Electronic control of the antenna array direction pattern of the vertical atmospheric probing radar station

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Abstract. The article is considered formation and control issues of a small-element antenna array direction pattern of vertical probing radar stations for monitoring the atmosphere. The features of the vertical probing radars functioning and construction with a small-element array are presented. In the article is presented comparative analysis, which based on results of the simulation and on change nature in the direction patterns when the main beam deviates from the vertical for rectangular and annular antenna arrays.

1. Introduction

Today, there are many different methods and tools for conducting atmospheric phenomena research (radiosondes, sodars, lidars, MST-radar, etc.) [1]. Using vertical probing radars (VP radars) is one of the promising directions for studying the processes in all atmospheric layers, obtaining operational information about the meteorological situation and the passage of atmospheric fronts, jet currents, turbulence in the free atmosphere in a certain area of space. Such radars use the effects of Fresnel and Bragg scattering from turbulent formations, various inhomogeneities in different layers of the atmosphere. As a rule, these are stationary, high-energy pulsed radar systems, which operate in the frequency range 45…1300 MHz and have rather large apertures of antenna systems [2].

This article discusses the process of forming and controlling the direction pattern (DP) of the antenna array (AA) for non-mechanical atmosphere scanning by using a small-element antenna array in a vertical probing radar station. The expediency of using a low-element AA is due to by decreasing in the mass and size parameters of the radar, by the cost, by high mobility and by low hardware costs for atmosphere electronic scanning organization. Such developing VP radar has the following features of construction:

- using from four to nine director antennas of the antenna array in order to minimize hardware costs;
- application of two-frequency directional antennas with circular polarization;
- using the solid-state amplifiers and, as a result, the distribution of the total power over the entire field of the phased array antenna;
- availability of a digital diagram-forming scheme (DFS) for remote control of the main beam of the antenna system;
- using coherent and incoherent accumulation digital methods in receivers when receiving complex signals to improve energy characteristics.
The use of electronic space scanning due to changes in the amplitude-phase distribution on the AP allows to use different laws of changing position in space of the main beam of the DP (within the working area of real angles ±60° from the vertical). At the same time, the synthesis of complex amplitudes of currents in the lattice elements allows us to use various direction finding amplitude-phase methods of atmospheric inhomogeneities, such as: the maximum, minimum, equisignal method and the comparison method, which directly leads to decreasing in the angular coordinates measuring error of inhomogeneities in the atmosphere, including against the background of multipath signal reception.

There is a comprehensive selection of use complex signals in VT radar with different types of modulation, of probing signal carrier frequency, of off-duty factor, of review space methods, of DP methods with various direction-finding characteristics by the same location object (heterogeneity of the atmosphere). This feature, firstly, allows to increase the probability of detecting the radar to altitudes of 800 km, to determine with higher accuracy its coordinates, speed of movement, see the distribution in space and build its altitude profile, and secondly, such complex selection approach of various instruments of the VT radar opens up new opportunities for the troposphere, stratosphere and mesosphere research to monitor physical processes and atmospheric phenomena.

2. Direction pattern synthesis of various antenna array configurations

As known, from the theory of antenna systems, the direction pattern of antenna array which consists of identical and equally oriented in space radiators system is equal to multiplication of separate emitter's direction pattern by a system multiplier, which does not depend on type of emitters in the system and it is determined by the amplitude-phase distribution of currents in the system and spatial arrangement of the radiators [3-6]. Based on this, operating by individual elements number, their geometric arrangement inside the array, the inter-element distance and by the type choice of individual antenna element, or rather its single direction pattern, it is possible to create the required direction pattern of antenna array. Moreover, the implementation of the amplitude and phase distribution of currents, which flow through the antenna elements, makes it possible to control the electrical scanning of space. These circumstances allow to control the side-lobe levels from direction pattern, to extract more information based on decision of the target radar from the received signals, to use adaptive algorithms for optimal spatio-temporal filtering of signals on the background of noise. In general, those circumstances improve detection of atmospheric inhomogeneities. It is necessary to constantly synthesize the amplitude-phase distribution on the antenna array elements to create the desired shapes of the direction pattern and track the sources of useful signals. For this, it is necessary to create special software for controlling the main beam or beams which depend of used direction-finding methods.

To form a narrow main beam, reduce the level of the side lobes of the bottom and eliminate the diffraction maxima, it is recommended to use filled (d/λ < 1) antenna arrays, wherein the value of the interelemental distance in the AA depends on specific geometric configuration of the array, on the number of antenna elements used, on their single direction pattern, and on the maximum deviation from the normal to the plane of the antenna array [7].

The AA is a tunable spatial filter with changeable amplitude-angular characteristic that is the direction pattern changes in accordance with the operating conditions such as the spatial-temporal characteristics of the received signal sources. The control and formation of the DP AA is carried out by changing the amplitude-phase distribution, namely by the values of the weight coefficients of the DFS channels [8]. It is possible to form special DP and to electronic scan of atmospheric inhomogeneities within the specified limits by changing the complex weight coefficients (W1, W2, ..., Wn) of the DFS, which are multiplied by probing signals.

It is necessary to use a two-dimensional (surface) array of upward-pointing antenna elements, to form a narrowly directed DP in a given direction in the azimuthal and angular planes and to provide beam control capabilities.

It is necessary to form phase shifts between nearby elements in the row and column according to expressions (1) and (2), to form the maximum of the DP, in the direction of inhomogeneity or of the atmosphere section.
\[ \Delta \psi_x = kd \sin(\beta) \cos(\varepsilon), \]  
\[ \Delta \psi_y = kd \sin(\beta) \cos(\varepsilon), \]  
where: \( \Delta \psi_x, \Delta \psi_y \) is the necessary phase shifts between adjacent elements in the row and column, \( \beta \) is the azimuth of the main beam of the DP, \( \varepsilon \) is the angle of the main beam of the DP.

However, in a flat rectangular grid, the main beam of the DP expands when the beam deviates from the normal to the grid plane and when scanning along the azimuth. This disadvantage is not present in ring antenna arrays, which, in comparison with flat arrays, have a number of advantages such as preserving the shape of the main beam of the bottom during electronic scanning in the circular sector of the atmosphere space, reducing the level of the side lobes.

A single vector can set the direction of the probing signal from the selected antenna element or by the phase center of the array to the source, according to the expression [9]:

\[ L(\beta, \varepsilon) = (\cos(\beta) \cos(\varepsilon) \cdot \sin(\beta) \cos(\varepsilon) \cdot \sin(\beta))^T \]

Then the vector of the amplitude-phase distribution over the lattice elements, which sets the direction of the main beam, will be determined by the expression:

\[ H(\beta, \varepsilon) = \left( F_1(\beta, \varepsilon) \cdot \exp\left\{ -2\pi j \cdot (RA <1>, L(\beta, \varepsilon)) \right\} \ldots F_N(\beta, \varepsilon) \cdot \exp\left\{ -2\pi j \cdot (RA <N>, L(\beta, \varepsilon)) \right\} \right) \]

where \( F_i(\beta, \varepsilon) \) is the amplitude-phase DP of the k-th lattice element; \((RA <1>, L(\beta, \varepsilon))\) is the scalar multiplication.

In this case, it is possible to form the beam of DP by using a diagram-forming scheme, which is a weight adder of signals, where the amplitudes of the signals on the individual elements of the antenna array will be added according to the rule of vectors addition. Then, to focus the beam of the DP AA in a certain direction, it is necessary to compensate the difference in the path of the probing signal between the antenna elements, by a given amplitude-phase distribution. The diagram-forming scheme performs operations according to the expression to form the required DP:

\[ X_{f,n} = \sum_{k=0}^{K} W_{k,n} S_{f,n} \]

where \( X_{f,n} \) is output complex signal of formed beam; \( S_{f,n} \) is signal of complex envelope; \( W_{k,n} \) is the complex weight vector of formation DP; \( k \) is number of DFS channels 1…N.

3. Operation simulation of the direction pattern of antenna array of the radar station for vertical atmospheric sensing

Consider the control of the direction pattern for the two antenna array configurations shown in figure 1. The simulation was performed in the Matlab environment. The model allows forming an AA of any configuration with the arrangement of antenna elements on a plane, or an arbitrary volumetric surface. The AA scanning algorithm provides the adjustment of the complex weight elements of the AA in order to position the main maximum of the DP AA in a given direction, within the limits imposed by the specific configuration of the AA. Let’s consider the synthesis of DP AA by using modeling for the AA configurations which shown in figure 1.

Figure 2a is shown the appearance of the designed two-frequency (50 and 55 MHz) director antenna with circular polarization for the VP radar. Figure 2b is shown the cross section of the DP in the vertical plane of this directional antenna which used as a single AA element. In the simulation, the amplitude-phase distribution on the AA elements was calculated to provide a spiral view of the scanning space.

The direction pattern has much narrowed DP and a large number of side lobes compared to the circular AA (figures 3a, 4a), which side lobes form has a circular cross-section in the plane perpendicular to the vertical, when the absence of deflection of the main beam from the normal to the array plane in a rectangular AA. It is seen from the analysis of the simulation results (table 1) and
direction patterns comparison of rectangular and circular AA. If in a rectangular AA the main beam from the normal deviate and the azimuth scan change, that the width of main DP beam increases, and rise highly the side lobe level compared to the circular AA (figures 3b, c, d; 4b, c, d), which save the form of direction pattern of main beam when the scan azimuth changes.

Figure 1. AA configurations: a – configuration №1, it is a rectangular flat AA 3×3. The distance between the elements is equal to λ/2 m; b – configuration №2, it is circular eight-element AA. The distance between the elements is equal to λ/2 m.

Figure 2. Appearance and cross-section of direction pattern in the vertical plane of the directional antenna.
Table 1. Comparative characteristics of the DP which based on the results of modeling of rectangular and circular AA.

| AA Configuration | Rectangular AA (3×3) | Circular AA (3×3) |
|------------------|----------------------|------------------|
| Position of the direction pattern main beam (azimuth, elevation angle) | $\beta = 90^\circ$ $\epsilon = 90^\circ$ $\beta = 60^\circ$ $\epsilon = 60^\circ$ $\beta = 45^\circ$ $\epsilon = 45^\circ$ $\beta = 30^\circ$ $\epsilon = 30^\circ$ | $\beta = 90^\circ$ $\epsilon = 90^\circ$ $\beta = 60^\circ$ $\epsilon = 60^\circ$ $\beta = 45^\circ$ $\epsilon = 45^\circ$ $\beta = 30^\circ$ $\epsilon = 30^\circ$ |
| Direction pattern width of the main beam, deg | 25 32 42 63 28 36 44 56 | 1.5 2.5 3.2 6.1 2.1 2.4 2.6 3.1 |

Figure 3. The direction pattern of a rectangular AA (3×3): a – $\beta = 90^\circ$, $\epsilon = 90^\circ$; b – $\beta = 60^\circ$, $\epsilon = 60^\circ$; c – $\beta = 45^\circ$, $\epsilon = 45^\circ$; d – $\beta = 30^\circ$, $\epsilon = 30^\circ$.

4. Conclusion

It is possible to form the necessary DP AA that satisfies the requirements of measurement error of the inhomogeneities angular coordinates of the atmosphere and that satisfies the level of the side lobes, which affect on level of multipath probing signals reception. This is possible due to the choice of the type of each antenna array element, its single DP, the geometric configuration of the AA, which determines its aperture, the inter-element distance, and the number of antenna elements.
It should be noted that the change in the amplitude-phase distribution of currents or excitation fields on the antenna elements of the DP radar antenna array forms the main reception direction of reflected probing signals, the shape of the corresponding direction pattern and it allows to realize various methods of scanning the atmosphere (circular, sector, spiral, conical, linear, etc.), which depend on weather conditions, type of atmosphere inhomogeneity, its intensity and turbulence.

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Figure 4. The direction pattern of a circular AA (3×3): a – β = 90°, ε = 90°; b – β = 60°, ε = 60°; c – β = 45°, ε = 45°; d – β = 30°, ε = 30°.

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