Estimation of the Error in Determining the Location of Radio Emission Sources at Satellite Radio Monitoring

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Abstract

The work is devoted to the estimation of errors in determining the coordinates of the location ground-based radio emission sources at satellite radio monitoring. The proposed method of determining the coordinates of the source using angle-measuring methods based on one small spacecraft was chosen as the basis. The measured angular parameters were determined, which affect the accuracy of determining the latitude and longitude of the source. Calculations and analysis of the influence of determining the scanning angles of antennas in different planes on the errors in determining the coordinates of ground sources have been carried out.

The obtained results of error calculations will allow us to determine the requirements for methods and equipment of radio monitoring to ensure a given accuracy in determining the location of ground-based radio emission sources.

Keywords

Radio frequency spectrum, radiomonitoring, radio-electronic means, satellite radio monitoring, source of radio emissions, low Earth orbit satellite, geolocation

1. Introduction

The rapidly growing number of operating radio emission sources and radio networks is significantly complicating the electromagnetic situation in conditions of a shortage of the radio frequency spectrum (RFS) and requires improvement of the functions and mechanisms of the radio monitoring system [1-3]. Currently, there are many approaches and methods to improve the efficiency of using RFCs such as: software defined radio, cognitive radio, dynamic/opportunistic spectrum access, spectrum sharing and licensed/unlicensed spectrum aggregation and so on. All these approaches and methods are aimed at achieving optimal use of the RFS and to improve the functions and mechanisms of the radio monitoring system. The current radio monitoring systems are implemented on the basis of ground-based radio monitoring facilities [4-6]. Using ground-based radio monitoring tools, providing complete, reliable information about the real state of the RFS in a metropolitan area is a difficult task to implement, and managing of RFS across the country is an even more difficult problem.

Thus, one of the obvious ways to solve the problem of increasing the efficiency and expanding the control area of radio monitoring systems is the creation of satellite radio monitoring systems based on low-orbit small spacecraft (SS) [7-9]. Such systems are especially necessary for countries with large territories in order to reduce the digital divide, promote economic growth, social integration and meet consumer demand for new digital economy services and to solve many scientific and technical problems. Thus, satellite technologies provide coverage of large areas despite the difficult terrain and climatic conditions; they are reliable and generally not

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subject to many of the risks that other terrestrial systems and communication networks are exposed to, including factors such as accidental damage, theft, etc. Therefore, such systems should be used in order to increase the efficiency of the radio monitoring system by using satellites as radio monitoring stations [10]. Also in works [11-12], the development of mobile platform that allows studying such a systems using augmented reality technology is considered.

In radio monitoring, a special place is occupied by determining the location of radio emission sources (RES), which is a complex task requiring the use of an automated complex of special equipment with specified technical characteristics to determine the location of the studied radio emission sources with maximum accuracy. Location estimation methods are necessary to determine the location of radio emission sources. In radio monitoring systems, effective methods and algorithms are needed to accurately determine the location of radio emission sources. Currently for determine the location of RES, such methods are known based on the level of the received signal strength (RSS - received signal strength), the phase of the carrier signal (POA - carrier phase of arrival), the time difference of arrival (TDOA), the angle of arrival (AoA) (or the direction of arrival DOA), the frequency difference of arrival (FDOA), Doppler frequency difference (DD) and combined methods consisting of two or more of the above methods The classification of the most common methods for determining the location of radio sources is shown in Figure 1.

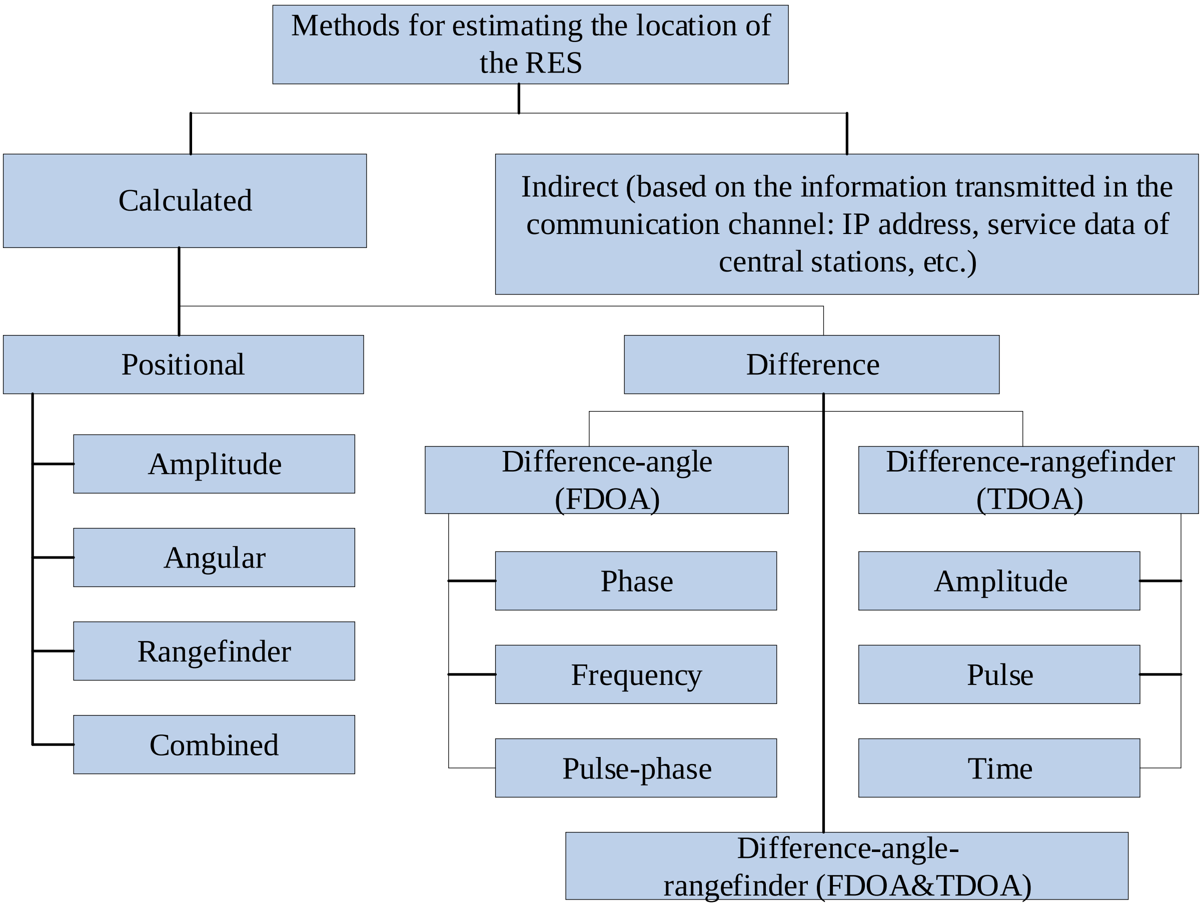


Figure 1: The most common methods for estimating the location of radio emission sources (RES)

However, in practice, combined methods consisting of two or more of the above methods are often used to increase reliability in determining the location of radio sources. This approach makes it possible to eliminate the disadvantages of one method by supplementing the properties of the other [13-16].

Thus, to date, TDOA-FDOA and other combined methods have become the most widespread in satellite systems. Such methods of determining the location of radio emission sources require several low-orbit SS, which is inefficient from an economic point of view. Therefore, the method of determining the coordinates of the source using the angle-measuring method, which is proposed in [7], is more effective.

The studies carried out in [17] showed that the application of the Kalman filter to the implementation of the signal detection task turned out to be a successful solution. However, when determining the location of radio emission sources with any degree of perfection and accuracy of on-board radio measuring equipment, as well as regardless of the thoroughness of the experiment, the measured value will always differ from the true one, since errors are inevitable when measuring.

When determining the location of a RES using one low-orbit SS with two active phased antenna arrays (APAA) on board, the accuracy of estimating the coordinates of radio emission sources will depend on a number of factors such as:

- signal level (signal-to-noise ratio) at the input of on-board measuring equipment;
- errors in determining the coordinates of the SS;
- errors in fixing phase angles between adjacent APAA elements $\Delta\varphi$;
- the width of the swinging sector of the APAA beams.

2. Calculation of the error in determining the location of RES

In this paper, the estimation of errors that will occur when determining the location of radio emission sources using a single low-orbit SS is based on the angle-measuring method, with the use of APAA-type scanning antennas on board the SS to determine the bearings on the RES. At the same time, all coordinates of radio emission sources will be determined using the developed algorithm, which is considered in [7], based on the angular method, where the coordinates of the location of radio emission sources are determined based on the analysis of geometric ratios of distances and angles between the SS, radio emission sources and the center of mass of the Earth, bearings on the source of radio emission using iterations. Errors of scanning angles β_1 and β_2 were set in arbitrary form.

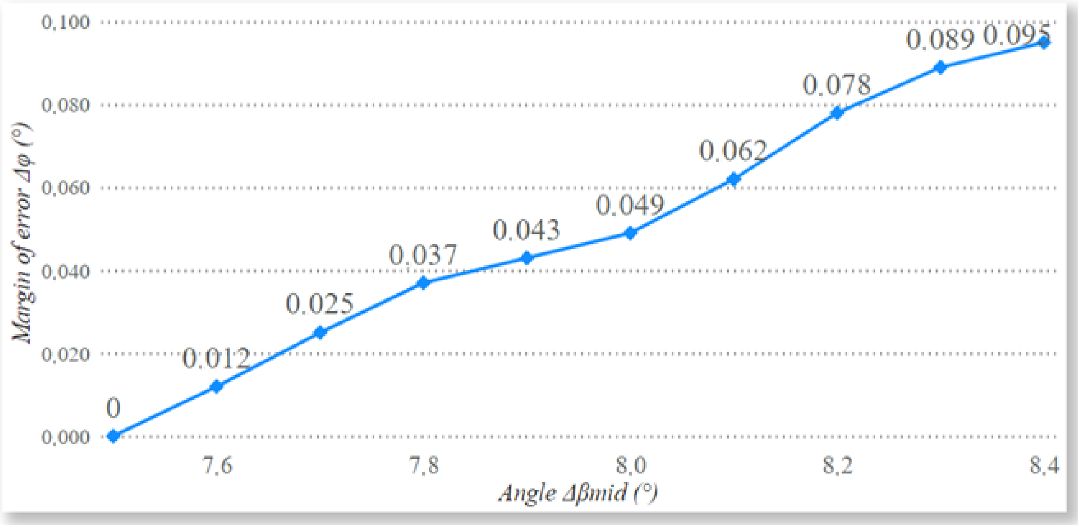
In this paper, the area of radio monitoring is the territory of the Republic of Kazakhstan, which is in the range of values from $\varphi = 40°$ to $\varphi = 56°$ north latitude (the average value of the radio monitoring area is $\varphi = 48°$), as well as in the range of values from $\nu = 45°$ to $\nu = 87°$ east longitude.

When determining the location of the RES by the algorithm and program presented in [7], the latitude of the RES location is first determined. So, the length of latitude (parallel) 0^0 (equator) is equal to 40.075,696 km. To find the length of one degree at latitude 0^0, it is necessary to divide 40.075,696 km by 360^0, we get 40 075,696 km / 360° = 111,321377778 km/° (111321,377778 m/°). It turns out that at latitude 0^0 length 1^0 = 111,321377778 km /° or 111321,377778 m/°. However, the length of the parallels are different - they increase as they approach the equator and decrease towards the poles, 0^0 at the poles. The length of the parallel is different at different latitudes and, accordingly, the length of 1^0 will also be different. To determine the length of 1^0, it is necessary to multiply the length of one degree at the equator multiplied by the cosine of the latitude angle. Taking into account the different parallel lengths at different latitudes, calculations of the error in determining the latitude of radio emission sources were made. Table 1 shows the results of calculating the error in determining the latitude of radio emission sources.

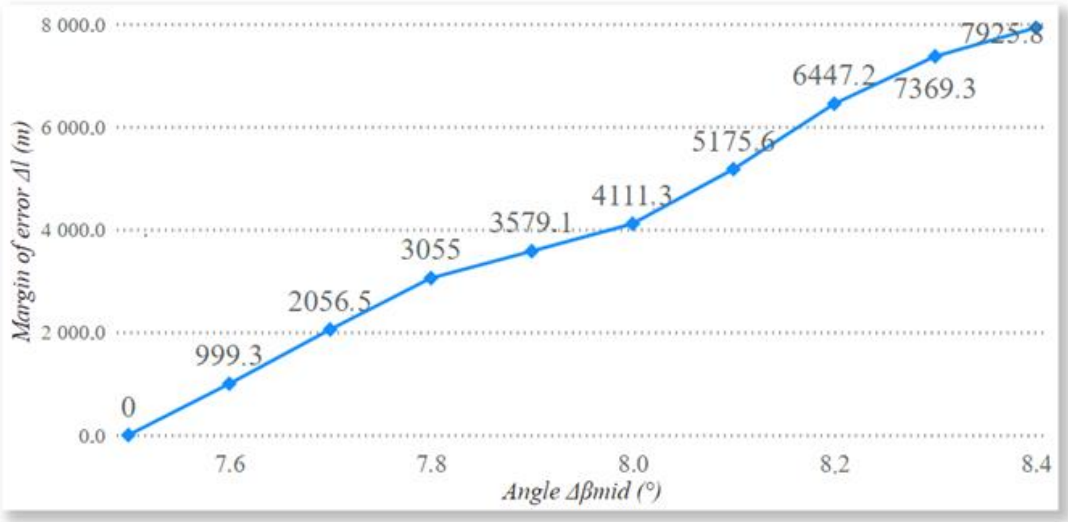
Table 1
Errors in determining the latitude of radio emission sources

β1(0)	7	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9
β2(0)	8	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9
Bcp (0)	7.5	7.6	7.7	7.8	7.9	8	8.1	8.2	8.3	8.4
ϕ (0)	41.5663	41.5783	41.5910	41.6030	41.6093	41.6157	41.6285	41.6438	41.6549	41.6616
Δϕ (0)	0	0.012	0.025	0.037	0.043	0.049	0.062	0.078	0.089	0.095
Δl (m)	0	999.3	2056.5	3055.0	3579.1	4111.3	5175.6	6447.2	7369.3	7925.8

The dependences of the latitude error on the errors in determining the scanning angles β_1 and β_2 (β_{mid}) that arise when determining the latitude of the RES location are shown in Figure 2.



a)



b)

Figure 2: Errors arising in determining the latitude of the RES in degrees (a), in linear dimensions (b)

After determining the latitude of the RES (φ) according to the algorithm and program presented in [7], the longitude of the terrestrial RES ν is further determined. To do this, you need to find the direction to the RES using the angle μ. It is also necessary to determine the sign of the correction for longitude η, which is determined relative to the direction: the longitude of the SS (θ) is the western direction (–), the eastern direction (+). After determining the sign of the correction for longitude η, it is necessary to find the longitude of the terrestrial RES (ν).

Also, when calculating, it is necessary to take into account the longitude lines, which are called meridians. The length of the meridian is equal to 40,008.55 km. To find the length of one degree in any meridian, it is necessary to divide 40,008.55 km by 360°, we get 40,008.55 km / 360° = 111,134861111 km/° (111134,861111 m/°). It turns out that the length of 1^0 = 111,134861111 km / ° or 111134,861111 m / ° and this length is the same in all meridians. Therefore, when calculating the error in determining the longitude of radio emission sources, the length of 1^0 will be the same everywhere. The calculated values of the longitude determination error are presented in Tables 2 and 3.

Table 2

Errors in determining the longitude of radio sources (correction sign "+")

μ (0)	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
ν (0)	60.5518	60.5657	60.5796	60.5934	60.6073	60.6224	60.6350	60.6489	60.6628	60.6767
Δ ν (0)	0	0.014	0.028	0.042	0.056	0.071	0.083	0.097	0.111	0.125
Δl (m)	0	1544.77	3089.55	4623.21	6167.98	7846.12	9246.42	10791.20	12335.97	13880.74

The dependences of the error on the errors in determining the scanning angles that arise when determining the longitude of the location of the RES depending on the scanning angle μ (correction sign "+") are shown in Figures 3 and 4.

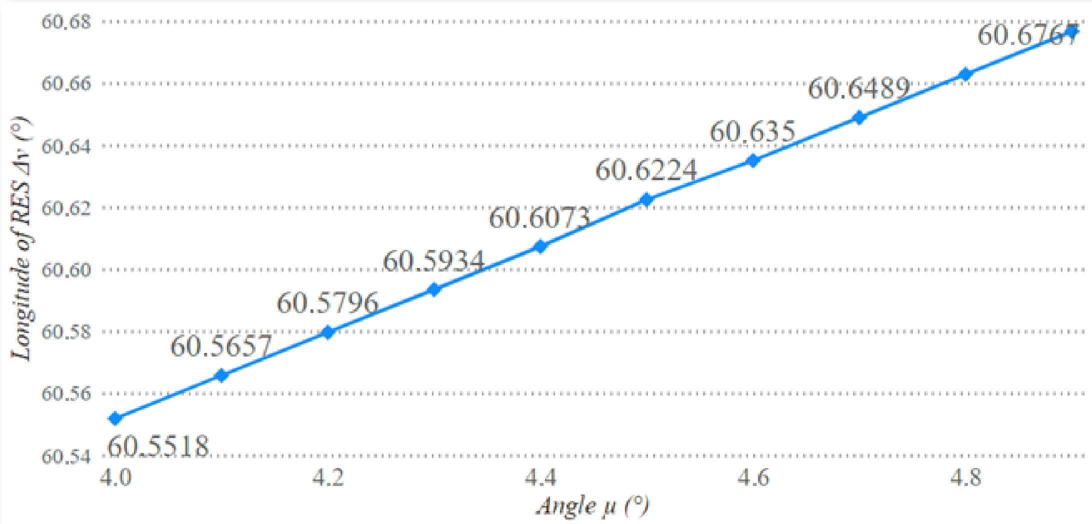
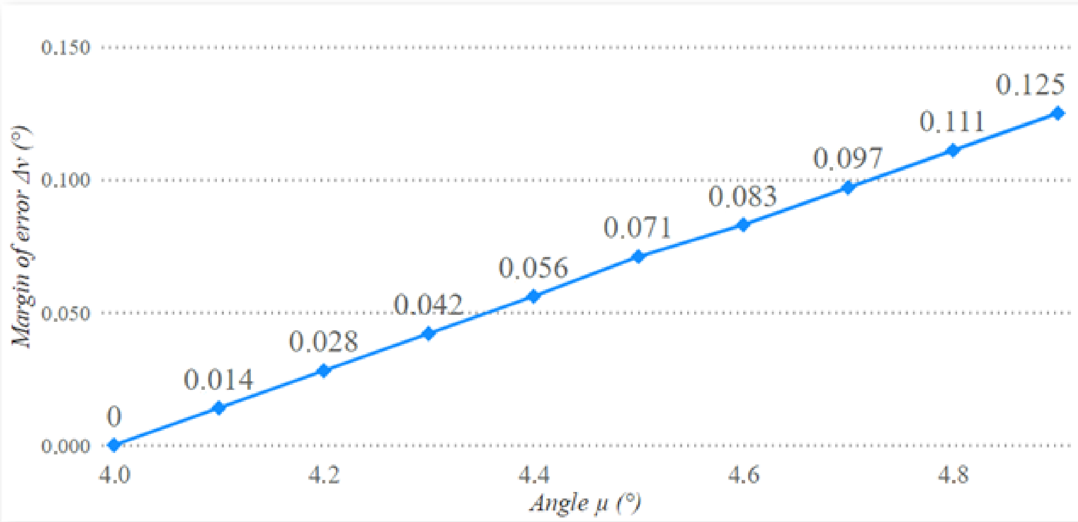
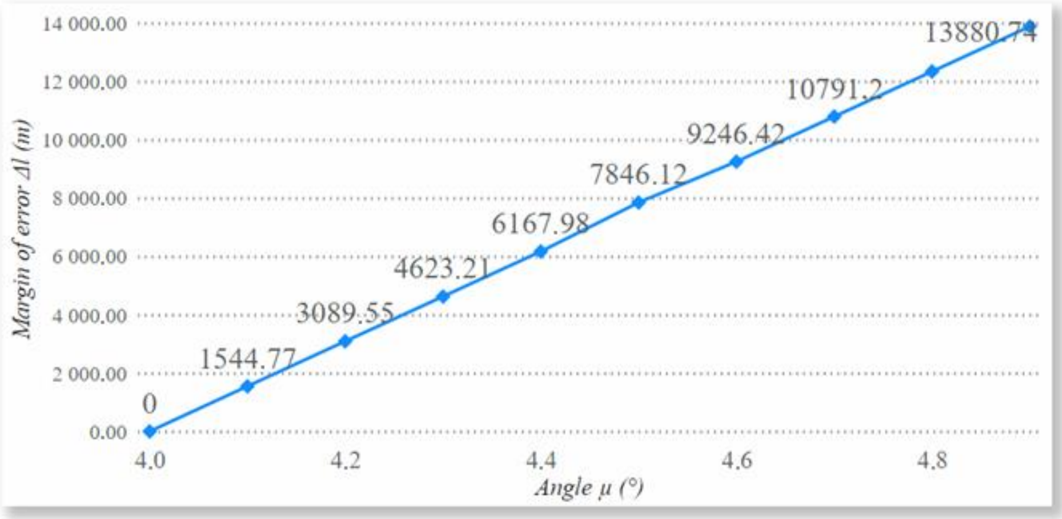


Figure 3: Errors arising when determining the longitude of radio emission sources depending on the scanning angle μ (correction sign "+")



a)



b)

Figure 4: Errors arising in determining the longitude of radio emission sources a) in degrees and b) in linear dimensions (correction sign "+")

Table 3

Errors in determining the longitude of radio sources (correction sign "+")

μ (0)	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
ν (0)	59.4482	59.4343	59.4204	59.4066	59.3927	59.3789	59.3650	59.3511	59.3372	59.3233
Δ ν (0)	0	0.0139	0.0278	0.0416	0.0555	0.0693	0.0832	0.0971	0.111	0.1249
Δl (m)	0.00	1544.77	3089.55	4623.21	6167.98	7701.65	9246.42	10791.20	12335.97	13880.74

The dependences of the longitude error on the errors in determining the scanning angles μ that occur when determining the longitude of the location of the RES (correction sign "-") are shown in Figures 5 and 6.

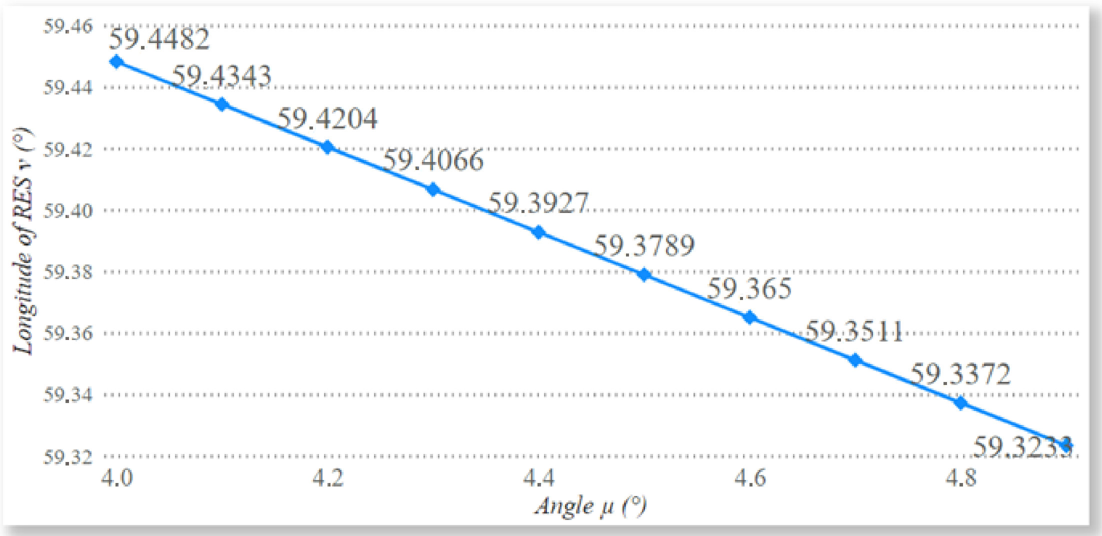
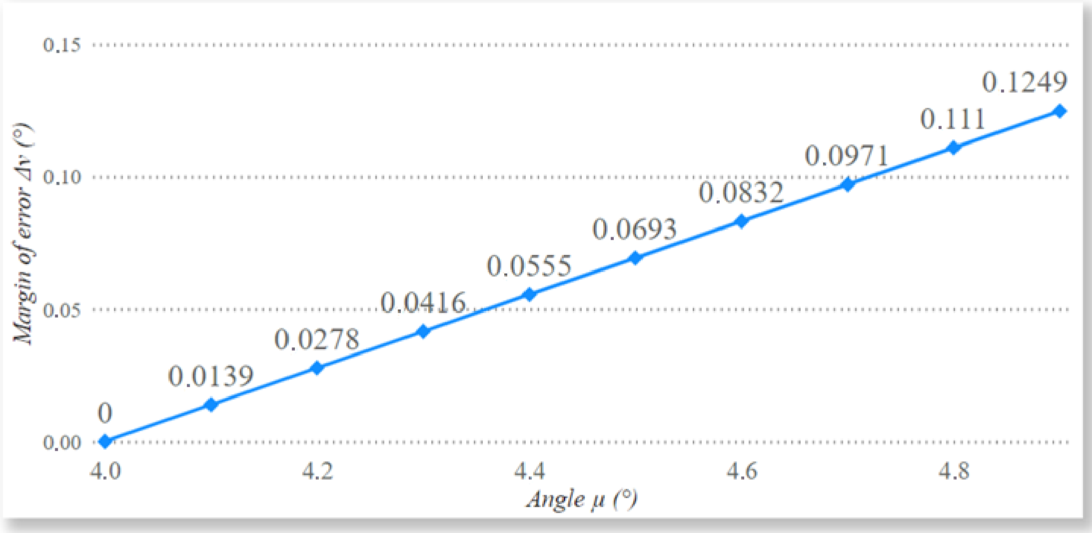
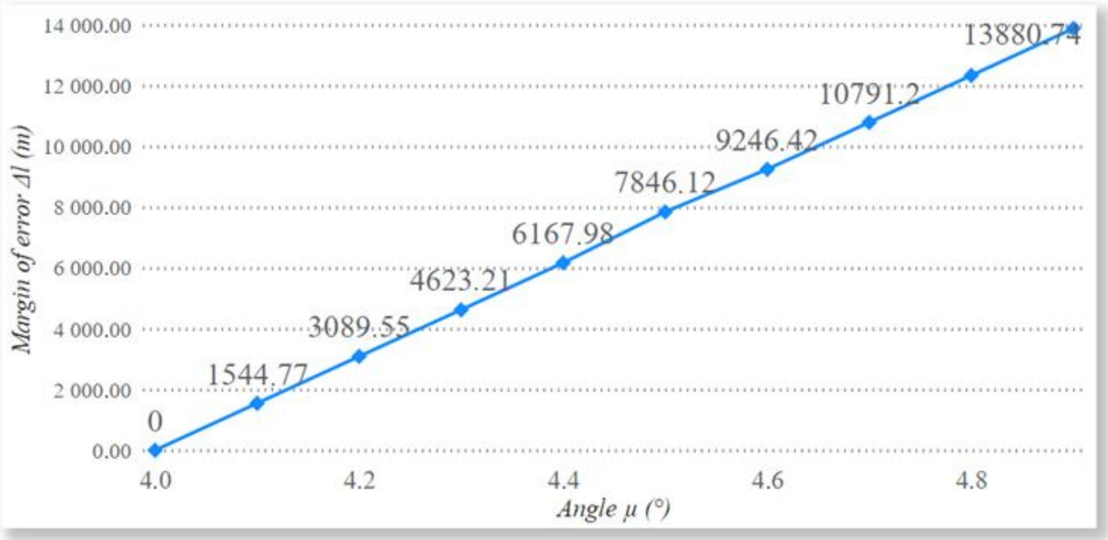


Figure 5: Errors arising when determining the longitude of radio emission sources depending on the scanning angle μ (correction sign "-")



a)



b)

Figure 6: Errors arising in determining the longitude of radio emission sources a) in degrees and b) in linear dimensions (correction sign "-")

Thus, when determining the coordinates of radio emission sources, the errors will grow linearly depending on the errors of the scanning angles β_1 and β_2 and on the angle μ, on which the choice of longitude correction angle η_2 or η_1 depends, which are shown in Figures 7 and 8.

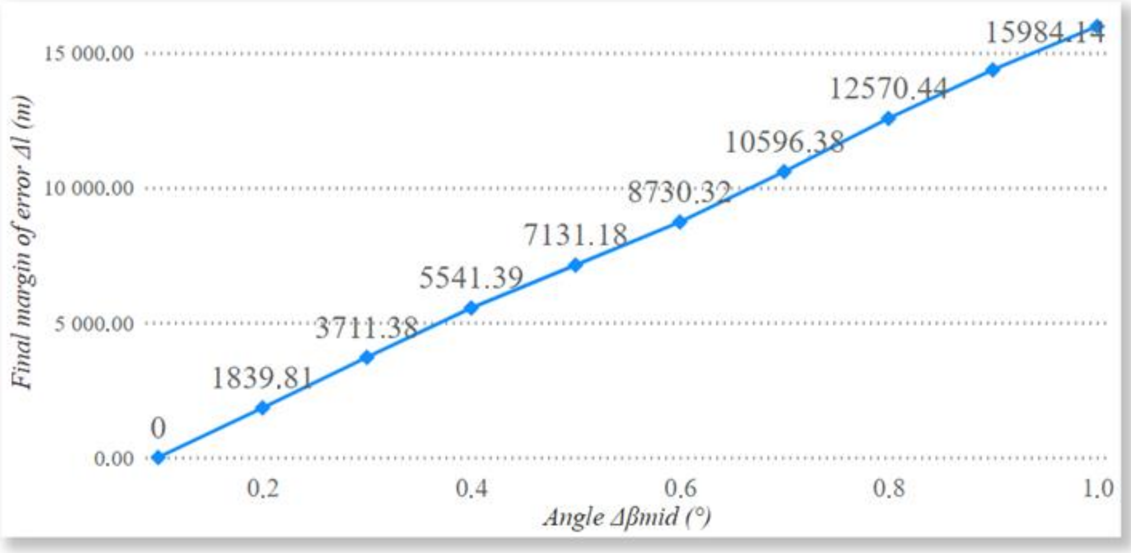


Figure 7: Errors arising when determining the coordinates of radio emission sources in linear dimensions (correction sign "+")

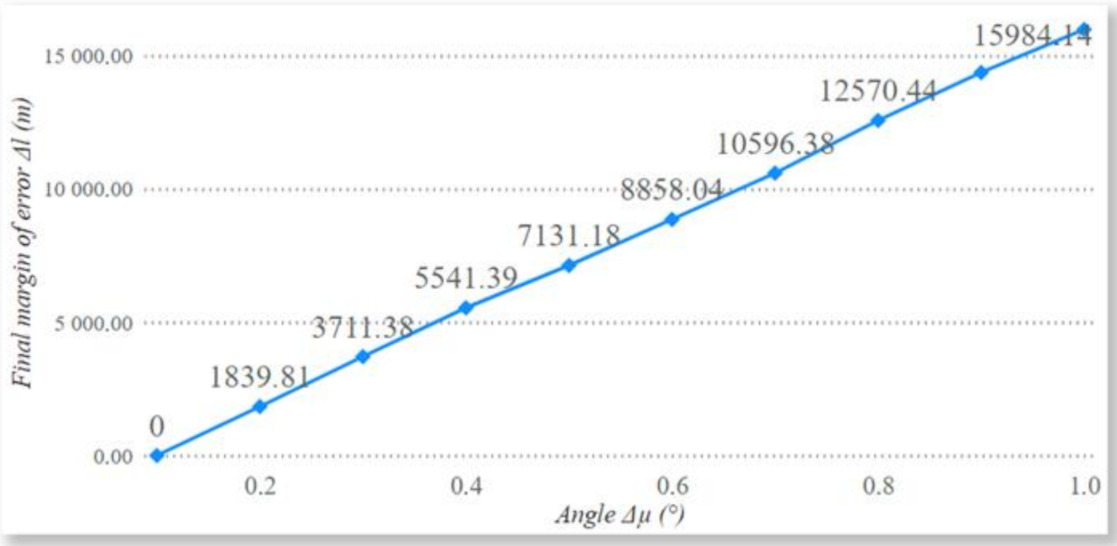


Figure 8: Errors arising when determining the coordinates of radio emission sources in linear dimensions (correction sign "-")

The use of spacecraft in radio monitoring systems will make it possible to determine the parameters of signals and the location of radio-electronic means over a large area with a diverse terrain, which will increase the efficiency of radio monitoring systems. Therefore, taking into account and estimating errors that occur when determining angular parameters using a single low-orbit SS is a very important task, since the accuracy of determining the location of the RES depends on the values of these errors. As the calculations have shown, the errors made in this work will grow linearly depending on the errors in determining the scanning angles. Therefore, in order to minimize these errors, it is necessary to carry out multiple measurements of the coordinates of the ground source of radio emission, in which the bearings are determined at several points of the orbit in the visibility zone of the low-orbit SS.

3. Conclusion

When estimating the errors that will occur when determining the location of radio emission sources using a single low-orbit SS, it was found that the errors will grow linearly depending on the errors of the scanning angles β_1 and β_2 and on the angle μ, on which the choice of longitude correction angle η_2 or η_1 depends.

The obtained results of error calculations will allow us to determine the requirements for methods and equipment of radio monitoring to ensure a given accuracy in determining the location of ground-based radio emission sources.

To improve the accuracy of determining the coordinates of radio emission sources, it is necessary to find new methods of angular measurements, or to carry out multiple measurements of the coordinates of a ground-based radio emission source, in which the bearings are determined at several points of the orbit in the visibility zone of a low-orbit spacecraft.

In addition, in order to implement radio monitoring systems based on small spacecraft, it is necessary to conduct a number of studies related to the evaluation and analysis of signals received by an on-board measuring receiver, evaluation of the accuracy of various location determination methods, selection of spacecraft designs and orbits.

4. References

[1] D. A. Arista Ramirez, M. Cardenas-Juarez, U. Pineda-Rico, A. Arce and E. Stevens-Navarro (2018). Spectrum Occupancy Measurements in the Sub-6 GHz Band for Smart Spectrum Applications. 2018 IEEE 10th Latin-American Conference on Communications (LATINCOM), Guadalajara, Mexico, 2018, pp. 1-6. doi: 10.1109/LATINCOM.2018.8613211.

[2] J. Reed, M. Vassiliou and S. Shah (2016). The Role of New Technologies in Solving the Spectrum Shortage [Point of View]. Proceedings of the IEEE, volume 104, no. 6, pp. 1163-1168, June 2016, doi: 10.1109/JPROC.2016.2562758.

[3] J. Zhang, Y. Chen, Y. Liu and H. Wu (2020). Spectrum Knowledge and Real-Time Observing Enabled Smart Spectrum Management, in: IEEE Access, volume 8, pp. 44153-44162. doi: 10.1109/ACCESS.2020.2978005.

[4] H. Mazar (2016). Radio spectrum Management: Policies, regulations and techniques, John Wiley & Sons, Hoboken, NJ.

[5] A. Rembovsky, A.V. Ashikhmin, V.A. Kozmin, S.M. Smolskiy (2018). Radio Monitoring: Automated Systems and Their Componentsю Cham Switzerlan, Springer. doi:10.1007/978-3-319-74277-9.

[6] Handbook on Spectrum Monitoring. Geneva, Electronic Publication, 2011.

[7] A. Aitmagambetov, Y. Butuzov, V. Tikhvinskiy, A. Kulakayeva, Zh. Ongenbayeva (2021). Energy budget and methods for determining coordinates for a radiomonitoring system based on a small spacecraft, in: Indonesian Journal of Electrical Engineering and Computer Science, 21(2), pp. 945–956.

[8] K.Sarda, N. Roth, R. Zee, D. CaJacob, G.O. Nathan (2018). Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission, in: Proceedings of the 4S Symposium, Sorrento, Italy, 28 May–1 June 2018.

[9] Hao C. et al. (2021). Satellite-Based Radio Spectrum Monitoring: Architecture, Applications, and Challenges. IEEE Network, 35(4), pp.20-27.

[10] HawkEye 360. The Leader of Spectrum-Based RF Geoanalytics, 2023. URL: https://www.he360.com/.

[11] Y. Daineko, D.Tsoy, M. Ipalakova, B. Kozhakhmetova, A. Aitmagambetov and A. Kulakayeva (20220. Development of an Interactive Mobile Platform for Studying Radio Engineering Disciplines Using Augmented Reality Technology. International Journal of Interactive Mobile Technologies (iJIM), 16(19), pp. 147–162, doi:10.3991/ijim.v16i19.32373

[12] Y. Daineko, et al (2021). Development of Virtual Laboratory Work on the Base of Unity Game Engine for the Study of Radio Engineering Disciplines, in: De Paolis, L.T., Arpaia, P., Bourdot, P. (eds) Augmented Reality, Virtual Reality, and Computer Graphics. AVR 2021. Lecture

Notes in Computer Science, Springer, Cham, vol 12980, pp. 419-427, doi:10.1007/978-3-030-87595-4_31.
[13] Merrill I., Skolnik. Radar Handbook, Third Edition. - McGraw-Hill Education, 2008. ISBN: 9780071485470.
[14] A. G. Dempster, E. Cetin (2016). Interference Localization for Satellite Navigation Systems, in: Proceedings of the IEEE, 104(6), pp. 1318-1326. [7439734]. https://doi.org/10.1109/JPROC.2016.2530814.
[15] L. Zhao, G. Yao and J.W. Mark (2006). Mobile positioning based on relaying capability of mobile stations in hybrid wireless networks, in: IEE Proc.-Commun., vol. 153, No. 5, October.
[16] V. O.Sotnikov, F. T. Zap (2019). Analysis of methods for estimating the position of a ground-based radio source in a satellite communication system with direct retransmission, in: Collection of scientific articles based on the results of the International Scientific Forum, vol.1, p. 91-100.
[17] A. Kulakayeva, A. Aitmagambetov, Y. Daineko, B.Medetov, Zh. Ongenbayeva, (2022). Improvement of Signal Reception Reliability at Satellite Spectrum Monitoring System, in: IEEE Access, vol.10, pp. 101399-101407, doi: 10.1109/ACCESS.2022.3206953.