place in the range of inclinations of 95°-100°. Whereas in1998 this fraction was 18 % (1150 SOs), in 2007 it increased up to 52 % (4760 SOs). That is, in the given 5-deg. range of inclinations the number of SOs increased 3.5! Obviously, the essential increase of the number of objects in the inclination interval of 95°-100° should be taken into account in updating SD characteristics.

On the basis of the above analysis the following recommendations were formulated:

1. The parameters of the model should be corrected in such a manner, that the modeled altitude distribution of SOs larger than 20 cm in size coincided with the real catalogue's data in the acceptable manner. This recommendation is important because of the fact, that the intensity of an increment of a number of catalogued SOs at various altitudes underlay the modeling of the evolution of smaller SD objects.
2. The normalized distributions of eccentricities and inclinations in 2007 should be used as basic characteristics of the situation in the geocentric coordinate system.

The parameters of the model have been updated as follows. The altitude distribution of the nominal intensity of an annual gain of catalogued SOs *dph(h,cat)* was selected in such a way, that, as a result of forecast from 1960 to 2005, from 2005 to 2007 and from 2007 to 2009 the resulting SO distribution in the perigee altitude coincided with the corresponding real distribution of catalogued SOs. Thus obtained averaged estimations of annual gain in the SO number are presented in Fig. 4.

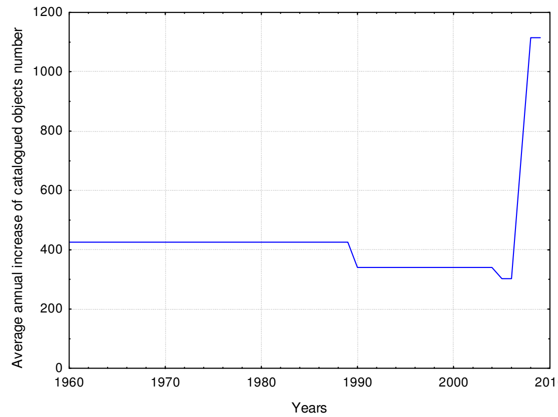

Figure 4. Annual gain in the number of catalogued SO

It is evident from these data that during 2007 - 2009 the annual gain in the number of catalogued objects increased 3 times. Fig. 5 presents the distributions of annual gain in the SO number on the altitude: averaged ones according to the data, obtained before 2005 and after 2006.

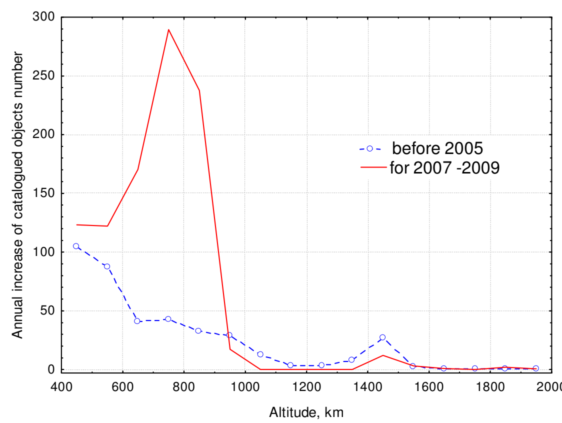

Figure 5. Comparison of intensities of the annual gain dph(h,cat)

It is seen from the data of figure, that updating of the distribution *dph(h, cat)* affected, basically, the ranges of altitudes of 600-900 km. The annual gain of the number of SOs increased to the greatest extent (six times) in the altitude layer of 700-800 km.

The results of correlation of altitude distributions are presented in Fig. 6.

The presented results show rather well coincidence. In this connection, the parameters of the model, used in forecasting, and the results of its application for determining SD characteristics were accepted as basic ones.

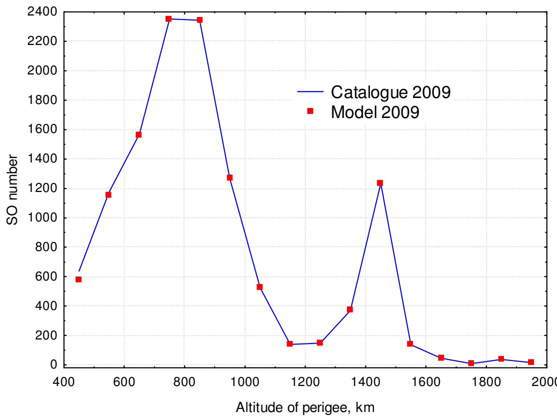

Figure 6. Modeled and real SOs distribution in the perigee altitude in 2009.

In conclusion to the Section we present the results of comparison of altitude-latitude distributions of spatial density of catalogued SOs – modeled and calculated by the catalogue for 2007.

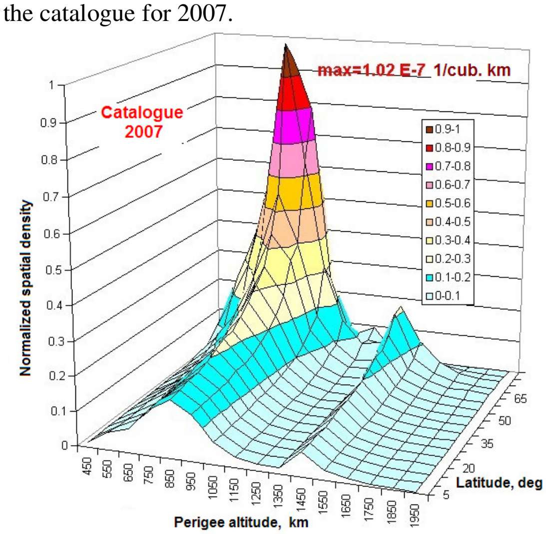

Figure 7. Altitude-latitude distribution of spatial density according to the catalogue data

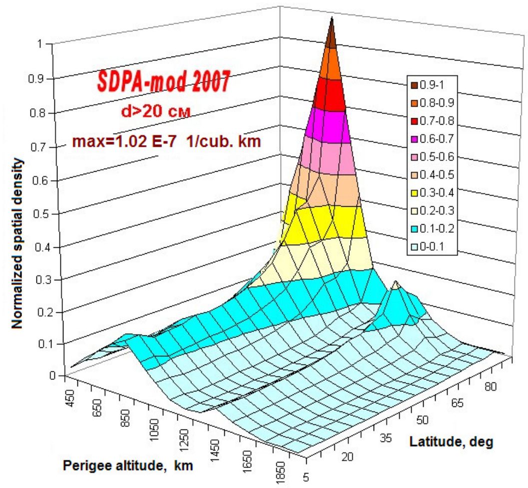

Figure 8. Altitude-latitude distribution of spatial density according to the SDPA-2007 model data

They are presented in Fig's 7 and 8.

These data show well consent of modeled and real distributions.

The updated parameters of the SD model are "tied" to 2007 and to 2009. The file of these data for 2007 was inserted into the file of SD model's parameters. This file is "sewed" into the body of the software and, therefore, it is inaccessible for updating in the process of application of the space debris model.

Tab. 1 presents the estimates of the maximum spatial density of SD of various sizes in 2007 and in 2009 and their comparison with the corresponding data of 2003.

It is seen from these data, that the values of the maximum spatial density of SD of various sizes increased 1.7 - 1.9 times in 2007 as compared to 2003. The corresponding values of spatial density for 2009 increased 2.3 – 2.6 times. This is a consequence of the Chinese Fegun-1C satellite destruction in January, 2007.

Table 1. Estimates of the maximum SD spatial density, km^{-3}

Year	Range of sizes, 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
2003	4.068E-4	3.312E-5	6.375E-6	1.035E-6	2.092E-7	7.140E-8	2.336E-8	5.454E-8
2007	7.117E-4	5.976E-5	1.156E-5	1.978E-6	4.032E-7	1.369E-7	4.488E-8	1.020E-7
2009	1.039E-3	8.775E-5	1.626E-5	2.731E-6	5.539E-7	1.851E-7	5.995E-8	1.264E-7

2. RESULTS OF TEST CALCULATIONS

Test calculations on estimating the effect of updating the SD model parameters were performed in two stages. At *the first* stage the characteristics of the situation relative to the given orbit were estimated, and at *the second* stage the consequences of collisions were evaluated. Tab. 2 presents the estimates of cross-sectional area flux of SD of various sizes relative to the International Space Station (ISS) corresponding to SD model parameters before and after updating.

It is seen from these data, that the estimates of the cross-sectional area flux of SD of various sizes relative to ISS increased 2.4 - 2.7 times in 2007 as compared to 2003. The corresponding gain for 2009 reached 4.0 – 4.5 times. This increase is about 1.5 times greater, than the data on increasing the maximum spatial density given in Tab. 1. This effect is explained by the fact, that the altitude distribution of SD is quite non-uniform. Its spatial density at the ISS flight altitude 30-40 times differs from the maximum values (in the altitude range of 800 - 900 km).

Table 2. ISS. Comparison of estimates of cross-sectional area flux of SD of various sizes

Size range, см	Flux, 1/(sq.m·year)		
	2003	2007	2009
0.10-0.25	0.293E-2	0.714E-2	0.124E-1
0.25-0.50	0.236E-3	0.611E-3	0.108E-1
0.50-1.0	0.501E-4	0.121E-3	0.210E-3
1.0-2.5	0.902E-5	0.224E-4	0.379E-4
2.5-5.0	0.213E-5	0.506E-5	0.854E-5
5.0-10.0	0.815E-6	0.209E-5	0.333E-5
10-20	0.304E-6	0.815E-6	0.123E-5
>20	0.379E-6	0.101E-5	0.142-5

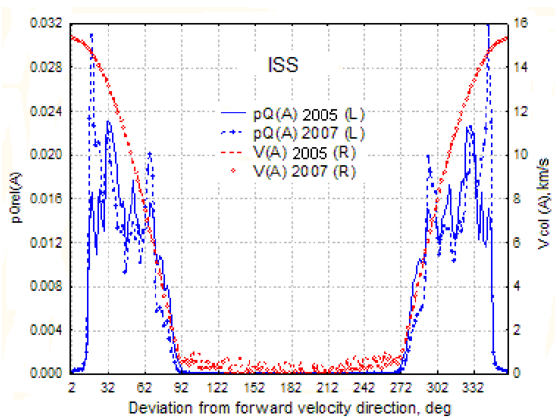

Figure 9. Comparison of pQrel(A) and Vcol(A) functions before and after updating the model

Fig. 9 presents the normalized distributions of the SD cross-sectional area flux over possible directions of its approach (*pQrel (A)*), as well as the dependences of the averaged velocity of collisions on its direction (*Vcol(A)*) calculated on the basis of parameters of the SD model before and after its updating. The comparison of corresponding distributions of collision velocity is presented in Fig 10.

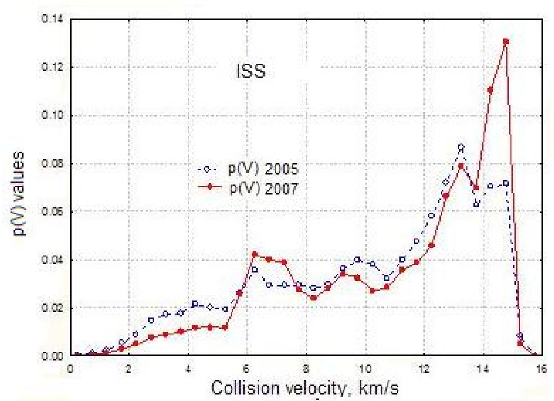

Figure 10. Comparison of distributions of collision velocity (Vcol)

It is seen from the data of these figures that, after SD model updating, the fraction of collisions in the range of approach angles of ± (10-20°) has essentially (about 2 times) increased. As a consequence, the fraction of collisions at velocities of 14.5-15.0 km/s increased about two-fold.

Thus, on the basis of estimation of the change of characteristics of the situation relative to the given spacecraft (SC), one can expect the (2-3)-fold increase of penetration probabilities of walls, especially for those structure elements, which are subject to head-on impacts.

At *the second* stage of test calculations we estimated the consequences of SC – SD collisions corresponding to application of parameters of the SD model before and after its updating. The considered test structure of SC is presented in Fig. 11.

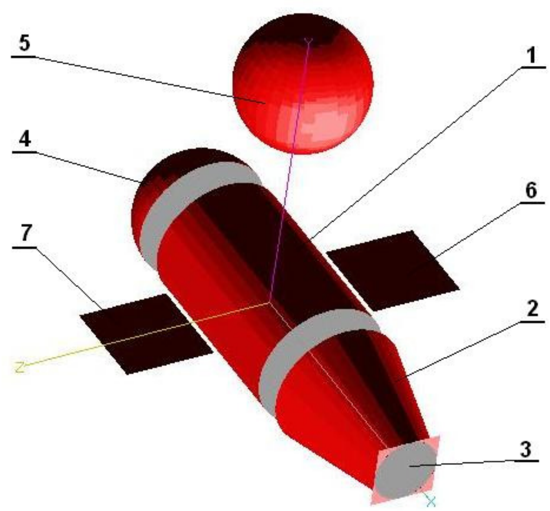

Figure 11. Test structure of SC, t_b=0.05 cm, t_S=2.0 cm, t_w=0.16 cm

Tab's 3 and 4 presents corresponding estimates of collision probability with SD sizing more than 1 mm and walls penetration probability for all structure elements.

It is natural that changes in the collision probability are coordinated with the appropriate changes in the cross-sectional area flux (Tab. 2).

It is seen from the results of test calculations, that in using the parameters of the SD model of 2007 the walls penetration probabilities increased 2-3 times as compared to application of parameters of the 2003 model. According to the results of updating the parameters of model in 2009 the corresponding increase in the penetration probability of walls reached 3.5 - 5.4 times. As expected, this increase affected to the greatest extent (5.4 times) the panel, the normal to which coincided with the SC velocity direction. The lowest increase affected the hemisphere located in the back side of SC.

Table 3. Comparison of collision probability before and after updating the SD model

№	Shape	Values Pcol[No]			Ratio	
		2003	2007	2009	2007/ 2003	2009/ 2003
1	cylinder	0.01309	0.02972	0.05166	2.27	3.93
2	cone	0.00939	0.02241	0.03896	2.38	4.14
3	panel	0.00214	0.00558	0.00970	**2.60**	**4.53**
4	hemi-sphere	0.00172	0.00364	0.00632	2.11	3.68
5	sphere	0.01016	0.02480	0.04312	2.44	4.26
6	panel	0.00009	0.00024	0.00042	2.62	4.56
7	panel	0.00009	0.00024	0.00042	2.62	4.46
	Sum=	0.03670	0.08664	0.15063	2.26	4.11

Table 4. Comparison of walls penetration probability before and after updating the SD model

№	Shape	Values PP[No],%			Ratio	
		2003 г	2007 г	2009	2007/ 2003	2009/ 2003
1	cylinder	0.1276	0.2608	0.4560	2.04	3.59
2	cone	0.1136	0.2562	0.4484	2.25	3.95
3	panel	0.0459	0.1411	0.2473	**3.07**	**5.39**
4	hemi-sphere	0.0112	0.0225	0.0393	2.00	3.51
5	sphere	0.1353	0.3502	0.6130	2.58	4.54
6	panel	0.0000	0.0000	0.0000	-	-
7	panel	0.0000	0.0000	0.0000	-	-
	Sum=	0.4336	1.0309	1.8040	2.37	4.16

At conclusion of the Section we consider the values of the SD cross-sectional area flux relative to SC Iridium according to the data of the SDPA model before and after correction of its parameters. Corresponding estimates are presented in Tab. 5.

Table 5. Iridium. Cross-sectional area flux, 1/sq.m·year

d1-d2, cm	**SDPA 2003**		**SDPA 2007**	
	Flux(d1,d2)	Flux(d>d1)	Flux(d1,d2)	Flux(d>d1)
0.10-0.25	0.0242348	0.0267325	0.0424231	0.0469062
0.25-0.50	0.0020020	0.0024977	0.0035862	0.0044831
0.50-1.00	0.0004028	0.0004957	0.0007246	0.0008968
1.00-2.50	0.0000680	0.0000928	0.0001268	0.0001722
2.50-5.00	0.0000144	0.0000248	0.0000266	0.0000454
5.00-10.0	0.0000051	0.0000103	0.0000092	0.0000187
10.0-20.0	0.0000017	0.0000051	0.0000031	0.0000095
>20	0.0000034	0.0000034	0.0000064	0.0000064

The (1.7 – 1.9)-fold increase of the cross-sectional area flux in 2007, as compared with the data for 2003, agrees with corresponding values of spatial density, presented in Tab. 1. Fig's 12 and 13 show the distributions of the directions of the collision velocity according to the data of models SDPA-2003 and SDPA-2007. It is evident that in 2007 the portion "frontal" collisions substantially increased. This result is agreed with the data of modeling the SD flux characteristics relative to ISS (Fig's 9 and 10).

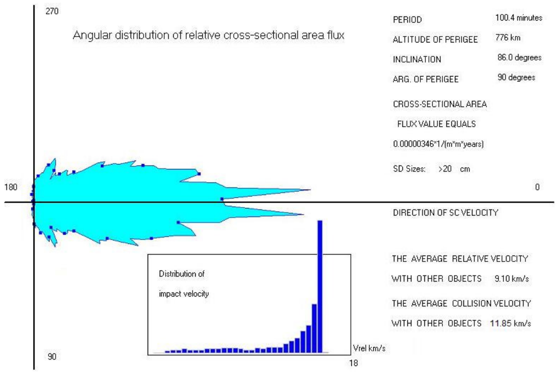

Figure 12. Characteristics of SD flux relative to SC Iridium in 2003.

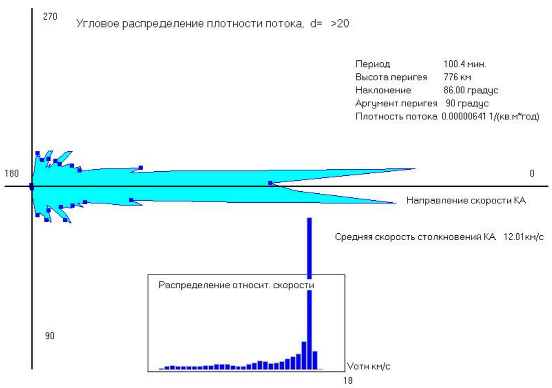

Figure 13. Characteristics of SD flux relative to SC Iridium in 2007.

CONCLUSION

The updating of parameters of the Space Debris Prediction and Analysis Model (SDPA) is performed on the basis of matching the results of environment forecasting in the time interval from 1960 through 2009 with the data of real catalogue of space objects.

After correction of the parameters of SDPA model, it is found that recent years the space pollution is substantially increased in the interval of altitudes of 600 - 900 km and the interval of inclinations of 95 - 100°. The values of the maximum of SD spatial density are increased 1.7 - 1.9 times in 2007 as compared to 2003. For 2009, the corresponding values of spatial density are increased 2.3 - 2.6 times.

Test calculations for estimating the effect of updating SD model parameters were performed in two stages. At the first stage, the SD flux relative to the given orbit was evaluated, and at the second stage the consequences of collisions were estimated. The cross-sectional area flux of SD of various sizes relative to ISS was found to be grown 4.0 – 4.5 times in 2009 as compared to the 2003 data. It was found also, that the penetration probability of walls with using the SD model of 2009 increased 3.5 – 5.4 times as compared to using the similar model of 2003.

Thus, as a result of the Chinese Fegun-1C satellite destruction in January, 2007, the level of SD pollution increased very substantial. Such an isochronous increase of SD quantity is unprecedented, in fact.

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