

ALGORITHM FOR ASSESSING THE READINESS OF A WIDEBAND RADAR FOR CONSTRUCTING RADAR PORTRAITS OF SPACE OBJECTS

DOI: 10.36724/2072-8735-2025-19-8-64-71

Alexander V. Timoshenko,
Moscow State University, Moscow, Russia, u567ku78@gmail.com

Anatoly Yu. Perlov,
Moscow State University, Moscow, Russia, aperlov@yandex.ru

Denis S. Chirov,
Moscow Technical University of Communications and Informatics,
Moscow, Russia, den-chirov@yandex.ru

Alexander S. Zakharov,
Moscow State University, Moscow, Russia,
zakharov.as17@physics.msu.ru

Manuscript received 27 June 2025;
Accepted 25 June 2025

This research was supported by MSU Program of Development, Project №24-S1-04

Keywords: broadband radar, radar portraiture, space objects, readiness factor, space monitoring

The article presents the developed algorithm for assessing the readiness of a space monitoring radar station (SMR) to operate with the required accuracy characteristics in the radar portraiture mode (RP) for information support for solving the problems of operational updating of the space catalog (SC). It has been shown that the quality of the RP can be improved by selecting the parameters of the probing signals taking into account the current unevenness of the frequency response of the receiving system of the RP. The main operations of the algorithm for assessing the readiness of the SMR to construct a RP for controlling the parameters of the probing signals based on the results of calculating the Spearman rank correlation are presented, which ensures the best accuracy characteristics of the RP taking into account the influence of destructive factors on the characteristics of the receiving and transmitting channels of the active phased array antenna (APAA).

Information about authors:

Alexander V. Timoshenko, Moscow State University, Senior Lecturer, Doctor of Engineering Sciences, Professor, Moscow, Russia. ORCID: 0000-0002-9791-142X

Anatoly Yu. Perlov, Moscow State University, Senior Lecturer, PhD of Technical Sciences, Associate Professor, Moscow, Russia. ORCID: 0000-0001-8480-3772

Denis S. Chirov, Moscow Technical University of Communications and Informatics, Head of the Department of Radio Engineering Systems, Doctor of Engineering Systems, Professor, Moscow, Russia. ORCID: 0000-0001-8509-4373

Alexander S. Zakharov, Lomonosov Moscow State University, Laboratory Assistant, Moscow, Russia. ORCID: 0009-0000-2617-5317

Для цитирования:

Тимошенко А.В., Перлов А.Ю., Чиров Д.С., Захаров А.С. Алгоритм оценки готовности широкополосной РЛС к построению радиолокационных портретов космических объектов // Т-Comm: Телекоммуникации и транспорт. 2025. Том 19. №8. С. 64-71.

For citation:

A.V. Timoshenko, A.Yu. Perlov, D.S. Chirov, A.S. Zakharov, "Algorithm for assessing the readiness of a wideband radar for constructing radar portraits of space objects", T-Comm, 2025, vol. 19, no. 8, pp. 64-71.

Introduction

The steady growth in the number of spacecraft launched [1] necessitates the improvement of information support technologies for near-Earth space monitoring (SMR) by obtaining non-coordinate information about the radar portraits (RP) of spacecrafts [2-6], which is especially important when solving the problem of promptly updating the main catalog of spacecraft, including during SC maneuvering [7]. In this article, the radar portrait is the distribution of the reflected signal intensity depending on the range and angular coordinates from the radar to the spacecraft [3].

To construct a RP, it is necessary to ensure a uniform amplitude-frequency response (AFR) of the transmit-receive path (TRP). This issue is especially relevant for spacecraft with three-axis stabilization, which can take absolutely random positions in space relative to their axis [4]. In this case, the noise pollution of a part of the radar will not allow the accurate classification of the spacecraft in the catalog of spacecraft, and in turn, an increase in the unevenness of the frequency response leads to an increase in the signal-to-noise ratio.

Currently, for spacecraft with three-axis stabilization, Costas signals are used, which provide resolution of reflection points from the spacecraft [8]. In this case, the use of this signal allows information to be accumulated during coherent processing and does not lead to a decrease in the signal-to-noise ratio. However, there is a high sensitivity of the Costas signal to the unevenness of the frequency response due to special frequency coding. Most often, when working with a spacecraft, the choice of signal is determined by the capabilities of the hardware and software complex (HSC) of the radar, as well as the uncertainty function (UF).

The definition of the UF in integral form for a signal S with a given delay time τ and frequency shift Δf is given as:

$$\chi(\tau, \Delta f) = \int_{-\infty}^{+\infty} S(t)S^*(t - \tau)e^{j2\pi\Delta f t} dt, \quad (1)$$

where S – signal amplitude, τ – delay time, Δf – frequency shift. The Costas signal uncertainty function is a nearly ideal delta function with very small sidelobes, while most other signals have main lobe extensions or increased sidelobes.

Existing and future wideband L-band SMR radars with large-aperture active phased array antennas (APAA) have the potential to form one-dimensional incoherent long-range radars required for the catalog of space objects, including solving problems of:

- estimating the orientation of a spacecraft and various parameters of its design [9];
- continuous refinement of trajectories and orbital parameters;
- proactive determination of spacecraft maneuvering [10];
- estimating the degree of spacecraft fragmentation and destruction [11];
- predicting the areas of fall of deorbited spacecraft [12-14].

However, the guaranteed receipt of the specified information is largely determined by the choice of the most effective algorithms for signal and trajectory processing for specific conditions of radio portraiture.

The conducted analysis of works in the field of super-resolution algorithms showed that the potential values of the range resolution are largely determined by the band and types of probing signals [15].

The considered theory of constructing resolution algorithms using wideband signals was revised in [16]. The procedures presented in the work work with known correlation coefficients of

noise and the useful signal, which is often impossible to calculate due to the presence of non-Gaussian noise.

Another well-known method is the procedure for estimating the quantitative composition of the spacecraft using the criterion of minimum average risk with an asymmetric loss function [17]. In other words, the loss function is understood as an incorrect determination of the number of components of the spacecraft in a greater or lesser direction. There are many methods and ways of choosing the optimal loss function.

The last method is the method for solving the inverse problem of group scattering [18]. This method describes the multidimensional structure of the echo signal of a complex spacecraft taking into account background correlated interference. Also, as a result of signal processing by this method, multidimensional images are obtained after coherent probing. Because of this, the result of constructing a RP in correlation, filter and correlation-filter processing schemes will be intensity blurred by noise due to coherent processing.

The considered methods have become widespread in constructing RP in near-earth electromagnetic wave propagation systems, where a sufficient condition for resolving an object is obtaining single measurements about the target. In this regard, to construct a RP, it is necessary to obtain the intensity of reflections of the amplitudes and the target's EPR over a long period of time, which corresponds to several intervals of spacecraft flights to maintain a catalog of space objects.

The conducted research of works [4, 16, 19] in the part of information support of the catalog of space objects allowed to specify the following negative factors requiring complex consideration in dynamics and real scale during operation of the SMR radar in the RP mode:

- technical and functional condition of the radar (temperature dynamics of the receiving and transmitting models, non-uniformity of the frequency response) in combination with the parameters of the probing signals (band, modulation type, duration, duty cycle);
- environmental parameters (ionospheric and tropospheric corrections);
- uncertainty of the spacecraft parameters (local inhomogeneities, distortion of the phase center).

The specified factors and features of the radar operation in the barrier mode of coverage determine the efficiency of using the methods of inverse synthesis of the aperture. At the same time, the efficiency of this method of constructing the RP is determined by the shape of the frequency response. Thus, non-uniformity over several dB in the frequency band can lead to a critical decrease in resolution and the impossibility of constructing the RP.

Analysis of modern methods of constructing RP based on both reverse aperture synthesis [3, 20-22] and digital processing of reflected radar signals [23, 24] showed that a necessary condition for their application in the interests of updating the catalog is compensation for the following destructive factors caused by:

- non-identity of the amplitude-phase distribution (APD) in the receiving and transmitting channels of the APAA;
- propagation medium;
- fluctuations of the phase center of the object;
- insufficient accuracy of data on the trajectory parameters of the object.

At the same time, the most significant non-stationary destructive factor affecting the accuracy of coordinate measurements for

large-aperture and wideband radars is the non-identity of the APD in the receiving and transmitting channels of the APAA [25]. The results of modeling the passage of linear-chirp signals in the receiving system of a modern L-band SMR radar, formed due to the non-identity of the phased array antenna in the receiving and transmitting channels of the APAA, are presented in Figure 1.

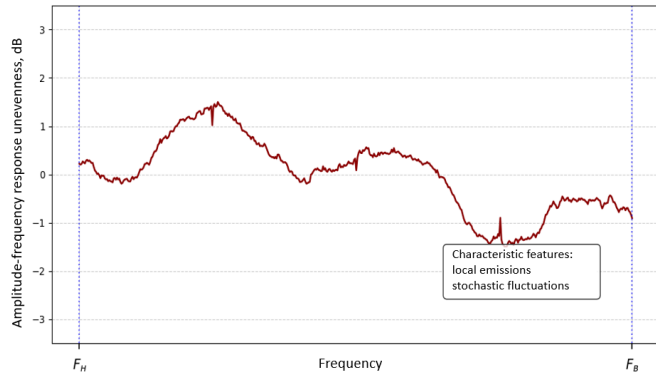


Fig. 1. Uneven frequency response of the receiving system of the SMR

The specified unevenness has a non-stationary nature, which significantly reduces the efficiency of using known algorithms for reverse aperture synthesis to construct one-dimensional RP with the required accuracy characteristics for classifying spacecraft. The studies conducted by the authors [26-31] allowed us to formulate a hypothesis about the possibility of reducing the influence of destructive factors on RP parameters by adapting signal parameters to the current unevenness of the frequency response in real time based on the results of assessing the readiness of radar hardware to form radar portraits.

Formalization of the indicator of readiness for constructing a RP

The process of updating the satellite catalog in wideband radars can be presented as an assessment of the readiness of the hardware to build a RP according to the criterion of maximizing the accuracy characteristics (by minimizing the errors in measuring coordinates and radial velocity).

In the article, the indicator of radar readiness to build a RP is understood as a value characterizing the degree of readiness of the radar to operate with the required accuracy of determining coordinates, according to the results of the assessment of which the influence of destructive factors on the unevenness of the frequency response is compensated for by a reasonable choice of corrections to the amplitude and a change in the amplitude-frequency spectrum of the signal.

According to [31-37], the accuracy of determining coordinates by range and by angle is estimated using the formulas for the dependence of the bandwidth B , the signal-to-noise ratio q and the half-width of the radiation pattern $\theta_{0,5}$:

$$\delta r = \frac{c}{2B\sqrt{q}}, \quad (2)$$

$$\delta \theta = \frac{\theta_{0,5}}{2\sqrt{q}}. \quad (3)$$

Using formulas (2) and (3), we determine the volume of space in which an erroneous detection of a spacecraft is possible as:

$$\begin{aligned} \delta V &= \delta r \delta r_2 \delta r_3 = r^2 \delta r \delta \psi \delta \theta, \\ \delta r_2 &= r \delta \psi, \delta r_3 = r \delta \theta, \end{aligned} \quad (4)$$

where δr – range measurement accuracy; $\delta \psi$, $\delta \theta$ – azimuth and elevation measurement accuracy. Due to the presence of range and angular coordinates determination error, the spacecraft location will be determined with an accuracy of δr , δr_2 , δr_3 .

To obtain an analytical expression for the indicator of readiness for constructing a radar station, we transform the accuracy of determining coordinates by range δr into the volume of space through accuracy characteristics that depend on the signal-to-noise ratio (SNR):

$$\delta V = \frac{r^2 c \theta_{0,5}^2}{4Bq}. \quad (5)$$

The expression for estimating the signal-to-noise ratio q taking into account the non-uniformity of the frequency response in the radar receiving system can be represented as:

$$q = \frac{\int_{f_{min}}^{f_{max}} |H|^2 |S_{in}|^2 df}{\int_{f_{min}}^{f_{max}} |H|^2 |N(f)|^2 df}, \quad (6)$$

where S_{in} – is the amplitude-frequency spectrum of the reflected signal, $N(f)$ – is the spectral power of the noise, f_{max} and f_{min} – are the upper and lower operating frequencies. Then the formula for calculating the volume of measurement uncertainty in the radar can be represented as follows:

$$\delta V = \frac{r^2 c \theta_{0,5}^2}{4B} \frac{\int_{f_{min}}^{f_{max}} |H|^2 |N(f)|^2 df}{\int_{f_{min}}^{f_{max}} |H|^2 |S_{in}|^2 df} \quad (7)$$

We will assume that the optimal values of the signal bandwidth B for constructing the RP are determined by ranking the frequency response data using the Spearman rank correlation coefficient. Thus, according to [34], the non-parametric Spearman rank coefficient allows us to estimate the relationships between ordinal variables from small-volume samples and variables whose distribution is unknown. In the case of non-uniform frequency response when the radar is operating with wideband signals, the use of the Spearman coefficient is legitimate due to the occurrence of stochastic changes in the frequency response of the signal.

The Spearman rank correlation coefficient has several advantages over other methods for measuring the relationship between variables. First, it does not require the assumption of linearity of the relationship and normality of the data distribution, which makes it more universal and applicable in real-world research, where the data is often nonparametric. Second, the Spearman coefficient is resistant to outliers, since it works with ranks, not with the original values, which reduces the influence of anomalous observations on the final result. This is especially useful when analyzing data with a large scatter or non-obvious patterns.

Another advantage of the Spearman coefficient is its ease of interpretation and calculation. Unlike some other methods, such as the Pearson correlation coefficient, it estimates a monotonic rather than strictly linear relationship, which expands the scope of its application. In addition, it is suitable for working with ordinal data, which many parametric methods cannot handle. Due to this, Spearman's coefficient is widely used in psychology, sociology, biology and other fields where precise quantitative measurements are not always available, but it is important to assess the general trend of the relationship between features.

In general, Spearman's coefficient is written:

$$\rho = 1 - \frac{6 \sum_i d_i^2}{n(n^2 - 1)} \quad (8)$$

where d_i – the difference between the ranks of values, while the Spearman coefficient varies from -1 to 1; n is the number of ranks.

Thus, the indicator of readiness for RP in the interests of increasing the efficiency of updating the catalog by optimizing the parameters of the signal band can be represented as:

$$\Gamma = \frac{r^2 c \theta_{0,5}^2 \int_{f_{min}}^{f_{max}} |H|^2 |Noise|^2 df}{4B\rho(H, S_{in}) \int_{f_{min}}^{f_{max}} |H|^2 |S_{in}|^2 df}. \quad (9)$$

The given analytical dependence allows us to determine the main operations of the algorithm for assessing the readiness of the SMR radar to build radar portraits of spacecraft, the structural and logical diagram of which is shown in Figure 2.

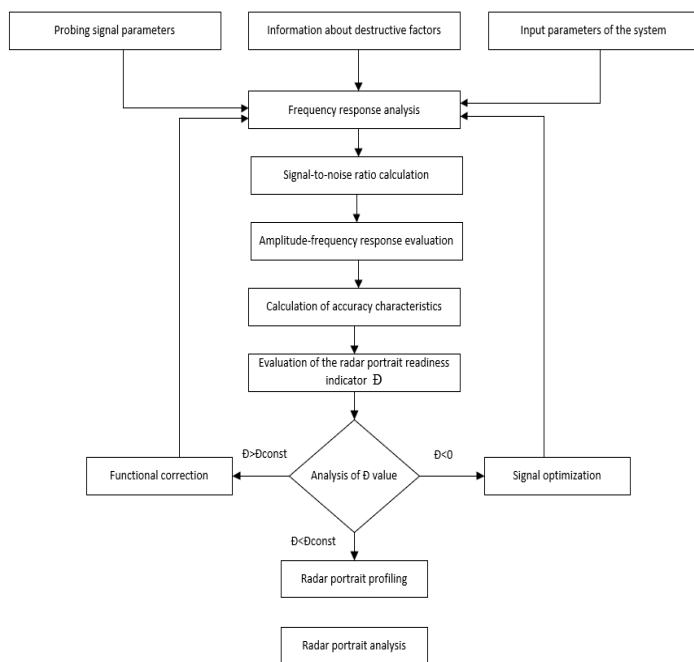


Fig. 2. Scheme of the algorithm for assessing the readiness of the SMR radar to build radar portraits of spacecraft

The proposed algorithm evaluates the frequency response, phase response and SNR under the influence of destructive factors. All information about the processed signal and destructive factors is then combined into a single array of information to assess the accuracy characteristics, with subsequent calculation of the indicator of readiness for RP.

The presented algorithm for assessing the readiness of the radar for RP defines the following procedure for different values of the readiness indicator:

- for negative values of the readiness indicator, the shape of frequency response is optimized, with the signal band being optimized based on an iterative calculation of the frequency change law using the criterion of minimum side lobes of the autocorrelation function;
- if the indicator exceeds the specified value, it is necessary to simultaneously optimize the frequency response shape to the maximum along with the phase response correction;

- if the values of the readiness factor are within the limits necessary for the required accuracy of coordinate measurement, it is necessary to proceed to constructing a radar portrait.

Evaluation of the algorithm efficiency

To evaluate the efficiency of the algorithm for assessing the readiness of the SMR radar for constructing spacecraft radar portraits, we will represent the radar portrait as a convolution of the probing signal with the target impulse response after processing in the transmitting and receiving path. As initial data, we will assume that there are two spheres approaching each other during movement in the radar's field of view, and we will assume that at the moment T_0 , destructive factors affect the SMR radar equipment, which change the uniformity of the frequency response and the identity of the phase response, as a result of which the values of the readiness indicator become negative ($\Gamma < 0$). The values of the reflected signal intensity were normalized to the maximum value and logarithmed to the base 10.

Then the RP will have the form shown in Figure 3, which displays the maximum intensity of the reflected signal at 0 dB, and a decrease in intensity and noise - negative values.

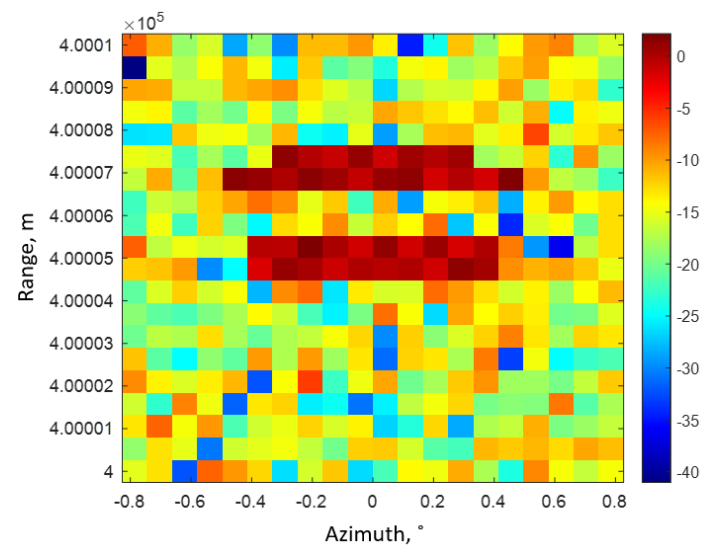


Fig. 3. Sphere radar plot based on radar data with a negative indicator of readiness for the RP

As follows from Figure 3, there is no clear picture of the two spheres, which significantly reduces the ability to classify and determine the type and parameters of an object, and accordingly, the radar does not receive information about the type and shape of the object, which is why it is necessary to spend more time on measurements and increase the catalog update time.

If, when introducing correction amendments, the Γ indicator still remains negative, then the probing signal changes from a linear-frequency signal to a discrete-frequency-coded signal, which ensures that the maximum of frequency response signal is combined with the maximum of frequency response, after which amendments are reintroduced to the phase response and SNR (to increase the tracking accuracy), which leads the Γ indicator to small positive values. Figure 4 shows the sphere radar plot with a radar ready for the $V = 1,5 \text{ m}^3$.

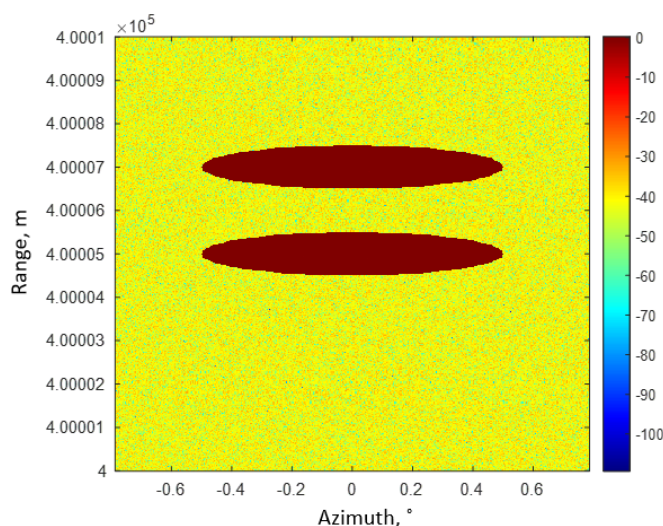


Fig. 4. RP of two spheres during the two-stage procedure of equalizing the frequency response

The images in Figure 5 can be used to estimate the shape and size of two spherical objects, while the noise level remains stable and does not exceed the established threshold values, which allows classifying objects and increasing the frequency of updating the catalog.

The resulting detailing of the spherical spacecraft RP using the readiness indicator Γ allows increasing the level of information support and maintaining the catalog based on the results of assessing the sizes and parameters of the observed objects with a high degree of accuracy.

Thus, the developed algorithm for assessing the readiness of the L-band SMR broadband radar for constructing radar portraits of space objects in the interests of maintaining the catalog of space objects can be used to solve the following problems:

- more accurate classification of spacecraft;
- reliable determination of the values of the effective scattering area of the spacecraft, including maneuvering ones;
- obtaining additional non-coordinate information about the observed objects.

Conclusion

A new algorithm for assessing the readiness of wideband L-band radars for constructing high-precision SMR radars based on the readiness indicator has been developed. The algorithm integrates the assessment of the current technical condition of the radar (primarily the unevenness of the frequency response and the non-identity of the phased array antenna in the APAA channels) and adaptively optimizes the parameters of the probing signals to compensate for destructive factors.

Experimental assessment of the quality of two-dimensional RP of two spheres has shown the effectiveness of the algorithm for assessing the readiness of the SMR radar for constructing a RP for controlling the parameters of probing signals based on the results of calculating the Spearman rank correlation.

Increasing efficiency of the catalog is achieved due to the guaranteed receipt of the RP required for cataloging in the conditions of non-stationary destructive factors in the radar, affecting the quality of the algorithms for constructing the RP.

Acknowledgements

This research was supported by MSU Program of Development, Project №24-S1-04.

References

- [1] B.A. Lagovskiy, I.A. Nasonov, E.Ya. Rubinovich, “Solution of inverse problems of achieving superresolution using neural networks”, *Bulletin of the South Ural State University. Series: Mathematical modeling and programming*. 2024. Vol. 17. No. 1. (in Russian)
- [2] A.Yu. Perlov, A.S. Zakharov, A.V. Timoshenko, M.F. Bulatov, “Model of thermal distortions of the amplitude-frequency characteristic of the receiving system of a radar station in the super-resolution mode”, *Science-intensive technologies in space research of the Earth*. 2024. Vol. 16. No 5. P. 26-34. DOI: 10.36724/2409541920241652634. (in Russian)
- [3] A.A. Manukyan, “Construction of two-dimensional radio images of objects based on non-equidistant coded frequency-time pulse sequences”, *Radio engineering and electronics*. 2015. Vol. 60. No. 3. P. 282. DOI 10.7868/S0033849414120134. (in Russian)
- [4] S. Anger et al., “High-resolution inverse synthetic aperture radar imaging of satellites in space”, *IET Radar, Sonar & Navigation*. 2023. P. 1-20.
- [5] H. Du et al., “Integrated convolution network for ISAR imaging and target recognition”, *IEEE Journal on Miniaturization for Air and Space Systems*. 2023.
- [6] K.P. Likhodenko, G.M. Seregin, V.B. Suchkov, A.Yu. Perov, “Mathematical modeling of polarization radar portraits of complex-shaped objects based on their multipoint models in radars with inverse aperture synthesis”, *Advances in modern radio electronics*. 2024. Vol. 78. No. 2. P. 13-24. DOI: 10.18127/j20700784-202402-02. (in Russian)
- [7] J. Stober, J. Gunter, D. Christoph, “Distortion of meteor count rates due to cosmic radio noise and atmospheric particularities”, *Advances in Radio Science*. 2010. Vol. 8. P. 237-241. DOI: 10.5194/ars-8-237-2010.
- [8] L. Barker, K. Drakakis, R. Scott, “On the Complexity of the Verification of the Costas Property”, *Proceedings of the IEEE*. 2009. Vol. 97. P. 586-593. DOI: 10.1109/JPROC.2008.2011947.
- [9] H. Du et al., “Integrated convolution network for ISAR imaging and target recognition”, *IEEE Journal on Miniaturization for Air and Space Systems*. 2023.
- [10] G. Xu et al., “Manifold Low Rank and Sparse Tensor Method for High-Resolution Radar Imaging”, *IEEE Transactions on Geoscience and Remote Sensing*. 2025. Vol. 63. P. 1-14.
- [11] J. Zhang et al., “From Coarse to Fine: ISAR Object View Interpolation via Flow Estimation and GAN”, *IEEE Transactions on Geoscience and Remote Sensing*. 2024. Vol. 62. P. 1-20.
- [12] Z.N. Khutorovskiy, V.F. Boykov, L.N. Pylaev, “Control of space objects at low altitudes”, *Near-Earth astronomy (space debris), Russian Academy of Sciences*. 1998. P. 34-101. (in Russian)
- [13] Z.N. Khutorovskiy, V.F. Boikov, L.N. Pylaev, “Catalog Maintenance of Low-Earth-Orbit Satellites: Principles of the Algorithm”, *Journal of Guidance, Control, and Dynamics*. 1999. Vol. 22. No. 6. P. 745-758.
- [14] M. Ceresoli, A. Colagrossi, S. Silvestrini, M. Lavagna, “Robust, Onboard Orbit Determination Through Error Kalman Filtering”, *Aerospace*. 2025. Vol. 12. P. 45. DOI: 10.3390/aerospace12010045.
- [15] Y. Zhang et al., “A Fast Target Imaging Model Based on Electromagnetic Scattering Solution and Machine Learning”, *IEEE International Geoscience and Remote Sensing Symposium*. 2024. P.10587.
- [16] Zh. Chen et al., “A Novel Method for PolISAR Interpretation of Space Target Structure Based on Component Decomposition and Coherent Feature Extraction”, *Remote Sensing*. 2025. Vol. 17. No. 6. P. 1079.
- [17] J. Miao, L. Tu, H. Liu, J. Zhao, “Astronomical Image Superresolution Reconstruction with Deep Learning for Better Identification of Interacting Galaxies”, *The Astrophysical Journal Supplement Series*.

2025. Vol. 278. P. 35. DOI: 10.3847/1538-4365/adca34.

[18] V.I. Erokhin, A.P. Kadochnikov, S.V. Sotnikov, "Linear Binary Classification under Interval Uncertainty of Data", *Scientific and Technical Information Processing*. 2024. Vol. 51. No. 6. P. 539-544. DOI: 10.3103/S0147688224700485.

[19] A. Zakharov, A. Perlov, et al., "Model for calculating changes in the radiation pattern and amplitude-phase distribution in the subarray of a large-aperture apaa based on a modified thermal conductivity equation", *IEEE Systems of Signals Generating and Processing in the Field of on Board Communications*. 2024. P. 1-4. DOI: 10.1109/ieec-conf60226.2024.10496770.

[20] A. Manukian, "Constructing the 2D Radio Image of Objects with the Use of Multifrequency Signals with Coded Carrier-Frequency Hopping (Costas signals)", *Journal of Communication Technology and Electronics*. 2011. Vol. 56. P. 160-171. DOI: 10.1134/S1064226911010074.

[21] A.I. Ladygin, "Signature Analysis: Theory and Practice of Radar Recognition of Space Objects and Space Tragedies through the Eyes of Signature Analysts", Moscow: Univ. Book. 2008. 255 p. ISBN 978-5-98699-044-6. (in Russian)

[22] A. Leukhin, A. Voronin, A. Merzlyakov, N. Parsaev, "Application of the autofocusing algorithm for the synthesis of X and L band radar images", *Journal of Physics: Conference Series*. 2020. Vol. 1679. P. 042009. DOI: 10.1088/1742-6596/1679/4/042009.

[23] A.N. Detkov, I.A. Makarov, "Model of space object motion and formation of its radar portrait", *Journal of Radio Electronics*. 2013. Vol. 12. P. 1-18. (in Russian)

[24] E.A. Bolelov, O.V. Vasiliev, S.A. Zyabkin, D.S. Chirov, "Development of a fuzzy-logical classifier of the phase state of hydrometeors for the algorithm for classifying zones of probable icing of aircraft in X-band weather radars," *T-Comm*. 2023. Vol. 17. No. 10. P. 4-12. (in Russian)

[25] A. Sharma, N. Suraj, M. Rokade, N. Ghodpage et al., "Study of variations in the absorption of cosmic radio noise using Riometer at Casey station", *Library & Information Science Research*. 2012. Vol. 3. P. 149-155.

[26] S.N. Razinkov, A.Yu. Perlov, A.S. Zakharov, Ya.A. Temnik, "Operational calibration of active phased antenna arrays of ground-based radar stations", *VKS. Theory and Practice*. 2024. Vol. 29. P. 94-102. (in Russian)

[27] A.S. Zakharov, V.V. Shamanov, A.Yu. Perlov, K.S. Sokolov, V.Yu. Pozdyshev, "Multiparameter optimization of the design process of space monitoring radars based on ontological analysis of the dependencies of functional characteristics on a variety of technical solutions", *Radio Engineering*. 2024. Vol. 88. No. 10. P. 110-117. DOI: 10.18127/j00338486-202410-12. (in Russian)

[28] A.Y. Perlov, A.V. Timoshenko, S.N. Marfin, and A.S. Zakharov, "Model of Compensation for the Influence of Non-Identicality of Phase Distribution of the Active Phased Antenna Array on Radar Accuracy Characteristics", *Systems of Signals Generating and Processing in the Field of on Board Communications*. 2025. P. 1-4. DOI: 10.1109/IEEE-CONF64229.2025.10947699.

[29] S. Matseevich, U. Vladko, A. Zyuzina, M. Mochalov, A. Zakharov, "Application of the cognitive load indicator of a graphic element to substantiate the requirements for a long-range radar visualization system", *Scientific Visualization*. 2024. Vol. 16. No. 3. P. 87-96. DOI: 10.26583/sv.16.3.09.

[30] E.A. Pafikov, A.V. Timoshenko, A.S. Zakharov et al., "Spatio-temporal characteristics of signals from radar stations with synthetic aperture taking into account reflection from targets and local objects", *News of higher educational institutions. Aviation technology*. 2025. Vol. 1. P. 120-137. (in Russian)

[31] A.S. Zakharov, A.V. Timoshenko, A.M. Savchuk et al., "Evaluation of distortions of the directional diagram of a radar station under non-stationary influence of thermal processes on a low-noise amplifier of the receiving path", *Digital signal processing*. 2025. Vol. 1. P. 23-27. (in Russian)

[32] A.V. Zyuzin, A.V. Gomozov, V.I. Gomozov, N.G. Baturin, "Dynamic theory of formation of complex microwave signals with high modulation rate", Monograph. Yaroslavl: Publisher LLC «Trading company NORD». 2010. 552 p. (in Russian)

[33] A.V. Zyuzin, A.S. Zakharov, A.Yu. Perlov, A.V. Timoshenko, "Methodology for selecting optimal parameters of the probing signal when operating in a high-resolution mode", *Proceedings of MAI*. 2024. Vol. 138. (in Russian)

[34] A. Penuela et al., "Correlates of ChatGPT use intention among freshmen health sciences students", *Journal of Education and Learning*. 2025. P. 1615-1622. DOI: 10.11591/edulearn.v19i3.22348.

[35] D.S. Chirov, E.O. Lobova, "Wideband hf signals dispersion distortion compensator based on digital filter banks. Theory and approbation", *T-Comm*. 2020. Vol. 14. No. 4, pp. 57-65.

[36] A.S. Kryukovsky, D.S. Lukin, D.V. Rastegaev, Yu.I. Skvortsova, "The numerical modeling of propagation of space-time frequency-modulated radiowaves in ionospheric to medium", *T-Comm*. 2015. Vol. 9, no. 9, pp. 40-47.

[37] S.S. Ajemov, E.M. Lobov, N.A. Kandaurov, E.O. Lobova, V.I. Lipatkin, "Algorithms of estimating and compensating the dispersion distortions of wideband signals in the hf channel", *H&ESReserch*. 2021. Vol. 13, no. 5, pp. 57-74.

АЛГОРИТМ ОЦЕНКИ ГОТОВНОСТИ ШИРОКОПОЛОСНОЙ РЛС К ПОСТРОЕНИЮ РАДИОЛОКАЦИОННЫХ ПОРТРЕТОВ КОСМИЧЕСКИХ ОБЪЕКТОВ

Тимошенко Александр Васильевич, Московский государственный университет имени М.В. Ломоносова, Москва, Россия, u567ku78@gmail.com

Перлов Анатолий Юрьевич, Московский государственный университет имени М.В. Ломоносова, Москва, Россия, laperlov@yandex.ru

Чиров Денис Сергеевич, Московский технический университет связи и информатики, Москва, Россия, d.s.chirov@mtuci.ru

Захаров Александр Сергеевич, Московский государственный университет имени М.В. Ломоносова, Москва, Россия, zakharov.as17@physics.msu.ru

Работа выполнена при поддержке Программы развития МГУ (проект № 24-S1-04)

Аннотация

В статье представлен разработанный алгоритм оценки готовности радиолокационной станции мониторинга космического пространства (РЛС МКП) к работе с требуемыми точностными характеристиками в режиме радиолокационного портретирования (РЛП) для информационного обеспечения решения задач оперативного обновления каталога космического пространства (ККП). Показано, что повышение качества РЛП может быть достигнуто за счет выбора параметров зондирующих сигналов с учетом текущей неравномерности АЧХ приемной системы РЛС. Представлены основные операции алгоритма оценки готовности РЛС МКП к построению РЛП для управления параметрами зондирующих сигналов по результатам расчета ранговой корреляции Спирмена, что обеспечивает наилучшие точностные характеристики РЛС с учетом влияния деструктивных факторов на характеристики приема-передающих каналов АФАР.

Ключевые слова: широкополосная радиолокационная станция, радиопортретирование, космические объекты, коэффициент готовности, мониторинг космического пространства

Литература

1. Лаговский Б.А., Насонов И.А., Рубинович Е.Я. Решение обратных задач достижения сверхразрешения при использовании нейронных сетей // Вестник Южно-Уральского государственного университета. Серия: Математическое моделирование и программирование. 2024. Т. 17. № 1.
2. Перлов А.Ю., Захаров А.С., Тимошенко А.В., Булатов М.Ф. Модель тепловых искажений амплитудно-частотной характеристики приемной системы радиолокационной станции в режиме сверхразрешения // Научные технологии в космических исследованиях Земли. 2024. Т. 16. № 5. С. 26-34. DOI: 10.36724/2409541920241652634.
3. Манукьян А.А. Построение двумерных радиоизображений объектов по неэквидистантным кодированным частотно-временным последовательностям импульсов // Радиотехника и электроника. 2015. Т. 60. № 3. С. 282. DOI 10.7868/S0033849414120134.
4. Anger S. et al. High-resolution inverse synthetic aperture radar imaging of satellites in space // IET Radar, Sonar & Navigation. 2023. P. 1-20.
5. Du H. et al. Integrated convolution network for ISAR imaging and target recognition // IEEE Journal on Miniaturization for Air and Space Systems. 2023.
6. Лихоеденко К.П., Серегин Г.М., Сучков В.Б., Перов А.Ю. Математическое моделирование поляризационных радиолокационных портретов объектов сложной формы на основе их многоточечных моделей в радиолокаторах с инверсным синтезированием апертуры // Успехи современной радиоэлектроники. 2024. Т. 78. № 2. С. 13-24. DOI: 10.18127/j20700784-202402-02.
7. Stober J., Gunter J., Christoph D. Distortion of meteor count rates due to cosmic radio noise and atmospheric particularities // Advances in Radio Science. 2010. Vol. 8. P. 237-241. DOI: 10.5194/ars-8-237-2010.
8. Barker L., Drakakis K., Scott R. On the Complexity of the Verification of the Costas Property // Proceedings of the IEEE. 2009. Vol. 97. P. 586 - 593. DOI: 10.1109/JPROC.2008.2011947.
9. Du H. et al. Integrated convolution network for ISAR imaging and target recognition // IEEE Journal on Miniaturization for Air and Space Systems. 2023.
10. Xu G. et al. Manifold Low Rank and Sparse Tensor Method for High-Resolution Radar Imaging // IEEE Transactions on Geoscience and Remote Sensing. 2025. Vol. 63. P. 1-14.
11. Zhang J. et al. From Coarse to Fine: ISAR Object View Interpolation via Flow Estimation and GAN // IEEE Transactions on Geoscience and Remote Sensing. 2024. Vol. 62. P. 1-20.
12. Хуторовский З.Н., Бойков В.Ф., Пылаев Л.Н. Контроль космических объектов на низких высотах // Околосземная астрономия (космический мусор), Российская Академия Наук. 1998. С. 34-101.
13. Khutorovsky Z.N., Boikov V.F., Pylaev L.N. Catalog Maintenance of Low-Earth-Orbit Satellites: Principles of the Algorithm // Journal of Guidance, Control, and Dynamics. 1999. Vol. 22. No. 6. P. 745-758.
14. Ceresoli M., Colagrossi A., Silvestrini S., Lavagna M. Robust, Onboard Orbit Determination Through Error Kalman Filtering // Aerospace. 2025. Vol. 12. P. 45. DOI: 10.3390/aerospace12010045.
15. Zhang Y. et al. A Fast Target Imaging Model Based on Electromagnetic Scattering Solution and Machine Learning // IEEE International Geoscience and Remote Sensing Symposium. 2024. P.10587.
16. Chen Zh. et al. A Novel Method for PolISAR Interpretation of Space Target Structure Based on Component Decomposition and Coherent Feature Extraction // Remote Sensing. 2025. Vol. 17. No. 6. P. 1079.

17. Miao J., Tu L., Liu H., Zhao J. Astronomical Image Superresolution Reconstruction with Deep Learning for Better Identification of Interacting Galaxies. // *The Astrophysical Journal Supplement Series*. 2025. Vol. 278. P. 35. DOI: 10.3847/1538-4365/adca34.
18. Erokhin V.I., Kadochnikov A.P., Sotnikov S.V. Linear Binary Classification under Interval Uncertainty of Data // *Scientific and Technical Information Processing*. 2024. Vol. 51. No. 6. P. 539-544. DOI: 10.3103/S0147688224700485.
19. Zakharov A., Perlov A., et al. Model for calculating changes in the radiation pattern and amplitude-phase distribution in the subarray of a large-aperture apaa based on a modified thermal conductivity equation // *IEEE Systems of Signals Generating and Processing in the Field of on Board Communications*. 2024. P. 1-4. DOI: 10.1109/ieeconf60226.2024.10496770.
20. Manukian A. Constructing the 2D Radio Image of Objects with the Use of Multifrequency Signals with Coded Carrier-Frequency Hopping (Costas signals) // *Journal of Communication Technology and Electronics*. 2011. Vol. 56. P. 160-171. DOI: 10.1134/S1064226911010074.
21. Ладыгин А.И. Анализ сигнатур: теория и практика радиолокационного распознавания космических объектов и космические трагедии глазами аналитиков сигнатур. Москва: Унив. кн. 2008. 255 с. ISBN 978-5-98699-044-6.
22. Leukhin A., Voronin A., Merzlyakov A., Parsaev N. Application of the autofocusing algorithm for the synthesis of X and L band radar images // *Journal of Physics: Conference Series*. 2020. Vol. 1679. P. 042009. DOI: 10.1088/1742-6596/1679/4/042009.
23. Детков А.Н., Макаров И.А. Модель движения космического объекта и формирование его радиолокационного портрета // *Журнал радиоэлектроники*. 2013. Т. 12. С. 1-18.
24. Болелов Э.А., Васильев О.В., Зябкин С.А., Чиров Д.С. Разработка нечетко-логического классификатора фазового состояния гидрометеоров для алгоритма классификации зон вероятного обледенения воздушных судов в метеолокаторах X-диапазона // *T-Comm: Телекоммуникации и транспорт*. 2023. Т. 17. № 10. С. 4-12.
25. Sharma A., Suraj N., Rokade M., Ghodpage N. et al. Study of variations in the absorption of cosmic radio noise using Riometer at Casey station // *Library & Information Science Research*. 2012. Vol. 3. P. 149-155.
26. Разиньков С.Н., Перлов А.Ю., Захаров А.С., Темник Я.А. Оперативная калибровка активных фазированных антенных решеток наземных радиолокационных станций // *ВКС. Теория и практика*. 2024. Т. 29. С. 94-102.
27. Захаров А.С., Шаманов В.В., Перлов А.Ю., Соколов К.С., Поздышев В.Ю. Многопараметрическая оптимизация процесса проектирования РЛС мониторинга космического пространства на основе онтологического анализа зависимостей функциональных характеристик от множества технических решений // *Радиотехника*. 2024. Т. 88. № 10. С. 110-117. DOI: 10.18127/j00338486-202410-12
28. Perlov A.Y., Timoshenko A.V., Marfin S.N. and Zakharov A.S. Model of Compensation for the Influence of Non-Identity of Phase Distribution of the Active Phased Antenna Array on Radar Accuracy Characteristics // *Systems of Signals Generating and Processing in the Field of on Board Communications*. 2025. P. 1-4. DOI: 10.1109/IEEECONF64229.2025.10947699.
29. Matseevich S., Vladko U., Zyzina A., Mochalov M., Zakharov A. Application of the cognitive load indicator of a graphic element to substantiate the requirements for a long-range radar visualization system // *Scientific Visualization*. 2024. Vol. 16. No. 3. P. 87-96. DOI: 10.26583/sv.16.3.09
30. Пафилов Е.А., Тимошенко А.В., Захаров А.С. и др. Пространственно-временные характеристики сигналов радиолокационных станций с синтезированной апертурой с учетом отражения от целей и местных предметов // *Известия высших учебных заведений. Авиационная техника*. 2025. № 1. С. 120-137.
31. Захаров А.С., Тимошенко А.В., Савчук А.М. и др. Оценка искажений диаграммы направленности радиолокационной станции при нестационарном воздействии тепловых процессов на малошумящий усилитель приемного тракта // *Цифровая обработка сигналов*. 2025. № 1. С. 23-27.
32. Зюзин А.В., Гомозов А.В., Гомозов В.И., Батулин Н.Г. Динамическая теория формирования сложных СВЧ-сигналов с высокой скоростью модуляции: Монография. Ярославль: Изд-во ООО "Торговая фирма НОРД". 2010. 552 с.
33. Зюзин А.В., Захаров А.С., Перлов А.Ю., Тимошенко А.В. Методика выбора оптимальных параметров зондирующего сигнала при работе в режиме с повышенным разрешением // *Труды МАИ*. 2024. № 138.
34. Penuela A. et al. Correlates of ChatGPT use intention among freshmen health sciences students // *Journal of Education and Learning*. 2025. P. 1615-1622. DOI: 10.11591/edulearn.v19i3.22348.
35. Chirov D.S., Lobova E.O. Wideband hf signals dispersion distortion compensator based on digital filter banks. Theory and approbation // *T-Comm: Телекоммуникации и транспорт*. 2020. Т. 14. № 4. С. 57-65.
36. Крюковский А.С., Лукин Д.С., Растягаев Д.В., Скворцова Ю.И. Численное моделирование распространения пространственно-временных частотно-модулированных радиоволн в анизотропной среде // *T-Comm: Телекоммуникации и транспорт*. 2015. Т. 9. № 9. С. 40-47.
37. Аджемов С.С., Лобов Е.М., Кандауров Н.А., Лобова Е.О., Липаткин В.И. Алгоритмы оценки и компенсации дисперсионных искажений широкополосных сигналов ионосферных радиолоний связи // *Научные технологии в космических исследованиях Земли*. 2021. Т. 13. № 5. С. 57-74.

Информация об авторах:

Тимошенко Александр Васильевич, Московский государственный университет имени М.В. Ломоносова, старший преподаватель, доктор технических наук, профессор, Москва, Россия. ORCID: 0000-0002-9791-142X

Перлов Анатолий Юрьевич, Московский государственный университет имени М.В. Ломоносова, старший преподаватель, кандидат технических наук, доцент, Москва, Россия. ORCID: 0000-0001-8480-3772

Чиров Денис Сергеевич, Московский технический университет связи и информатики, заведующий кафедрой "Радиотехнические системы", доктор технических систем, профессор, Москва, Россия. ORCID: 0000-0001-8509-4373

Захаров Александр Сергеевич, Московский государственный университет имени М.В. Ломоносова, лаборант, Москва, Россия. ORCID: 0009-0000-2617-5317