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Mathematical Model and Identification Method and Recognition of Radio Electronic Means of Satellite Services of Radio Communications

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Abstract

The article presents a mathematical model and numerical methods for identification and recognition of radio-electronic means based on probabilistic indicators of spectral-energy characteristics and parameters of functioning of radio-electronic means placed on orbiting satellites and earth stations of satellite communications. It is shown that the wide and intensive use of satellite telecommunications determines the relevance of the formulation and solution of the problem of ensuring the proper use of the radio frequency spectrum and radio electronic means of satellite radio communication services through the implementation of radio monitoring measures for the use of the allocated radio frequency spectrum, the functioning of radio electronic means of satellite communication space stations in geostationary orbit and earth stations satellite radio communication services by instrumental measurement and assessment of the parameters of permitted radio-electronic emissions, searching for unauthorized ones, identifying sources of unacceptable radio interference, as well as identifying radio-electronic means. The systematization and identification of the key spectral-energy features of recognition of identification objects was carried out, on the basis of which a method was proposed for solving the problem of identifying satellite radio electronic means using stationary satellite radio monitoring stations based on samples of the values of their

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registered parameters based on the implementation of TDOA / FDOA geolocation. In addition, to reduce the size of the ellipse of uncertainty, a solution is proposed based on improving the spectral characteristics of synthesized signals in the radio electronic means of space stations of satellite communications by automatically compensating for phase distortions of direct digital synthesizers.

Keywords: Radio frequency service, radio control and monitoring, radio electronic means, parameters and indicators of the state of radio electronic means, earth stations of satellite radio communications services, space stations of satellite communications, stationary satellite radio monitoring stations, spectral and energy indicators of recognition of radio electronic means, methods and models for determining the coordinates of points location on the earth's surface, geolocation, frequency synthesizers, spectral characteristics, phase distortions, automatic compensation.

Introduction

The wide and intensive use of satellite telecommunications in almost all spheres and activities of the modern information society, the increase in its economic and social significance, determines the relevance of the formulation and solution of the problem of ensuring the proper use of the radio frequency spectrum and the corresponding radio electronic means (REM) of satellite radio communication services. An important tool for such support is the implementation of organizational and technical measures for radio monitoring (RM) for the proper use of the allocated radio frequency spectrum, the functioning of the REM of space stations of satellite communications (SSSC) in the geostationary orbit (GSO) and working through them, in the mode of direct relaying of signals from earth stations of satellite services radio communications (ESSS).

The required RM should provide: instrumental measurement and assessment of the parameters of permitted, legitimate radio-electronic emissions of the REM of SSSC and ESSS, the search not allowed for use REM of satellite radio communication services, the identification of sources of unacceptable radio interferences, as well as control over the emissions of the REM in order to ensure international legal protection (ILP) [1-3]. Of great importance is the solution of a particular relatively independent problem of identifying REM of SSSC and ESSS, and the result of its solution should be an instance of recognition of legitimate and illegally operating SSSC and ESSS transponders, as well as possible sources of radio interference arising in the frequency range of the existing SSSC and ESSS functioning.

Formulation of the problem

The solution to the problem of practical identification of the desired objects is a theoretical and methodological complexity, which leads, respectively, to the technical complexity of the implementation of radio monitoring measures, which consist in the features and specifics of the functioning of the SSSC and ESSS, which are the actual objects of identification (OI), as well as in the peculiarities of receiving and processing their radio emissions. by means of the RM. These features are determined by the fact that any OI can potentially be identified in the presence of the required volume of recognition signs (RS), which does not exceed the amount of a priori information about the parameters of its functioning established by the current regulatory documents [1-3], including international ones [4]. The analysis of these regulatory documents made it possible to systematize and highlight the following RS: Orbital position; Operator; Frequency; Band; Polarization; Emission class; Effective radiated power; Installation site, geographic coordinates; Antenna suspension height; Azimuth of the direction of radiation; Antenna type, size. These RSs in the amount of a priori information for identification are higher for domestic OIs than foreign ones.

On the basis of these RSs, a technique has been proposed that reflects the features of the identification of the ESSS using mobile complexes of the satellite RM (MCSRM) [3]. Taking into account these identification features, the article presents a method for solving the problem of identifying satellite REM using stationary stations of the satellite RM (SSSRM) based on samples of the values of their recorded parameters in terms of procedures for the single-instance recognition of SSSC and ESSS, taking into account new opportunities for identifying ESSS based on determining their coordinates by signals relayed by SSSC, i.e. implementation of geolocation.

The practical implementation of the solution of the problems of identification of SSSC and ESSS is carried out on the basis of the existing geographically distributed complexes of the SSSRM as part of the integrated system of the target automated complex of the satellite RM [2], which solves as priority particular tasks: determination of spectral - energy recognition signs; determination of coordinates of earth stations of satellite communications, the solution of which can be represented by appropriate mathematical models and an algorithm for identification and recognition of OI.

Model for determining the spectral - energy features of OI recognition.

Determination of recognition signs using the SSSRM according to the results of radio engineering measurements (REI) of the spectral and energy parameters of radio emissions from the SSSC is associated with random and systematic measurement errors (ME), which affect the identification accuracy of the OI. To reduce the ME on a regular basis, the problem of choosing numerical methods and measuring instruments developed on their basis should be solved, using probabilistic indicators of the accuracy of recording the SSSRM of the RS values, based on taking into account the stochastic nature of fluctuations of the energy, frequency and phase characteristics of the OI signals at the point of their reception and processing methods signals in the receiving paths of the SSSRM.

Registration of the spectral and energy parameters of the SSSC radiation can be represented by an effective mathematical model of fluctuations of satellite signals at the input of the receiving path of the SSSRM, in which the signal is presented with a constant amplitude and a random initial phase [5, 6]. Then the probability of correct signal detection for such a model is determined by the expression (1) of the Rayleigh-

Rice distribution [7]:

$$P_{\det} = \int_{q_{thr}}^{\infty} \upsilon \cdot \exp\left(-\frac{\upsilon^2 + q^2}{2}\right) \times I_o(\upsilon \cdot q) d\upsilon, \tag{1}$$

$$q_{thr} = \sqrt{-2 \cdot \ln P_{FA}}, \tag{2}$$

where q is the ratio of the signal power of the SSSC to the noise power at the input of the signal detector in the signal band; $I_o(x)$ - modified Bessel function of the zero order; q_{thr} - threshold level of signal detection; P_{FA} - the probability of a false alarm.

From (2) it follows that when the set probability values are limited within $10^{-2}...10^{-3}$, the signal detection threshold is 2.15 ... 2.63 dB. With an increase in the requirements for the values of the probability of a false alarm to $10^{-5}...10^{-6}$, the values q_{thr} increase to 4.79 ... 5.25 dB. The indicated boundaries of the mutual correspondence of the values q_{thr} and P_{FA} determine the practically significant range of mutual correspondence of the possibility and reliability of detecting SSSC emissions.

For the fluctuation model (1), the representation of the signal envelopes of the SSSC in the form of radio pulses of a Gaussian shape and $q > 5$ dB values, the posterior probability densities of the distributions of its frequency and amplitude components at the input of the receiving path of the SSSRM will have a normal distribution, and the probabilities of correct measurements of their values can be determined by the known expression (3) [7]:

$$P_\gamma = 2 \cdot erf(Z_\gamma) - 1, \gamma = f, \Delta F, a, w, \tag{3}$$

$$erf(Z_\gamma) = \frac{1}{\sqrt{2 \cdot \pi}} \times \int_{-\infty}^{Z_\gamma} \exp\left(-0{,}5 Z_\gamma{}^2\right) dZ_\gamma\,, \tag{4}$$

where $erf\left(Z_\gamma\right)$ is the probability integral function; Z_γ - parameter of integration; γ - the index of the integration parameter corresponding to the dimension of the physical characteristics of the measured quantity.

The parameter Z_γ values are determined by known methods, taking into account the physical characteristics of the measured quantities. So, to take into account their variability in expressions (1) and (2), an index γ is used equal to: $\gamma = f$ - when measuring frequencies; $\gamma = \Delta F$ - when measuring strips; $\gamma = a$ - when measuring amplitudes; $\gamma = w$ - when measuring signal power; a priori information about the parameters of the distributions of their values; parameters of measurement error distributions, depending on the metrological characteristics of the RM equipment, methods and number of measurements performed; measurement conditions specified by the parameter q.

The values of the integration parameters z_{γ} are determined by the well-known [8] expressions

$$Z_f = 1{,}183 \cdot \delta_f \cdot q \cdot \sqrt{n} / \Delta f, \tag{5}$$

$$Z_{\Delta F} = 0{,}6143 \cdot \delta_A \cdot k_{A-f} \cdot q \cdot \sqrt{n} / A, \tag{6}$$

$$Z_a = 1{,}37 \cdot \delta_A \cdot q \cdot \sqrt{n} / A, \tag{7}$$

$$z_w = \delta_w \cdot q \cdot \sqrt{n} / \sigma_w, \tag{8}$$

where δ_f is the admissible ME of the signal frequency; δ_A - permissible ME of measurement of the amplitudes of the spectral components of the signal; δ_w - allowable ME of the signal power flux density; σ_w - total ME signal power; Δf - width of the spectrum of the signal of the SSSC; n –number of measurements of the registered signal parameter; k_{A-f} - coefficient of proportionality; A is the mathematical expectation of the maximum amplitude in the signal spectrum.

The values of the corresponding integration parameters determined by expressions (5) and (6) are calculated under the following conditions (assumptions): the ME frequencies of the spectral components of the SSSC signals are significantly less than their instability, which corresponds to the real conditions of the satellite RM. For the sought frequencies, the relative ME frequencies of satellite signals are not worse than $10^{-9} \ldots 10^{-12}$ with permissible relative deviations of the carrier frequencies of the SSSC emissions from the nominal values of 10^{-6} and permissible deviations of the occupied frequency band 10^{-1} from the required band, ranging from tens of kilohertz to tens of megahertz.

In expression (6), the coefficient k_{A-f} takes into account the shape of the signal and shows the ratio of the amplitude of the envelope of the signal spectrum at a point located at a given frequency distance f from its center to the amplitude of its central frequency.

Analysis of the values of the integration parameters defined by expressions (5–8) allows us to conclude that, all other things being equal, the parameter q characterizing the ratio of the signal power of the SSSC to the noise power at the input of the signal detector in the signal band has a significant effect on the reliability of recording the values of recognition signs , which is confirmed by the corresponding dependences (Figure 1, which shows the dependences of the probability of correct registration of the level of equivalent isotropic radiated power (EIRP) of the ESSS (P_w) on the values q at δ_w = 1,5 dB and $\sigma_w = 0{,}5$ dB (solid lines) and dB (dashed line) [8] at performing single $n = 1$, and multiple measurements $n = 10$, carried out to improve their accuracy).

Analysis of the values of the dependences presented in Figure 1 shows what $P_w \geq 0{,}9$ can be achieved with values q in the range from 8 to 16 dB.

Methods for determining the reliability of registration of such RSs as the type of signal polarization and subsatellite points (SSP) of the SSSC are based on estimates of the probabilities of correct measurements of the levels of satellite signals.

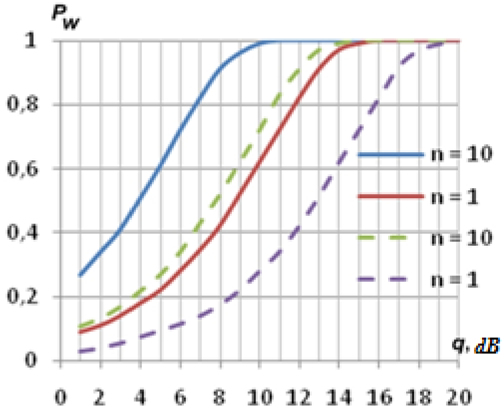

Figure 1 - Dependence of the probability of correct measurement of the EIRP of the ESSS on the signal-to-noise power ratio in its band

Calculated ratios for determining the reliability of registration of the type of polarization of the SSSC signals can be obtained under the following conditions for the implementation of the measurement procedure:

1) it is assumed that the antenna system (AS) of the SSSRM is equally adapted to the reception of signals with different types of polarization, and the level of its cross-polarization decoupling ensures the attenuation of crosstalk between the orthogonal polarization planes not less than the level set for the KS transponders;

2) in the receiving system of the SSSRM, when changing different types of polarization of the speaker, the levels of the received signals are measured.

Taking into account these conditions, the decision to use a certain type of polarization is made in accordance with the rule:

$$D = \max\left(A_{s,l}\right) \quad l \in L, s \in S , \tag{9}$$

where $A_{s,l}$ is the amplitude of the s–th signal, measured when adjusting the receiving path of the SSSRM for receiving signals of the l–th type of polarization; L - the number of types of polarization of the receiving system of the RM facility; S - the number of measured signals.

In turn, the probability of correct registration of the type of polarization (10) will be determined by the probabilities of correct measurements of the amplitudes of all components of the ensemble of signals measured when changing all possible types of polarization of the AS:

$$P_A = \frac{1}{S} \sum_{s \in S} (1 - \prod_{l \in L} (1 - P_{A_{s,l}})), \tag{10}$$

where $P_{A_{s,l}}$ is the probability of correct measurement of the s-th signal level when adjusting the receiving antenna of the SSSRM for receiving signals with the l-th type of polarization, calculated in accordance with (3,4,7).

When setting up the AS stations of the RM for receiving signals with linear polarization, it is necessary to take into account the inclination of the plane to the horizon at the receiving point (τ), which is defined as the angle between the horizon plane at the station location and the polarization plane of the SSSC signal and is due to the influence of geometric factors of relative position on the earth sphere of the SSSRM and sub-satellite points (SSP) in the equatorial plane. The angle τ is calculated using the known relationships [9] and, in particular, for linear horizontal polarization by the formula

$$\tau = arctg(\sin(Lo_{sat} - Lo_{es}) / tg(La_{es})), \tag{11}$$

where La_{es} is the geographic latitude of the SSSRM (for the northern hemisphere - the "+" sign, for the southern - the "-" sign); Lo_{es} - the geographical longitude of the SSSRM (for the eastern hemisphere - the "+" sign, for the western - the "-" sign); Lo_{sat} - the geographic longitude of the SSP (for the eastern hemisphere - the "+" sign, for the western - the "-" sign).

By the stations of the satellite RM, the orbital positions of the SSSC in the geostationary orbit (GSO) can be determined passively by pointing their ASs to the SSP according to the maximum of the received signals and registering the corresponding azimuths of the antenna orientation angles. The error of such measurements σ_{az} is determined by the directional patterns (DP) of the receiving antennas of the SSSRM and has the form of a functional dependence

$$\sigma_f = \Psi(\lambda, d, G, \eta), \tag{12}$$

where λ is the wavelength, cm; d - diameter of the antenna mirror, m; G - antenna gain in the direction of the maximum of its antenna pattern, dB; η is a correction factor that takes into account the antenna pointing method.

For the considered model of signal fluctuations (1) and the distribution of measurement errors of their amplitudes (3), the integration parameter in (4) is determined by the well-known expression [8]

$$Z_{\gamma} = \delta_{ss} / \sigma_{az}, \tag{13}$$

where δ_{ss} is the permissible error of keeping the SSSC in the GSO in longitude relative to its nominal value.

Figure 2 shows the graphs of the probability of correct identification of SSSC in the GSO by their SSP (P_{GSO}) at the middle frequencies of the C- and Ku-satellite frequency bands (blue and red graphs, respectively) using parabolic two-mirror receiving antennas (Cassegrin) of various diameters d.

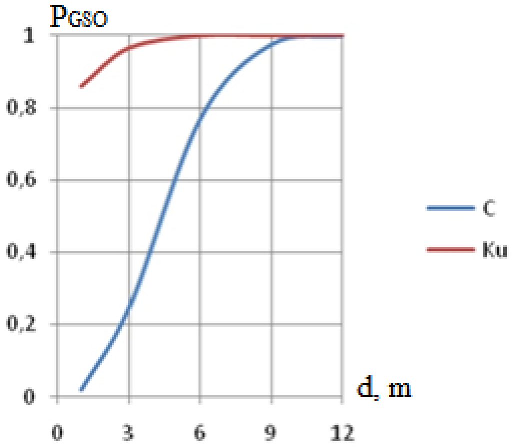

Fig. 2. Dependence of the probability of correct measurement of the sub-satellite points of SSSC from the diameters of the receiving antennas of the SSSRM

These probabilities are calculated using expressions (3,4,13) and the values of the functional dependence, calculated according to the well-known [10] formula (12). When calculating the desired probability, the value $\delta_{ss} = 0.1$ accepted in [11] was used. The results of the calculated values allow us to conclude that the probability P_{GSO} of no worse than 0.9 is provided when using in the C- frequency range of an AC with a diameter of at least 7.5 m and Ku- range with a diameter of at least 2 m.

The above provisions allow us to draw the following conclusions:

1) reliable registration of the values of frequency-energy characteristics of the

recognition of SSSC and ESSS and SSP SSSC by satellite radio emissions is characterized by probabilistic indicators;

2) the values of the frequency and energy characteristics of the recognition of the SSSC and ESSS and SSP SSSC by satellite radio emissions depend both on the propagation conditions of radio waves and the parameters of radio emissions of the REM of satellite radio communication services, and on the characteristics of radio monitoring equipment and methods of measurements;

3) to determine the reliability indicators of the required measurements, it is necessary to determine the current values q, taking into account which the calculations of the measurement reliability indicators should be carried out;

4) in any conditions, the procedure for maximizing the reliability of registration should consist in the correct choice of the SSSRM for measurements, proceeding from the condition of achieving the maximum possible ratio of the signal power to the noise power in its band;

5) in the operating subsystem of the satellite RM of the radio frequency service, the possibility of the correct choice of the SSSRM is provided by its spatially distributed structure and the centralized control of the functioning of the SSSRM as part of an integrated geographically distributed automated measuring complex.

Model for determining the coordinates of earth stations of satellite communication

The model for determining the coordinates of earth stations of satellite communication can be represented by a well-known numerical method for determining the coordinates of the location points on the earth's surface (geolocation) of the ESSS by their relayed signals, which is implemented in hardware and software complexes (HSC) of the RM and allows solving the problems of obtaining reliable results of identification of the ESSS by means of the satellite RM of the radio frequency service, modernization of these PAKs, ensuring the automated control of the functioning of the HSC of RM as part of the existing data transmission system of the satellite RM subsystem of the country, which significantly reduces the time for solving RM problems and resource costs. The content of the required method and the peculiarities of its implementation in the HSC of RM are as follows.

To determine the location of the ESSS by the PM, the TDOA / FDOA geolocation method is used, which consists in differential measurements of the time and frequency of the signals of the desired ESSS, relayed by two SSSC located in different orbital positions during their orbital movements and the subsequent determination of the intersection point on the Earth's surface of the time lag isolines (TDOA) and frequency offset (FDOA) of the relayed signals. The time lag arises due to the difference in the distances between the ESSS and SSSC in different orbital positions. The frequency shift is caused by the Doppler effect during the natural drift of the SSSC along a trajectory similar to the figure eight in the direction transverse to the GSO (meridian).

The measurement assumes that one of the SSSC, called the main (MSSSC), serves to receive and retransmit the signal emitted by the main lobe of the antenna pattern of the transmitting antenna of the ESSS, and the other SSSC, called the auxiliary (ASSSC) - the signal emitted by one of the side lobes of its antenna pattern. According to the measurements, two corresponding bearings are constructed, mainly oriented in the North-South and East-West directions. The point of their intersection gives the location of the desired ESSS. The choice of ASSSC is carried out taking into account the provision of a possible small angular distance from the MSSSC, the coincidence of the frequency-polarization plan (FPP) of one of its transponders with the FPP of the MSSSC transponder, through which the ESSS operates, as well as the coincidence of the coverage areas of the beams of the MSSSC and ASSSC transponders on the "ground - space" line. When choosing ASSSC, preference is given to a station in the transponder of which there is no other signal overlapping in the occupied frequency band the signal of the desired ESSS.

In TDOA / FDOA geolocation, the reception and processing of MSSSC and ASSSC signals are performed by two sets of equipment that implement the principle of mutual correlation signal processing and can be located at one or two spatially separated positions. In all cases, one of the sets performs the functions of the master, providing: TDOA and FDOA measurements of MSSSC signals; issuing target designations to another (slave) set for measuring ASSSC signals; crosscorrelation processing of the results of own measurements and measurements of the slave set and the final calculations of the ESSS positioning. To receive the MSSSC signal, an AS with a diameter of 3.5 ... 7 m is sufficient, and to receive a ASSSC signal, an AS with a diameter of more than 7 m is needed, since its attenuation due to cross-polarization losses and the mutual orientation of the ESSS and ASSSC antenna systems can be 40 ... 50 dB. In both cases, the necessary conditions for making measurements are high-precision determination of the coordinates of the AS and synchronization of measurements.

In existing geolocation systems, a scheme of spatially separated measurements is implemented, in which each SSSRM has a full set of capabilities to perform the functions of a master and slave station. The advantage of such a scheme: the ability to adapt the measurement scheme to the conditions for receiving satellite signals; assigning a station for measurements, for which the best spatial and energy conditions for receiving signals from the MSSSC or ASSSC are provided. These advantages are important when the SSSC operates for transmission with narrow beams, which currently takes place in the Ku-band, and in the near future, with the beginning of the active use of the Ka-band, will be systematic. For such operating conditions of the SSSC, the spatial-territorial diversity of the SSSRM in combination with the use of each 12 m AS gives an important energy gain, which, according to the estimates of the options for performing geolocation tasks, is estimated at 5–7 dB.

The solution of practical geolocation problems is carried out by special hardware and software geolocation systems, consisting of two identical geographically dispersed sets of the SSSRM, each of which consists of signal processing equipment (Digitization System), synchronization equipment, Ethernet switch, computer equipment (blade server) and a special software. The signal processing equipment is built according to the scheme of cross-correlation processing of copies of the signal of the ESSS, retransmitted through the MSSSC and ASSSC. The implementation of the procedure for such processing is ensured by the presence of a uniform time scale for the elements of the complex and an associated source of data on the ephemeris of the SSSC. Such processing makes it possible to detect the ESSS signal when it is retransmitted through the ASSSC against the background of standard signals. In this case, the energy gain in the signal-to-noise ratio in the signal band in the channel for receiving ASSSC emissions can reach 60–70 dB, which in most cases compensates for cross-polarization losses and the presence of interfering signals in the receiving band. Measurements of signal parameters are performed at times corresponding to exactly known SSSC ephemeris. The complex implements measurement procedures and processing of their results, which can be represented by the following mathematical models and numerical methods.

The functional links between the results and conditions of performance $TDOA\,(\Delta R_{i,j}(\cdot))$ and $FDOA\,(\Delta F_{i,j}(\cdot))$ measurements (without taking into account the parameters characterizing the energy conditions of geolocation and their ME) are as follows:

$$\Delta R_{i,j}(\alpha,\beta_i,\beta_j) = c\cdot\Delta\tau_{ij}(\alpha,\beta_i,\beta_j), i=1, j=2, \tag{13}$$

$$\Delta F_{i,j}(\alpha,\beta_i,\beta_j) = c^{-1}\cdot f_c(\alpha,v_i,v_j,\beta_i,\beta_j,), i=1, j=2, \tag{14}$$

$$v_k = v_k^{*}\cdot\cos\varphi_k, k=i, j, \tag{15}$$

where $\Delta R_{i,j}(\alpha,\beta_i,\beta_j)$ is the difference between the distances from the ESSS to the i-th and j-th SSSC; α - the vector of coordinates of the ESSS in the Cartesian coordinate system; β_i and β_j - vectors of coordinates of SSSC with numbers i or j; $\Delta\tau_{ij}(\alpha,\beta_i,\beta_j)$ - the difference between the times of arrival of the signal from the ESSS to the i-th and j-th SSSC; f_c - frequency of the ESSS signal; c - the speed of light; v_k - radial speed of the k-th SSSC relative to the ESSS; v_k^{*} - speed of the k-th SSSC; φ_k is the angle between the velocity vector of the k-th SSSC and the direction to the ESSS.

Based on the results and measurements from the condition $TDOA = const$ and $FDOA = const$, the surfaces of the second order are constructed, the foci of which coincide with the orbital positions of the SSSC. The intersection of these surfaces with the Earth's surface gives the isolines and. The point of intersection of the isolines determines the location of the ESSS.

The content of the known procedure [12] of cross-correlation signal processing can be represented by the following model. For temporal sequences of signals relayed by

MSSSC and ASSSC, using fast Fourier transforms (FFT), a three-dimensional function of mutual uncertainty (FMU) of signals is calculated, referred to as a correlation map. The FMU values determine the cross-correlation of the two signals as a function of time and frequency offset. The time of coherent integration of signals required to calculate the FMU is determined by the duration of the signals and the stability of the synchronization equipment. The position of the cross-correlation peak serves to determine the area of the probable location of the ESSS on the correlation map.

Due to the ME, this region is defined by the uncertainty ellipse. The ellipse is elongated in the meridian direction because *TDOA*measurements are more accurate than *FDOA* measurements. The distribution densities of the dimensions of the semiaxes of the ellipse are determined by ME and obey the normal law for the minor axis, expression (17) and for the major axis, expression (18).

$$P(x) = (2\pi)^{-2} \exp(-(x - m_{TDOA})^2 / 2\sigma_{TDOA}{}^2), \tag{17}$$

$$P(y) = (2\pi)^{-2} \exp(-(y - m_{FDOA})^2 / 2\sigma_{FDOA}{}^2), \tag{18}$$

where m_{TDOA} and m_{FDOA} are the mathematical expectations of the results *TDOA* and *FDOA* measurements; σ_{TDOA} and σ_{FDOA} - RMS of results *TDOA* and *FDOA* measurements.

It is known [12] that the dimensions of the uncertainty ellipse, as a function of ME, depend on: the diameters of the transmitting antenna of the ESSS and the receiving antennas of the SSSRM; drift of local oscillators and phase noise of MSSSC and ASSSC; phase noise of the high-frequency part of the SSSRM receiving path; the accuracy of determining the ephemeris SSSC; signal-to-noise ratios in the bands of the measured signal in the paths for receiving the ASSSC and MSSSC emissions; parameters of the relative position and movement of the SSSC relative to each other and their position relative to the SSSRM; level, bandwidth and duration of ESSS signals, in order to reduce the size of the ellipse, it is necessary to increase the duration of measurements, set the exact coordinates of the antenna systems of the SSSRM, compensate for the errors in determining the ephemeris of the SSSC. To compensate for the error in determining the ephemeris of the SSSC, their verification is carried out, for which one or several reference ESSS are used - sources of reference signals emitted on the ground-to-space line from precisely known geographic points, which ensures a high correlation of their copies when retransmitted through the MSSSC and ASSSC. Verification is based on a comparison of the measured coordinates of points on the earth's surface $(x_{г}, y_{г})$ and the known geographic coordinates $(x_{г}, y_{г})$ of the points of the location of the reference ESSS. In this case, the geolocation error of each reference ZSSS is determined as:

$$E = ((x_o^2 - x_{г}^2) + (y_0^2 - y_{г}^2))^{0,5}. \tag{19}$$

If necessary, based on the comparison results, the error in setting the ephemeris is calculated, which is subject to compensation. Compensation of errors of ephemeris corrects the ephemeris data by means of reverse calculation using the results of measurements of coordinates of points on the earth's surface in which the reference ZSSS are located.

Determination of the linear distances of the sought ZSSS from the given geographical points is carried out according to the formula (19). These linear distances, together with the results of calculating the indicators according to formulas (3-8,17,18), are the initial data necessary for identifying the ESSS.

Application of the method of automatic compensation to improve the spectral characteristics of the REM of space stations of satellite communications

Earlier it was shown that the dimensions of the uncertainty ellipse largely depend on the spectral characteristics of signals synthesized in the REM of space stations of satellite communications and determined by the level of discrete parasitic spectral components and phase noise.

Until recently, devices based on one of three methods of frequency synthesis [13-15] were used as signal conditioners for such REMs: direct analog, indirect based on phase-locked loop (PLL) systems, and direct digital based on direct digital synthesizers (DDS). Each of these synthesis methods has both advantages and characteristic disadvantages that limit their application. The hybrid method of frequency synthesis can significantly reduce the effect of the disadvantages of each of the above-mentioned methods of signal generation. It consists in the fact that a synthesizer built according to one of the synthesis methods is complicated by the introduction into its circuit of the structural elements of a frequency synthesizer built according to a different synthesis method. Thus, some of the disadvantages inherent in some synthesizers are offset by the advantages of others.

Theoretical and experimental studies of modern authors have shown that hybrid frequency synthesizers that combine direct digital and indirect synthesis seem to be the most promising. They provide a wide range of synthesized frequencies (up to tens of gigahertz), a small tuning step (hertz - fractions of a hertz), have the ability to programmatically control and generate oscillations with complex modulation laws (in particular, ultra-wideband). However, at present, these synthesizers have insufficient spectral purity of the synthesized signals. This is, first of all, due to the presence of DDS in the composition of such hybrid synthesizers, the output signal spectrum of which contains a lot of parasitic spectral components and phase noise. In this case, the frequency range in which these components are present is determined by the cutoff frequency of the PLL filter and can be tens to hundreds of MHz due to the need to achieve a compromise between the degree of filtering and the PLL performance.

At present, several methods are known for improving the spectral characteristics of DDS as part of hybrid frequency synthesizers. However, they all have characteristic drawbacks and are not effective enough. So, when filtering the output signal of a digital-to-analog converter (DAC) DAC, there is an extremely high probability of spurious spectral components of large amplitude falling into the filter passband, and the randomization of this signal is accompanied by a significant deterioration in the signal-to-noise ratio.

To improve the spectral characteristics of the DDS and, accordingly, the hybrid frequency synthesizers used as signal conditioners for the REM of space stations of satellite communications, the method of automatic compensation of phase distortions can be used. The idea of this method is that in the presence of phase distortions of the DDS output signal, all components of its output spectrum are modulated according to the same law as the synthesized frequency [16-18]. Since the clock frequency of the synthesizer is constant, having selected it in the output spectrum of the DDS, it is possible to automatically compensate for the phase distortions of the synthesizer output signal at the specified frequency.

The block diagram of one of the options for the formation of the control signal of the auto-phase distortion compensator of the DDS is shown in Figure 3.

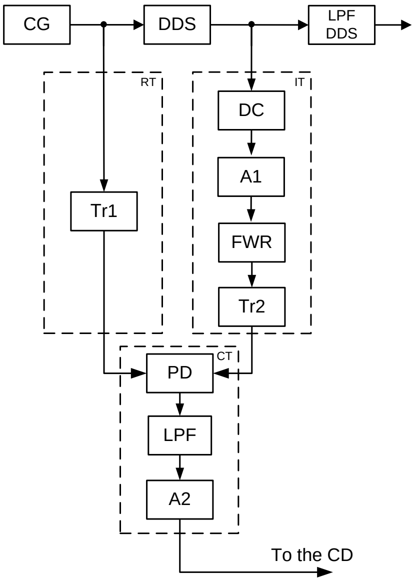

Figure 3 - Block diagram of the path for the formation of the control signal of the auto-compensator of phase distortions of the DDS

The diagram uses the following designations: CG - clock generator, DDS - direct digital synthesizer, LPF - low-pass filter, DC - differentiating circuit, Tr - trigger, FWR - full-wave rectifier, PD - phase detector, A - amplifier, RT - reference tract , IT - information tract, CT - control tract.

The signal from the DDS output with phase distortions enters the information tract of the autocompensator, from the input - to the reference tract. At the inputs of the reference and information tracts, the signals differ not only in phase, but in amplitude and shape. Processing these signals in both tracts allows you to align their shapes and amplitudes. In this case, the phase shifts of these signals are preserved. To obtain an information signal, the output signal of the DDS is differentiated, amplified and fed in series to a full-wave rectifier and a T-flip-flop Tr2, to obtain a reference signal, it is fed to a T-flip-flop Tr1 without preliminary processing. As a result, signals from the reference and information tracts are sent to the control tract of the autocompensator, where their subsequent processing is carried out. In the phase detector of this path, the phases of the input signals are compared, in the low-pass filter, the DC component of the signal is extracted, and in the amplifier, the control signal is converted to the required level.

The theoretical and experimental study of this scheme has shown the effectiveness of the autocompensation method and the possibility of improving the spectral characteristics of hybrid frequency synthesizers by 10-15 dB, which can significantly reduce the size of the uncertainty ellipse. The results obtained are confirmed by circuit simulation and experimental study of the phase distortion compensator developed for the AD9854 DDS.

Algorithm for identification and recognition of satellite communication objects

The existing algorithms for iterating a multiple procedure for determining the RS values, based on the well-known recommendations [10], allow solving only the problems of controlling the SSSC and are of a general nature without specifying information about the preferred procedure for determining the RS, and also do not provide the definition of criteria for the sufficiency of the measurement cycles from the standpoint of the reliability of identification and recognition. To eliminate this drawback, an algorithm is proposed for solving the problem of identification and recognition of OIs based on samples of values of the registered RS parameters

The problem of identifying and recognizing OI is posed as a problem of classifying and checking the homogeneity of groups, the content of which includes the steps: 1) according to the results of registration of the RS of objects (SSSC or ESSS), an unordered set (set) of N vectors is formed, specified in the m-dimensional space of the RS; 2) taking into account the fact that the recognition signs are obtained with different reliability and have different physical dimensions, and the set of RSs is formed by their measured values and calculated estimates of their correct (reliable) determination, each vector is determined as $X=(x_1, x_2,\ldots, x_m)$; 3) the space of definite vectors $E(X\in E)$ is divided into disjoint subspaces (classes) according to the criterion of their similarity.

To solve the problem, a geometric representation of the classification of a set of vectors X is used, based on the concept of the mutual proximity of points belonging to the same class in the RS space and using any of the acceptable (in specific conditions) metrics. In this case, each of the analyzed OIs is assigned a point in the space E, the position of which is determined by the values of the attributes $x_1, x_2,\ldots, x_m$.

The actual distance $R(u,x)$ between two arbitrary points $u=(u_1,u_2,\ldots, u_m)$ and $x_1, x_2,\ldots, x_m$ in the space E is defined as

$$R(u,x)=\left\{\sum_{i=1}^{m}\left|u_i-x_i\right|^2\right\}^{1/2} \tag{20}$$

The measures of proximity of points corresponding to a given set of OIs are determined by the following particular algorithm.

Step 1. Search for the nearest, among the set of classified points, fictitious in the sense of the minimum distance determined by expression (20), where *u* is a fictitious classification point (FTP), and *x* is the current point from the original set *X*. The found point is assigned an index equal to 1, and the value of the corresponding measure of proximity f_1 is set equal to 0 (zero). The value of each FTP coordinate is transformed in accordance with the expression

$$U_i = U_i^{(1)} + (1 - f_k)(x_i - u_i^{(1)}),\ i = 1, \ldots m \tag{21}$$

where: U_i is the new value of the FTP coordinates; $U_i^{(1)}$ - previous U_i, "old" value of the U_i coordinate; f_k is the current value of the measure of proximity of some point *x* to the FTP.

The transformation of expression (21) at the initial stage, when k=1, corresponds to the movement of the FTP from the origin of coordinates to the point with the index "1", since in this case f_1=0. consideration is excluded.

Step 2. Among the remaining N-1 points, the point closest to the FTP is found according to a rule similar to the rule of the first step, and the found point is assigned the index "2". The proximity measure f_2 at the second step of the classification is taken equal to 0.5, which ensures the movement of the FTP, according to expression (21), to the middle of the segment connecting the first two found points.

Step 3 and subsequent steps. Determination of the proximity measure $f_k(k = 3,4,\ldots, N)$ at the third and subsequent k –th steps, according to expression

$$f_k = \frac{R_{\mathrm{av}}^{(\mathrm{k\text{-}1})}}{R_{\mathrm{k}}} \tag{22}$$

where $R_{\mathrm{av}}^{(\mathrm{k\text{-}1})}$ is the average value of the distance from the FTP to the nearest point, obtained for the previous (k-1) steps of the algorithm; R_k is the value of the distance from the current FTP position to the nearest point, obtained at the k-th step. The point found in this case receives the corresponding index "*k*".

It should be noted that each next *k*-th step of the classification algorithm is completed by adjusting R_{av} calculated by the formula

$$R_{\mathrm{av}}^{(\mathrm{k})} = R_{\mathrm{av}}^{(\mathrm{k\text{-}1})} + \frac{R_{\mathrm{k}} - R_{\mathrm{av}}^{(\mathrm{k\text{-}1})}}{\mathrm{k}} \tag{23}$$

The algorithm ends when the entire original set of unordered points is exhausted.

Thus, according to the considered algorithm, a sequence of proximity measures $f_k(k = 3,4,\ldots, N)$ and the corresponding sequence of point indices are generated. The analysis of the sequences obtained allows us to conclude about the relative position of points corresponding to their original set in the considered space of the RS, as well as about their grouping into classes (subsets of a given set of points).

The presented classification algorithm, based on determining the proximity measure of points corresponding to a given set of OIs, belonging to the same class in the RS space and using any of the acceptable (in specific conditions) metrics, has the following advantages:

- is invariant to the physical dimension of the RS and does not require preliminary testing to determine the values of the initial parameters;
- adaptive to the density of the relative position of points within the space of the same class due to constant correction of the current value of the average distance.
- provides the ability to be implemented by a complex of programs for automated measuring instruments of the subsystem of the satellite RM in the form of a separate executable module operating according to the initial data representing the measurement results obtained from the database of the desired subsystem.

Conclusion

The availability of the possibilities for reliable identification and recognition of all types of radio electronic means of satellite radio communication services by radio emissions from space stations makes it possible to increase the overall efficiency of satellite RM measures implemented by stationary stations of the satellite RM.

An increase in the reliability of the identification of satellite earth stations is possible through the use of the method for determining the coordinates of stations based on the results of measurements of time delays and frequency shifts of their signals relayed by spacecraft in geostationary orbit. The software and hardware implementation of this method allows you to effectively use the existing infrastructures of satellite radio monitoring stations, provides their automated operation control as part of automated measuring complexes of satellite radio monitoring subsystems of the radio frequency service, which significantly reduces the cost of the operating resource.

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