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Igor N. Kartsan[1,2], **Aleksandr O. Zhukov**[3,4], **Vladimir O. Skripachev**[5]

MODEL FOR CALCULATING THE SPEED OF DELIVERY OF REMOTELY SENSED EARTH OBSERVATION INFORMATION

ABSTRACT

In full accordance with the observed intensive growth of the global market for products and services based on space-based information provided by space-based Earth observation assets, satellite missions and space-based Earth remote sensing technologies are currently undergoing rapid development. Space images are important for monitoring emergency situations: floods and inundations, forest fires and earthquakes. A wide range of Earth remote sensing satellites equipped with many types of target equipment are used to obtain all that information. In the course of developing the design of a space-based operational data transmission system, which is based on a heterogeneous orbital constellation using a network of relay satellites, it is necessary to model the ballistic structure of the Earth remote sensing orbital constellation. The efficiency of Earth remote sensing information delivery to consumers should be considered under various options of building a network of relay satellites, taking into account the characteristics of existing and prospective high-speed radio lines of satellites. During modeling it is also necessary to take into account that in the case of a single repeater satellite the best picture on the minimum times of information delivery efficiency from the Earth remote sensing satellite is observed for a low-orbit repeater satellite, and the best picture on the maximum times of information delivery efficiency from the Earth remote sensing satellite is observed for a geostationary repeater satellite. An algorithm for model formation of an orbital constellation of different types of satellites with given initial ballistic characteristics is created. The presented algorithm consists in sequential calculation of initial conditions of reference satellites for each plane, and then, according to the initial conditions of the reference satellite, calculation of initial conditions of other satellites of the given plane.

KEYWORDS: Earth remote sensing, satellites, transponder satellite, orbit, efficiency of information delivery

INTRODUCTION

Russia successfully operates a constellation of Earth remote sensing satellites (ERS satellites) for socio-economic purposes, consisting of the following actively operating satellites:

- Meteor-M satellites;
- Elektro-L satellites;
- The Kanopus-V family (including the Kanopus-V-IR satellites);
- Arktika-M satellites.

Strategic planning documents in the area of space activities in the interests of socio-economic development set the task of ensuring the development of the main technical

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[1] Marine Hydrophysical Institute, Russian Academy of Sciences, 2, Kapitanskaya str., Sevastopol, 299011, Russia, *e-mail:* **kartsn2003@mail.ru**

[2] Reshetnev Siberian State University of Science and Technology, 31, Gazety Krasnoyarsky Rabochy ave., Krasnoyarsk, 660037, Russia, *e-mail:* **kartsn2003@mail.ru**

[3] Expert and Analytical Center, 33, Talalikhina str., Moscow, 109316, Russia, *e-mail:* **aozhukov@mail.ru**

[4] Institute of Astronomy of the Russian Academy of Sciences, 48, Pyatnitskaya str., Moscow, 119017, Russia, *e-mail:* **aozhukov@mail.ru**

[5] Expert and Analytical Center, 33, Talalikhina str., Moscow, 109316, Russia,
e-mail: **skripatchevv@inbox.ru**

characteristics of domestic satellites for socio-economic, scientific and dual-use applications to a level not inferior to the best foreign analogs.

In terms of remote sensing of the Earth from space, the goal is to ensure round-the-clock and all-weather observation of Russia territory, as well as to create a scientific and technical foundation for Russia full-fledged representation in all segments of the world market of space services [*Agapov*, 2000; *Ozdogan*, 2010; *Kartsan* et al., 2018; *Erunova*, *Yakubailik*, 2019; *Ivanova* et al., 2019; *Erunova*, *Yakubailik*, 2020; *Barkova*, *Zhukov*, 2021].

The main requirements of consumers to ERS data are to achieve the following characteristics of space data in the future:

- In terms of spatial resolution. The maximum value is set at the level of the best world analogs (0.2 m for optical and 0.5 m for radar data).
- Frequency and efficiency of ERS data acquisition depend on the technical capabilities of Russian ERS satellites, except for tasks related to monitoring of emergency situations (ES) and dynamics of natural processes, as well as on the development of multi-satellite orbital constellations (OC). For such tasks overestimated requirements from the side of information users, for example, from 0.1 hours (close to real time mode), are a guideline for the development and improvement of technical means of receiving, receiving, processing and delivery to the consumer; and also depend on the development of multi-satellite OC.
- On radiometric resolution of optical data. It is defined by 3 intervals: 8–12 bits, 12–14 bits (for oceanography) and up to 16 bits (for tasks of power agencies).
- Radiometric resolution of infrared (IR)- and ultra-high frequency (UHF)-surveys is set in accordance with the requirements of the World Metrology Organization (WMO) and the level of world analogues.
- By spectral range. The values are chosen in accordance with the zones of solar radiation transmission by the Earth's atmosphere. In general, the intervals correspond to the visible, near, middle and far infrared ranges of the electromagnetic spectrum. To account for atmospheric scattering and to solve individual tasks, the visible range includes the blue channel (0.43–0.45 μm). Solution of thematic tasks related to vegetation cover and chemical composition of compounds in the atmosphere implies narrow-band spectral imaging.
- In terms of georeferencing accuracy. For medium resolution optical data, the sub-pixel accuracy is assumed, for high and ultra-high resolution optical data the accuracy of orbital parameters referencing is set at the level of world analogs (not more than 2–5 pixels of the initial resolution), for radar data and low-resolution optical data the accuracy is not set;
- Frequency of ERS data update will be increased by more than an order of magnitude from 0.2 times per day to 8 times per day.

RESEARCH MATERIALS AND METHODS

Formation of the OC model of different-type satellites with given initial ballistic characteristics consists of 2 stages:

1. Formation of the ballistic structure of the satellites included in the OC as a solution to the problem of determining the initial conditions of each satellite from the OC.
2. Assignment to each satellite of its own type(s) by specifying the characteristics of the onboard equipment placed on it.

The following terminology is used in the development of the algorithm for the formation of the ballistic structure of the OC. The first satellite of the first orbital plane is called fundamental, and the first satellite of each subsequent orbital plane is called a reference for this plane.

The algorithm consists in sequential calculation of initial conditions of the reference satellites for each plane, and then, according to the initial conditions of the reference satellite, calculation of the initial conditions of the other satellites of the given plane.

All calculations of initial conditions are performed in the form of osculating Keplerian elements in the true equatorial date system, i. e. the initial conditions of the fundamental satellite are reduced to Keplerian elements; on their basis, the Keplerian elements of the reference satellites for the other planes are calculated, and then the Keplerian elements of all other satellites in each plane are calculated.

This set of Keplerian elements is further referred to as Keplerian formants. Finally, if necessary, the Keplerian formers of all satellites are reduced to the type of initial conditions required for the chosen algorithm (TLE for the SGP algorithm, phase vector for numerical integration) [*Redowan* et al., 2014; *Kartsan* et al., 2016; *Tyapkin* et al., 2017; *Sankey* et al., 2018; *Wang* et al., 2018; *Vermeulen* et al., 2021].

As input data for the algorithm of OC model formation is given:

1. The number of orbital planes *N*.
2. The number of satellites in each orbital plane *M*.
3. Initial conditions of the fundamental satellite (the first satellite of the first plane) in the form of Keplerian orbit elements in the true equatorial date system:
   a) major semi-major axis of the orbit $a_{1,1}$;
   b) orbital eccentricity $e_{1,1}$;
   c) orbital inclination $i_{1,1}$;
   d) longitude of the ascending node of the orbit $d_{1,1}$;
   e) orbital perigee argument $w_{1,1}$;
   f) average orbital anomaly $m_{1,1}$;
   g) the time at which the initial conditions are given $t_{1,1}$.
4. Angle between ascending nodes of neighboring orbital planes d_{ln}g.
5. Algorithm of satellite location in the orbital plane; determines which of the initial conditions parameters of satellites located in the same plane changes: mean anomaly, latitude argument or initial conditions time.
6. The value by which the parameter specified in clause 5 is changed: the angle between the mean anomalies of neighboring satellites of the d_m plane, the angle between the latitude arguments of neighboring satellites of the d_{arg_lat} plane, or the time shift between the initial conditions time of neighboring satellites of the d_t plane. Hereafter, this value is referred to as the separation.
7. The value by which the parameter specified in clause 5 is changed for all satellites of each subsequent plane: the angle between the mean anomalies of the corresponding satellites of neighboring planes $dshift_m$, the angle between the latitude arguments of the corresponding satellites of neighboring planes $dshift_{arg\_lat}$, or the time shift between the times of the initial conditions of the corresponding satellites of neighboring planes $dshift_t$. Setting this value to non-zero will allow us to introduce asynchrony of location of corresponding satellites in neighboring planes. Hereinafter this value is called phase shift.

The algorithm of OC model formation consists of the following steps:

1. Calculation of the longitude of the ascending node of the reference satellites of each plane. The Keplerian elements of the reference satellites of each plane differ from the Keplerian elements of the fundamental satellite by the longitude of the ascending node and phase offset.

2. Depending on the algorithm specified in item 5 of the input data, the initial data of the reference satellites are calculated in different ways.
3. Calculation of the Keplerian elements of the remaining satellites. The Keplerian elements of the satellites of a fixed plane differ from the Keplerian elements of the reference satellite of this plane either by the mean anomaly or by the time of initial conditions, depending on the algorithm specified in item 5 of the input data.

Thus, the algorithm allows obtaining the values of the Keplerian shapes and initial conditions for all satellites of a given OC.

When solving the problem of synthesizing the orbital constellation, different parameters of Keplerian formations of different satellites appear to be related.

Thus, the values of the Keplerian frames of the reference satellites are related to the values of the Keplerian frames of the fundamental satellite, and the frames of all other satellites are related to the frames of the reference satellites [*Artyushenko*, *Kucherov*, 2013; *Kobets* et al., 2015; *Aleksakhina* et al., 2016; *Kucherov*, 2018; *Loupian* et al., 2019; *Mukhamedjanov* et al., 2019].

In this case, some relationships between the Keplerian formants should change with the change of the parameter of the reference or fundamental satellites. For example, if the large semi-major axis of the fundamental satellite changes, its orbital period $drac\_p_{1,1}$ will change.

In case the satellites in the plane were spaced uniformly in time, i. e. the initial condition times were tied to the draconic period of the fundamental satellite, they should be recalculated based on the new value of the period. The same applies to the phase shift between the corresponding satellites of neighboring orbital planes.

Separately, the inclination, which ensures solar synchronization of the orbit, should be taken into account. If the satellite's semi-major axis or eccentricity changes, the inclination should be recalculated.

Thus, in a sun-synchronous constellation with uniform separation and with uniform phase shift in time, if the semi-major axis of the fundamental satellite is changed, the semi-major axis of all reference satellites should be changed, followed by all other satellites.

Recalculation of the sun-synchronous inclination of the fundamental satellite should be performed, followed by a change in the inclination of all reference satellites, and then all other satellites.

The draconic period of the fundamental satellite should be recalculated, as well as the magnitude of the time shift of the initial conditions of the satellites in one plane, and the magnitude of the time phase shift of the initial conditions of the corresponding satellites on neighboring orbital planes.

Subsequent typification of satellites is achieved by adding satellites with appropriate equipment [*Congalton*, *Green*, 2009; *Kolecka*, *Kozak*, 2014; *Patel* et al., 2016; *Jain* et al., 2018; *Chymyrov*, *Bekturov*, 2019; *Proshin* et al., 2019].

For remote sensing satellites, the following characteristics of the on-board equipment are specified:

- maximum roll angle of a satellite or a platform with a remote sensing complex;
- maximum inclined range from the remote sensing satellite;
- pitch deflection angle;
- lens focal length;
- element size;
- matrix line length;
- information flow (possible recalculation from the number of matrices, matrix size, radiometric resolution);
- time of shooting of one object of observation;

- compression parameter of on-board information processing system;
- algorithm of LRM calculation.

The listed characteristics of remote sensing satellites make it possible to determine the following parameters:

- remote sensing satellite swath of view;
- instantaneous viewing area of the satellite;
- assessment of remote sensing information quality by pixel projection size;
- assessment of remote sensing information quality by LRM level, including for the matrix in time delay and accumulation mode;
- estimation of data volume of received ERS data.

The listed characteristics allow determining the following parameters:

- estimation of the data volume of the received ERS data.

The geostationary orbit parameters of relay satellites (SR) are calculated for a given longitude of the SR sub-satellite point. The following radio link (RL) characteristics are specified for SRs:

- list of remote sensing data transmission rates;
- range.

RESEARCH RESULTS AND DISCUSSION

Comparison of different options for building space remote sensing systems can be made on the basis of criteria related to their probabilistic time characteristics. In this case, both separately functioning objects, such as OC, and the system as a whole, which is a set of its constituent objects, can be analyzed.

In the simplest variant of calculating the efficiency of remote sensing information delivery to consumers, the time interval of spacecraft observation of the object of observation (OO) and the time interval of spacecraft location in the radio visibility zone of the information reception point (IRP), which can also be considered as the IRP line-of-sight zone, are taken into account.

Let us consider the problem of analyzing the frequency of spacecraft observation from a point on the Earth's surface. If we focus only on the potential possibility of direct contact, then the fact of finding a satellite in the line of sight of the OO or IRP will be determined by the phase of the satellite flight and is quite simply determined mathematically. However, the choice of the time of attempting to detect a satellite may be random.

On the other hand, when analyzing the characteristics of a particular orbit or orbital constellation, mathematical models are used for which the initial conditions for calculating the satellite motion are set, relating to a specific but arbitrarily chosen moment of time.

Accordingly, despite the predetermination of the satellite motion and the given location of the IRP point or the grid of OO nodes, the result of the satellite detection attempt is completely determined by the moment of setting the initial conditions and the moment of the detection attempt.

The resulting analysis value of spacecraft (or satellite constellation) observation frequency normalized by 1 can be interpreted as an indicator of spatial accessibility or simply accessibility. If continuous intervals of time of absence of at least one satellite over the subscribers will be investigated, the maximum and average time obtained as a result of the study has a physical meaning of the time of waiting for the readiness of the satellites OC.

If we study the distribution of waiting times for satellites to approach a given location of ground receiving and transmitting points, the obtained characteristic describes the efficiency of information delivery. For the analysis of satellite availability, the choice of time interval during which mathematical modeling is performed and, accordingly, during which the results are averaged, is of great importance.

Let us consider the example of a low-flying spacecraft with a flight altitude of 1 500 km, inclination of 82.5° and zero eccentricity. We limit the zone of spatial accessibility of the satellite for subscribers to a place angle of 10°. Accordingly, we can allocate several time intervals for mathematical modeling.

Time intervals, not exceeding the time of satellite passage over the OO: being in the range from 1 to 16 minutes. Time interval: 1 period of satellite orbit — approximately 116 minutes. Time intervals: 1 day, which is 1 440 minutes, and a time interval much longer than 1 revolution — for example, 100 revolutions or 11 600 minutes.

The time intervals of 1–16 minutes allow us to investigate issues related to estimating the duration of satellite contact with OOs located at different latitudes. Accordingly, the parameter describing these characteristics is called “operational readiness”.

From a practical point of view, the problem of finding the average time of continuous contact between satellites and satellites is of great interest, since this time determines the average load on the onboard equipment of satellites, and the maximum time naturally does not exceed the time of the satellite overflight over satellites located along the path of the subsatellite point. In the case under consideration, this time is 16 minutes. The minimum time of the subscriber’s contact with the satellite respectively is 1 minute — the order of the main time discretes of modeling.

By changing the formulation of the event to be investigated as a result of mathematical modeling it is possible to consider events related to continuous time intervals of satellite observation. In this case, in the course of calculations the events related to the formed continuous observation intervals are detected with the subsequent processing allowing to find the frequency of occurrence of the continuous observation time interval not less than a given value and, on this basis, to determine the most frequently recurring situation.

On the other hand, the time intervals of satellite motion modeling from 1 to 16 minutes allow to accumulate satellite observation results for subscribers located in the areas covered by the consecutive position of 1 to 16 visibility zones and, accordingly, cover a small part of the Earth surface.

Therefore, such a sample is not representative for analyzing the entire Earth surface, which forms the event space. By changing the formulation of the event to be investigated by simulation modeling, operational readiness can be investigated. Thus, when considering the problem concerning the case of a single satellite, it is possible to consider events characterizing continuous intervals of satellite observation time.

In this case, in the course of calculations, the events concerning the formed continuous observation intervals are detected with the subsequent accumulation of values of their duration and finding the maximum and average value of the realized interval of continuous visibility of the satellite. Let us consider a time interval equal to 1 period of satellite orbit.

When a single satellite moves along the orbit for a time interval of 1 revolution, some part of the Earth’s surface for the considered case of the satellite orbit, at least once, will be within its visibility. Accordingly, this area will be called the working area of the revolution.

The part of the Earth’s surface, which during 1 revolution will not fall within the visibility of the satellite even once, will be called the blind region of the revolution (Fig. 1). Attempts to detect satellites are made every minute at points on the Earth’s surface located at the nodes of a uniform rectangular grid tied to the Mercator projection. The event associated with successful detection of a satellite is denoted by the number 1, and the event associated with the absence of a satellite is denoted by the number 0. Accumulating by summing the results of attempts to detect a satellite over a subscriber in each node of the grid, and then dividing by the total number of attempts, it is possible to calculate the frequency of satellite detection over the OO in the working area of the coil. Accordingly, the sample time interval for modeling 1 turn is also not representative, because on the surface of the Earth there are areas with OO, located in which no satellite has ever been observed. This is evidenced by the presence of the blind region of the revolution (Fig. 1).

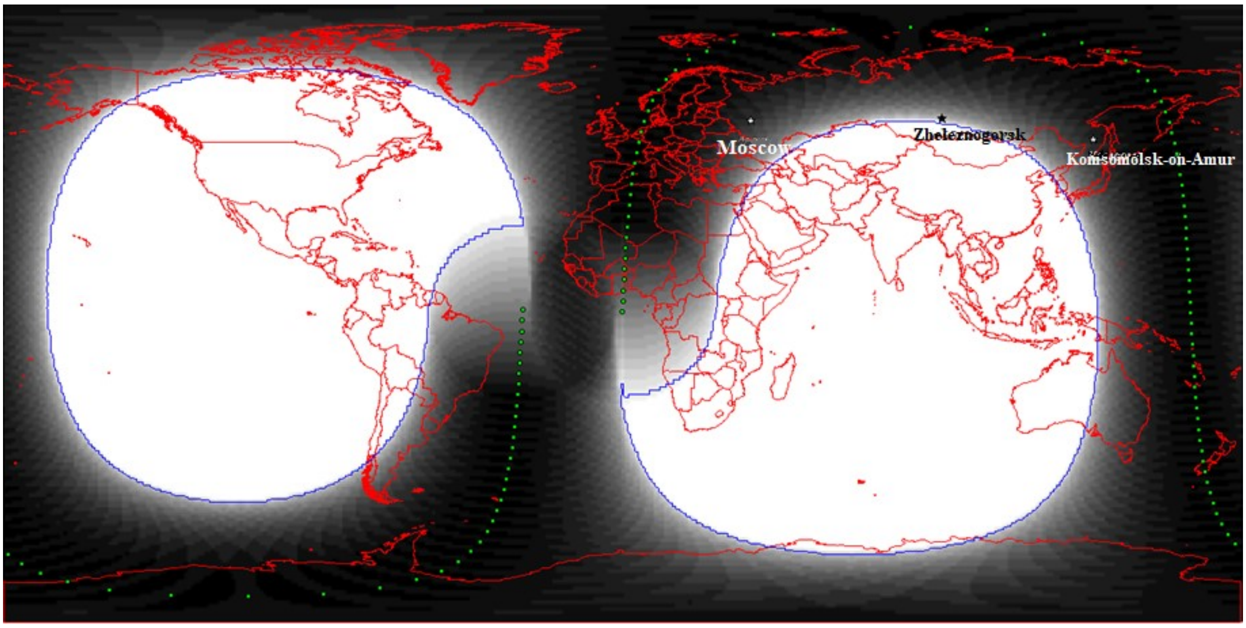

Fig. 1. Blind coil area

Fig. 1 shows that the working region of the turn is formed by successive superposition of the instantaneous visibility zones of satellites, forming the so-called visibility zone track. At the moment of the beginning and end of the turn, the visibility zones overlap each other with an offset equal to the angle of rotation of the Earth for the time 1 of the satellite rotation period. In the considered case, this angle will be 15° * 116 / 60 = 29°. The angle of 29° is approximately half of the size of the visibility zone.

In order to correctly analyze the average time of contact between the spacecraft and the satellite, it is necessary to process the accumulation results only in those nodes of the grid where non-zero data accumulation results are registered, namely, only in the working part of the turn.

Otherwise, the contribution to the final processing of the grid nodes not covered by the visibility zones during the duration of 1 revolution may distort the results obtained. In the case of an orbit with a satellite flight altitude of 1 500 km and an inclination of 82.5°, the orbital period is almost exactly equal to 116 minutes.

Then, the time interval of 1 day will be 1 440 minutes and, on this time, interval will fit approximately 12.5 turns. The value of about 100 turns is considered to be quite large and in the case of the orbit under consideration is a time interval of about 8 days. For this time interval, the simulation of the distribution of the frequency of satellite appearance over the OO, expressed as a percentage of the total number of analyzed moments of time is shown in Fig. 2.

The blue lines in Fig. 2 show the distribution isolines. Thus, the isoline value of 14 % limits the region where the detection frequency of a single satellite in the considered orbit is about 14 % or slightly higher. The specified area is located in the circumpolar region. The shape of the isoline is a line lying along the latitude of 80°. The linear shape of the isoline indicates that the calculation time interval is sufficient and the obtained distribution is very close to stationary.

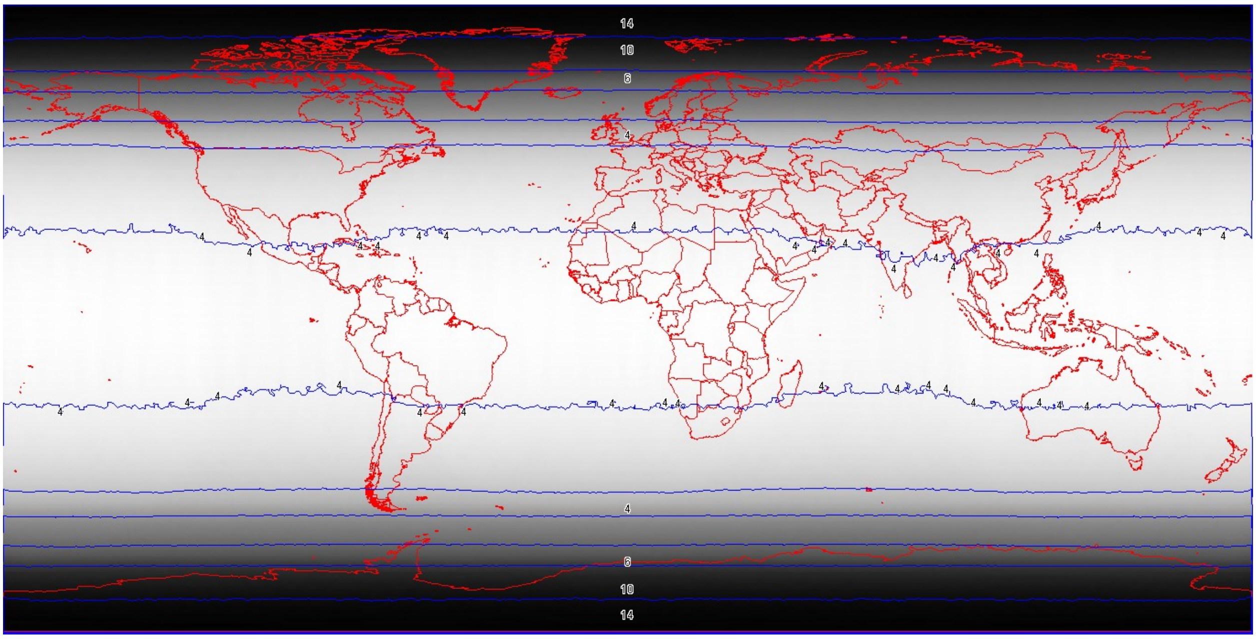

Fig. 2. Two-dimensional distribution of the frequency of occurrence of the satellite over OO, averaged to the total number of analyzed time points

Accordingly, if the accumulation time is sufficiently long, we can characterize the two-dimensional distribution by a one-dimensional distribution obtained by averaging the two-dimensional distribution over all longitude values. This will result in the graph shown in Fig. 3.

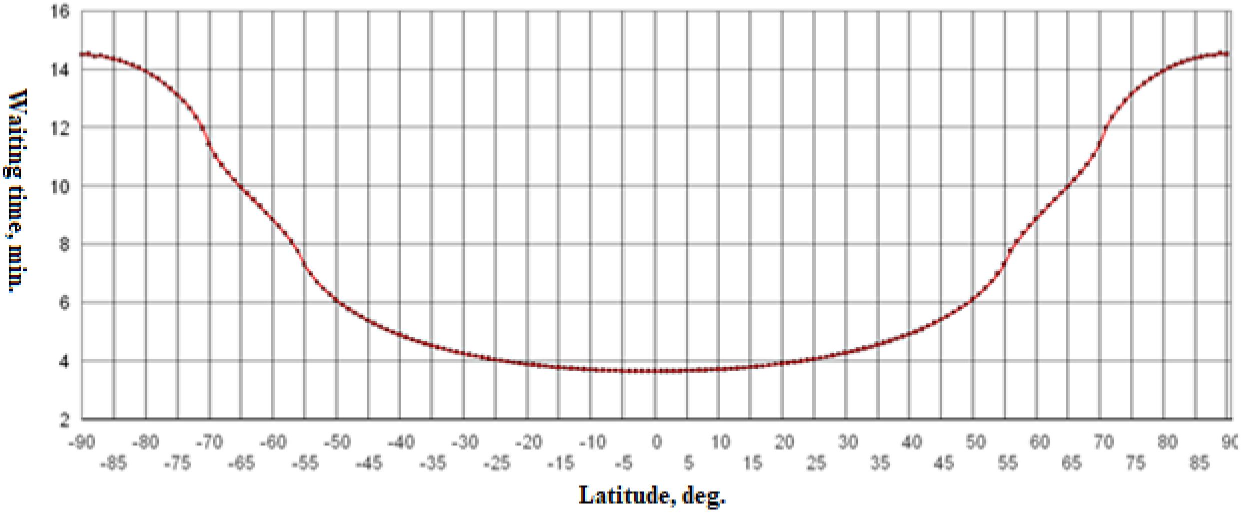

Fig. 3. The dependence of the relative frequency of the presence of satellite over OO located at different latitudes, expressed as a percentage — averaging over all longitude values

Continuous time intervals during which there is no contact between the OO and the satellite are considered below. Fig. 1 shows the working and blind regions of one revolution. Accordingly, the ground points located in the blind region of a revolution will gradually cover the working region as the Earth rotates daily. However, the daily rotation rate of the Earth is 15° per hour, and the size of the blind area of a single revolution of a single satellite is tens of degrees.

In the case under consideration, the maximum longitude size of the blind spot is approximately 160°, and it is this size that will determine the maximum waiting time for the satellite approach by an observer located in the most unfavorable place of the blind spot, which will be about 10.8 hours, or 653 minutes (Fig. 4).

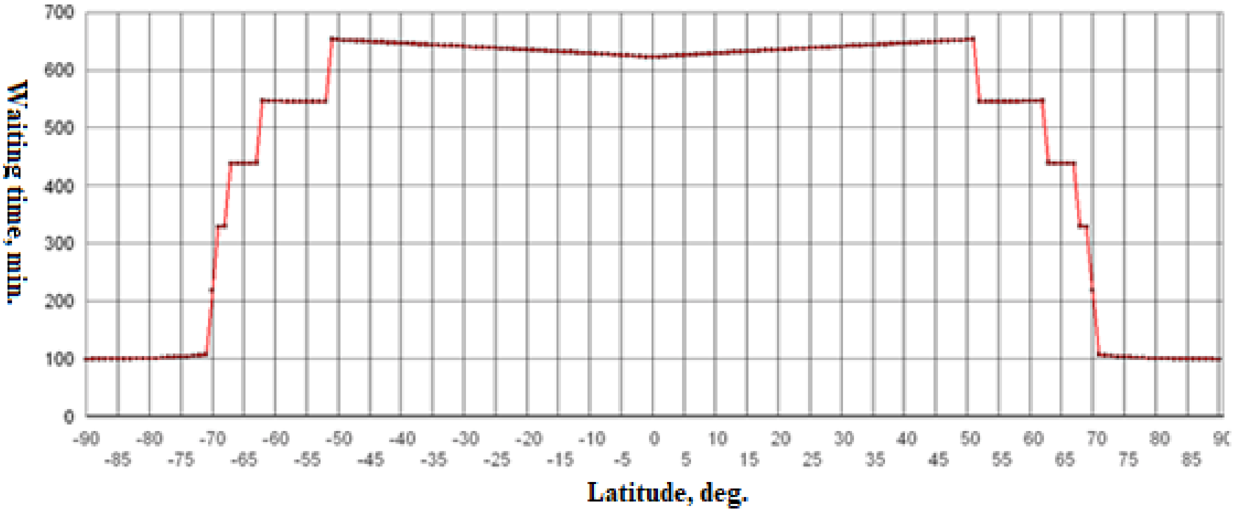

Fig. 4. Maximum realizable waiting time for reentry of a single satellite for different latitudes

It is also possible to consider not the maximum realized waiting time, but the average waiting time. However, due to the fact that the maximum waiting times are quite large, boundary effects in the simulation time interval can be of significant importance in the averaging procedure. In order to avoid them, only those time instants should be averaged that are within the simulation time interval to a sufficient depth determined by the maximum realized waiting time.

CONCLUSIONS

The presented algorithm includes several modeling stages, including various possible parameters, various stages, various types and number of orbits, and many other features that must be taken into account when solving the problem of modeling the formation of an orbital grouping of satellites of various types with specified initial ballistic characteristics. All calculations of the initial conditions are performed in the form of contiguous Keplerian elements in the true equatorial date system.

A model for calculating the operability of remote sensing information delivery to consumers for different variants of building space remote sensing systems can be presented on the basis of criteria related to their probabilistic time characteristics.

In the course of further work, a study was conducted on ways to promptly deliver Earth remote sensing information to consumers in various variants of building a network of repeater satellites, including a comparison of the time of operational delivery of information for an orbital grouping with a different number of Earth remote sensing spacecraft in low Earth orbit.

The presented model also allows us to compare the methods of operational delivery of Earth remote sensing information, including a comparative analysis of the minimum, average and maximum delivery times.

The result of simulation modeling within the framework of the conducted research was the identification of general and particular patterns for a single Earth remote sensing spacecraft in low Earth orbit and an orbital grouping of 36 Earth remote sensing spacecraft also in low Earth orbit based on graphical diagrams displaying statistics for calculating the efficiency of information delivery in various variants of building a network of repeater satellites.

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