Automated Measuring Complex For Studies of Antenna Arrays

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Abstract—**The article discusses an automated measuring system based on an unmanned aerial vehicle, created for the study of antenna arrays - measurements of their characteristics in the design and testing process. A general description of the complex, including the measurement methodology is given. A description of the hardware and software. An example of a real application of the complex for experimental studies of the antenna array of the radio monitoring system in the VHF and UHF bands is considered.**

I. INTRODUCTION

Automation of the measurement processes of antenna characteristics is currently acquiring significantly wider opportunities. This is due to the possibility of using small-sized unmanned aerial vehicles of a helicopter type (drones) to fly around antennas [1], [2]. The benefits of this approach are:

- the antenna is measured, but not its model, placed in an anechoic chamber;
- the studied antenna is in the normal position in the conditions of the actual environment;
- rotation of the studied antenna is not required;
- there are a lot of possibilities to automate measurement processes;
- high accuracy of determining the coordinates of the drone is provided by the space navigation systems;
- the drones usage is significantly less expensive compared to manned vehicles.

Known methods using a drone provide measurements of amplitude radiation patterns for a given type of polarization in the operating mode of the antenna. This is quite enough when studying antennas of radio communication systems, single-pass (mirror antennas, Uda-Yagi antennas, etc.), as well as antenna arrays, which in radio communication systems operate in only one mode — the mode of maximizing the gain in a given direction. Meanwhile, antenna arrays in radio monitoring systems, etc. work in various modes - maximizing gain, direction finding, “blind” separation of signals (signals and interference), etc. In these cases, knowledge of the amplitude radiation pattern of antenna array in the maximum gain mode is not enough. Measurements in various modes are too costly due to the large number of modes. In this regard, the most appropriate approach is based on the principle of decomposition. This approach involves measuring the basic radiation patterns of the antenna array and individual measurements of the scattering parameters (S-parameters) of the beam-forming device, followed by computer simulation of radio system in the various modes.

The set of all possible radiation patterns formed by the N-element antenna array belongs to the N-dimensional subspace in the corresponding Hilbert space [3], [4]. This means that any radiation pattern of antenna array can always be represented by a linear combination of N radiation patterns of the same array, provided that they form a linearly independent (including orthogonal) system. Other words, these N radiation patterns are basic — they form a linearly independent (including orthogonal) basis of the above-mentioned subspace. This circumstance provides a fundamental opportunity for an experimental study of the antenna array to restrict itself to measuring only the basic radiation patterns.

As the base can be selected any array radiation patterns that satisfy the condition of linear independence. In the most common variant, partial radiation patterns of single array elements determined in the S-parameters determination mode are taken as the basis (when determining the k-th radiation pattern, the k-th element is excited by a matched generator, the rest are loaded with matched loads). With respect to the circular antenna array in some cases it is more efficient to use orthogonal bases - the system of radiation patterns in the multipath mode [3], or the system mode radiation patterns [4]. A common specific feature here is the fact that any basic radiation pattern must be defined as complex-valued functions. This makes it necessary to measure phase patterns in addition to amplitude, which is appropriately reflected in hardware and software.

In this paper, an automated measuring complex based on a small-sized helicopter-type drone is considered, which implements the decomposition approach discussed above. The complex was designed at the branch of FSUE NIIR - SONIIR for its own needs and has been successfully operated for a number of years. It provides measurement of amplitude and phase baseline antenna arrays of antenna arrays and is intended for measurements performed in the design process, experimental debugging, tuning, etc., as well as for measurements performed during testing, for example, in the framework of preliminary tests of prototypes (with such the application of the possibility in part of the phase measurements are unclaimed).

II. GENERAL DESCRIPTION OF AUTOMATED MEASURING COMPLEX

The instrument-measuring complex of the drone uses the mode of radiation from the drone and receiving by the elements of the antenna array. In addition, the reception is carried out by an auxiliary antenna, which forms the reference channel for phase measurements. The use of the opposite direction of signal transmission would significantly complicate the joint processing of the measuring and reference signals in phase measurements, since in this variant a part of the receiving equipment would be on board the drone. In this embodiment, the drone is only a transmitter with an antenna and auxiliary equipment, fixing the current coordinates of the device, providing telemetry and telemechanics, etc.

The drone flies around the measured antenna array in the far zone along a trajectory approximating a certain surface — a hemisphere or a circular cylinder. The difference from a spherical surface does not matter, since changes in the signal level caused by changes in the distance to the drone are easily taken into account by calculation (as determined by the module of the Green function), and significant variations in the signal level due to interference effects appear exactly as well as for its angular displacements, which are unavoidable when measuring the radiation pattern.

The construction of a hardware-measuring complex of a drone and the implementation of the measurement process are schematically shown in Fig. 1 (using the example of measurements of partial radiation patterns of an 8-element ring array). All elements of the antenna array, except for the measured one, are loaded on matched loads. The element to be measured is connected via a high-frequency feeder (coaxial cable) to the corresponding input of a 2-channel digital radio receiving device. The auxiliary antenna feeder is connected to another input of the radio receiving device. A transmitter mounted on board a drone with an antenna emits a monochromatic signal, which is received by a measured element of the antenna array (measurement signal) and an auxiliary antenna (reference signal). The measuring and reference signals are sent to a radio receiver, where, after all the necessary analog processing, they are digitized. Digitized signals in the form of vectors - samples of complex samples of the original signals arrive at the computer, where all the necessary mathematical processing is carried out with the definition of the normalized amplitude of the measuring signal, the offset of its initial phase relative to the initial phase of the reference signal and ultimately the amplitude and phase pattern.

It is highly desirable that the antenna of the onboard drone transmitter provide a high uniformity of the azimuth pattern. This requirement is not mandatory, but its implementation removes the difficulties associated with stabilizing the azimuth orientation of the drone. In the case of meridional polarization (θ-polarization), this requirement is best satisfied by a vertical vibrator. In the case of azimuthal polarization (θ-polarization), in order to ensure azimuthal isotropy, it is advisable to use ring antenna arrays operating in the in-phase mode. In the software-hardware complex of the drone both technical solutions are implemented. Providing in the antenna of the onboard transmitter drone meridional isotropy along with the azimuth is difficult. In this regard, the polar angle directivity is taken into account by other means implemented in the design stages.

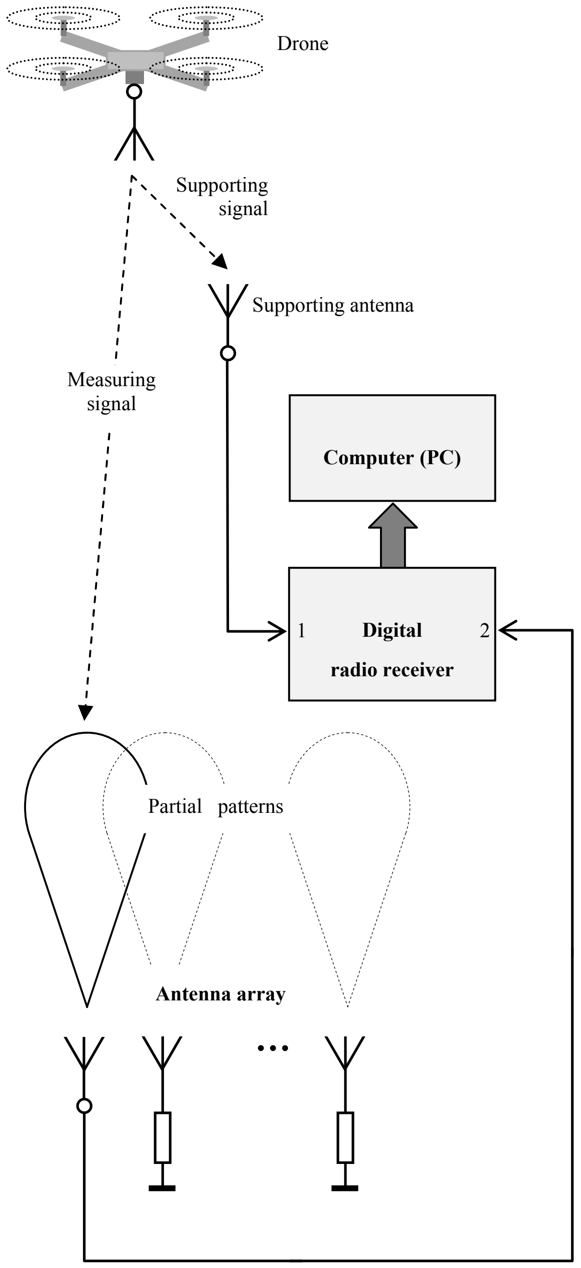

Fig. 1. The structure of the complex and implementation of the measurement process

The auxiliary antenna is placed in the conditional center of the studied antenna array. This point is taken as the origin of the local coordinate system associated with the studied antenna array. Relative to this point all phase patterns are determined. The auxiliary antenna is subject to the requirements of high uniformity of the azimuthal phase pattern and a high level of matching. The corresponding requirement for the amplitude radiation pattern is not so rigid, since this antenna is not used for amplitude measurements. As for the matching, it is required to minimize additional phase shifts introduced by the auxiliary antenna. When measuring in a fairly narrow frequency band, these shifts are insignificant additive constants, but when measured over a fairly wide range of frequencies, their frequency dependencies are significant.

The coordination of the auxiliary antenna allows to significantly reduce the indicated factor of the phase error. However, in the case of range measurements, it is difficult to completely eliminate it in this way, and the final refinement of the phase is carried out by the calculated correction.

Corrective additive amendment, $\Delta_S(f)$, ***^{0} (f*** - current frequency, MHz), subtracted from the measured phase (the difference between the initial phases of the measuring and reference signals), is determined by the formula:

$$\Delta_S(f) = -57{,}3 \cdot \mathrm{arctg}\left(\frac{\mathrm{Im}\left[\left(1 + S_{11}^{(\mathrm{A})}(f)\right) / \left(1 - S_{11}^{(\mathrm{A})}(f)\right)\right]}{1 + \mathrm{Re}\left[\left(1 + S_{11}^{(\mathrm{A})}(f)\right) / \left(1 - S_{11}^{(\mathrm{A})}(f)\right)\right]} \right)$$

where $S_{11}^{(\mathrm{A})}(f)$- input reflection coefficient of the auxiliary antenna, the frequency characteristic of which is measured by the vector network analyzer after the antenna is installed in the normal position.

When creating an auxiliary antenna in relation to various types of polarization, the same technical solutions are implemented as in the part of the antenna of the onboard drone transmitter.

Another significant factor affecting the accuracy of phase measurements is the inequality of the lengths of the feeders of the measuring and reference channels. Here also occurs a frequency-dependent additive, which is desirable to minimize. The alignment of the lengths of the feeders is performed on the basis of measurements of the electrical lengths of the phases of the reflection coefficients in the idle mode (electrical lengths are defined as taken with the opposite sign of the half phases of the reflection coefficients). At the same time, the connectors are not installed at the feeder outlets, which allows you to quickly cut the longer feeder. Upon completion of the process of aligning the lengths of the feeders, connectors are installed on their outputs, and the reflection coefficients $S_{11}^{(\mathrm{meas.})}$ (measuring channel feeder) and (reference channel feeder) are finally measured at a certain frequency f_0, MHz, within the measurement range.

The formula for the full (taking into account both factors that affect the accuracy of phase measurements) of the corrective additive correction, $\Delta(f)$, ***^{0}***, subtracted from the measured phase, has the form:

$$\Delta(f) = \Delta_S(f) + 57{,}3 \cdot (f / f_0) \cdot \left(\arg\left[S_{11}^{(\text{изм.})}\right] - \arg\left[S_{11}^{(\text{оп.})}\right]\right)$$

where $\arg(x)$ is the main value of the argument of the complex number x, rad.

The main task solved within the framework of processing digitized signals in a computer is the determination of the amplitude and phase patterns. This procedure is performed on the basis of calculations of the scalar products of vectors - samples of complex samples of the measuring and reference signal. The values of the amplitude radiation pattern F and the phase radiation pattern *Ψ, ^{0}* are determined based on the calculations of the scalar square of the measuring signal and the scalar product of the measuring and reference signals, respectively, using the formulas:

$$F = \alpha \sqrt{\sum_{k=1}^{M} u_k u_k^*} \cdot \left(\sqrt{\sum_{k=1}^{M} v_k v_k^*} \right)^{-1}, \tag{1}$$

$$\Psi = 57{,}296 \cdot \arg\left(\beta \sum_{k=1}^{M} u_k v_k^* \right)$$

where α, β – normalizing factors, M – is the number of samples in the sample (the dimension of the vector is the sample), u_k – complex readings of the measuring signal; v_k – complex samples of the reference signal.

In the formula (1), due to the normalization to the norm of the reference signal, the meridional directivity of the antenna of the onboard drone transmitter is taken into account. At the same time, it should be noted that a full account of the multipathing factor acting on the reference channel antenna is a problem that is manifested in measurements of meridional radiation patterns, and which currently cannot be considered finally resolved.

Another important task to be solved at the final stage of processing is the regularization of azimuthal radiation patterns. With a sufficiently large electrical suspension height of antenna elements, which is typical for the VHF and UHF bands, the experimentally determined meridional radiation pattern will have a rapidly oscillating component due to the interference of direct waves and reflected from the earth's surface. That is precisely the meridional radiation pattern in the actual conditions of antenna placement. Meanwhile, there should be no such fast oscillations in the azimuthal directivity pattern, but they inevitably appear due to local irregularities of the earth's surface, changes in the drone height when circling, and other multipath factors. According to the mechanism of its occurrence, this phenomenon is similar to the phenomena of instability of solutions of problems that are incorrect in the sense of Hadamard, for which a powerful methodological apparatus was developed to effectively combat [5]. In this case, the simplest version of the problem takes place, since it is not about solving an incorrect equation (vector, functional, etc.), but about reducing the variation of some given function, which is achieved by using a smoothing (regularizing) operator. Studies conducted within the framework of the creation of a software-hardware drone complex showed that in this case the method justified in [6] used for regularizing unstable solutions of integral electrodynamics equations with approximate (Fredholm) kernels and involving the use of completely continuous integral operators (the main the idea here is to use for regularization the property of complete continuity, which, in fact, in the original equation, leads to the incorrectness of the problem) . In this case, the regularizing operator is constructed by analogy with [6], the function — the result of the action of the operator — is defined as follows:

$$\widetilde{F}(\varphi)=\int_{0}^{2\pi}\frac{F(\varphi')\cdot\exp[i\cdot\Psi(\varphi')]}{4\pi\sqrt{(\varphi-\varphi')^{2}+a^{2}}}d\varphi'$$

where φ, φ' – azimuth (point of observation and source, respectively); a - parameter selected in relation to specific electrical heights of the suspension of antenna elements.

It should be noted that other methods of suppressing rapidly oscillating components of azimuthal radiation patterns are being investigated (they are currently under development). The first is to conduct multiple overflights at different, slightly different, heights, followed by averaging (using a significant spatial variation of the signal). The second method consists in carrying out a series of measurements at each point with frequency scanning followed by averaging. It uses the fact that under conditions of strong interference, small changes in frequency lead to significant spatial displacements of nodes and antinodes of the interference pattern.

The use of software and hardware complex drone during testing involves the measurement of the radiation pattern generated by the antenna array as a whole. In this case, all regular modes of operation can be considered, which ensures direct verification of the product in all modes. However, if it is necessary to reduce the time and cost of measuring, you can limit yourself to a single mode (not necessarily regular), which, taking into account parallel computer simulation using previously measured basic radiation patterns, will provide a comprehensive test of the performance of the antenna array with all diagramming devices.

In this sense, the autofocus mode is of considerable interest, in which the weight vector of the receiving antenna array is determined by the signal vector optimally in the sense of maximizing the directional coefficient in the direction of arrival of the received wave (the direction itself is not required to know). When using this mode, the onboard transmitter signal is first received by all elements of the array, then the autofocus mode is activated and received on the array. The effect of autofocus is determined by the ratio of the signal levels received on a separate element of the antenna array and on the antenna array. It is possible to record signals with a posteriori processing, including the transition to the frequency domain; however, the effect can be evaluated by the degree of signal / noise increase. Estimation of the reliability of the results obtained and the performance of the antenna array (with diagramming devices) is carried out on the basis of a comparison of experimental data with the results of computer simulation of the autofocus mode.

III. HARDWARE SUPPORT OF THE COMPLEX

A. Title of sections

The composition of the automated measuring complex (hardware of the complex):

- drone consisting of: the actual drone; remote control; ground station; auxiliary equipment (battery pack, charger, etc.);
- complex of onboard transmitters - transmitters for frequency ranges: 1 ... 30 MHz; 20 ... 200 MHz; 100 ... 400 MHz; 300 ... 1000 MHz;
- a complex of onboard antennas - antennas for the frequency ranges 1 ... 30 MHz; 20 ... 200 MHz; 100 ... 400 MHz; 300 ... 1000 MHz;
- a complex of auxiliary antennas;
- 2-channel digital radio receiver;
- computer.

The main technical characteristics of the drone:

- maximum take-off weight - up to 6 kg;
- weight of transported payload - up to 2 kg;
- maximum flight speed - 10 m / s;
- maximum flight range - 1000 m;
- maximum flight time from one set of batteries - 25 minutes;
- GPS positioning accuracy - no more than 2.5 m;
- battery - LiPo (6S, 5800 mA, 40C).

The appearance of the drone with the indication of the positions of the main elements is shown in Fig. 2.

Drone flight control can be done in two ways:

- manually with a remote control;
- from the ground station.

In addition, an autonomous flight mode is provided for a given route with automatic take-off and landing and with the possibility of operative interception of control to manual. In the process of measuring flights, the flight data are transmitted over the radio channel in real time to the ground station. Part of the flight data (coordinates, speed, condition of the onboard equipment) are also stored in non-volatile memory on board the drone.

Main technical characteristics of the onboard transmitter:

- output power - up to 10 dBm;
- power level adjustment range - from minus 30 dB to 0 dB relative to maximum power;
- power level adjustment step - 0.5 dB;
- frequency tuning step - 1 kHz.

The external view of the board of the onboard transmitter of the range 100 ... 400 MHz is shown in Fig. 3.

Fig. 2. The appearance of the drone

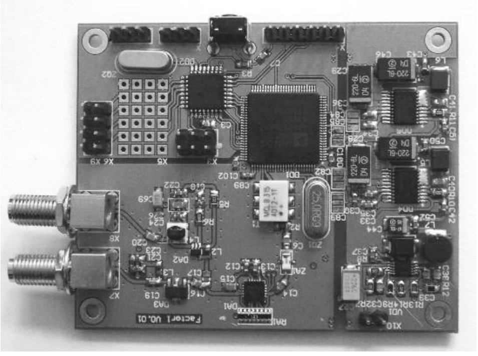

Fig. 3. Onboard transmitter board range 100 ... 400 MHz

The complex of on-board antennas includes in its composition one antenna θ-polarization for the ranges 1 ... 30 MHz and 20 ... 200 MHz and two antennas, θ- and φ-polarization, for the ranges 100 ... 400 MHz and 300 ... 1000 MHz. All airborne antennas are azimuth omnidirectional. The irregularity of the azimuthal radiation patterns of the antennas is not worse than ± 1 dB. θ-polarization antennas are based on vertical vibrators. Antennas φ-polarizations are implemented in the form of annular antenna arrays of frame emitters. Due to this technical solution of polarization antennas, it was possible to significantly suppress the cross-polarization radiation of polarized waves. As shown by calculations made on the basis of electrodynamic modeling, the power of cross-polarization radiation does not exceed –20 dB relative to the total radiated power.

Fig. 4 shows the appearance of the on-board antenna - polarization of the range 100 ... 400 MHz.

When flying around on a drone, one single onboard transmitter of the desired range and one antenna of the same polarization range are installed.

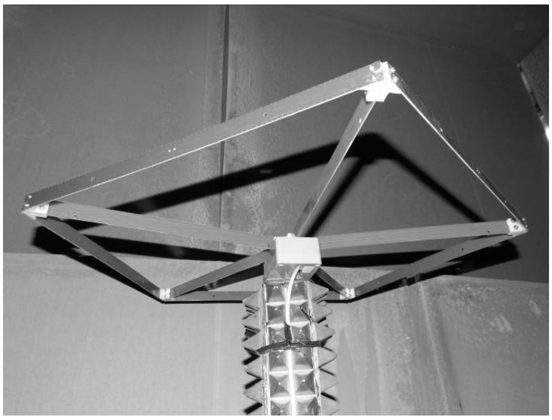

Fig. 4. Onboard antenna range 100… 400 MHz (azimuth polarization)

Auxiliary antennas are made similar to the onboard.

As a 2-channel digital radio receiver as part of a complex, an experimental, debugged and tested prototype of a 4-channel digital radio receiver developed in its time is used for its own needs, in which 2 channels are used for operation as part of a complex. The appearance of the digital radio receiver board is shown in Fig. 5.

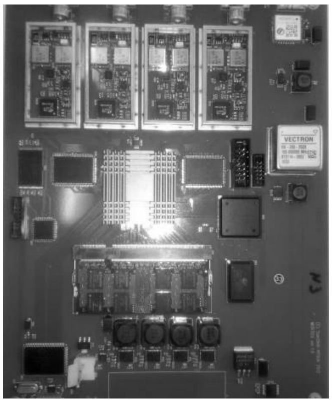

Fig. 5. Digital board radio receiver

The main characteristics of the digital radio receiver:

- nominal input resistance - 50 Ohm;
- VSWR at the entrance - not more than 1.5;
- noise ratio - 4.5 ... 6 dB;
- limits of adjustment of the reception channel band - from 100 Hz to 30 MHz;
- dynamic ranges: single-signal - 135 dB; on blocking - 110 dB; 3rd order intermodulation - 100 dB; on intermodulation of the 2nd order - 90 dB;
- suppression of side reception channels - 70 dB.

Dynamic ranges are defined as applied to the 3 kHz main channel reception band. Single-signal dynamic range is determined by the compression point of 1 dB, its reduced value takes into account the effect of automatic gain control.

IV. SOFTWARE COMPLEX

The software of the automated measuring complex solves the following four groups of tasks:

- tasks related to the control and management of UAVs;
- tasks associated with the digitization of the measuring and reference signals;
- tasks of vector signal processing of digitized measurement and reference signals;
- the tasks of the final (a posteriori) processing of experimental data.

Private software, which is responsible for monitoring and managing UAVs, provides the following tasks:

- stabilized flight;
- automatic take-off and landing;
- automatic flight according to a predetermined program;
- automatic flight control using a real-time ground station;
- real-time transmission of telemetry flight data to the ground station;
- automatic tracking of emergency situations (loss of signal from the remote control, satellites, telemetry; battery depletion) and the choice of ways to exit from them (emergency landing, emergency return to the take-off point, interruption of the autonomous flight program with the transition to manual control);

- search for UAVs on the map in case of its loss.

This ensures the implementation of the following flight modes:

- steady flight using the remote control;
- automatic hold position (hang);
- automatic return to the take-off point, followed by automatic landing;
- automatic flight according to a predetermined program;
- automatic landing.

All automatic modes allow you to switch to manual control at any time using the remote control.

The hardware of this software is implemented as follows. In the flight controller, the freely distributed software ArduPilot is flashed. OpenTX freeware is stitched into the remote control. At the ground station, the freely distributed Mission Planner software was installed, which allows firmware, update and configuration of the flight controller and remote control, as well as receive telemetry data, control the flight of the drone and real-time payload operation modes.

Monitoring the position of the drone in real time is provided, in addition, a standalone GPS-GPRS-tracker.

Software that solves the problems associated with the digitization of the measuring and reference signals provides all the necessary functions in this part - band digitization, digital filtering (with the formation of the final band of the main reception channel), etc. Hardware this software is implemented as part of the receiving device. Software for vector signal processing and final processing is installed on the computer. It provides a solution to vector signal processing tasks (calculating scalar squares and scalar products of vectors - samples of signal samples, etc.), calculating amplitude and phase radiation patterns as functions of angular spherical coordinates corresponding to the current positions of the drone, regularizing the pattern, solving a series auxiliary tasks - visualization of the radiation pattern, recording of signals, documentation of results, generation of data files for computer simulators of the antenna array modes, etc.

V. EXPERIMENTAL RESEARCH OF VHF-UHF ANTENNA GRID OF RADIOMONITORING SYSTEM

The automated measuring complex was created for its own needs and was quite successfully used in the design and testing of a number of products based on antenna arrays of various frequency ranges and purposes. In particular, the complex was intensively used in the design of the antenna array of the radio monitoring system of the VHF and UHF bands, which was developed as part of the relevant development work. The radio system is designed to detect signals, direction finding and tracking of the angular coordinates of their sources, measure the basic parameters of signals, etc. The antenna array in its composition has a complex hierarchical structure. At the macro level, it is formed by a system of antenna subarray (partial antenna arrays) installed on U-shaped supports, the next level is formed by a partial antenna array of active (combined with low-noise amplifiers) antenna elements that form a quasi-ring spatial structure. The specificity of the tasks to be solved significantly actualizes the problem of the influence of local factors: the underlying surface as such, its local irregularities, foreign objects, the influence of which could be completely neglected when solving connected problems, etc.

The automated measuring complex was used as the main tool for experimental studies of the antenna array carried out as part of its design (placement on the ground at a specific location of dislocation) and testing. The main part of the test was an experimental study of the autofocus mode of the antenna array, which is one of the standard modes of operation of the radio system used to measure the parameters of monitored signals. The sequence of actions performed in this study is described above. Some examples of this experimental study are given below as an example.

Fig. 6 shows the azimuthal radiation pattern in autofocus mode before regularization. Fig. 7 shows the same radiation pattern, but after the regularization procedure. It can be seen that this procedure has a significant effect on filtering the rapidly oscillating component.

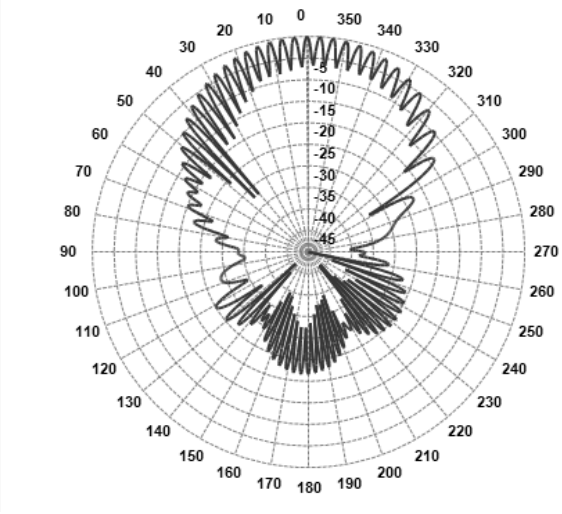

Fig. 6. Azimuth pattern in autofocus mode (before regularization)

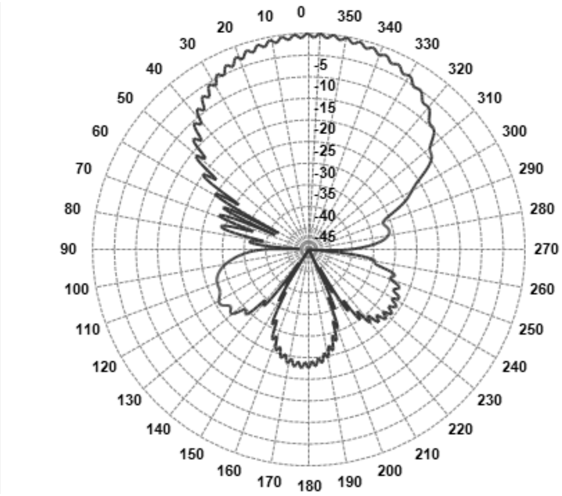

Fig. 7. Azimuth pattern in autofocus mode (after regularization)

Fig. 8 shows the spectrograms of the received signal before turning on the autofocus mode (curve 1) and after turning it on (curve 2). Spectrograms are obtained by computer simulation using pre-recorded time samples of digitized signals. It is seen that the increase in the signal-to-noise ratio is at least 10 dB. A more accurate calculation of the measured signal levels (determined from the calculation of the corresponding scalar squares) shows that the signal level (and, accordingly, the signal-to-noise ratio) in the autofocus mode increases by 12.5 dB. In this case, computer simulation of the autofocus mode using previously measured partial amplitude and phase radiation patterns gives an increase in the signal level when this mode is turned on by 12.8 dB. The discrepancy between the experimental and experimental-calculated values of only 0.5 dB indicates that the results obtained are quite reliable.

VI. CONCLUSION

The experience of design and operating an automated measuring complex shows that this complex is a very effective tool in the design of antenna arrays as part of radio systems of various frequency ranges and purposes. A very significant moment is the implementation of phase measurements, which brings the funds of this class to a new qualitative level. The use of an automated measuring complex and its methodological support in designing antenna arrays of radio systems designed to solve various radio monitoring and related tasks is particularly relevant, since it is in these cases that knowledge of the basic radiation patterns, both amplitude and phase, is required. In such an application, the use of the complex allows to remove a number of problems that are practically intractable in the framework of purely theoretical studies, even conducted on the basis of the most advanced powerful tools of electrodynamic computer simulation. First of all, this refers to taking into account the influence of various local factors, a more or less accurate accounting of which in theoretical studies is not possible due to their multiplicity, diversity, the presence of a factor of significant uncertainty in the electrophysical parameters of the impact, etc.

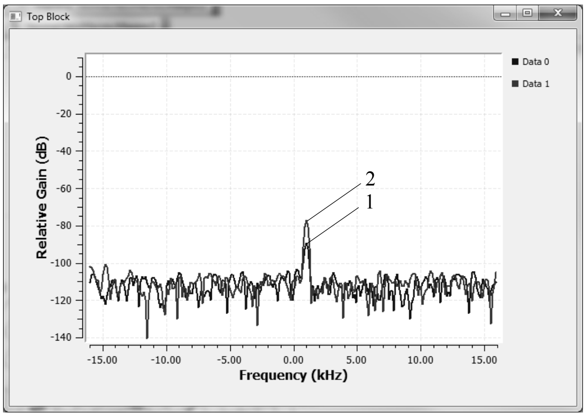

Fig. 8. Spectrograms of the received signal before turning on the autofocus mode (curve 1) and after turning it on (curve 2)

REFERENCES

[1] Buslov D.S., Kizima S.V., "Design and operation of radio monitoring complexes on the basis of small-size helicopter type UAV", Electrosvyaz, 7, 2018, pp. 53-59.

[2] KLASSEN V.I., PROSVIRKIN I.A., SEDELNIKOV Yu.Eu., “Measurement of radio communication antenna pattern using small-size UAV”, Electrosvyaz, 8, 2018, pp. 57-62.

[3] Sazonov D.M., Multi-element antenna systems. Matrix approach., Radiotechnika, Mockow, 2015.

[4] Yudin, V.V., “Ring antenna arrays: circuit-spatial multiplex and directional radiation” ,Radio and communication, 2001.

[5] A.N. Tikhonov, V.Ya. Arsenin, “Methods for solving ill-posed problems”, Moskow Science, 1986.

[6] V.A. Yatskevich, S.F. Karshakevich, «Stability of the process of convergence of a numerical solution in electrodynamics». Radioelectronics. 2, 1981. pp. 66-72.