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SIMULATION MODEL OF GNSS COORDINATE-TIME REFERENCE IN ENVIRONMENTAL MONITORING

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KEY WORDS: environmental monitoring, GNSS, simulation model, coordinate-time reference, signal shading, signal attenuation by vegetation.

ABSTRACT:

It is necessary to monitor the environment to control the state and assess the negative dynamics of changes in the environmental situation. In the case of long-term forecasting of environmental quality, monitoring makes it possible to prevent or reduce the risks of deterioration of environmental conditions within the boundaries of the territory under consideration at the time of observation. To determine these boundaries and time intervals, coordinate-time reference is used using various methods. For the time being, high accuracy, specified regularity and automation of information acquisition can only be achieved using global navigation satellite systems (GNSS). The GNSS receiver works best when there is a direct line of sight to the satellites transmitting navigation signals. Obscuring the receiver antenna with objects that violate this condition leads to a decrease in the accuracy of the coordinate-time reference. In addition, when monitoring the environment in forestland, it is necessary to consider the attenuation of GNSS signals by vegetation. To plan monitoring sessions with coordinate-time reference, a simulation model is required that includes these factors. Such a model makes it possible to predict the best time for carrying out coordinate-time referencing sessions.

1. INTRODUCTION

The main purpose of environmental monitoring is the collection and analysis of data on the environmental situation to provide information support in making various management decisions. First of all, we are talking about the organization of observations and long-term forecasting of the state of environmental quality. The most important practical action in this case is the control and assessment of the state of the environment and the determination of trends in its change (Awange, 2018). Such actions require coordinate-time reference, that is, determining the exact coordinates of the object at a specific point in time in given reference systems. Coordinate-time reference is necessary when monitoring the environment of industrial facilities and infrastructure, forest resources, production waste (garbage dumps, rock dumps), habitats of wild animals, protected areas, as well as critical objects (Bojkov and Peresadko, 2017).

The use of satellite positioning methods for monitoring the environment provides a high level of automation, all-weather application and high accuracy. However, a GNSS receiver requires a line of sight to the satellites it is tracking. In conditions of high urban density or in the presence of terrain features, the signal from the navigation satellite is blocked by objects such as buildings, mountains, bridges. In addition, in the range of GNSS operating frequencies, forest tracts are a highly absorbing environment, which leads to a significant attenuation of navigation signals (Andreas et al., 2019). A possible solution to these problems is for the receiver to track more than one constellation of GNSS satellites.

At present, when assessing positioning accuracy typically measurements of only two GNSS GLONASS and GPS are used since they are fully deployed and used everywhere. Using signals from China’s rapidly developing BeiDou navigation system, which has been providing global services since the end of 2018, can improve positioning accuracy. Interest in using BeiDou in the Russian Federation is steadily growing. In November 2018, the Government of the Russian Federation and the Government of the People’s Republic of China signed an “Agreement on cooperation in the use of global navigation satellite systems GLONASS and BeiDou for peaceful purposes”, and at the beginning of October 2021, Russia and China agreed on the integration of satellite systems GLONASS and BeiDou.

The above leads to the need to develop a simulation model of coordinate-time reference for GLONASS/GPS/BeiDou GNSS, which will be used to plan environmental monitoring sessions in a specific location, including obscuration and attenuation of navigation signals in the forestland.

In this paper, we consider the problem of obscuration and attenuation of GNSS signals in a forestland with coordinate-time reference of environmental monitoring.

The main contributions of the study are: (1) a method that to consider the influence of obscuration and signal attenuation in a forestland; (2) simulation model of the coordinate-time reference of environmental monitoring using GNSS GLONASS/GPS/BeiDou signals that includes the obscuration or attenuation of GNSS signals in the forestland; (3) comparative evaluation of obscuration and attenuation of navigation signals in the forestland for combined GLONASS/GPS and GLONASS/BeiDou modes.

2. RELATED WORK

The problem of the accuracy of the coordinate-time reference of environmental monitoring is an actual problem. For example, (Padró et al., 2019) studies the accuracy of georeferencing methods for environmental monitoring using GNSS data for satellite remote sensing. Several positioning methods are considered, including direct and indirect georeferencing. However, only two main GNSS GPS and GLONASS are considered in the work. The georeferencing of unmanned aerial vehicle (UAV) images was also considered in (Rabah et al., 2018). However, there is no comparison of various combined modes of operation of GNSS in the work, and the main emphasis is on a comparison of traditional and satellite methods. In addition, in these works, there is no verification of the conditions for obscuration GNSS signals and attenuation in the forestland.

Typically, only one of the factors influencing the accuracy of coordinate-time referencing (positioning) is considered in the

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framework of research. For example, in (Tomaštík and Varga, 2021) investigated the influence of vegetation on the accuracy of coordinate-time determinations and evaluated the possibility and accuracy of positioning at three different observation sites (absence, partial and full crown of trees). A multi-constellation GNSS was used in the work, however, a study by vegetation type and season was not conducted. In (Hoi-Fung et al., 2020) the study is devoted to the problem of accurate positioning in high urban density. The effects of multipath and out-of-sight reception from surrounding buildings were considered. Multi-GNSS receivers capable of tracking GPS, GLONASS, Galileo and BeiDou satellites were selected for testing. The attenuation of the signal in the forestland was not considered.

Research is currently underway to assess the positioning accuracy of multi-system GNSS (Fei et al., 2017, Topal and Akpinar, 2022), but they focus on combinations of GNSS operating modes and do not study the influence of these factors.

3. MATERIALS AND METHODS

The simulation model of the coordinate-time reference of environmental monitoring includes the determination of the visible constellations GLONASS / GPS / BeiDou according to the GNSS almanacs, that to consider the obscuration or attenuation of navigation signals in the forestland. The general scheme of the model is shown in Figure 1.

To calculate the coordinates of the satellite constellations of the simulation model, the current GLONASS/GPS/BeiDou almanacs are required. During the simulation, the GLONASS and GPS almanacs were obtained from the Internet resource www.glonass-iac.ru - "Information and Analytical Center for Coordinate-Time and Navigation Support". Almanacs of the BeiDou system were obtained from the Internet resource http://www.csno-tarc.cn - "Test and Assessment Research Center of China Satellite Navigation Office".

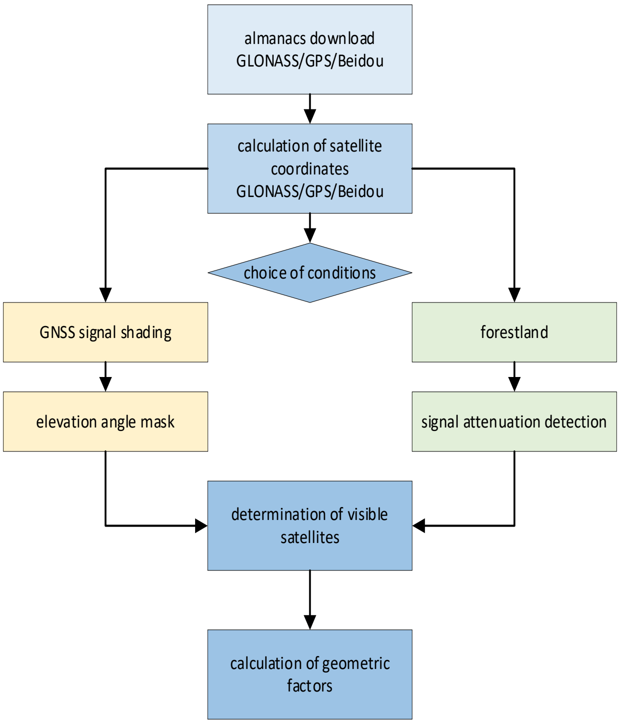

Figure 1: General scheme of the simulation model

After determining the coordinates of the satellites, the modeling conditions are selected: signal obscuration or signal weakening in the forest.

3.1 Receiver antenna obscuration

In the simulation model, the antenna obscuration conditions were determined based on geometric calculations (Andreaset al., 2015) of the relative position of the receiver antenna and obstacles (Figure 2).

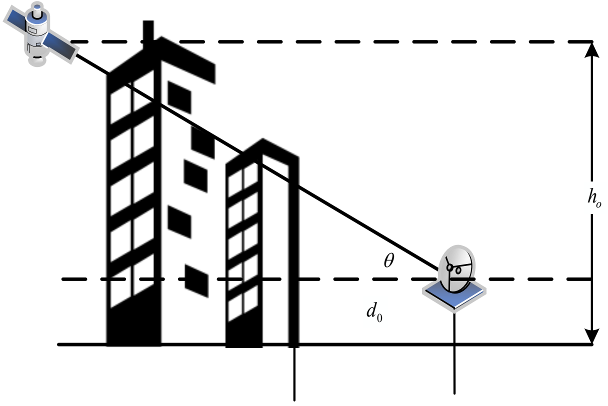

Figure 2: Antenna obscuration

where: $d_o =$ obstacle - GNSS antenna distance;
$h_o =$ obstacle height;
$\theta =$ satellite elevation angle.

Two obscuration options were considered: (1) medium obscuration; (2) strong obscuration. The value of the elevation mask for satellites located in the direction of obstacles is shown in Table 1.

Obscuration option	descriptions	h_o, m	d_0, m	θ, degress
1	medium	30	100	15
2	strong	600	500	30

Table 1: Value of the elevation mask

It should be noted that in dense urban areas, the multipath effect also has a great influence. A large number of experimental studies have shown a large spread in the values of the ranging error due to multipath (Vagle et al., 2016). When using multibeam antennas, the multipath error is 0.5 - 2 m. In high urban density with high-rise buildings, the multipath error can reach 100 m. The use of receivers with narrow-band correlators in this case makes it possible to reduce the error by an order of magnitude. In the simulation model, the multipath error value was taken into account as an additional pseudo range measurement error and was determined as a random value with a standard deviation of 20 m.

3.2 Signal attenuation in a forestland

The navigation signal when passing through the forest is further attenuated by vegetation. Such a weakening of the signal is an important factor in monitoring the environment of forest resources, protected areas, and habitats of wild animals.

Figure 3 shows a typical radio path of a satellite signal received by a receiver antenna located in a forest area.

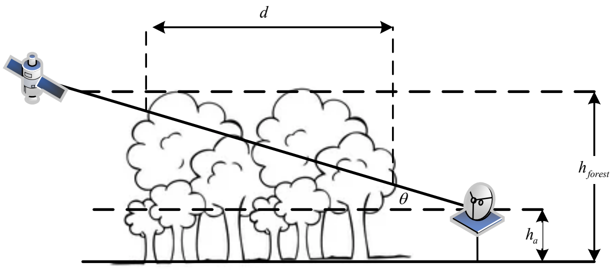

Figure 3: Typical radio path of a satellite signal in a forest area.

where: $d =$ path length with vegetation;
$h_a =$ GNSS receiver antenna height;
$h_{forest} =$ average forest height;
$\theta =$ satellite elevation angle.

The attenuation of the signal during the passage of the navigation signal through the forestland was defined as (Recommendation ITU-R P.833-10):

$$L = Af^B \log_{10}(d)\left(\theta + E\right)^G - 4 \tag{1}$$

where: $L =$ signal attenuation (dB);
$f =$ frequency signal transmitted (MHz);
$\theta =$ elevation angle (degrees);
$A, E, G =$ parameters determined empirically.

The parameter in (1) shows the effect of seasonal characteristics on signal attenuation and is determined by the relation (for points located in the North Hemisphere):

$$B = \frac{0.30281 - 0.003624\left|month - 6.5\right|}{\left(0.001f\right)^{0.0013118 - 0.026236\left|month - 6.5\right|}} \tag{2}$$

where: $month =$ current month (1, 2, 3, …, 12).

For modeling monitoring points located in the Southern Hemisphere (2) will have the following form:

$$B = \frac{0.30281 - 0.003624\left(6 - \left|month - 6.5\right|\right)}{\left(0.001f\right)^{0.0013118 - 0.026236\left(6 - \left|month - 6.5\right|\right)}}. \tag{3}$$

The parameters in (1) are determined empirically and depend on the type of forestland. In this paper, two types of forestlands were considered: (1) deciduous falling forest; (2) coniferous evergreen forest. For these types, the following parameter values were defined (Table 2).

Types of forest	Description	A	E	G
1	deciduous falling	0.187	0.01	-0.12
2	coniferous evergreen	1.5	0.01	-0.12

Table 2: Types of forestlands

The length of the navigation signal path in the forestland is determined as (Makarov et al., 2019):

$$d = \frac{\left(h_{forest} - h_a\right)\cos(\theta)}{\cos(\theta)\sin(Az)} \tag{4}$$

where: $d =$ path length with vegetation;
$h_a =$ GNSS receiver antenna height;
$h_{forest} =$ average forest height;
$\theta =$ satellite elevation angle;
$Az =$ satellite azimuth angle.

The attenuation of the signal when passing through the forestland, determined using (1), is a criterion for determining the visibility of the satellite.

In the simulation model under consideration, it was assumed that with an additional attenuation obtained using (1) of more than 18 dB, the signal is not used to solve the navigation problem.

4. RESULTS AND DISCUSSION

Simulation was carried out using the presented simulation model. The following options for the conditions of coordinate-time referencing in environmental monitoring were considered: (1) obscuration of GNSS signals; (2) attenuation of GNSS signals when passing through a forestland.

Various combinations of GNSS operating modes were considered (Table 3).

number	GNSS
1	only GLONASS
2	GLONASS/GPS
3	GLONASS/BeiDou
4	GLONASS/GPS/BeiDou

Table 3: Combinations of GNSS operating modes

4.1 Modeling under conditions of GNSS signal obscuration

For each of the GNSS collaborative modes under consideration, the following receiver antenna obscuration scenarios were simulated: (1) no GNSS receiver antenna obscuration, no multipath effect, the elevation mask is 0 degrees; (2) average obscuration of the GNSS receiver antenna (presence of high structures), there is a multipath effect, the elevation mask is 15 degrees; (3) strong obscuration of the GNSS receiver antenna (high-rise buildings, narrow mountain gorges), there is a multipath effect, the elevation mask is 30 degrees.

In a comparative analysis, the number of visible satellites and position dilution of precision (PDOP) were estimated. The position dilution of precision in the simulation model is calculated as:

$$PDOP = \sqrt{D_{xx} + D_{yy} + D_{zz}} \tag{5}$$

where $Dxx, Dyy, Dzz =$ matrix elements D.

The matrix is a covariance matrix, which is determined on the basis of the gradient matrix of the coordinates of the navigation satellites according as:

$$D = \left(G^T G\right)^{-1} \tag{6}$$

$$G = \begin{Vmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\gamma_1 & 1 \\ \cos\alpha_2 & \cos\beta_2 & \cos\gamma_2 & 1 \\ \dots & \dots & \dots & \dots \\ \cos\alpha_N & \cos\beta_N & \cos\gamma_N & 1 \end{Vmatrix} \tag{7}$$

где $\alpha_i, \beta_i, \gamma_i =$ angles of the line of sight "GNSS receiver antenna - satellite";
$N =$ number of visible satellites.

The angles of the line of sight are determined as:

$$\cos\alpha_i = \frac{x_a - x_i}{\sqrt{(x_a - x_i)^2 + (y_a - y_i)^2 + (z_a - z_i)^2}}$$
$$\cos\beta_i = \frac{y_a - y_i}{\sqrt{(x_a - x_i)^2 + (y_a - y_i)^2 + (z_a - z_i)^2}} \quad (8)$$
$$\cos\gamma_i = \frac{z_a - z_i}{\sqrt{(x_a - x_i)^2 + (y_a - y_i)^2 + (z_a - z_i)^2}}$$

where $x_a, y_a, z_a =$ receiver antenna coordinates;
$x_i, y_i, z_i =$ satellite coordinates.

The simulation was carried out for a time interval of 24 hours from the beginning of the day with a step of 15 minutes.

The results showed that when using only GLONASS signals for coordinate-time determinations with an average signal obscuration, the number of satellites decreases (Figure 4), and PDOP increases (Figure 5), which indicates a deterioration in the spatial arrangement of satellites.

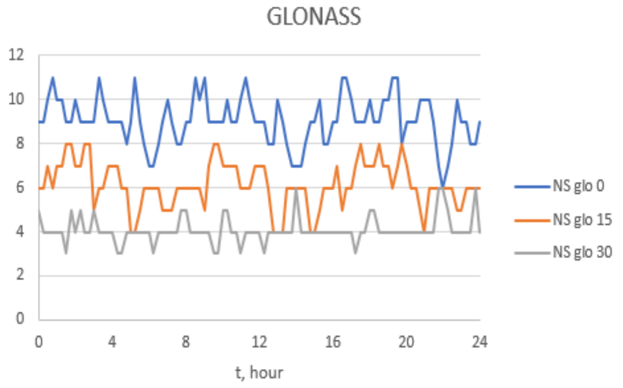

Figure 4: Number of visible satellites GLONASS

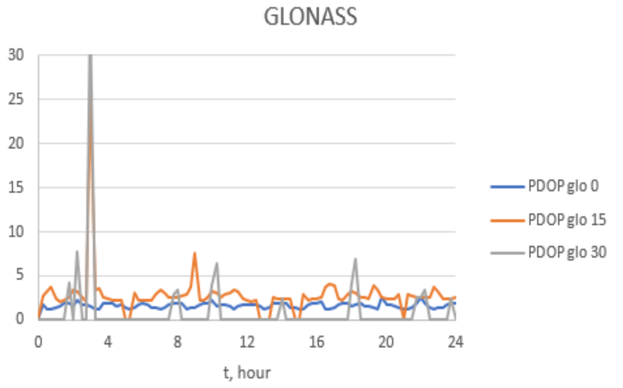

Figure 5: PDOP GLONASS

With strong obscuration of GNSS signals, the number of satellites is significantly reduced, which leads to the impossibility of calculating the geometric factor in some time intervals. The period of lack of navigation was approximately 2 hours per day.

For other operating modes, there is an obvious decrease in visible satellites in the presence of obscuration and a deterioration in the spatial arrangement of satellites (Figure 6, 7). Moreover the use of all three GNSS signals gives the best PDOP values (PDOP = 1-3), which leads to an increase in the accuracy of the position-time reference. The GLONASS/BeiDou combination showed better accuracy and PDOP (PDOP = 1.5-2.5) than the GLONASS/GPS (PDOP = 1.5 - 3) combination.

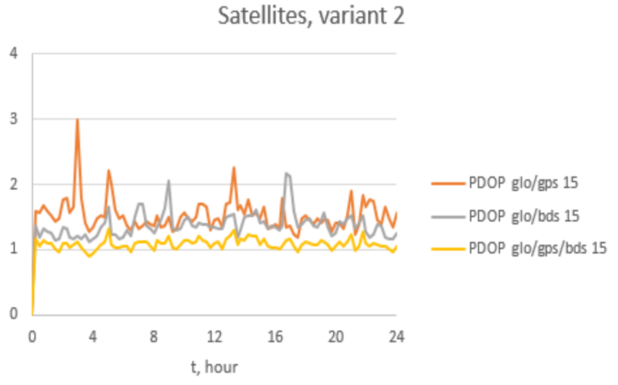

Figure 6: PDOP combinations of GNSS

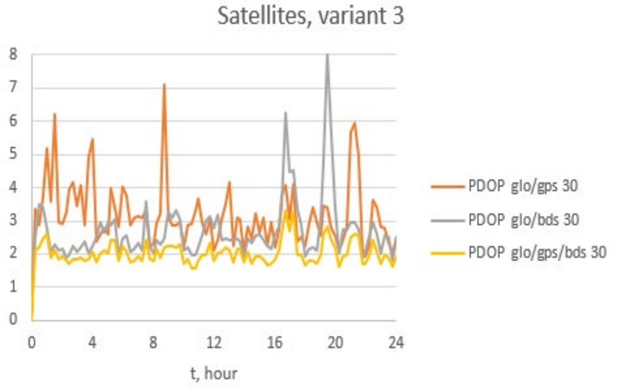

Figure 7: PDOP combinations of GNSS

Also, for a comparative assessment of the accuracy of coordinate-time determinations during the obscuration of GNSS signals, statistical modeling was carried out and the root-mean-square (RMS) deviations of the errors in measuring the latitude σ_B (Figures 8, 9) and height σ_h (Figures 10, 11) were obtained.

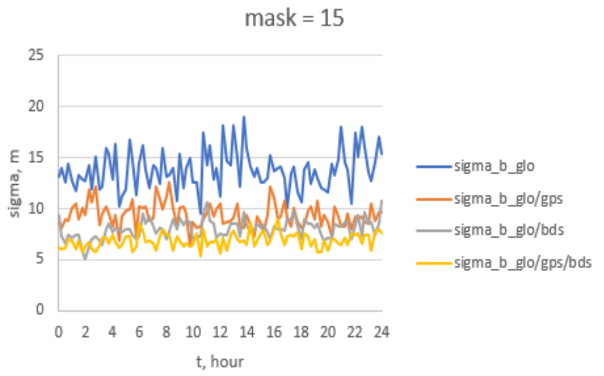

Figure 8: Root-mean-square deviations of the errors in measuring the latitude

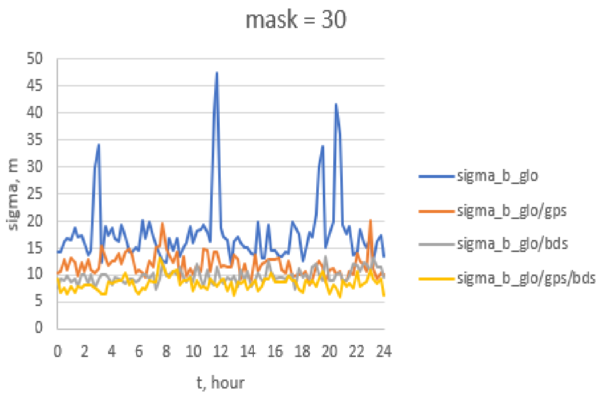

Figure 9: Root-mean-square deviations of the errors in measuring the latitude

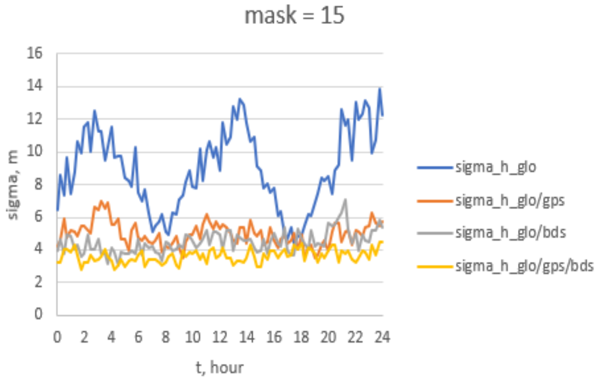

Figure 10: Root-mean-square deviations of the errors in measuring the height

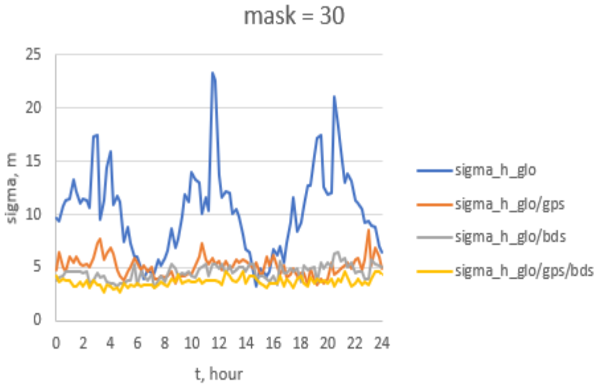

Figure 11: Root-mean-square deviations of the errors in measuring the height

The results of a comparative analysis of the measurement errors GNSS operating modes are presented in Table 4.

GNSS	σ_B , m		σ_h , m	
	15^0	30^0	15^0	30^0
only GLONASS	13.8	17.8	8.9	9.6
GLONASS/GPS	9.3	11.8	4.9	5.1
GLONASS/BeiDou	8.1	9.8	4.4	4.5
GLONASS/GPS/BeiDou	6.8	8.4	3.6	3.6

Table 4: Root-mean-square deviations of the errors in measuring

4.2 Simulation under conditions of GNSS signal passing through the forestland

Modeling was carried out to compare the attenuation of navigation signals for two types of forests: (1) deciduous falling and (2) coniferous evergreen. Two GNSS combinations were considered: GLONASS/GPS; GLONASS/BeiDou. The results were obtained for two seasons: spring (March); autumn (September).

The results showed that the presence of vegetation significantly reduces the number of satellites in the processing of the GNSS receiver for two types of forest (Figure 12). This worsens the PDOP (Figure 13) and, accordingly, reduces the accuracy of the coordinate-time reference.

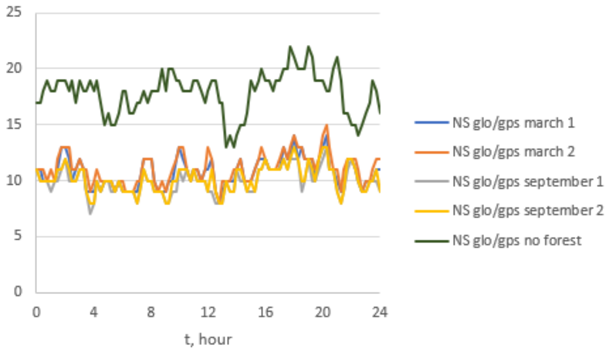

Figure 12: Number of visible satellites for two types of forests

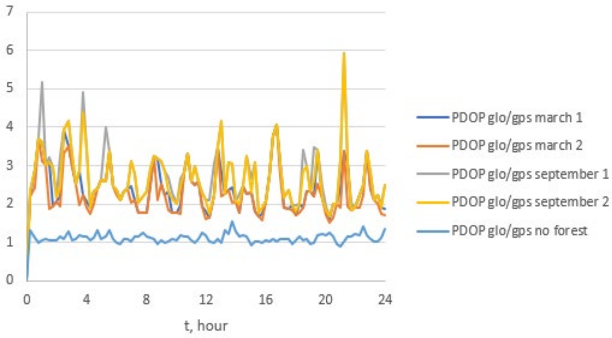

Figure 13: PDOP for two types of forests

Studies have shown that the type of forest area also affects the number of satellites in the working constellation (Figure 14) and PDOP (Figure 15).

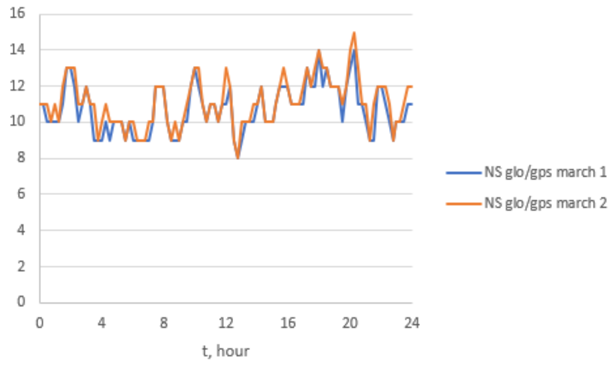

Figure 14: Number of visible satellites for two types of forests

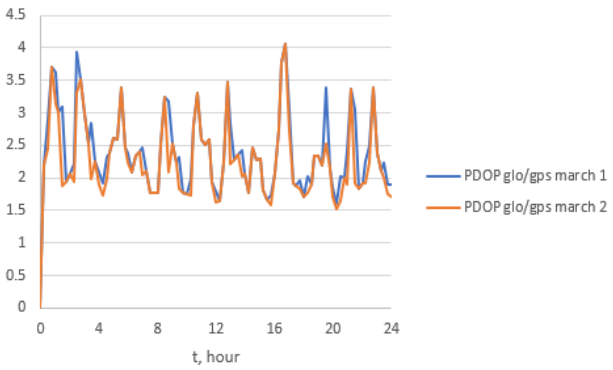

Figure 15: PDOP for two types of forest

It can be seen that the navigation signal is attenuated more strongly in deciduous forests than in coniferous forests, which reduces PDOP and the accuracy of determinations.

The attenuation of the signal due to vegetation depends not only on the type of array, but also on the season when the coordinate-time reference of environmental monitoring is carried out.

For example, below are graphs of the number of satellites for the two considered seasons for a deciduous falling forest (Figure 16) and a coniferous evergreen forest (Figure 17) for the GLONASS/GPS.

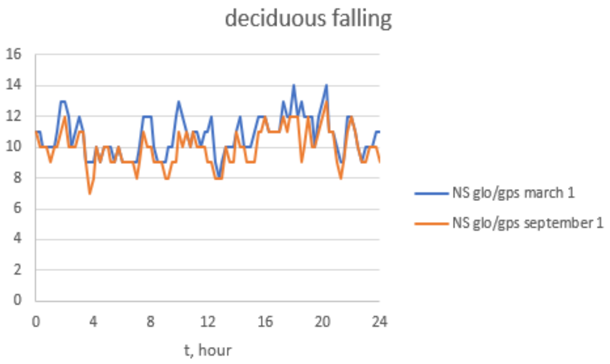

Figure 16: Number of visible satellites for a deciduous falling forest

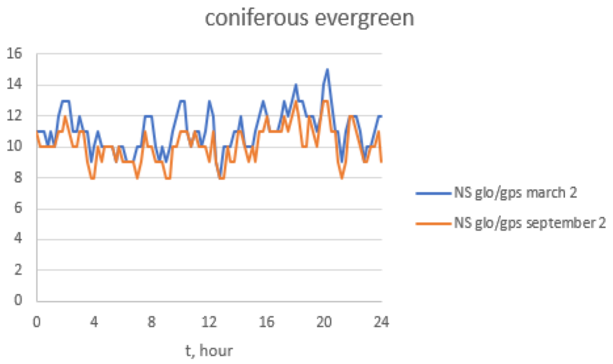

Figure 17: Number of visible satellites for the coniferous evergreen forest

In the autumn period vegetation has a greater effect on signal attenuation, which reduces the number of satellites and leads to a noticeable violation of the constellation geometry (Figures 18, 19).

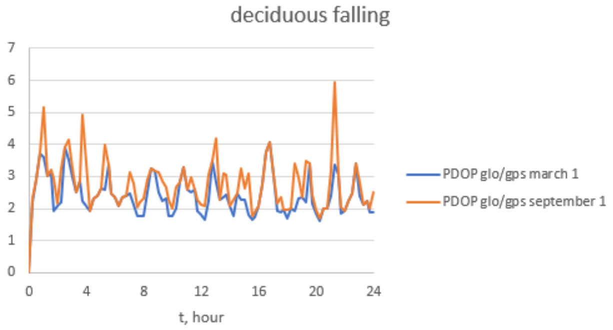

Figure 18: PDOP for a deciduous falling forest

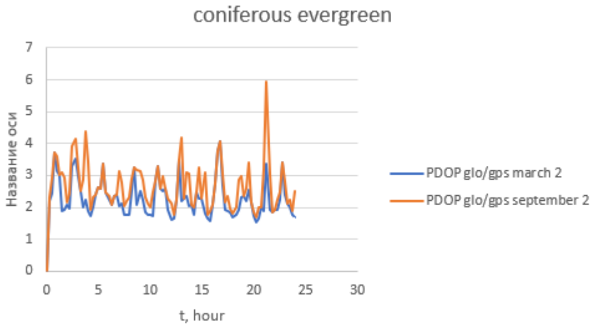

Figure 19: PDOP for the coniferous evergreen forest

A study was also carried out comparing the number of visible satellites and PDOP for GLONASS/GPS with and GLONASS/BeiDou. The results showed that GLONASS/BeiDou ensures the availability of more satellites (Fig. 20, 21) in the considered forest types, which gives significantly better PDOP values (Fig. 22, 23).

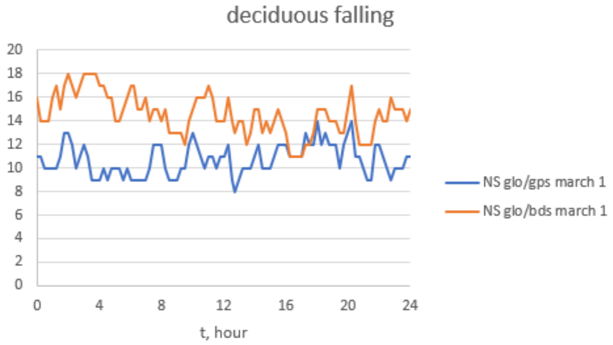

Figure 20: Number of visible satellites for a deciduous falling forest

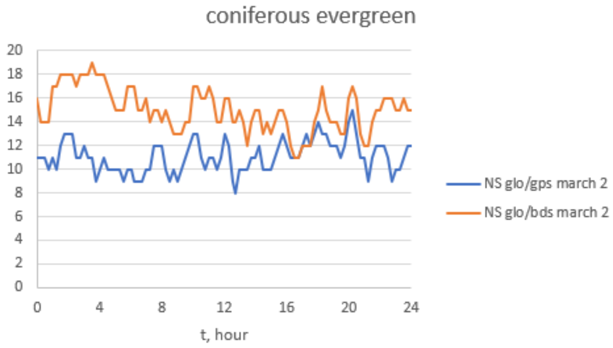

Figure 21: Number of visible satellites for the coniferous evergreen forest

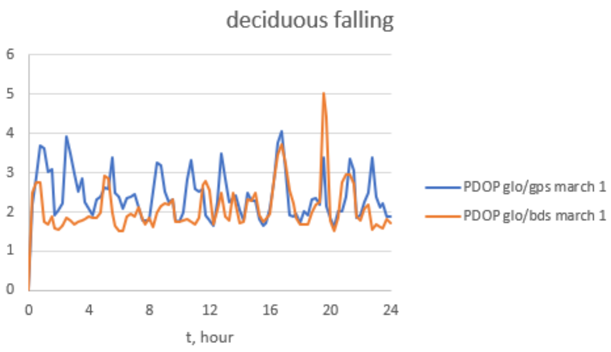

Figure 22: PDOP for a deciduous falling forest

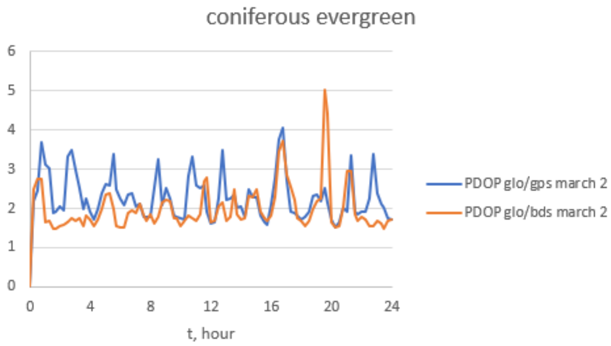

Figure 23: PDOP for the coniferous evergreen forest

5. CONCLUSION

The technique for analysis of factors, that influences on the accuracy of GNSS-based geo-referencing is proposed. It is based on the simulation model for the coordinate-time reference of environmental monitoring using GNSS GLONASS/GPS/BeiDou signals has been developed. The model considers the obscuration of GNSS signals and the effect of forestland on signal attenuation. The model implements three navigation systems, which makes it possible to conduct research for various combinations of GNSS.

The analysis of the obtained results showed that the GLONASS/BeiDou gives better results in comparison with the GLONASS/GPS, both when obscuration signals (reducing the RMS by 1-2 m) and taking into account signal attenuation in a forest area (improving the value PDOP by about 35%). The use of GLONASS/GPS/BeiDou systems makes it possible to improve the accuracy of coordinate-time references in environmental monitoring by approximately 25%.

In further research, it is planned to supplement the model with data for modeling signal attenuation in different types of forests, such as subtropical, mixed, and others. It is also supposed to add a more complete obscuration model including the geometries of the considered coordinate-time reference points.

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