FEATURES OF SPACE DEBRIS SURVEY IN LEO UTILIZING OPTICAL SENSORS

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ABSTRACT

This paper focuses on the features of optical observations of space debris (SD) in Low Earth Orbit (LEO) in a survey mode. These issues for LEO are at present time studied much less comparing to High Earth Orbit (HEO) and, particularly, geostationary orbits.

Preferable regions of celestial sphere for LEO SD observation in a survey mode are localized by modeling passes of catalogued SD through the telescope's coverage area and taking into account the conditions of optical visibility. The dependence of these area characteristics on local time, season of observation and latitude of telescope location are studied.

The results can represent practical interest for development of the efficient strategies for LEO SD searching, planning the observation campaigns, analysis of the obtained measurement data and validation of the SD models based on the optical observations.

1. INTRODUCTION

A considerable progress was achieved in the development of optical sensors for space debris (SD) observations in the last years. In particular, the efficient wide field telescopes with fields of view (FOV) about several tens of square degrees were created. In spite of this, optical sensors are so far unable to cover the whole visible part of the sky at once or over a short period of time. Therefore, optical sensors in the survey mode perform consecutive scanning of sky sectors in the visibility zone, in accordance with the applied strategy, instead of global coverage of SD.

It is obvious that the choice of survey area and search strategy depends on the type of SD orbits to cover. These issues were studied in more details and already used in practice for the case of Geostationary Earth Orbit (GEO) surveys [1-5]. There are study cases dedicated to SD in Medium Earth Orbit (MEO) and High Earth Orbit (HEO) [2, 5]. In regards to optical observations of SD in LEO, the problem of area localization and planning of surveys remains insufficiently explored for this type of orbits.

To localize the survey area of SD in LEO we have used the method based on modeling of catalogued SD passes over the telescope and finding parts of space with more dense distribution of visible objects satisfying geometrical conditions of optical visibility. Application of geometrical approach is equivalent to having an optical sensor with unlimited sensitivity and performance. The specific characteristics of optical sensor can be taken into account in our approach by including its performance model into computation process.

In spite of the fact that our calculations have deterministic character, it is possible to believe that the obtained results can be also used for search of the uncatalogued small-sized SD in LEO with only statistical information about their distribution in near-Earth space. With this, we use a reasonable assumption of proximity of distribution in space of the catalogued and uncatalogued man-made SD due to same sources of their creation.

2. DISTRIBUTION OF CATALOGUED LEO SD

Two-Line-Elements (TLE) datasets were used as initial data to simulate SD passes over the optical sensor. TLE sets for catalogued objects are updated regularly at Space Track web-site [6]. SD was considered as LEO in a catalogue if its apogee was not greater than 3500 km. The number of such objects for Feb. 16, 2009 was equal to 9134, what testifies about good representativeness of our sample.

Fig. 1 presents the orbit altitude and inclination distribution of selected catalogued SD in LEO. One can see that the majority of catalogued LEO SD is located inside of inclination range from 60 to 100 degrees. Distribution in altitude has maximums at about 800 and 1500 km [7].

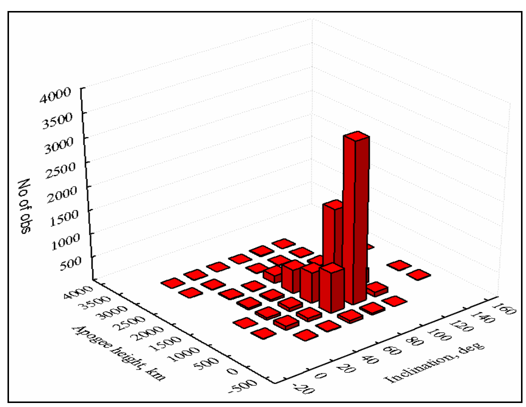

Figure 1. LEO SD distribution in altitude and inclination

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Fig. 2 gives the distribution of normalized density of LEO SD in latitude and altitude, plotted using SD model developed by Nazarenko A.I. [8]. Fig.2 shows the marked maximum for LEO SD density in the 60-85 latitude range and close to 800 and 1500 km altitude. The specified features of LEO SD distribution strongly impact conditions of their optical observations.

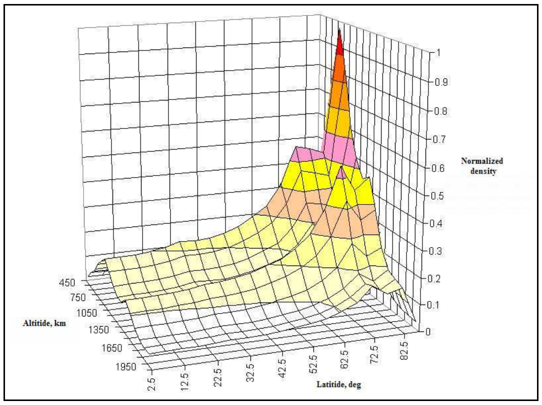

Figure 2. Distribution of LEO SD normalized density in latitude and altitude

3. CALCULATION TECHNIQUE

Two cases of on-ground telescope locations were modeled. For convenience of analysis and calculations, telescopes were located in both cases at the prime meridian, i.e. at the Greenwich meridian. It is necessary to note, that choice of longitude for telescope location influences calculation results less significantly than choice of latitude. This is explained by the relatively uniform distribution of LEO SD orbits' longitude of the ascending node, by effects of evolution of LEO planes and by Earth's rotation.

As to latitude, its value was assigned zero for the first case, i.e. a telescope was located at the intersection of Greenwich meridian and equatorial plane. The calculations for the second case were carried out for telescope location at 45 degrees of Northern latitude.

The following conditions are necessary to satisfy optical visibility of SD in our computations:

- SD is sunlit;
- Telescope is in the dark and the sunset is at least at 8 degrees;
- SD is above the horizon and its elevation is greater 10 degrees;
- Phase angle (an angle between directions «SD – Sun» and «SD – telescope») does not exceed 120 degrees.

SD passes were modeled for the following three cases of observation epoch to estimate their influence on output results:

- Winter solstice (hereinafter - Winter);
- Vernal equinox (hereinafter - Spring);
- Summer solstice (hereinafter - Summer).

Calculations for autumnal equinox were not carried out in view of their similarity to the vernal equinox.

To calculate the visibility characteristics, state vectors of all chosen LEO SD were predicted for the same daily intervals for each considered epoch and moments of time within these intervals determined by the constant step of calculation. This step has been chosen equal to 30 seconds for all modeling cases. The universal semi-analytic propagation method was used to predict the SD orbits [9]. The geometrical visibility constraints were checked for each prediction point through daily interval. If SD was visible in some point, the predicted state vector and corresponding additional parameters such as azimuth, elevation, range, etc were recorded into a database for this case. For each SD pass satisfying conditions of visibility, the corresponding length of passing time over the telescope was calculated.

4. GENERALIZED RESULTS

The generalized results of modeling are presented in Tab. 1. The following characteristics are shown in this table for both cases of telescope location and for three epochs of observation:

1. A total number of apparent points, i.e. the number of predicted points in which the geometrical conditions of optical visibility described above are satisfied. The data shows that for a specific location of telescope the value of this parameter can vary within 20% depending on the observation season. Observations during an epoch of the winter solstice are more favorable from the point of view of the given parameter. The latitude of telescope location strongly influences this parameter: the total number of visible points is almost two times greater for a telescope located at middle latitudes than for equatorial site. Two reasons can explain this fact: 1) twilight interval at equator is shorter than one at middle latitudes and 2) the dense area of LEO SD population, located at higher latitudes (see Fig. 2), is not accessible for observation from equator.
2. A total number of visible LEO passes through telescope's visibility zone, described by an 80-degree cone. The maximum value of this parameter (14254) corresponds to computations for an epoch of spring equinox and for a telescope location at latitude of 45 degrees. This value is 2.8 times greater than one for a case of observations during the same epoch using a telescope located at equator. It is also seen that the number of SD passes through a viewing field of optical sensor can vary up to 40% depending on observation season.
3. A number of observable SD, i.e. number of different catalogued LEO objects, with passes registered in the telescope's coverage area. The same table row also

contains relative values of this number as percentage of the total number of modeled SD (9134). The presented data show that the equatorial optical sensor can potentially observe from 42 to 55 percent of LEO population depending on observation season. At the same time a telescope located at 45 degrees of latitude is able to observe 60-79 percent of LEO SD. It is revealed, that the given parameter is extremely sensitive to such constraint parameter of observations, as the minimal elevation. Fig. 3 demonstrates the influence of the minimal elevation of telescope observations on the number of observable objects. The plotted data correspond to the summer observation season. These plots show that the increase of the minimal elevation of observations from 10 to 30 degrees results in double decrease of total number of observable LEO SD for both considered cases of telescope location.

4. A number of apparent points in elevation range from 10 to 50 degrees and the same number expressed as percentage of the total number of apparent points (see parameter #1). Fig. 4 gives the histogram for distribution of apparent positions of LEO SD in elevation. These plots correspond to calculations for Spring, with site location at 45 degrees. One can see the regularity of distribution of apparent points in elevation: the higher the elevation, the less the number of such points. This regularity remains valid for other cases of simulation. The main part, from 86 to 90 percent, of apparent points corresponds to the visible path sections where the elevation does not exceed 50 degrees.

5. A number of observable SD for elevations of less than 50 degrees. Comparing values of parameters 3 and 5, we can conclude that the restriction of the maximum elevation of observations by 50 degrees reduces the total number of observed LEO SD by less, than 0.5 %. Hence, without substantial damage, the search area for LEO SD can be limited by range of 10 to 50 degrees in elevation.

Let's consider now in more details the spatial-temporal distributions of apparent positions of LEO SD obtained as a result of modeling of SD passes for considered cases of epoch and observation site locations.

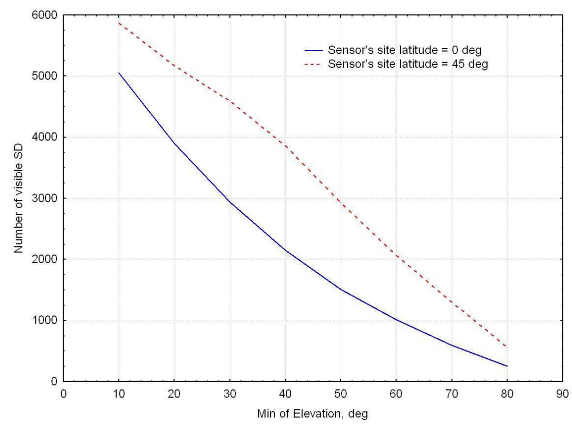

Figure 3. Dependence of observable SD on minimal elevation

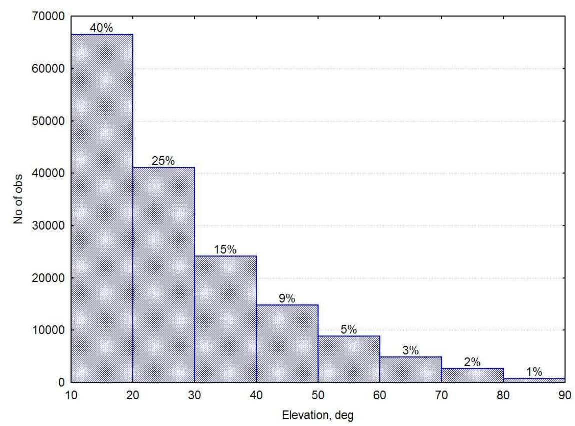

Figure 4. Histogram for distribution of apparent positions of LEO SD in elevation

Table 1. Generalized modeling results

##	Characteristics	Telescope location and observation epoch					
		Latitude=0 degrees			Latitude=45 degrees		
		Spring	Summer	Winter	Spring	Summer	Winter
1	Total number of apparent points	74195	79444	86017	164253	137589	167070
2	Total number of passes	5119	6801	6632	14254	10652	12169
3	Number of observable SD (% of total number of LEO SD)	3876 (42%)	5055 (55%)	4940 (54%)	7201 (79%)	5872 (64%)	5517 (60%)
4	Number of apparent points in elevation range from up to 50 degrees (% of parameter #1)	65876 (89%)	70688 (89%)	76100 (88%)	146987 (89%)	118567 (86%)	149602 (90%)
5	Number of observable SD for elevations of less than 50 degrees	3876	5053	4938	7200	5856	5517

5. SPATIAL-TEMPORAL DISTRIBUTION OF APPARENT DENSITY FOR LEO SD

Graphs in Figs 5 - 7 characterize the spatial-temporal distribution of LEO SD, visible from an equatorial sensor during winter, spring and summer seasons of observation respectively. The top graph in these figures illustrates the dependence of azimuth distribution of visible objects on local time. Hereinafter the positive direction of azimuth is counted clockwise in the plane of local horizon from the North direction. The bottom graph represents dependence of elevation distribution on local time. The plots for the Sun's azimuth and elevation vs. local time are drawn in these figures as well.

For the case of a telescope location at 45 degrees latitude similar graphs for spatial-temporal distribution of angular characteristics of observation are presented in Figs 9 - 11.

The analysis of spatial-temporal characteristics of LEO SD visible passes through the optical sensor field of view can be summarized as follows:

1. Favourable conditions of LEO SD strongly depend on latitude and epoch of observation. From the point of view of duration and efficiency of LEO SD observations the location of telescope site at 45 degrees is more preferable, than at equator. For example, Figs from 5 to 7 show that in the case of equatorial site there are 4-5 -hour midnight breaks in LEO SD observation depending on observation season. These breaks are longer at spring and autumn equinox, than at winter and summer solstice. Figs 8-10 show that such breaks occur only in winter for observations of LEO SD using a telescope at 45 degrees latitude. In other seasons observations can be carried out from this site continuously all night.
2. Distribution of apparent density of LEO SD in a telescope visibility zone is extremely non-uniform. There are observation angles, characterized by increased density of visible SD. These directions represent the greatest interest from the point of view of application of effective LEO survey strategies used by optical sensors. Other directions are characterized by the rare presence, or full absence of SD satisfying visibility conditions. Parameters of the specified directions depend on local time and observation epoch.
3. The major factors defining the spatial-temporal distribution of SD in a coverage area of a telescope and, accordingly, the preferable directions of SD survey are angular position parameters of the Sun with respect to sensor's site. The survey areas of LEO SD can be explicitly defined by the Sun's azimuth and elevation. So, Figs 5-10 show that during evening and morning twilight when the Sun is below the horizon at less than 15-18 degrees, the LEO survey can be carried out in all azimuth directions, except for "illuminated zone". The "illuminated zone" is ±50 degrees in azimuth around the direction "sensor site-Sun". For the majority of SD in this zone observation conditions will be rather adverse – with large phase angles and increased brightness of sky background. The "illuminated zones" on the top graphs in Figs 5 - 10 are shown as lighter areas of apparent density of SD in azimuth. The range of elevations for SD observations during evening and morning twilight can be chosen sufficiently large, from 10 to 50 degrees.

In the beginning of astronomical night the angular range of favorable observations of LEO SD is about 40 degrees in elevation, and the total size of angular sectors in azimuth is about 150 degrees. As the Sun immerses below the horizon, the upper boundary of elevations for favorable observations starts to descend gradually and at the same time slant visual ranges start increasing (see Fig. 11). Simultaneously, the angular sectors of favorable observations of LEO SD in azimuth, located outside the "illuminated zone" almost symmetrically relative to the direction to the Sun, are getting narrower (see Figs 5-8). When the Sun's immersion below the horizon reaches 55-60 degrees, the upper boundary of elevation of favorable optical observations descends below 10 degrees. This leads to full disappearance of LEO visibility and a break in LEO observations. Figs 5-8 show that such situation is typical for cases of site location on equator or for winter observations at latitude of 45 degrees.

After the midnight the described pattern of LEO visibility repeats in the reverse order: the Sun rises and when its immersion angle becomes greater than the critical angle, the sunlit SD raise above horizon at elevations greater than 10 degrees. Observations of LEO SD can be started again, and the favorable area of observation starts extending gradually. LEO SD apparent density area in azimuth after midnight can be generated from a pattern before midnight by two mirror transformations: in local time – relative to midnight and in azimuth – relative to the North direction.

Figs 9 and 10 show that the critical immersion of the Sun below the horizon is not reached for spring and summer observations from site located at latitude of 45 degrees. Therefore observations of SD in LEO can be performed all night. The total width of areas of effective LEO observations in azimuth is about 150 degrees and remains practically constant through the night for these cases. As to elevation, its range remains also practically constant within night (Fig. 9) for summer observations. For spring surveys the elevation upper limit decreases to 30-40 degrees (Fig. 8).

4. Calculation results show, that in more than 90% of favourable cases of observations the visible angular velocity of SD does not exceed 0.5 degrees/sec (see Fig. 12). In most cases the visible angular velocities have even less values, 200 to 700 arcsec/sec, when SD are observed at small elevations.

5. The length of passing time distribution of SD over a telescope is illustrated on the histogram in Fig. 13. This graphs show, that for approximately 75% of cases the length of LEO SD pass over the optical sensor exceeds 5 minutes. It testifies to a real opportunity of their detection during observations in a survey mode.

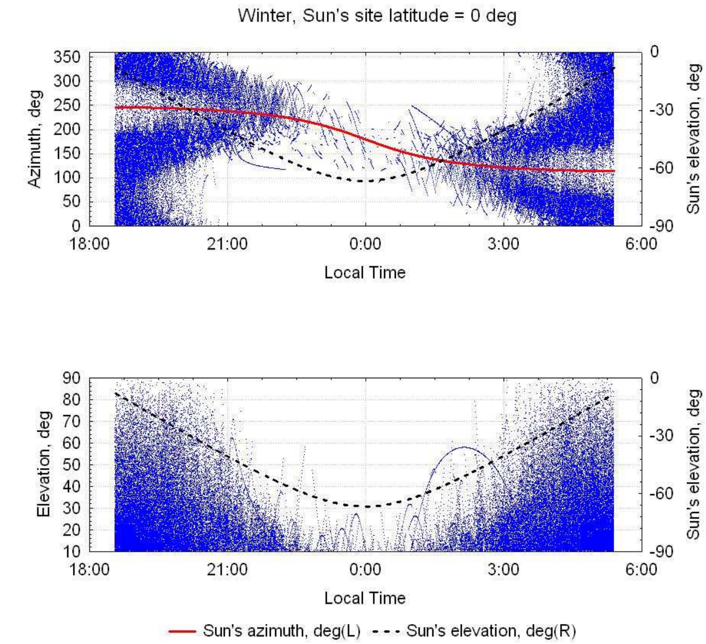

Figure 5. Spatial-temporal distribution of LEO SD apparent density for telescope at equator plane and winter solstice

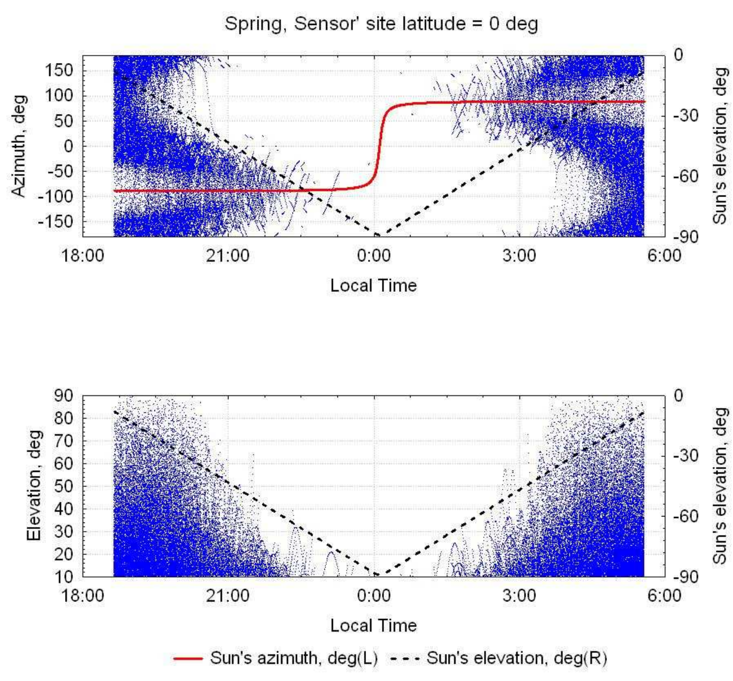

Figure 6. Spatial-temporal distribution of LEO SD apparent density for telescope at equator plane and vernal equinox

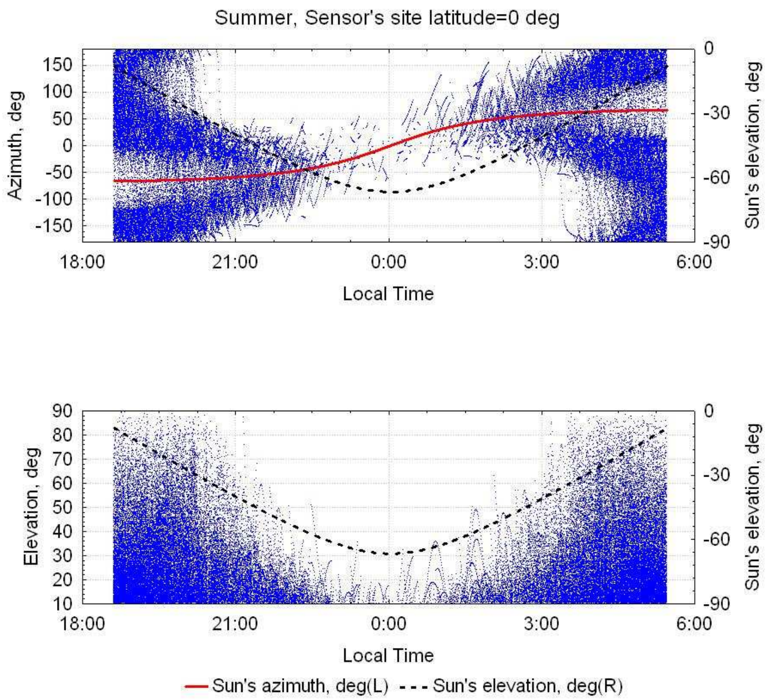

Figure 7. Spatial-temporal distribution of LEO SD apparent density for telescope at equator plane and summer solstice

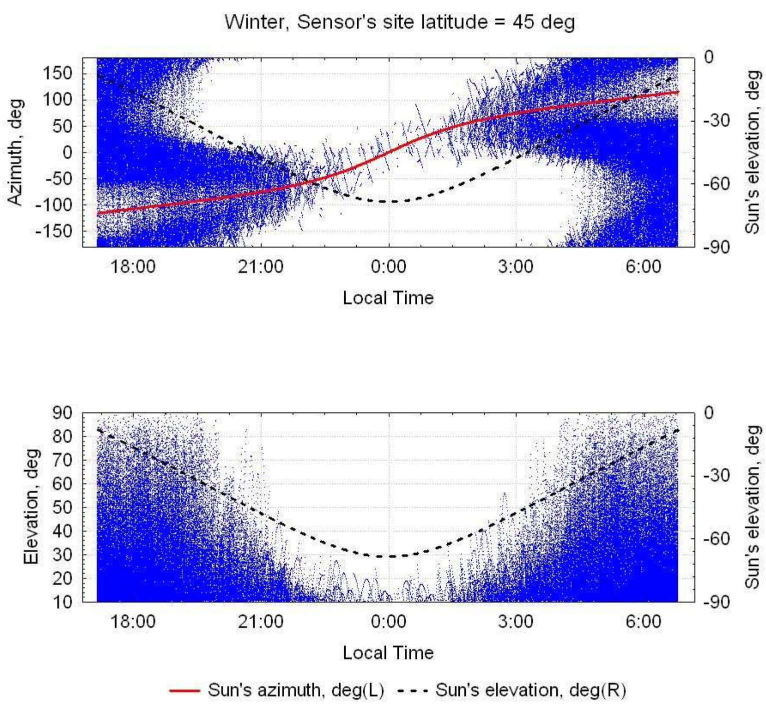

Figure 8. Spatial-temporal distribution of LEO SD apparent density for telescope at latitude of 45 degrees latitude and winter solstice

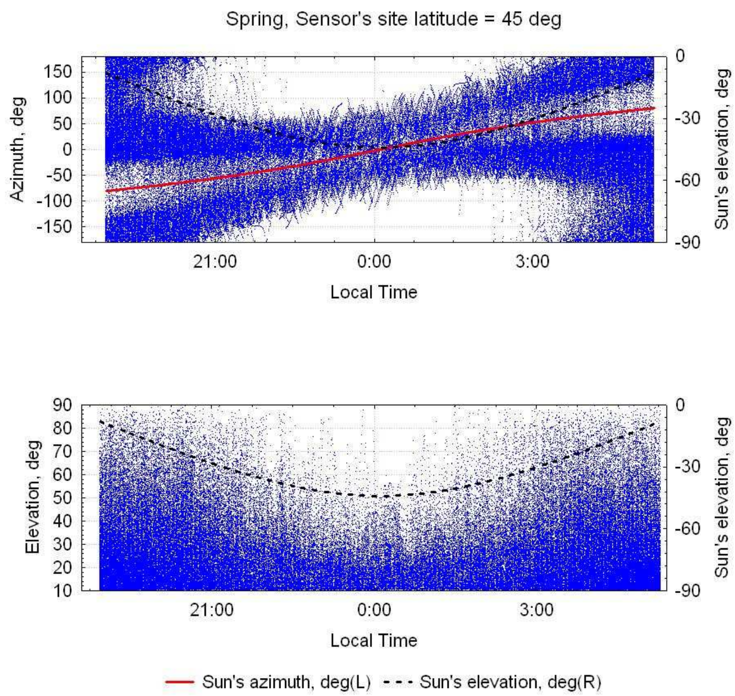

Figure 9. Spatial-temporal distribution of LEO SD apparent density for telescope at latitude of 45 degrees and vernal equinox

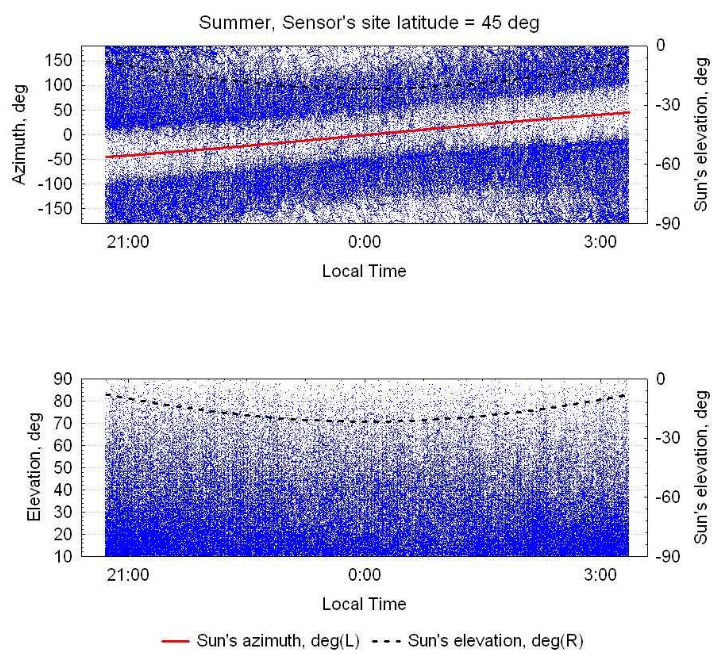

Figure 10. Spatial-temporal distribution of LEO SD apparent density for telescope at latitude of 45 degrees and summer solstice

The reported results of the geometrical analysis do not cover all problems related to LEO SD observations by optical sensors in a survey mode. They can be considered as preliminary data for more detailed modeling of LEO observation problems. These results can also represent practical interest for development of

SD search strategy, planning their observation campaigns, interpretations of the received measuring information, and also for verification of SD models using results of optical observations.

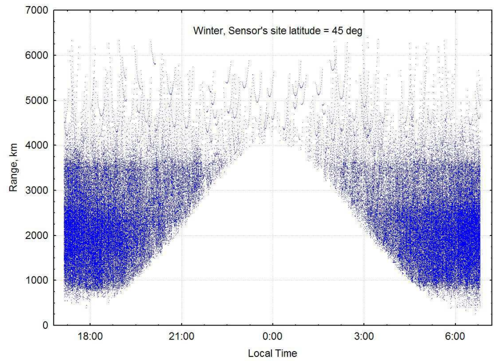

Figure 11. Visibility range dependence for telescope at latitude of 45 degrees and winter solstice

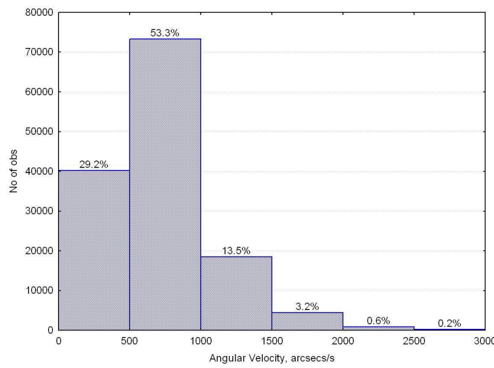

Figure 12. Visible angular velocity distribution of SD for telescope at latitude of 45 degrees and summer solstice

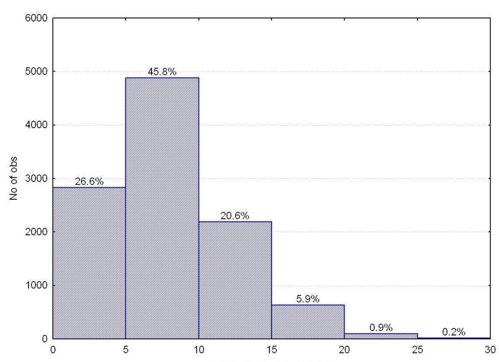

Figure 13. The length of passing time distribution for telescope at latitude of 45 degrees and summer solstice

6. CONCLUSIONS

The features of observation of LEO SD in a survey mode were studied by modeling of their passes over the optical sensors. Two cases of telescope locations on latitude were examined: on equator and at 45 degrees of northern latitude. It was shown, that site location at middle latitudes was preferable from the point of view of continuity and efficiency of LEO observations.

It was revealed also that distribution of apparent density of SD in the coverage area of optical sensor was not static and homogeneous. It depends on azimuth, elevation, season and local time of observations. It was found, that preferable areas of SD survey could be constrained by analysis of the Sun's position with respect to observation site.

We have limited our analysis here by examining geometrical characteristics and visibility conditions of SD passing. From this point of view, the presented results can be considered as the initial step for further research of application of optical sensors for SD surveys in LEO.

7. REFERENCES

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