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Study of the Possibility to Provide PNT Service to Users by Processing Signals from Quasars and Navigation Satellites in a Relocatable Radio Interferometer

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Abstract: A method is proposed for position, navigation and timing (PNT) support based on instant measurements of signals from the global navigation satellite system GLONASS and quasars in radio interferometry systems with very long baseline formed by relocatable small-sized radio telescopes (SRT) whose location is to be updated. This composition of signal sources and the possibility to relocate the SRT to form the radio interferometer's baseline increase the PNT process stability. The proposed approach relies upon the radio interferometry used for precision positioning of a user according to the coordinates estimation and the SRT time reference, with simultaneous coordinate referencing of the base telescope. It is assumed that in the radio interferometer formed in this manner, both positions do not have precision coordinate references, and the time scale of one of the telescopes, formed by the local standard, needs to be matched and updated regularly. This method can be useful when providing the PNT support to special users whose location has no essential infrastructure.

Keywords: GLONASS, navigation satellite, very long baseline interferometry (VLBI) systems, positioning, small-sized radio telescopes (SRT), relocatable SRT, quasars.

INTRODUCTION

Currently, the positioning of a wide class of users is based on the navigation data obtained using the signals of the GLONASS global navigation satellite system (GNSS) [1, 2, 12]. To ensure more stable PNT service under harsh conditions, it is proposed to arrange for joint reception and processing of signals from quasars and GLONASS satellites in relocatable SRT within a very long baseline interferometry (VLBI) system. It should be noted that the ultra-long baseline should not be understood as a baseline with an arbitrary length for a current survey; the SRT forming this baseline should receive signals simultaneously from a certain number of the same emitters: GNSS satellites and quasars.

This technology has recently become feasible due to the technical possibility to reduce the SRT antenna mirror diameter down to several meters. However, this would inevitably decrease the useful area of the arrays and lead to attenuation of signals which are already weak. Solving the navigation problem of PNT provision for remote users in the current situation, and new approaches aimed at finding a solution that would be appropriate in terms of accuracy in the problem space, taking into account the increasing influence of the GNSS constellation geometry, are the subject matters of this article.

REVIEW OF VLBI OPTIONS FOR RELOCATABLE SRT POSITIONING

Relocatable SRT [13–15] employing the interferometry baseline with changeable topology can be recommended as an alternative method for determining the position of a user at a peripheral location with poor technical infrastructure. The measured parameter of radio signal is the time delay of its reception on one SRT relative to another one from GLONASS satellites observed simultaneously, and from extragalactic sources, i.e. quasars. The proposed method improves the stability of the user's navigation measurements while maintaining the required positioning accuracy.

Large radio telescopes provide reliable reception of signals from weak sources, but their operation is not covert enough to solve the coordinate-related problems at modern level. However, the main reason for which they are not used as an alternative PNT method is that they cannot be operated at relocatable positions to form the radio interferometry baseline. Therefore, in recent years the movable SRT structures have been designed for applying the PNT technologies at remote locations with poor infrastructure or where the position needs to be refined.

Since the SRT with a small diameter are definitely less sensitive, this should be compensated by certain engineering solutions in the observation data processing systems: increased bandwidth, reduced gain-to-noise temperature in the feeder circuits, and improved algorithms for observation data processing [3].

In the Russian Federation, the research on the development of relocatable small-sized VLBI systems is currently in progress at the Institute of Applied Astronomy of the Russian Academy of Sciences [3–5].

Previously [10], the authors considered the problem of determining the position of the phase center of a relocated slave (movable) SRT antenna at an arbitrary point of the Earth surface, based on the quasars' signals observed in the VLBI system. This was done by solving a reverse navigation problem with assumingly known position of the master (non-movable) telescope [6–11]. This approach is attractive due to the use of natural radio signal sources, which increases the stability of navigation solutions. In addition, the SRT mirror antennas have a high directivity, and there are no critical requirements for the PNT support.

If it is proposed to use a technology of radio interferometry observations where both the slave and the master SRT can change their locations, the question of achievable positioning accuracy of both SRT compared to the fixed option will naturally be of applied interest, since in the latter case the error is known to be at the level of several millimeters in particular situations [10]. The studies conducted by the authors regarding the use of measurements with one relocatable SRT are presented in [10, 15]; the mathematical simulation has confirmed the achievable accuracy of the SRT phase center positioning with a root-mean-square error (RMSE) not exceeding 10 cm in the worst conditions.

At the same time, for certain situations when there is the need to improve the geometric factor in the PNT task for a number of users, for example, in the Arctic region, it is necessary to ensure a change in the radio interferometer baseline location. This will require simultaneous refinement of the coordinates of both relocatable SRT.

Indeed, in the Arctic zone, in the latitudes higher than 75°, the stability of navigational sighting process of the GLONASS user reduces due to the configuration features of the orbital constellation and due to the insufficient number of control and correction stations (they cannot be put in place due to the underdeveloped infrastructure and natural features of the region).

Let us consider the ways to achieve the required quality indicators of user's PNT, taking into account the limitations mentioned above. As has been confirmed by research, when using the accepted measurement function model, processing the signal parameters of quasars only makes it possible to specify only the size of the interferometry baseline, while the desired SRT state vector is not observable. In this regard, it is proposed to use the GLONASS satellites' signals as a source that increases the information content of measurements, and correspondingly, to jointly process the measurements of signal parameters from satellites and from extragalactic objects, i.e. quasars.

MATHEMATICAL MODEL OF SRT POSITIONING

Let us consider a method for clarifying the coordinates of a relocatable SRT by determining the time difference between the arrival of signals from one or more quasars and satellites at two SRT that form the base for interferometric measurements in space (Fig. 1).

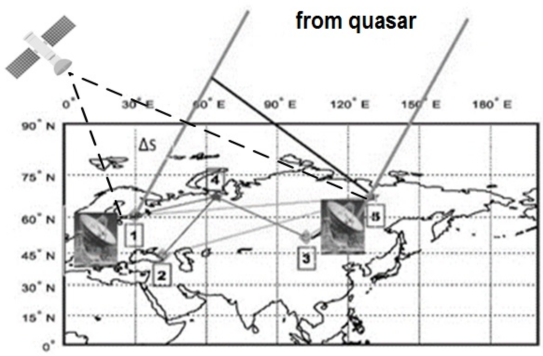

Fig. 1. An example of SRT location in VLBI system.

Based on sequential VLBI system observations of quasar and satellite signals, the current coordinates of both SRT can be calculated. Knowing these coordinates and the length of the interferometry baseline, one can synchronize the frequency and time scales of the slave and the master SRT standards by adding the time scale drift value of the slave SRT in the vector of estimated parameters.

In Fig. 1, points 1, 2, 3 are the SRT positions in the existing Quasar-KVO system, and points 4, 5 are the positions studied in the simulation of the relocatable SRT placement options.

The signals from quasar and satellite reach the SRT antenna located at position 1 (2, 3) with a delay τ relative to the SRT antenna at position 4 (5); τ is caused by the path difference $\Delta S = c\tau$, where c is the assumed speed of radio waves propagation.

The delay τ is measured using the correlation method. The signals $S(t)$ and $S(t+\tau)$ recorded on the SRT 4 (5) and 1 (2, 3) are processed in a software-based correlator [3] the output of which is a correlation function with the maximum at a value of τ corresponding to the actual delay in signal propagation to the SRT 1 (2, 3) relative to the SRT 4 (5).

An example of the correlation function of signals $S(t)$ and $S(t+\tau)$ is shown in Fig. 2 [15].

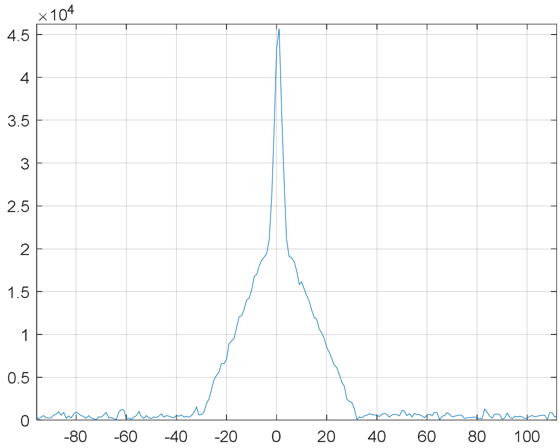

Fig. 2. Example of the correlation function of signals $S(t)$ and $S(t+\tau)$.

Below is a simplified mathematical description of the navigation function of measurements performed in the VLBI system using quasars and GLONASS satellites. Delay τ_i in the signal propagation from the i-th quasar to one SRT relative to another SRT can be described by the expression:

$$\tau_i = \frac{1}{c}\left(\cos\delta_i((x_1 - x_2)\cos(\alpha_i - \omega t) + (y_1 - y_2)\sin(\alpha_i - \omega t)) + (z_1 - z_2)\sin\delta_i\right),$$

where ω is the Earth's angular rate; x_1, y_1, z_1 are the coordinates of SRT 1 (assumed to be the master one); x_2, y_2, z_2 are the coordinates of SRT 2 (assumed to be the slave one); α_i, δ_i are the angles of the signal source's elevation and declination, respectively.

The signal records in the SRT are linked to the local time scale.

The time delay t_{Sat} of the signal propagation from GLONASS satellite to SRT 1 and 2 can be represented in a simplified form by the following relation:

$$t_{\text{Sat}} = \frac{1}{c}\left(\sqrt{(x_{\text{Sat}} - x_1)^2 + (y_{\text{Sat}} - y_1)^2 + (z_{\text{Sat}} - z_1)^2} - \sqrt{(x_{\text{Sat}} - x_2)^2 + (y_{\text{Sat}} - y_2)^2 + (z_{\text{Sat}} - z_2)^2}\right),$$

where x_{Sat}, y_{Sat}, z_{Sat} are the GLONASS satellite coordinates.

The SRT positioning error ΔR can be determined by the formula:

$$\Delta R = \sqrt{(x_{\text{est}} - x_{\text{true}})^2 + (y_{\text{est}} - y_{\text{true}})^2 + (z_{\text{est}} - z_{\text{true}})^2},$$

where x_{est}, y_{est}, z_{est} are the estimated coordinates of the SRT; and x_{true}, y_{true}, z_{true} are its true coordinates.

The Monte Carlo statistical test method with 100-1000 realizations of noise within the measured parameters was used to generate stochastic estimates of the navigation solution accuracy.

RESULTS OF STATISTICAL ESTIMATION OF SRT COORDINATES

Studies have shown that simultaneous positioning of two SRT based on the measurements of signal parameters of quasars only is characterized by a lack of observability.

To make this problem statement more correct, there should be a more informative scope of measurements.

The graph in Fig. 3 shows the error ΔR_1 of one SRT positioning based on the results of processing the signal parameters from two GLONASS satellites, depending on the time of their observation for the RMSE of delay measurements being $\sigma = 10^{-11}$ s. Here and in the following figures, the abscissa axis is the time of quasars and/or satellites observation (X–coordinate), and the ordinate axis is one SRT positioning error (Y-coordinate) (the values of ΔR_1 and ΔR_2 are actually of the same order of magnitude).

Figure 4 shows a graph of the SRT positioning error ΔR_1 versus the observation time, based on the measurements of signal parameters from six quasars and GLONASS satellite ($\sigma = 10^{-11}$ s).

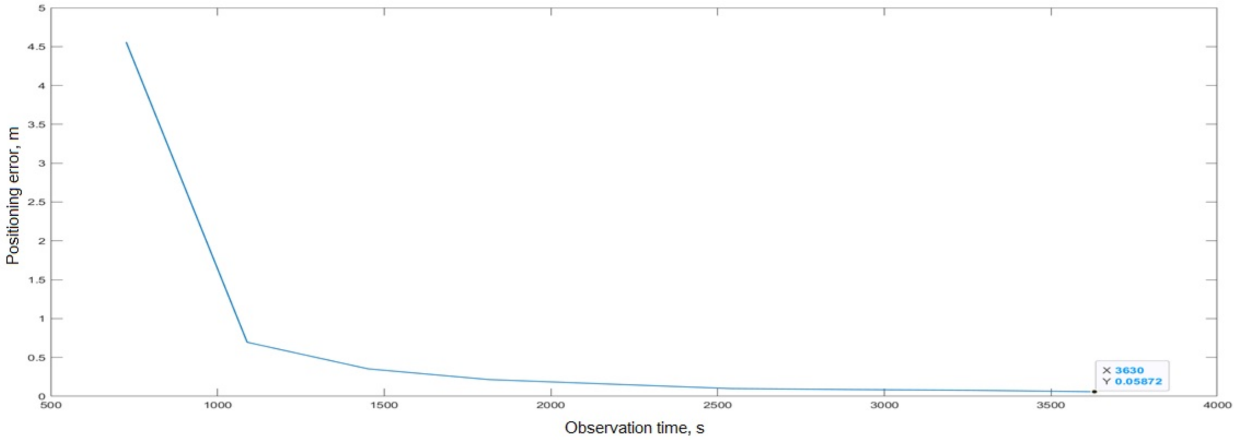

Fig. 3. The SRT positioning error ΔR_1 based on the results of processing signals from two GLONASS satellites, $\sigma = 10^{-11}$ s.

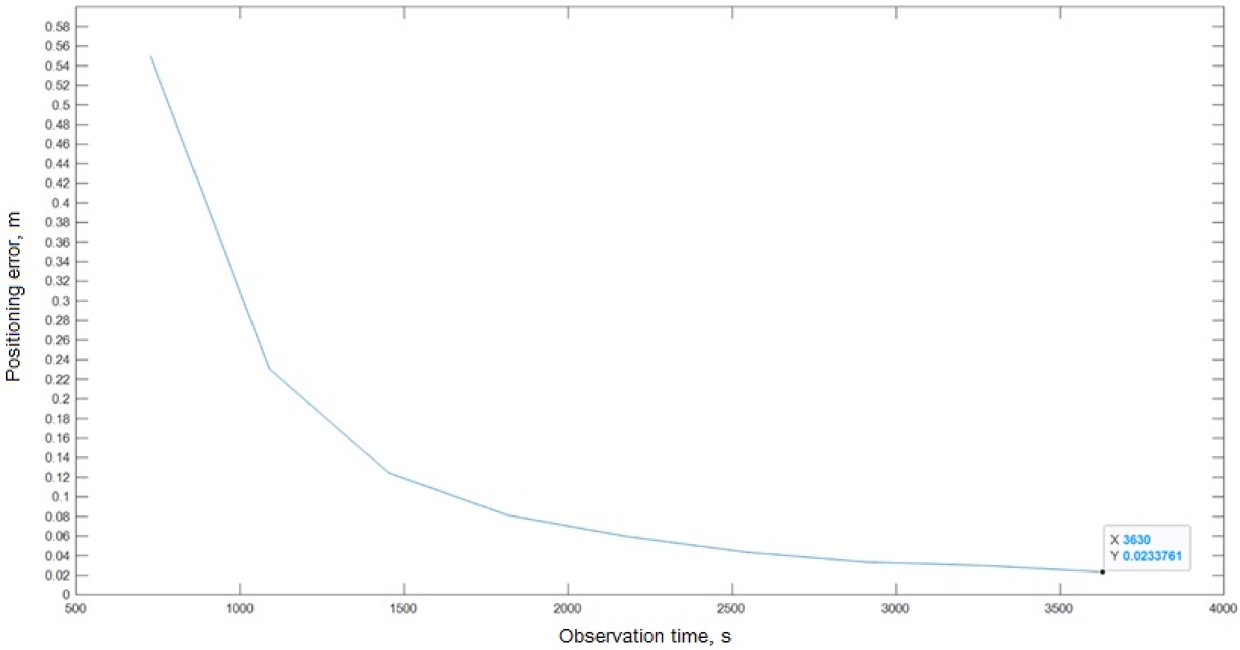

Fig. 4. The SRT positioning error ΔR_1 based on the observation of signal parameters from six quasars and GLONASS satellite, $\sigma = 10^{-11}$ s.

The simulation results show that the iterative process in the problem of coordinates refinement for two SRT at a time converges significantly faster and with higher accuracy when using combined measurements of satellite signal and quasar radiation parameters, in which case the accuracy reaches 2–3 cm per one hour of observations.

The problem of user PNT support can also be solved using only the GLONASS satellite signals; however, due to the additional VLBI measurements of quasar signals, the coordinates of both SRT can be determined faster and the same accuracy can be achieved within a shorter time of satellites observation.

Additionally, simulation with a systematic (constant) measurement error has been performed. This error does not take into account the real properties of changing errors in radiotechnical measurements, such as ionospheric and tropospheric delays and errors in the knowledge of satellite ephemeris, but it provides a more adequate estimation of positioning accuracy.

Figure 5 shows a graph of SRT positioning error depending on the observation time, based on the results of measurements of signal parameters from two GLONASS satellites with a random error of $\sigma = 10^{-10}$ s and with a residual systematic error from 0 to 10 cm in measuring the range.

Figure 6 shows a graph of similar dependence of ΔR_1 for SRT based on the results of joint measurements of signal parameters from six quasars and two GLONASS satellites.

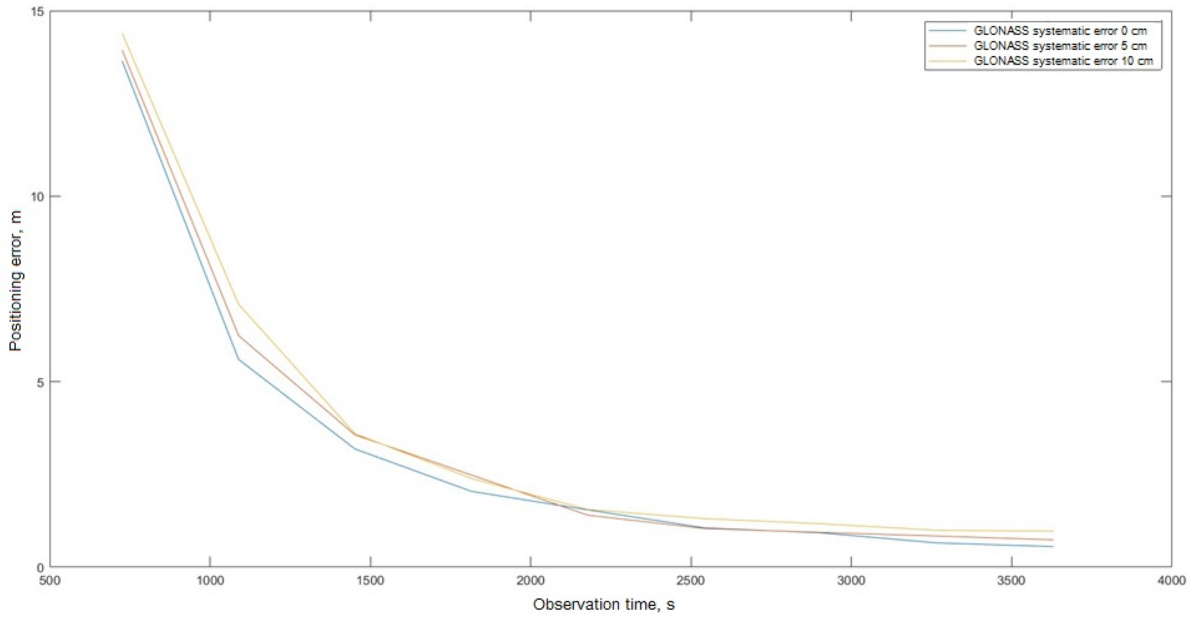

Fig. 5. The SRT positioning error based on the signals from two GLONASS satellites with a systematic measurement error.

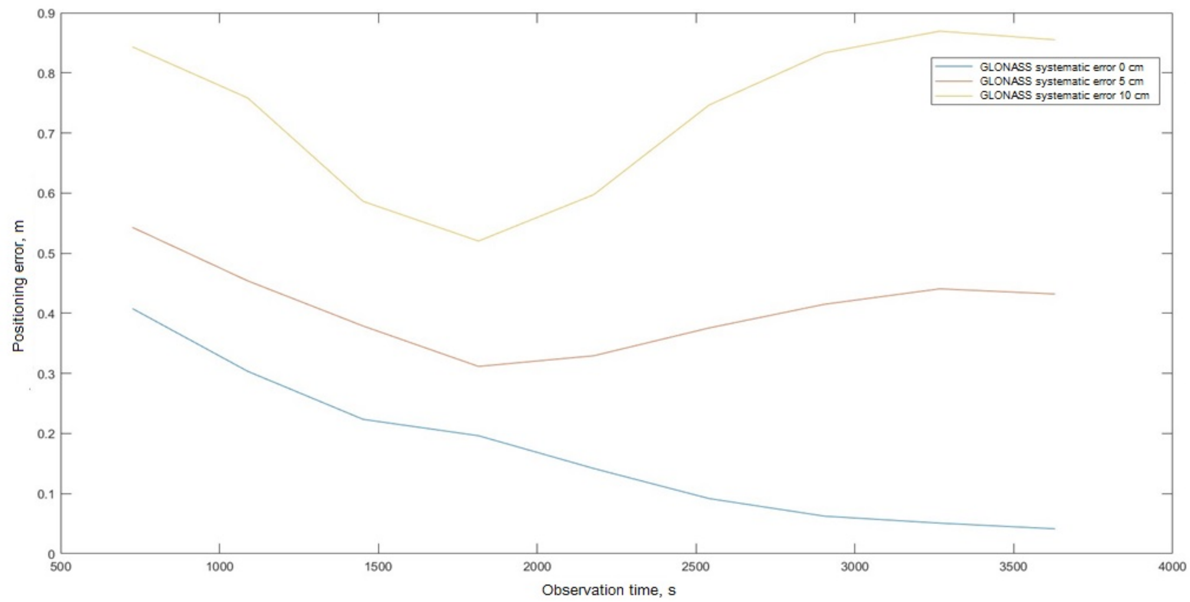

Fig. 6. SRT positioning error ΔR_1 based on observations of six quasars and signals from two GLONASS satellites, taking into account the systematic measurement error.

As can be seen in Figs. 5 and 6, when taking into account the systematic error in measuring the range to the satellite in absolute values up to 10 cm, the errors in determining the coordinates of both SRT by the signals from two GLONASS satellites and six quasars do not exceed 1 m with an observation time interval from 726 to 3630 s (in contrast to the use of satellite signals only).

In the course of the research, the authors have developed simulation software which implements the algorithms for simultaneous PNT of both SRT based on VLBI system observations of radiation from extragalactic sources and GLONASS satellites. The system performs comparative estimation of users positioning accuracy with different sets of the initial measurement data.

CONCLUSIONS

A comparative analysis of PNT methods based on the simulated observations of quasar radiation and GLONASS satellite signals, performed by relocatable VLBI SRT has been carried out. The simulation results show that the proposed PNT method using radio interferometry measurements of the parameters of satellite and quasar signals provides a stable update of the positions of relocatable VLBI SRT over relatively short time intervals.

The advantage of this method is higher reliability of the user positioning process in comparison with GNSS positioning. An important area of advanced research is search for the ways to get rid of the systematic measurement errors, e.g., by using the observation data from additional SRT.

Mathematical simulation has shown that for the average conditions of VLBI observations, the error in the real-time positioning of the SRT and, accordingly, of the user does not exceed several decimeters. This accuracy is quite sufficient for most situations.

CONFLICTS OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Antonovich, K.M., *Ispol'zovanie sputnikovykh radionavigatsionnykh sistem v geodezii* (Use of Satellite Radio Navigation Systems in Geodesy), vol. 1, Moscow: Kartotsentr, 2005.
2. Antonovich, K.M., *Ispol'zovanie sputnikovykh radionavigatsionnykh sistem v geodezii* (Use of Satellite Radio Navigation Systems in Geodesy), vol. 2, Moscow: Kartotsentr, 2005.
3. Ivanov, D.V., Mardyshkin, V.V., Lavrov, A.S., and Evstigneev, A.A., A three-band receiving system for radio telescopes with small antennas, *Trudy IPA RAN*, 2013, no. 27, pp. 197–201.
4. Aleshkin, A.P., Makarov, A.A., and Myslivtsev, T.O., Proposals on the development of a single time scale based on joint data processing of spatially distributed frequency standards, *Trudy IPA RAN*, 2016, no. 37, pp 19–22.
5. Dugin, N.A., Gavrilenko, V.G., Antipenko, A.A., Dement'ev, A.F., Nechaeva, M.B., Tikhomirov, Yu.V., Kalinin, A.V., and Chagunin, A.K., Radio interferometer with independent reception UNN-NIRFI-Irbene. First results, *Vestnik Nizhegorodskogo Universiteta im. N.I. Lobachevskogo*, 2013, no. 1(1), pp. 79–85.
6. Shebshaevich, V.S., Dmitriev, P.P., and Ivantsevich, N.V., *Setevye sputnikovye radionavigatsionnye sistemy* (Network Satellite Radio Navigation Systems), Moscow: Radio i svyaz', 1993.
7. Dulevich, V.E., *Teoreticheskie osnovy radiolokatsii* (Theoretical Fundamentals of Radio Detection and Ranging), study book for higher educational establishments, 2nd Ed., Moscow: Sovetskoe radio, 1978.
8. Gubin, V.A., Klyuev, N.F., Kostylev, A.A., Mel'nikov, B.G., Stepanov, M.G., and Tkachev, E.A., *Osnovy radionavigatsionnykh izmerenii* (Fundamentals of Radio Navigation Measurements), Moscow: The USSR Ministry of Defense, 1987.
9. Aivazyan, S.A., *Prikladnaya statistika. Osnovy ekonometriki* (Applied Statistics. Fundamentals of Econometrics), vol. 2, Moscow: Unity-Dana, 2001.
10. Aleshkin, A.P., Makarov, A.A., Ivanov, D.V., and Ipatov, A.V., The use of mobile long-base radio interferometers to improve stability of navigation and time measurements, *Izvestiya vuzov, Priborostroenie*, 2017, vol. 60, no. 6, pp. 529–537. https://doi.org/10.17586/0021-3454-2017-60-6-529-537.
11. *Parametry Zemli 1990 goda (PZ-90.11)* (Parameters of the Earth 1990 (PZ-90.11)), reference document, Moscow: VTU GSh VS RF, 2014.
12. Makarov A.A., Myslivtsev T.O., Zybin V.V., Kovalev M.A., Vinnik Yu.A. *Ground stationary receiving point of the 3rd accuracy class 14b763*: a methodological manual. St. Petersburg: VKA im. A.F. Mozhaisky, 2013. 91 p.
13. First-generation GNSS modules GLONASS/GPS – 1K-161, K-161. URL: https://rirt.ru/products/moduli-pervogo-pokoleniya-gnss-glonas (cited: 08 July, 2025).
14. Ivanov, D.V., Ipatov, A.V., Gayazov, I.S., Zotov, M.B., Mel'nikov, A.E., Stempkovskii, V.G., Surkis, I.F., and Chernov, V.K., Study of the possibility to use small VLBI systems in the PNT tasks, *Proc. of Conference KVNO-2017 (PNT-2017), St. Petersburg*, April, 2017.
15. National Institute of Information and Communications Technology. URL: http://www.nict.go.jp/en/index.html (cited: 08 July, 2025).
16. Aleshkin, A.P., Zubarev, K.K., Ivanov, D.V., and Makarov, A.A., A method for positioning and timing support of remote users based on mobile radio interferometry, *Gyroscopy and Navigation*, 2020, vol. 11, no. 1, pp. 77–84. https://doi.org/10.17285/0869-7035.0022.
17. Gavrilov, D.A., Zubarev, K.K., Sakhno, I.V., and Surkis, I.F., Prospects of radio interferometry application in space systems for the Earth remote sensing, *Trudy VKA im. A.F. Mozhaiskogo*, 2023, no. 689, pp. 27–37.