Space Debris Modeling in the GEO Vicinity

Andrey I. Nazarenko[(1)], Vasiliy S. Yurasov[(2)]

[(1)] *Space Observation Center, 84/32 Profsoyuznaya ul, Moscow 117810, Russia, E-mail:nazarenko@iki.rssi.ru*
[(2)] *Space Research Center "Kosmos". 10-59 Magadanskaya ul, Moscow 129345, Russia, E-mail: vyurasov@chat.ru*

ABSTRACT

The following basic issues are presented in the paper:
- the features of evolution of orbits in the GEO region;
- the description of the simulation technique;
- the density estimation for space debris of different sizes;
- the estimation of space debris cross-sectional area flux with respect to some spacecraft in the GEO region;
- the comparison of stochastic simulation results with the appropriate data determined on the basis of the deterministic approach;

1. INTRODUCTION

Our technique for modeling the man-caused contamination of GEO was delivered in the report presented at the 13th IADC Meeting [1]. For past five years many works were executed on perfecting the models [2, 3, 4, 5, 6, 7, 10] and on studying the features of orbit evolution in the GEO region [12, 13, 14, 15, 16, 17]. Our model (the SDPA_GEO) was improved as well. It was applied for studying various aspects of Russian spacecraft (SC) safety in the GEO vicinity. Below are presented: a) the brief description of the SDPA_GEO model; b) the features of evolution and spatial distribution of space objects (SO); c) some results of model application for studying the spacecraft safety.

The modeling of fragmentation situation in the vicinity of geostationary orbits was carried out on the basis of the statistical approach, which was developed and applied earlier for studies in the altitude range up to 2000 km [8, 9]. This approach differs from conventional one, since it refuses from "piece-by-piece" examination of space debris. Numerous investigations, carried out on the statistical approach basis, have demonstrated its efficiency for solving a rather wide scope of applied problems [10].

2. BASIC PRINCIPLES OF MODELING

1. The objects sizing larger than 1 mm are considered.
2. The data on the altitude-latitude distribution of catalogued SO spatial density, as well as the statistical distributions of SO velocity magnitude and direction are constructed on the basis of analysis of catalogued orbital elements of SOs.
3. All small-sized space debris particles are supposed to be generated as a result of spacecraft explosions on circular geostationary orbits having altitude of 35786 km.
4. The dependence of a number of generated particles on their size is assumed to be the same as in the SDPA model for low-Earth orbits (LEO). In particular, we use the $k(d)$ ratio of a number of particles sizing larger than d to the number of catalogued SOs, which is assumed to be known.
5. The dependence of a maximum velocity of particles' dispersion at explosion on their mass m is used according to the materials of some published papers [4, 11]. The dispersion velocities at explosion of particles are supposed to be random. All possible directions of dispersion are assumed to be equiprobable.
6. The relation between the size of particles and their mass is taken according to the data of Table 1.

Table 1

Mean mass of SOs of different size d_j, d_{j+1}, cm

# of size range	d_j, d_{j+1}, cm	m, kg
1	0.1-0.25	.86E-5
2	0.25-0.5	58E-4
3	0.5-1.0	28E-3
4	1.0-2.5	18E-2
5	2.2-5.0	0.01
6	5.0-10	0.064
7	10-25	0.40
8	25-75	5.0
9	>75	1750

7. The number of objects N (d_9) sizing larger than d_9 in the GEO vicinity is assumed to be equal to 1000.

Naturally, the listed assumptions are not free from a certain voluntarism. This is an objective consequence of the experimental data deficiency. Nevertheless, the use of some rules, which made it possible to reach well modeling accuracy for LEO, allows us to consider these assumptions as quite workable.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

3. STATISTICAL CHARACTERISTICS OF CATALOGUED SOs

The real SO catalog data are used for calculating the statistical characteristics of catalogued SO distribution [12-16]. In so doing the peculiarities of a current distribution of SO population in the geostationary region and the dynamics of evolution of the space-time distribution of SOs are taken into account. Let us consider these peculiarities in more detail.

1. The rates of growth of a relative number of SOs on GEO are much higher, than on LEO. Approximately 60 % space objects launched into geostationary orbits are active. At present, more than 900 catalogued space objects are on geostationary orbits, about 300 of which are active [16]. Because of large distance, only large-sized SOs, having dimensions more than 0.5-1.0 m, can be tracked. The smaller objects remain non-catalogued.

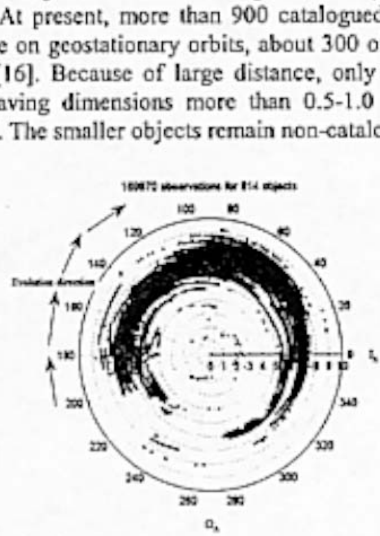

Fig. 1. Evolution of the inclination and ascending node longitude with respect to the Laplace plane for real SOs.

2. The majority of geostationary objects are launched into orbits with inclinations close to zero. However, during natural evolution their orbital planes deviate from the equatorial plane and vary in the range from 0 up to 15° (with the 54-year period). These regularities of geostationary SO evolution should be taken into account in long-term forecasting the statistical characteristics of the distribution of geostationary objects. The correct calculation of non-linear variations of orbit inclination and ascending node longitude with respect to the equatorial plane for geostationary SO is possible only by using semi-analytical or numerical theories of satellite motion. This is due to unacceptable large volume of calculations. By this reason it was proposed to use the Laplace plane for studying the long-term evolution of geostationary SO orbits [16]. With respect to this plane the inclination of geostationary orbits varies with 0.6°. amplitude and 28-year period, and the coefficients of secular variations of the ascending node longitude and perigee argument become almost constant (Figure 1) [16]. This enables us to construct a rather accurate and simple linear theory of geostationary SO motion [17].

3. A considerable part of active spacecraft regularly correct their orbits with the purpose of keeping the orbital plane close to the equatorial plane. Figure 2 presents the instant "picture" of a current distribution of geostationary objects in longitude and latitude for the date of February 3, 2001. The objects with nonzero inclinations in this figure represent, as a rule, the population of space objects launched previously. Ever more dense distribution of space objects in this region of space should be expected with time.

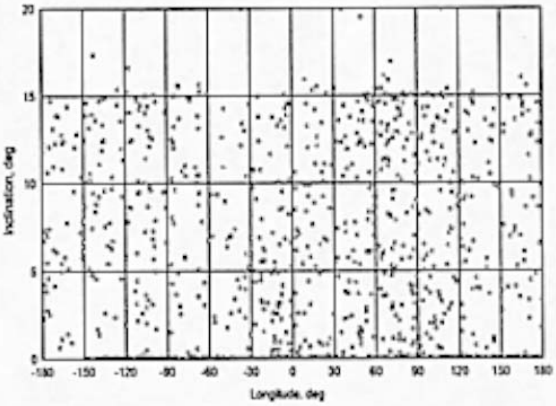

Fig. 2. Distribution of geostationary space objects in geographical longitude and inclination

4. One more peculiarity, characteristic for GEO, is the fact, that the majority of operative spacecraft are transferred to higher-altitude orbits after termination of their lifetime and become passive.

On the basis of the catalog data, the spatial distribution of SO spatial density was constructed. At the first stage, the large grid of space partition to "boxes" was applied: 100 km in altitude and 1° in latitude. The altitude-latitude dependence of spatial density was found to be quite irregular. The maximum of spatial density is reached in the altitude range of 35700–35800 km over the latitude interval of 0°–1° (and is very "acute"). At 400-500 km deviation from this range in altitude and at 12°-13° in latitude the spatial density decreases 3 orders of magnitude.

Therefore, it is expedient to consider the region of spatial density maximum in more detail, with a smaller step in altitude and latitude. Corresponding results are presented in Figure 3. The steps were taken here as follows: 10 km in altitude and 0.05° in latitude. These data show that in the considered relative narrow region the spatial density peak is "rather acute" as well: in its vicinity the value of spatial density changes 2-3 orders of magnitude. Thus, the characteristic feature of catalogued SO distribution in GEO is the presence of a prominent spatial density maximum in the equatorial region at the altitude of 35786 km. At 400-500 km deviation from this region the spatial density decreases 4-5 orders of magnitude or greater.

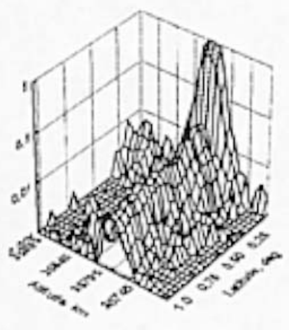

Fig. 3. The SO spatial density in the equatorial region (up to 1°) in the altitude range of 35700--35900 km

The regularity described above reveals itself in the fact, that the spatial density estimates at the point of maximum occur to be strongly dependent on the value of a step of GEO region partition into "boxes". This situation is illustrated by the data of Table 2.

Table 2

Estimates of catalogued SO's spatial density for various intervals of averaging in altitude and latitude

Δh, km	100	100	100	100	25	10	10
Δb, deg	1.0	0.5	0.25	0.1	0.25	0.10	0.05
$\rho, 10^{-9}$ km^{-3}	4.1	7.4	14	31	46	110	260

It is seen that the spatial density estimates can change almost two orders of magnitude depending on the averaging interval.

The statistical characteristics of catalogued objects' velocity have also been constructed by using the catalog data. The analysis of constructed statistical distributions of velocity values has shown the latter ones to be essentially dependent on the altitude. In the altitude range of 35780±50 km the range of possible values of velocity is rather narrow: for the mean velocity value of 3.074 the deviations from it do not exceed 0.005 km/s. But the character of velocity distributions in other altitude ranges is different. They are slightly displaced to the right or to the left side from the mean estimate of 3.074 km /s and are more "diffused".

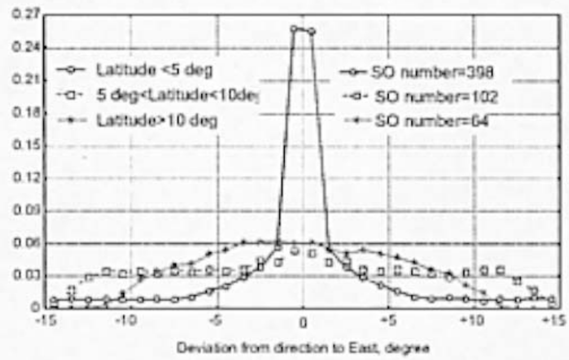

Fig. 4. Distribution of velocity directions for geostationary SOs

Figure 4 presents three distributions of SO velocity directions related to three latitude ranges: lower than 5°, from 5° to 10° and higher than 10°. The argument of distributions is the SO velocity vector deviation from the direction to East. It is seen from this figure, that in the latitude range of ±5° the distribution of possible velocity directions is rather "acute". In the overwhelming majority of cases the SO velocity vector does not deviate from the eastward direction more than by ±2.5°.

The distributions of velocity directions in the other latitude ranges have different character. With keeping the mean direction (to East) they are more "diffused". Here, for the latitude range of 5°-10° the scattering of possible directions (±15°) occurred to be slightly greater, than for latitudes exceeding 10°.

4. CHARACTERISTICS OF FRAGMENTAION CONDITIONS IN THE GEO REGION

The application of the principles formulated in Section 2 allowed us to construct the statistical distributions of orbital parameters for SOs of different sizes. Figure 5 presents the distribution of perigee and apogee altitudes of objects. The estimates of particles size (d_j) correspond to the data of Table 1.

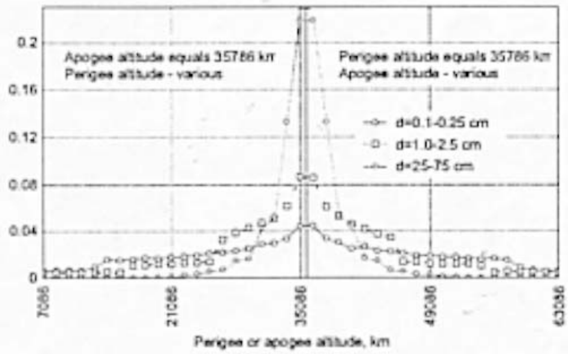

Fig. 5. The distribution of SO altitudes after fragmentation

The altitude-latitude distribution of spatial density for SOs sizing 0.1-0.25 cm in the altitude range of 35300-36200 km is shown in Figure 6.

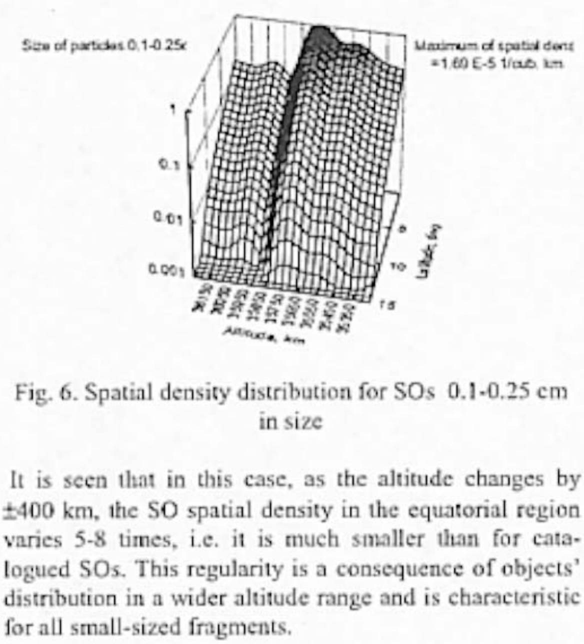

Fig. 6. Spatial density distribution for SOs 0.1-0.25 cm in size

It is seen that in this case, as the altitude changes by ±400 km, the SO spatial density in the equatorial region varies 5-8 times, i.e. it is much smaller than for catalogued SOs. This regularity is a consequence of objects' distribution in a wider altitude range and is characteristic for all small-sized fragments.

The maximum spatial density values for SOs of different sizes are presented in Table 3.

Table 3

Maximum spatial density values (km^{-3}) for SOs of different sizes

Number of size range							
1	2	3	4	5	6	7	8
1.69 E-5	1.50 E-6	2.44 E-7	4.15 E-8	1.01 E-8	4.00 E-9	1.96 E-9	1.36 E-9

The application of presented spatial density estimates allows us to turn to evaluation of the danger of spacecraft collisions with particles of different sizes. The distributions of the value of tangential velocity component for SOs of different sizes were constructed with the help of our model. One of the results (for SOs sizing 0.1-0.25 cm) is presented in Figure 7.

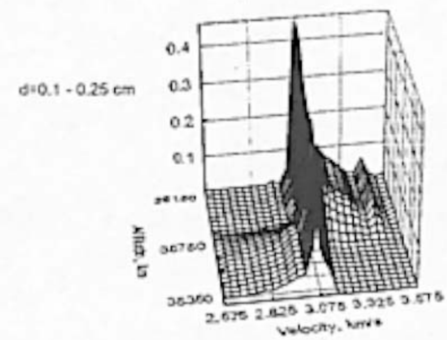

Fig. 7. Distribution of the tangential velocity component for SOs 0.1-0.25 cm in size

The distributions of velocity directions are assumed to be the same for all sizes, namely, such as shown in Figure 4.

5. ESTIMATION OF SPACE DEBRIS CROSS-SECTIONAL AREA FLUX WITH RESPECT TO SPACECRAFT IN THE GEO REGION

The solution of this problem requires specifying four orbital elements of SC: altitudes of perigee and apogee, orbit inclination and perigee argument. The technique includes the forecasting of SC motion on the interval of one revolution. The space debris' spatial density values are determined at various points of the trajectory. In addition, separate implementations of the vector difference of SC and space debris velocities (i.e. separate implementations of the relative velocity vector) are constructed. The product of relative velocity by spatial density characterizes the value of a cross-sectional area flux. The averaging of these estimates over all possible directions of the relative velocity and over various points of the trajectory provides the estimates of mean values of the cross-sectional area flux and of the mean velocity of collisions. Examples of such estimates for two types of SC orbits are given in Table 4. The first orbit is circular with the altitude of 35786 km and inclination of 0.2°. The altitudes of perigee and apogee for the second orbit are equal to 35636 and 35936 km, respectively. The inclination is 8° and the perigee argument equals 180°.

Table 4
Values of a cross-sectional area flux (Q) and relative velocity (V) of space debris

# of size range		1	4	8	9
Orbit	Q, m^{-2} $year^{-1}$	1.38E-4	2.23E-7	0.59E-8	156E-8
# 1	V, km/s	0.71	0.47	0.40	0.41
Orbit	Q, m^{-2} $year^{-1}$	0.39E-4	0.80E-7	0.24E-8	0.48E-8
# 2	V, km/s	0.76	0.59	0.51	0.52

It is seen from this data, that the cross-sectional area flux varies more than 4 orders of magnitude depending on the SO size. In this case the mean velocity of collisions changes 1.5-1.7 times. The change of orbital elements has especially strongly influenced the estimate of a cross-sectional area flux for catalogued SOs (the 9-th range of sizes): for a circular orbit with small inclination the estimates occurred to be 325 times greater, than for the orbit # 2.

Figures 8 and 9 present various characteristics of the relative velocity. The first of them shows the azimuth dependencies. The angle (Az) is measured in the horizontal plane clockwise from the velocity vector of SC. Obviously, in the given case the directions of possible SC collisions with SOs of different sizes strongly differ. For small-sized SOs the "frontal" collisions (Az=0°) predominate, whereas for large-sized catalogued objects the side collisions (Az=270°) are most probable. The other essential difference relates to the value of velocity of possible frontal collisions. For small-sized SOs it reaches 1 km per second, whereas for large-sized SOs it is negligible (and, in addition, low probable).

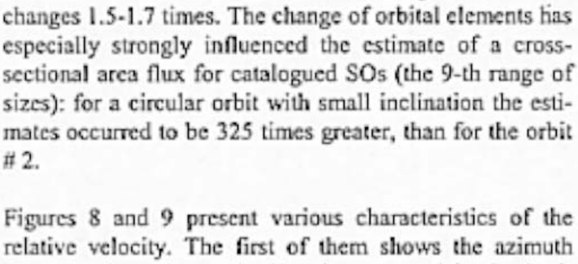

Fig. 8. Azimuth dependencies of the relative velocity characteristics for orbit #1

The data of Figure 9 allow us to estimate the influence of inclinations (for fixed altitudes) and SO size on the value of possible velocity of collisions. The characteristic feature of distributions related to small-sized SOs is the presence of a maximum near the velocity value of 1.3 km/s.

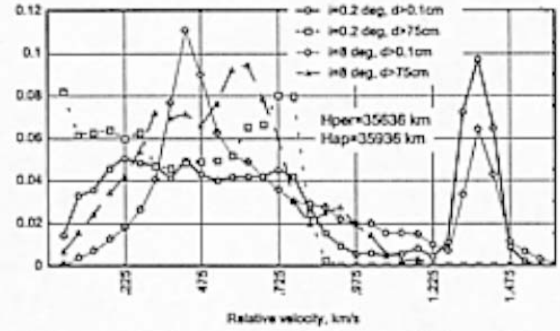

Fig. 9. Distributions of the velocity of collision of SC on different orbits with space debris of different sizes

The influence of inclinations is exhibited here in the fact, that in transition from SC with inclination of 0.2° to SC with orbit inclination of 8° the fraction of collisions at velocities of 0.5-0.7 km/s increases, which results in some increasing the mean relative velocity of collisions (see. Table 4).

The above results lead to the conclusion, that both the value of a cross-sectional area flux of space debris of the given size and the characteristics of the velocity of possible SC collisions with space debris particles strongly depend on the parameters of orbits of SC under consideration. Under these conditions it is expedient to evaluate the characteristics of possible collisions of various SC with space debris with using the model considered here.

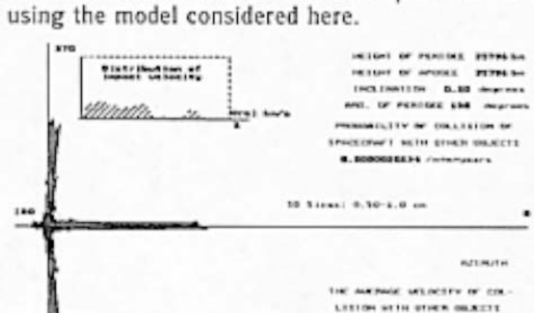

Fig. 10. Example of results output

At present, within the framework of the SDPA model a specialized module is developed for calculating the statistical characteristics of collisions of SC in the GEO region with SO of different sizes. This module is implemented on a conventional personal computer and provides a possibility of rapid and simple evaluations of various characteristics of possible collisions of SC in the GEO region with space debris of different sizes. Figure 10 reproduces the corresponding example taken off from monitor's screen.

6. CONCLUSIONS

1. The technique and the appropriate computer program are developed for determination of characteristics of possible collisions of SC in the GEO vicinity with space debris of different sizes.
2. The in-depth study of features of the distribution of SO population in the geostationary region and of the dynamics of variation of space-time distribution of SOs is carried out.
3. The statistical characteristics of spatial density and velocity for Sos of different sizes are constructed. Various characteristics of possible collisions of SC with space debris in the GEO region are investigated.
4. The developed computer programs are recommended for application in studying the changes of orbital elements and characteristics of possible collisions of SC with space debris in the GEO region.

7. REFERENCES

1. A.I. Nazarenko. Space Debris Modeling in the GEO Vicinity. *13th IADC Meeting, Darmstadt*, February-March 1996.

2. V.A. Chobotov. Orbital Debris Hazards Assessment and Mitigation Strategies. *Space Debris. Hazards Evaluation and Mitigation.* Chapter 1. Gordon&Breach Publishing, 2001.

3. T. Yasaka. Geostationary Orbit Pollution and its Long-Term Evolution. *Space Debris. Hazards Evaluation and Mitigation.* Chapter 5. Gordon&Breach Publishing, 2001.

4. Meteoroid and Space Debris Terrestrial Environment Reference Model, MASTER'99, ESA CD-CD03 Release 1.0, May 2000.

5. W. Flury. Space Debris Issues in the Geostationary Orbit and Geostationary Transfer Orbits, *IADC Report. UNCOPUOS*, Vienna February 2000.

6. P. Anz-Meador, P. Krisko, M. Matney. GEO_EVOLVE 1.0: A Long-Term Debris Evolution Model for the Geostationary Belt. *Orbital Debris Quarterly News, NASA*, Volume 5, Issue 4, October 2000.

7. L. Anselmo & C. Pardiny. Modeling of Space Debris in GEO. *CNUCE, 2000.*

8. G.M. Tshernjavsky, A.I. Nazarenko. Simulation of the Near-Earth Space Contamination. *Collision in the Surrounding Space (Space Debris).* Moscow, Cosmoinform, 1995, pp. 104-129.

9. A. Nazarenko. The Development of the Statistical Theory of a Satellite Ensemble Motion and its Application to Space Debris Modeling. *Second European Conference on Space Debris*, ESOC, Darmstadt, Germany 17-19 March 1997.

10. A.I. Nazarenko. The Solution of the Applied Problems Using the Space Debris Prediction and Analysis Model. *Space Debris. Hazards Evaluation and Mitigation.* Chapter 4. Gordon&Breach Publishing, 2001.

11. R. Jehn, Dispersion of Debris Clouds from In-orbit Fragmentation Events, *Esa Journal*, Vol 15, No 1, 1991.

12. Amelina, T.A., Batyr, G.S., Dicky, V.I., Yurasov, V.S. "Cataloging of Space objects in Geostationary Space Orbits," *Proceedings of the Conference on Programs of Observations of High Orbital Artificial Satellites and Bodies of the Solar System, ITA of RAN*, St. Petersburg, 1994, p 16.

13. Amelina, T.A., Batyr, G.S., Gorjanskij, S.V., Dikij, V.I., Yurasov, V.S. "Tracking of Geostationary Space Objects Based on Information of Optical Sensors," *Collisions in the Surrounding Space (Space Debris)*, Moscow, Cosmoinform, 1995, pp 288-306.

14. Cefola P., Yurasov V. "Optical Measurements Processing Technology on Geostationary Satellite," *Proceedings of the Third U.S.-Russian Space Surveillance Workshop*, Washington, DC, 1998, pp 311-338.

15. Yurasov, V.S. Moscovsky, A.A. "Geostationary Orbit Determination and Prediction," *Proceedings of the Third U.S.-Russian Second Space Surveillance Workshop*, Poznan, Poland, 1996, pp 132-149.

16. Yurasov, V.S. Shargorodskiy, V.D., Vygon, V.G. . Classification and Identification of Geostationary Space Objects by Using Coordinate and Photometric Observations. *Fourth US/Russian Space Surveillance Workshop*, US Naval Observatory, Washington, DC, October 2000.

17. Kiladze R.I., Sochilina A.S. On orbital evolution of geostationary satellites. *U.S.-Russian Second Space Surveillance Workshop 4-6 July 1996*, Poznan, Poland, 150-155, 1996.