IMPROVEMENT OF SPACE DEBRIS MODEL IN MEO AND GEO REGIONS ACCORDING TO THE CATALOG OF KELDYSH INSTITUTE OF APPLIED MATHEMATICS (RUSSIAN ACADEMY OF SCIENCES)

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ABSTRACT

The MEO and GEO regions represent a great interest for the utilization of space observation, communication and navigation systems as well as scientific researches. The quantity of the catalogued space objects in these regions has increased significantly, therefore space debris model for these regions needs to be improved.

The Russian space debris model «Space Debris Prediction and Analysis» (SDPA) has been developed and specified for a long time. Modelling is carried out on the basis of the developed unified statistical approach. The last researches of space debris population have allowed to improve and develop the SDPA model for the MEO and GEO regions using catalog data of the Keldysh Institute of Applied Mathematics of Russian Academy of Sciences.

On February 28, 2005 the Center for collecting, processing and analysis of scientific information on objects of anthropogenic origin of the FANO/Russian Academy of Sciences (TsSITO) was created in Keldysh Institute of Applied Mathematics for the purpose of ensuring activities on collecting, storage, processing and the analysis of scientific information on space debris in pursuance of the Order of Presidium of the Russian Academy of Sciences No. 10310-142 of February 28, 2001. Now the TsSITO catalog contains the most complete available information on the catalogued objects in GEO and MEO regions. As of September 2016 the catalog contained information on 2094 objects on GEO, 2635 objects on HEO and 338 objects on MEO.

This work provides the analysis of the characteristics of catalogued space objects, modeling principles, plans to verify model with data of dedicated statistical observations of small space debris fragments in GEO with data of dedicated statistical observations of small space debris fragments in GEO with large optical telescope, basic provisions and characteristics of improved space debris model, the results of collisions assessment.

1. CATALOG TSSITO KIAM RAS

Researches of satellites on Earth orbits are conducted in the Russian Academy of Sciences (RAS) from the moment of start the first satellite. They were directed mainly on measurements of large objects in high orbits for the purpose of specification movement model parameters, studying of uncontrollable movement dynamics of nonfunctioning upper stages and spacecraft (S/C), working off methods of astrometry and photometry, etc. Systematic researches on a problem of monitoring of near Earth Space (NES) in RAS it was not conducted, the received measurements of space objects (SO) did not collect organizations of RAS and were not analyzed in their set.

The condition of researches cardinally changed after the Presidium of RAS charged to KIAM RAS with a problem of monitoring of NES. The Russian Academy of Sciences Center for collecting, processing and the analysis of scientific information on SO (TsSITO) was organized.

Primary measuring information getting to TsSITO is exposed to processing during which tracklet - series of consecutive measurements of one object, are exempted from astrometric data. For each tracklet initial definition of an orbit is carried out, and its result together with the cleared astrometric and photometric measurements is used identifications of object of tracklet among objects of the catalog. Directly after successful identification specification of an orbit of object with use of the new measurements and data obtained earlier is made. Thus, with each receipt of measuring information dynamic updating of the catalog is carried out. The identifications given, not taken place a stage, remain for the subsequent solution of a problem of detection new objects. During detection an attempt to reveal not attached tracklet belonging to one and that object for creation of an orbit of sufficient accuracy for purposeful supervision by measuring means is made.

In 2016 TsSITO RAS received measuring information from 76 telescopes of 38 observatories in 15 countries of various departmental accessory (academies of Sciences, universities, Roscosmos, business firms, and also being in a private property) from which 6 main subsystems were created:

1) global, for the review of GEO (to 15,5 magnitude);

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Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

2) for expanded reviews of GEO (to 14 magnitude);

3) for maintenance weak (is weaker 15,5 magnitude) SD on GEO and geotransfer orbits;

4) for maintenance of bright objects on GEO and MEO;

5) for deep partial reviews of GEO (to 18 magnitude);

6) for measurments on targeting's of objects in low orbits and high-elliptic in perigee area.

The global subsystem is created - 15 telescopes with a field of view 3,5 – 4 degrees (8 on 22 cm, 4 on 25 cm, 1 on 20 cm, 1 on 30 cm and 1 on 50 cm). The subsystem for expanded reviews of GEO consists of 12 telescopes with a field of view of 7 degrees and more (1 telescope of 18 cm, 5 single 19.2 cm, 4 of two pipes, 2 of four pipes). The subsystem of maintenance of weak fragments turns on 21 telescopes an aperture from 40 to 80 cm. The subsystem of maintenance of bright objects consists of 15 telescopes an aperture of 25 cm. A subsystem for deep partial reviews from 6 telescopes (3 on 50 cm with a field 2,5 degrees and 3 telescopes on 65 cm with a field 2,2 degrees). The maintenance subsystem SO low-orbital area turns on 7 telescopes (4 on 12,5 cm, 2 on 25 cm and 1 on 50 cm). In addition one 18-cm telescope carries out reviews of high-elliptic objects in orbits like "Molnya" and two large telescopes (in Mondy and Terskol) make incidental observations small-sized SO in high orbits) [1].

2. GENERAL PROVISIONS OF SDPA MODEL

In the previous years a number of works on research of SD in MEO and GEO regions was executed. In SDPA modeling is carried out on the basis of statistical approach which was developed and applied to research SD in LEO region earlier. This approach differs from traditional in refusal of "piece" consideration of SD particles and consecutive application of the developed statistical theory of modeling of SD. The numerous researches conducted on the basis of application of statistical approach showed its efficiency for the solution of rather wide range of applied tasks [2, 3].

Basic principles of modeling.

1. Objects lager than 1 mm in size are considered.

2. Altitude-latitude distribution of spatial density catalogued SO, and statistical distributions of value and direction of their velocity are under construction on basis SO catalog.

3. The assumption that all small particles of space debris which are and crossing MEO and GEO regions, were generated as a result of explosions and destructions is used.

4. Dependence number generated particles on their sizes pays off with use of relation k(>*d*) number of particles the size lager *d* to number catalogued SO.

5. Maximum ΔV of particles at explosion depends from their mass, have a random values and equiprobable possible directions.

6. The ratio between sizes of particles and their mass is accepted fixed, according to data of table 1.

Table 1 - Average mass SD different sizes

j	1	2	3	4	5	6	7	8	9
d_j, cm	0.1	0.25	0.5	1.0	2.5	5.0	10	25	75
$k(>d_j)$	4 10^4	3.5 10^3	5.5 10^2	88	20	7.2	3.2	2.0	1.0
m, kg ($d_{j,j+1}$)	8.6 10^{-6}	5,8 10^{-5}	2.8 10^{-4}	1.8 10^{-3}	0.0 1	0.0 64	0.40	5.0	1750

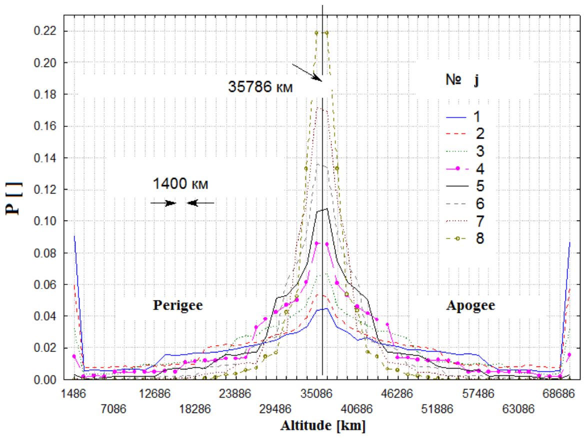


Figure 1 – Distributions of perigee and apogee altitudes SO different sizes after explosion on GEO

3. IMPROVEMENT SDPA MODEL IN GEO REGION

For the beginning of February, 2017 the catalog TsSITO contains data about 2190 SO. The major of them (2153) have inclinations less than 20^0. Data on these objects are given in figure 2. Blue points designated SO, having international numbers (further in the text - known), their number is equal 1302. Red points designated objects without international number (further in the text unknown). They managed to be found when maintaining the KIAM RAS catalog. Number of these objects equally 888.

Characteristic of unknown SO is significantly the bigger dispersion of their period in comparison with known. Other feature is that they are grouped in the vicinity of two values of an inclination: ~13^0 and ~6^0. This circumstance allows assuming that it is fragments of destruction two S/C in GEO region.

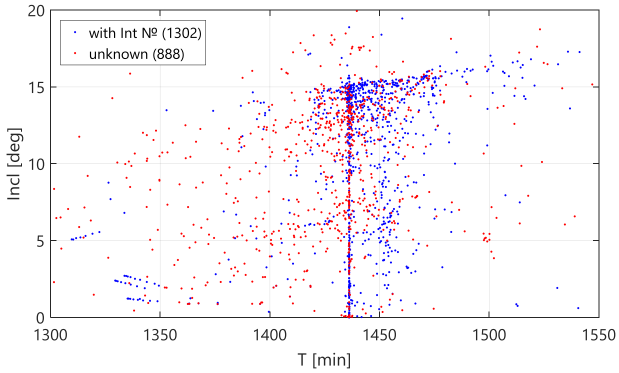
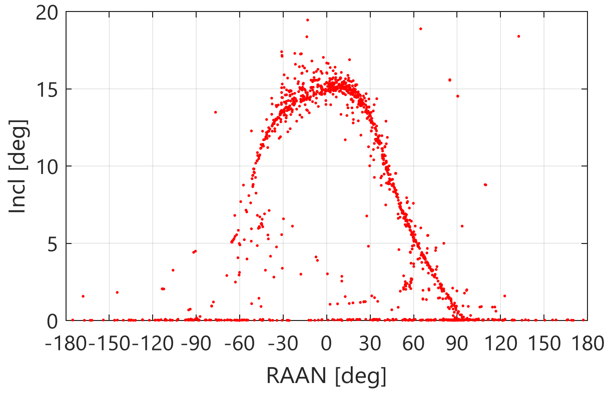
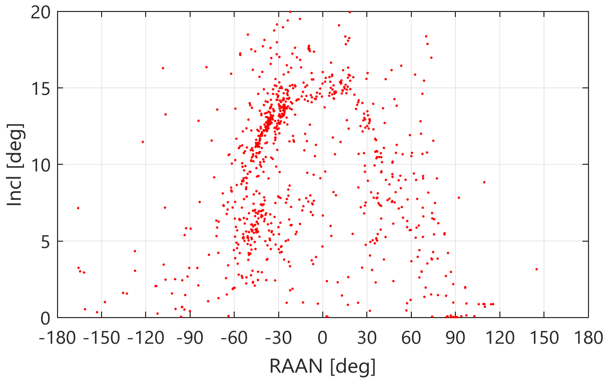


Figure 2 - Inclination(period) for known and unknown SO

Let's consider dependences of an inclination (i) on ($RAAN$), histograms of average magnitude and the relation of area to mass for two groups of the studied objects.



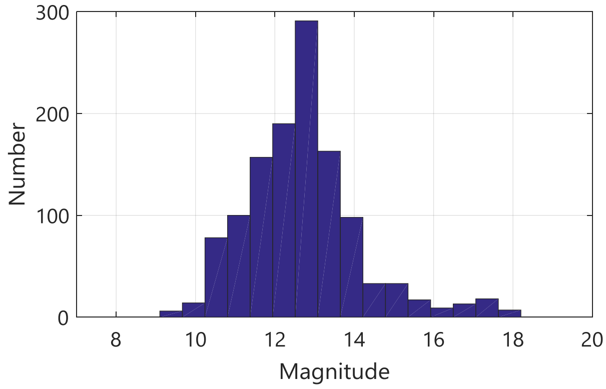
a) known



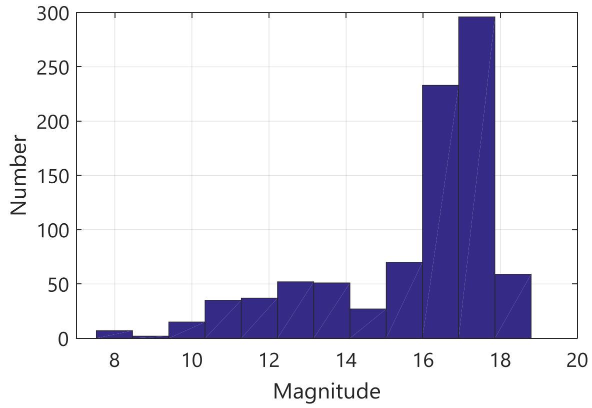
b) unknown

Figure 3 – Inclination(RAAN)

Dependence i *(RAAN)* for unknown objects has significantly big deviations rather characteristic for objects in GEO which is accurately expressed for known objects. The most part of these objects, most likely, is fragments of destructions as a result of which they received some increment of velocity which changed parameters of their orbits.



a) known



b) unknown

Figure 4 –Histograms of average magnitude

Comparison histograms of average magnitude shows that known objects generally have values in the range of 10-14, and 75% of unknown objects in the range of 15-19. This fact says that these objects have significantly smaller areas of the reflecting surface and as a result the smaller sizes.

Comparison histograms of average relations area to mass is shown that known objects generally have values to 0.03 m^2/kg, and 80% of unknown objects more than 0.1 m^2/kg. This fact says that unknown objects will be more subject to evolution as a result of influence of sunlight.

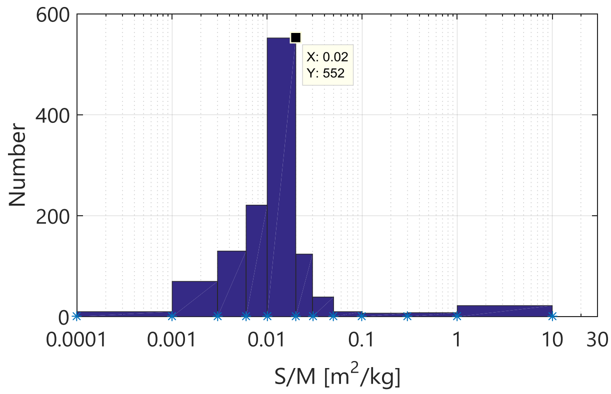
Estimates of S/m and magnitude allow to estimate the size and mass of fragments approximately. For calculation magnitude (m) of spherical SO with diameter d, and albedo ρ at range of R at zero phase angle formula is used

$$m = -26.73 - 2.5 \cdot \log\left(\rho \cdot d^2 / R^2\right) \qquad (1)$$

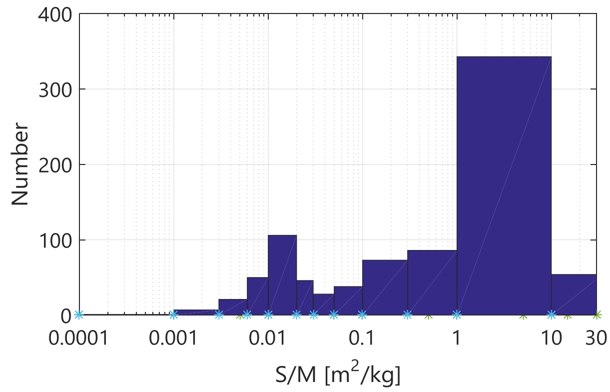
where ρ = 0.09-0.12 for SD and ρ = 0.2 for S/C and upper stages.

At known magnitude of objects it allows to calculate diameter of object and its visible area

$$S = \pi d^2 / 4 \qquad (2)$$



a) known



b) unknown

Figure 5 – Histogram of average S/m

The knowledge of the area and S/m provides possibility of determination mass of object

$$M = S/(\mathrm{S/m}) \quad (3)$$

Let's consider estimates of objects number depending on their sizes. They are constructed on the basis of estimates of magnitude and a formula (1) according to the catalog. Results are presented in figure 6. At interpretation of these data it must be kept in mind that for part of objects in catalog magnitude were absent.

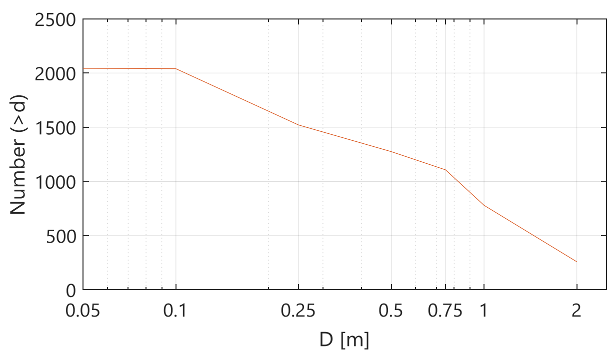


Figure 6 - Dependence of number SO from their sizes

In SDPA model for GEO region dependence number of generated particles on their sizes is accepted same as it is made in the SDPA model for low orbits. In particular, k (>d) is used. These data are provided in Table 2.

Table 2 - Values of coefficient k (>d) for GEO region

d, cm	0.1	0.25	0.5	1.0	2.5	5.0	10	25	75
k(>d)	40000	3500	555	88	20	7.2	3.2	2.0	1.0

Comparison of figure 6 data and table 3 is presented in figure 7.

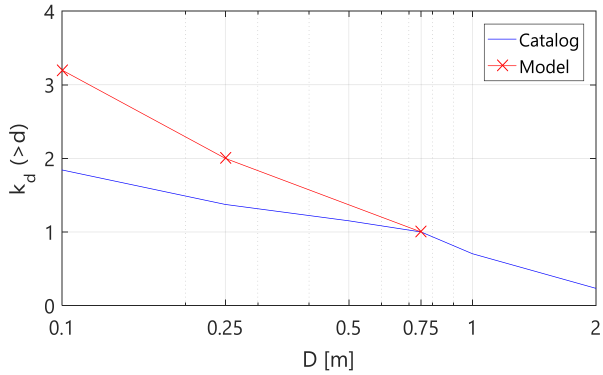


Figure 7 – k(>d) for catalog and model

The data shows the following:

- extrapolation of the model dependence given for objects smaller than 0.75 m in size to area of big sizes rather well will be coordinated with data of the catalog for objects lager than 0.75 m in size;
- for objects less than 0.75 m in size of number objects according to the catalog there are less than relevant model data. Distinction grows in process of reduction of the extent of objects. Such behavior of estimates number of objects according to the catalog is expected as not all objects less than 0.75 m in size may be catalogued. It is natural that in process of reduction of fragments sizes the share of the catalogued objects decreases.

Follows from materials of figures 6 and 7 that when modeling number of fragments in the GEO region it is expedient to use estimates of coefficient *k (>d)* given in the table 2 for objects lager than 0.1 m in size.

Let's estimate number of objects more than 0.1 m in size in GEO region which did not cataloged. The expected number of objects of this size equally

$$N(d>0.1) = k(d>0.1)\cdot N(d>0.75) = 3.2\cdot 1218 \approx 3897 \quad (4)$$

For definition the quantity of fragments of SD in the range of the sizes is used a formula

$$N_\Sigma(d_k) = [k(d_k) - k(d_{k+1})]\cdot N(d_9 > 0.75) \quad (5)$$

The SD number is equal in the catalog for the beginning of February - 2190. Thus, the approximate assessment of number of not catalogued objects lager than 0.1 m in size is ~1707 that makes ≈ 43% of an assessment of total number of objects.

For creation of spatial density distribution of SD 10-75 cm on the basis of statistical distributions of $p(h_p)$, $p(i)$, $p(e)$ elements of orbits (altitude of a perigee, an inclination and eccentricity), the modernized technique is applied, is in detail stated in a number of publications [2, 3].

In figure 8 the rated spatial density of SD 10 - 75 cm in size constructed with use of the SDPA technique is presented.

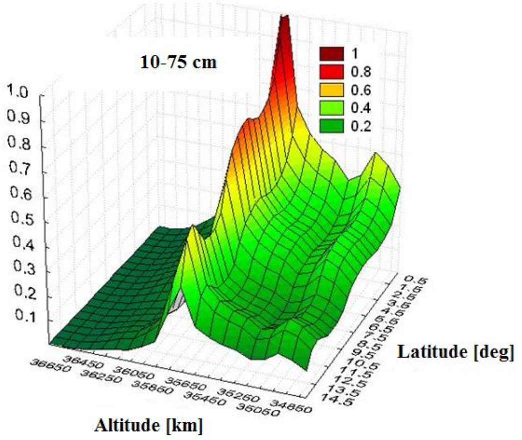


Figure 8 – Rated altitude-latitude distribution of spatial-density of SD 10 - 75 cm

Altitude-latitude distribution independence of fragments sizes. Therefore this distribution can be presented in the following form:

$$\rho(h,\varphi,d_k) = \rho_{\max}(d_k)\cdot \bar{\rho}(h,\varphi) \qquad (6)$$

Estimates of spatial density maximum and numbers of objects different size are presented in table 3.

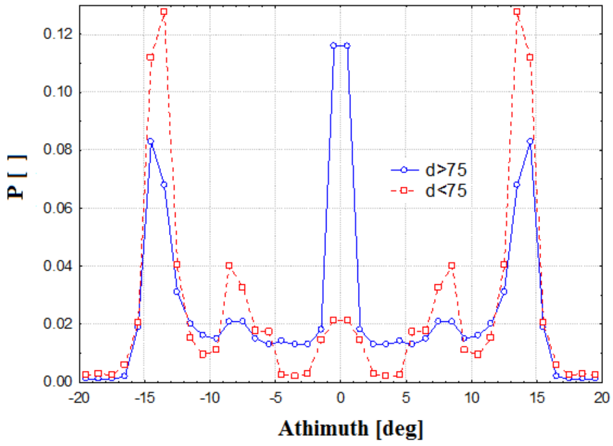
Table 3 - Estimates of spatial density maximum and number of objects

k	5	6	7	8
d_k, d_{k+1}, cm	2.5 - 5.0	5.0 - 10	10 - 25	25 - 75
$\rho_{\max}(d_k)$ 1/km^3	2.593 10^{-9}	8.506 10^{-10}	2.551 10^{-10}	2.126 10^{-10}
$N_\Sigma(d_k, d_{k+1})$	15900	4872	1461	1218

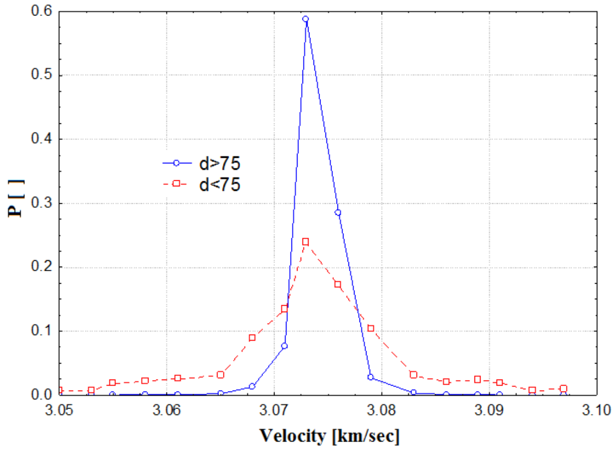
The number assessment given here SD the size from 25 to 75 cm by ~1,5 times exceeds number of unknown objects in catalog. According to modeling objects of the small sizes are more evenly distributed in the considered altitude-latitude “region”.

These tables 3 did not include objects smaller than 2.5 cm in size. It is connected with absence at authors of any experimental data about such objects in GEO region for correction of model.

With use of the techniques stated in [2,3] distributions of velocity values and directions concerning the direction on East for two groups of objects are developed. They are presented in figure 9.



a) directions



b) values

Figure 9 - Distributions of velocity values and for objects in GEO region

Azimuthal distributions are characteristic existence of local maximum in the vicinity of values 0º, ±8º and ±15º. For objects lager than 75 cm in size the first maximum is global. For smaller objects global maximum are located in the vicinity of values of an azimuth ±15º. These circumstances are a consequence of features of considered sizes objects inclinations distribution.

Let's consider estimates of mutual collisions SO different sizes in the most polluted part of the GEO region (from 35700 to 35900 km and from-1º to +1º latitude). The estimates number of collisions in a year calculated by the technique [2,3] presented in table 4. As all estimates significantly less than 1, them it is possible to consider as analog of probability of mutual collision j range sizes SD with catalogued SO (j=5).

Table 4 - Probabilities of collisions with catalogued SO in a year

d, cm	2.5-5.0	5.0 - 10	10 - 25	25 - 75	>75
P	0.0002678	0.0000258	0.0000032	0.0000026	**0.00627**

From these results it is visible that the probability of mutual collisions of catalogued objects (lager than 75 cm in size) makes 0.00627 in a year. It means that the average interval between such collisions is equal ≈ 160 years, at current state of SD population in GEO region. Probabilities of the collisions catalogued SO with objects from 2.5 cm to 75 cm in size are 2-3 orders less.

4. IMPROVEMENT SDPA MODEL IN MEO REGION

The MEO region is limited to altitudes of ~2000 and ~35586 km. The greatest number of the catalogued objects in region is concentrated in the field of functioning of the global navigation satellite systems (GNSS) owing to what MEO region is the most polluted. Spatial density in this region considerably exceeds average spatial density in other part of MEO. In this regard the main attention is paid to specification of model in GNSS region.

Let's consider data of the catalog for GNSS region, 290 objects meet the case. In figure 10 dependence of altitude of perigee and apogee as an inclination in 2017 is presented.

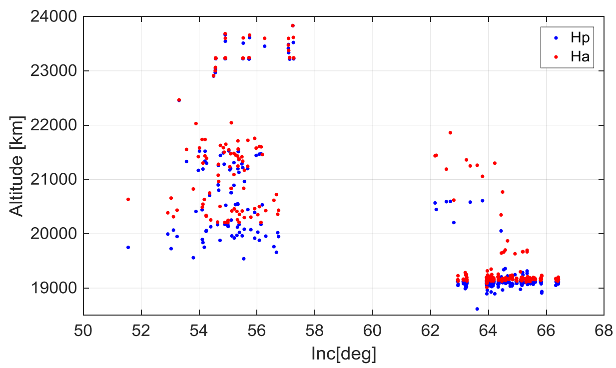


Figure 10 – Altitude of perigee and apogee as an inclination, 2017

In the near future SD will growth when it is completely developed GNSS Beidou groups at the altitudes ~ 21200 km and GALILEO ~ 23200 km is possible. It should be noted also that dispersion of SO on altitudes of GPS (NAVSTAR) system much more, than that for GLONASS system (COSMOS).

Figures 11 are characterized inclination of objects depending on RAAN.

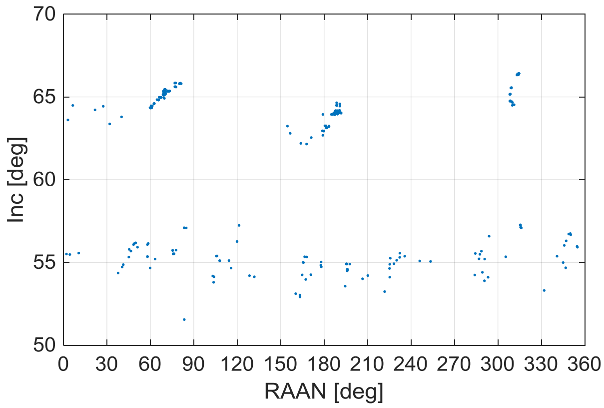


Figure 11 – Inclination (RAAN), 2017

Characteristic of these data is accurately expressed grouping of objects in the vicinity of certain values of RAAN (3 ranges for GLONASS and 6 ranges for NAVSTAR/GPS). This feature is explained by a special choice of satellites orbits in connection with their functional purpose as navigation. Influence of longitude on spatial distribution of objects is a consequence of the specified feature. In the future, owing to expansion of new GNSS, these dependences will be added by new objects.

Spatial density for GNSS region in 2017 is presented in figure 12. Apparently from this figure, in region of functioning GLONASS system essential values of spatial density are reached in the range of altitudes from 19000 to 19200 km. The maximum value is $1.526 \cdot 10^{-9}$ km^{-3} in ~19100 km and 65º. This value is more than order for altitudes of GPS functioning.

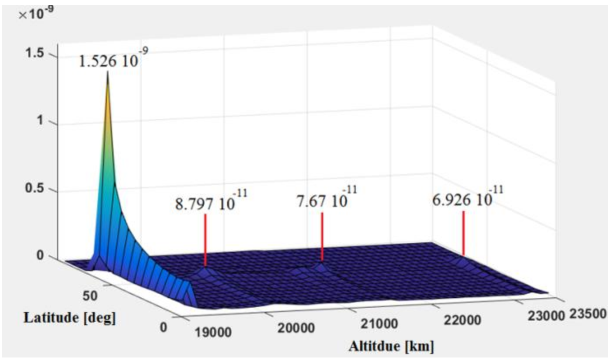


Figure 12 – Spatial density in GNSS region

In GPS system functioning region spatial density "is smeared" in the wide range of altitudes from 19500 to 22000 km.

For estimation spatial density of not catalogued SD (the size more than 1 cm), uses the technique, general for SDPA model, with use of coefficients of k (>d). Taking into account fact that in GNSS region not recorded any catastrophic destructions, the assumption is used that all fragments of the small sizes were generated as a result of separation from large objects without big increment of velocity. Therefore at them rated distribution of spatial density on altitude and latitude coincides with the corresponding distribution for catalogued objects. Estimates of coefficients of k(>d) are presented in table 5. For obtaining values of concentration in NES points at different altitudes and latitudes it is necessary to increase values of the maximum spatial density by suitably value of rated distribution.

Table 5 - Estimates of spatial density maximum and k(>d)

k	0,01	0,1	0,2	2,5
d_k, d_{k+1}, cm	128,0	7,75	3,66	1,00
$\rho_{\max}(d_k)$, 1/km^3	10,01 10^{-8}	6,06 10^{-9}	2,86 10^{-9}	1,526 10^{-9}

Thus, spatial density distribution for objects in the range of altitudes 19000-23500 km is constructed. This distribution is a basis of further development of model by inclusion of smaller SD fragments. The received spatial density estimates SO the size should be considered less than 2,5 m as preliminary.

In figures 13 and 13 distributions tangential and radial velocity of objects are presented. From data of figure 13 it is visible that on an interval of altitudes from 18600 km to 22000 km average value of tangential component of velocity monotonously decreases from value of 4.10 km/s to value of 3.67 km/s. Possible deviations of velocity from average value with probability of 99% do not exceed ±0.07 km/s. As for a radial component of the speed (figure 14), with probability of 99% it are in range of values of ±0.2 km/s.

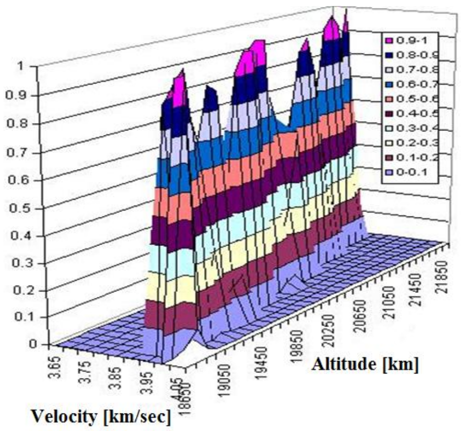


Figure 13 - Distributions of a transversal velocity

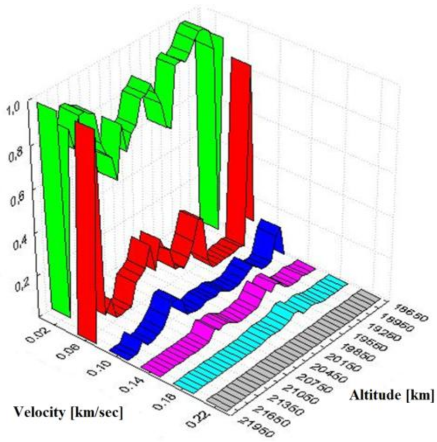
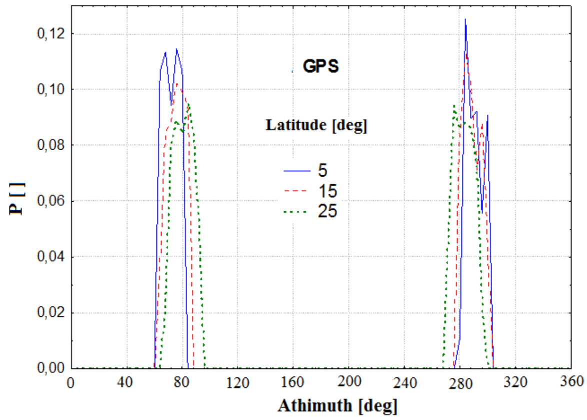
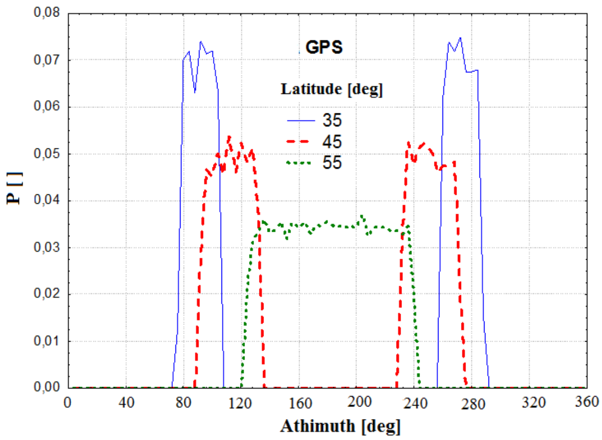


Figure 14 - Distributions of radial velocity

The main characteristic of the direction of objects velocity is the geographical azimuth of its projection to the horizontal plane. Values of this azimuth depend on the width of a point and an inclination of the satellite. Because GPS and GLONASS satellites have different inclinations and have different altitudes, distributions of possible azimuth values for them are constructed separately.



a)

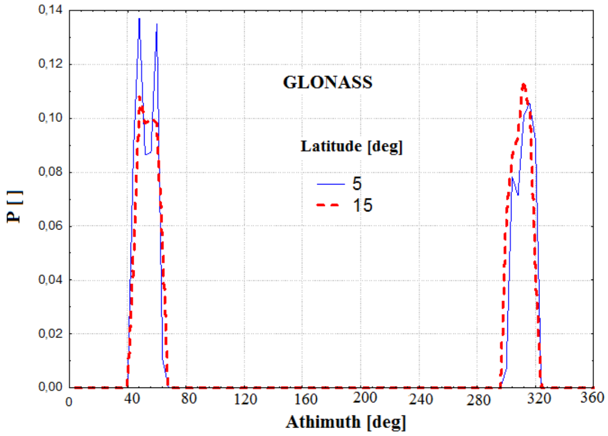


b)

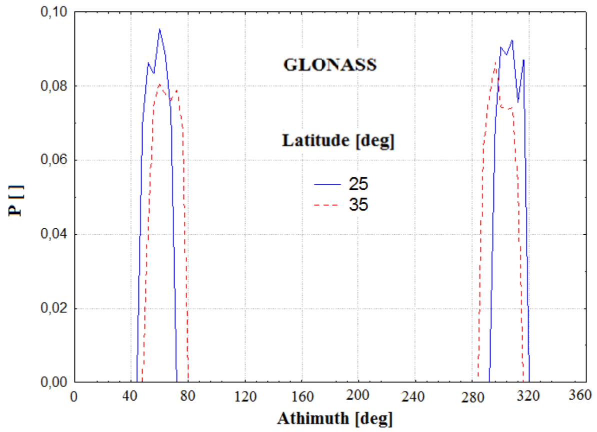
Figure 15 – GPS. Distribution of velocity directions (azimuth)

In figures 15 distributions for the GPS satellites having i≈55° inclinations are presented. They are constructed for latitude values from 0° to 60° by a step 10 °.

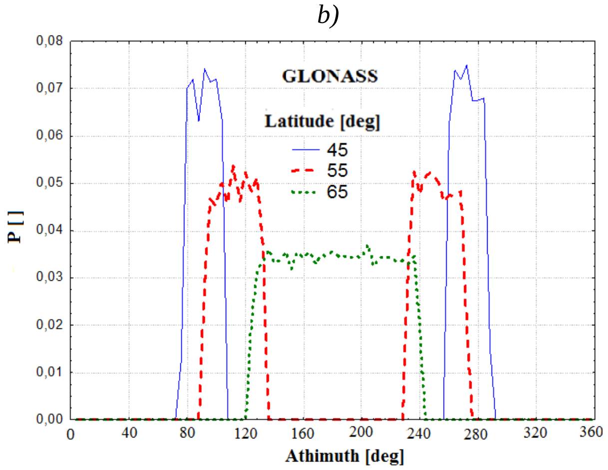
In figures 16 the corresponding distributions for GLONASS satellites having i≈65° are presented. They are constructed with a step 10° for latitude values from 0° to 70°.



a)



b)



c)

Figure 16 - GLONASS. Distribution of velocity directions (azimuth)

Nature of these distributions – same, as at the corresponding azimuthal distributions of GPS satellites. Difference only that here latitude 65° which satellites of GPS system with i≈55° inclination cannot reach was added.

The estimation probability of mutual collisions between objects in the field of GNSS is around 3 10^{-7}.

5. OFFERS ON STATISTICAL SD MEASUREMENTS ON HIGH ORBITS

One of possible calibration methods of model coefficients k $(>d)$ for the MEO and GEO regions is statistical measurements of objects with small values of magnitude.

In 2016 in Terskol optical observations of the GEO region by the K-800 telescope with an aperture of 80 cm were made. Big diameter and a magnitude allowed detecting objects with magnitude up to 18.5. Observations were made from August 21 to September 27, 2016. In total 10466 measurements of objects with reliable measurements of visible magnitude, united in 967 tracklet were received.

For each tracklet the average size of magnitude was calculated. The histogram of average magnitude distribution for objects which got to measurements is given in Figure 17.

More than a half of measurements was carried out at small phase corners from 0o to 30^{o} (see Figure 19) that promoted detecting of small size objects. The essential part of observed objects had visible magnitude more weakly the 16 magnitude and with high probability belonged to not catalogued objects. Histogram of magnitude for observed objects is represented in Figure 17. From Figure 18 it is visible that the main measurements in latitudes from -15 to 15 degrees, the longitude of observed objects was limited to the provision of measuring point.

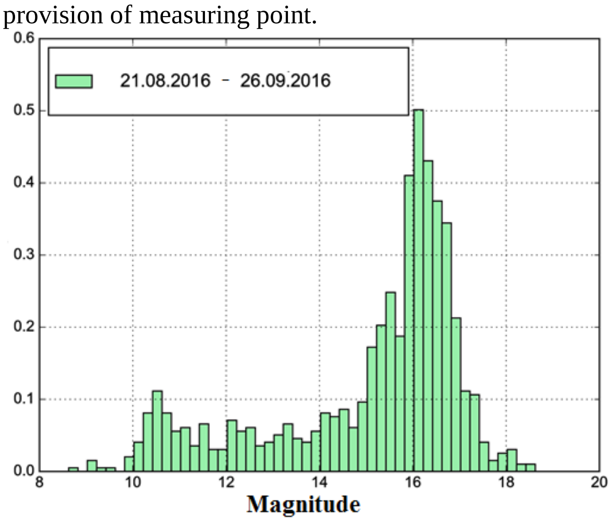


Figure 17 - Histogram of objects magnitude received from passing photometric measurements

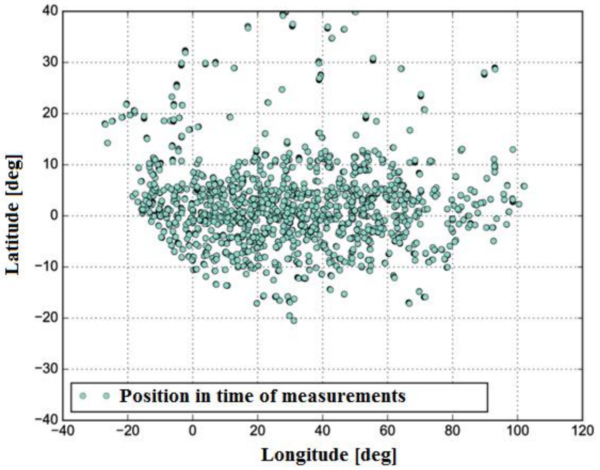


Figure 18 - Angular coordinates of measuring objects

Estimates of the characteristic extent of observed object are calculated in the assumption of its spherical form and a surface providing diffusion reflection, received to measurements of visible gloss of object. Unknown value of coefficient of reflection of a surface of object was established at the level of *Cd=0.4*. The distance from the observer to object, necessary for receiving an assessment of the characteristic size, was defined from the assumption that the observed object is on the geocentric sphere of the radius of 42 164 km. For each measurement in tracklet of object the assessment of visible magnitude on magnitude measurement, estimated distance to object and to the current phase corner was under construction. The total estimation of the characteristic size was accepted equal to diameter the reflecting sphere average on all measurements in tracklet.

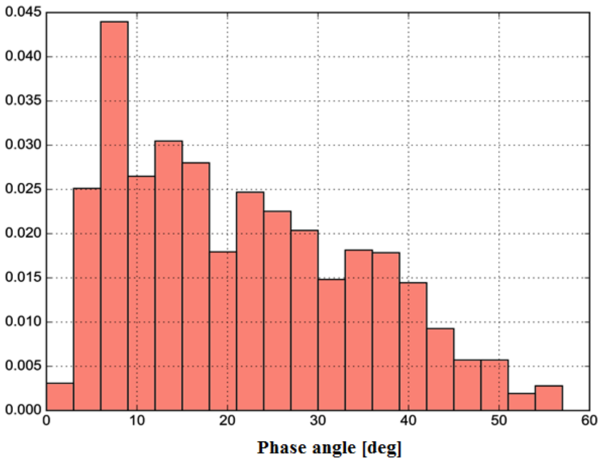


Figure 19 - Distribution of phase angles

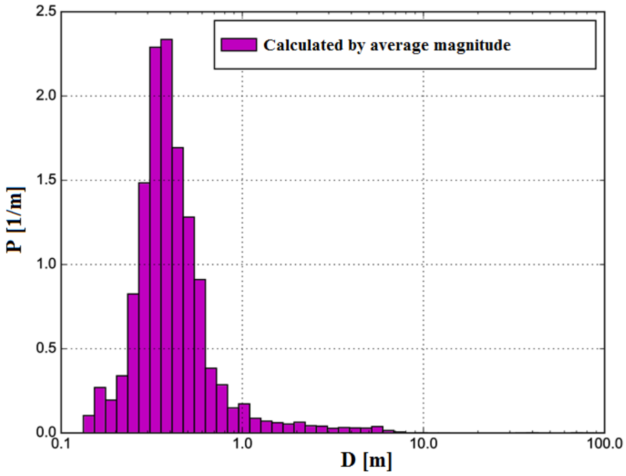


Figure 20 - Histogram of estimate sizes

Received as a result of an estimation of the characteristic size were used for creation of selective density of distribution of objects in observed area in a logarithmic scale of the sizes (see Figure 20). The peak of probability density constructed on selection of objects corresponds to the characteristic size of 0.5 meters. Further reduction of density and amount of objects with reduction of the characteristic size is connected with reduction of detecting probability of objects with weak magnitude signal level from which comes nearer to the level of extraneous noises.

CONCLUSIONS

1.The analysis of TsSITO KIAM RAS catalog is carried out

2.With use of the catalog data SD model parameters are improved.

3.The assessment of probability of mutual collisions in the vicinity of a maximum of spatial density protected GEO region is carried out.

4.The analysis of experimental measurements for verification of SDPA model is carried out.

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