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RESEARCH OF COLLINEAR ANTENNA PARAMETERS FOR ADS-B RECEIVING SYSTEM USING NUMERICAL METHODS

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Виконано розрахунки напруженості електромагнітного поля та діаграм спрямованості колінеарної антени на основі методу моментів з використанням двох програмних комплексів. Порівняння показало високий рівень збіжності результатів. Побудовано зразок антени, яка використовується в діючій системі для приймання ADS-B сигналів бортових відповідачів літаків.

Проведены расчеты напряженности электромагнитного поля и диаграмм направленности колинеарной антенны на основе метода моментов с использованием двух программных комплексов. Сравнение показало высокий уровень совпадений результатов. Построен образец антенны, которая используется в действующей системе для приема ADS-B сигналов бортовых ответчиков самолетов.

Calculations of electric field intensity and directional diagrams for a collinear antenna using a method of moments in the framework of two program complexes are carried out. Comparison has shown high level of results coincidence. The sample of the antenna which is used in operating system for reception of ADS-B signals from airborne transponders is constructed.

Key words: radiation pattern, collinear antenna, air traffic surveillance, system for reception of ADS-B signals.

Formulation of the problem

ADS-B (Automatic Dependent Surveillance – Broadcast) is a new technology for air traffic surveillance, which is being implemented in Europe, the USA and other countries. EUROCONTROL CASCADE Programme coordinates the implementation of ADS-B technology in Europe [1].

The actual task is to inform students about this new technology, to build a simple system for receiving ADS-B signals and to watch air traffic with its help.

A ground system which is receiving ADS-B signals from the Mode S airborne transponder at a frequency of 1090 MHz can be used as virtual radar to create a real-time picture of air traffic and consists of four components: an antenna, a receiver, a decoder, and computer software.

To create a real model of a ground ADS-B system it is necessary to investigate the antenna parameters.

Analysis of researches and publications

For electromagnetic field calculations and obtaining corresponding antenna patterns usually numerical methods of electrodynamics are used, including the method of moments [2], in which the metal antenna elements are replaced by equivalent surface electric currents and equivalent mesh model of the object is created. Then the problem of finding the electromagnetic field that is created by these currents is solved. For this the metal surface is divided into elementary segments and electrical currents within the segment are represented as decomposition over basis functions with weighting factors [3 – 5].

In a software complex developed at the National Aviation University [5, 6] for approximation of currents are used piecewise-constant basis functions and along a metal wire with a current the boundary conditions for the electromagnetic field are imposed. In a result of using the boundary conditions the system of integral equations is obtained for the coefficients of the basic functions, which are the amplitudes of currents within the elementary segment. The system of equations in this software complex [4] is solved relatively interdependent currents using the Kraut's method [2].

The moment's method accuracy is higher for the smaller elementary segment size. It is considered that in order to achieve acceptable accuracy a segment size should not exceed $\lambda/10$, where λ – is a wavelength in a free space. The number of integral equations is equal to the number of elementary segments N, which increases with the size of an object or with increasing of a frequency. Therefore, solving the problem of radio waves scattering on an object using the method of moments requires solving of integral equations system in matrix form with a large dimension.

The purpose of the investigation

The aim of this work is: 1) to study the electromagnetic field radiated by a collinear antenna using the software complex [4] on the basis of the method of moments; 2) to create experimental model antenna of a ground system for ADS-B signals receiving at a frequency of 1090 MHz; 3) to analyze the results of air traffic surveillance using created ADS-B system.

A sequence of radiation pattern calculation for the collinear antenna

The vector of the electric field which is excited by an electrodynamic object in general case is determined as the vector sum of projections:

$$\bar{E}_\Sigma = \bar{l}_r E_{r\theta\Sigma} + \bar{l}_\theta E_{\theta\Sigma} + \bar{l}_\varphi E_{\varphi\Sigma} \;;$$

which must be defined.

For numerical calculation by the method of moments a collinear antenna is divided into N segments, each of the length z which is much smaller than the wavelength. The complex amplitude of the individual components of the vector $\bar{E}_\Sigma$ in the far field radiation of any segment is defined by the following relation [2]:

$$\dot{E}_\theta = -i\,\frac{ik^2}{\omega\varepsilon}G(z,z')\{r_2[\sin\theta_2\cos\theta\cos(\varphi_2 - \varphi) - \cos\theta_2\sin\theta_2] - r_1[\sin\theta_1\cos\theta\cos(\varphi_1-\varphi) + \cos\theta_1\sin\theta]\}\;;$$

$$\dot{E}_\varphi = -i\,\frac{ik^2}{\omega\varepsilon}G(z,z')[r_2\sin\theta_2\sin(\varphi_2-\varphi) - r_1\sin\theta_1\sin(\varphi_1-\varphi)]\;;$$

$$\dot{E}_r \cong 0\;.$$

Indexes 1 and 2 belong to the spherical coordinates of points [r,θ,φ], which define the beginning and end of the elementary segment of antenna with complex amplitude of the current $\dot{I}$.

$$\omega = 2\pi f\;;$$

$$k = \frac{2\pi}{\lambda}\;;$$

$$G(z,z') = \frac{e^{-ikr}}{4\pi r}\;;$$

$$r = \sqrt{(z-z')^2 + a^2}\;;$$

where a – radius of the rod of antenna; z – coordinate of the observation point on the surface; z' – coordinate of a point on the axis of the model grid element length L, in which is placed a partial source of the linear current:

$$I(z') = \int_L j(z)dz\;.$$

The procedure for determining the currents in the elements of the model is the numerical solution of the Pocklington's equation [3]:

$$\int_{-\frac{L}{2}}^{\frac{L}{2}} I(z')\left[\frac{\partial^2 G(z,z')}{\partial z'^2} + k^2 G(z,z')\right]dz' = -i\omega\varepsilon E_z^i(z). \quad (1)$$

For solving equations (1) by the method of moments the unknown current distribution $I(z')$ along the axis z of any fragment models must be decomposed over the system of selected basis functions $J_n(z')$:

$$I(z') = \sum_{n=1}^{N} I_n J_n(z'),$$

where the unknown constants I_n must be determined. Then the Pocklington's integral equation takes the form:

$$\sum_{n=1}^{N} I_n \int_{-\frac{L}{2}}^{\frac{L}{2}} j_n(z')\left[\frac{\partial^2 G(z,z')}{\partial z'^2} + k^2 G(z,z')\right]dz' = -i\omega\varepsilon E_z^i(z).$$

Using the weighting functions W_m of the mutual influence of m-th element on the n-th element the Pocklington's equation takes the form

$$\sum_{n=1}^{N} I_n \int_{L_n}\int_{L_m} W_m(z) j_n(z')\left[\frac{\partial^2 G(z,z')}{\partial z'^2} + k^2 G(z,z')dz'\right]dz = -i\omega\varepsilon\int_{L_m} W_m(z)E_z^i(z)dz.$$

According to the Galerkin's method weighting function W_m must be chosen the same as the basis functions $J_m(z')$:

$$W_m = J_m(z').$$

The integrand of the Pocklington's equation has the dimension of a resistance, is denoted as Z_{mn} and is called as the generalized impedance. The right side of the equation is generalized excitation voltage U_m. The system of equations in matrix form looks like

$$[Z]\times[I] = [U],$$

where $[Z]$ – the generalized impedance matrix; $[I]$ – the vector of unknown coefficients in the expansion of currents; $[U]$ – the vector of excitation sources. The system of equations in matrix form can be solved using special software after its transposition:

$$[I] = [Z]^{-1}[U],$$

or converting to an equivalent system of equations:

$$\left.\begin{array}{l}\dot{I}_1 = \dot{Y}_{11}\dot{U}_1 + \dot{Y}_{12}\dot{U}_2 + \cdots + \dot{Y}_{1n}\dot{U}_n;\\ \dot{I}_2 = \dot{Y}_{21}\dot{U}_1 + \dot{Y}_{22}\dot{U}_2 + \cdots + \dot{Y}_{2n}\dot{U}_n;\\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots ;\\ \dot{I}_n = \dot{Y}_{n1}\dot{U}_1 + \dot{Y}_{n2}\dot{U}_2 + \cdots + \dot{Y}_{nn}\dot{U}_n\end{array}\right\},$$

where $\dot{I}_p$ – is an amplitude and a phase of the current flowing through the clamps of *p*-th antenna element; $\dot{Y}_{pq}$ – a mutual complex conductivity between the *p*-th and *q*- th elements; $\dot{U}_p$ – an amplitude and a phase of the voltage at the clamps of *p*-th element. The system of equations was solved in the program using interdependent currents in the Kraut's method. Their values are used for defining the modules of electric field resulting vector projections and their normalized values [3].

Formulas presented in papers [2, 3] constitute the basis in the software complex [4] for calculations of the intensity of the radiation field and the antenna radiation pattern.

Calculations of a radiation pattern

First of all requirements for the ADS-B antenna ground system were identified and the collinear antenna design was chosen.

A ground antenna for reception of ADS-B signals should provide circular radiation pattern in the horizontal plane with the vertical field polarization. A range of secondary radar with Mode S should provide a coverage area for air traffic control center not less than the distance of the line of sight. Therefore, to ensure a high gain in the vertical plane a collinear antenna is designed in form of three inphase half wave wire segments between which is installed two phase shift knee with length λ/2 for inphase mode excitation of vibrators.

The field of radiation for collinear antenna was calculated using the programs [4, 5] and obtained results were compared.

Initial data for calculation of the radiation field are identical. It was considered an antenna location above the ground with the following characteristics: relative permittivity $\varepsilon = 9{,}0$ and conductivity of underlying surface $\gamma = 0{,}01$ $(\text{ohm*m})^{-1}$. In both programs the method of moments with antenna conductors breakdown into elementary segments were used. The program [4] allows performing calculations with a constant number of segments. The program MMANA-GAL [5] can select segments of variable density from 40 to 4000 along the antenna. For comparison of results a number of segments was chosen as 400. The antenna is installed at a height above the ground λ/10.

The selected antenna configuration is shown in Fig. 1. As a phase shift element the coil wire with a length λ/2 was taken and was approximated by an octagon (Fig. 2,*a*).

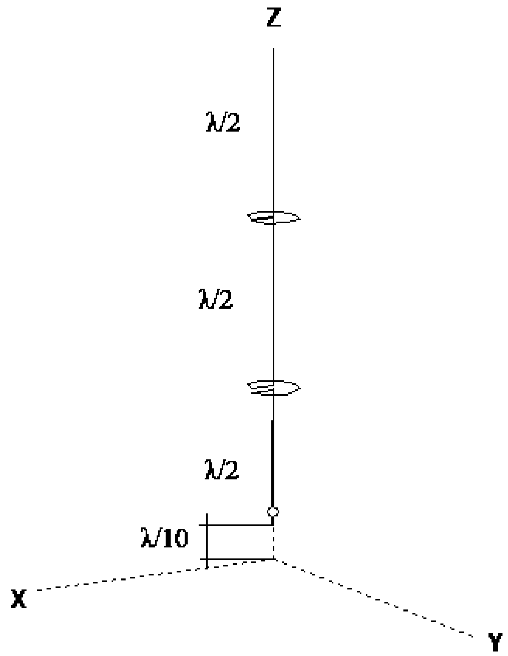
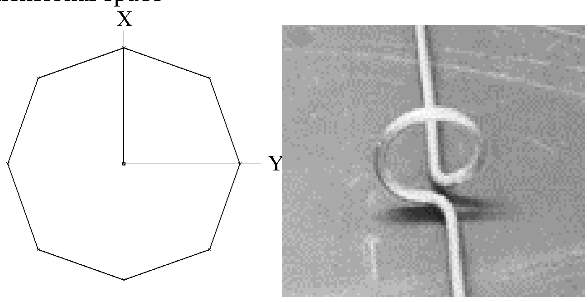


Figure. 1. A model of the collinear antenna in three dimensional space



а *б*

Figure. 2. The collinear antenna:

а – an antenna model in the plane XOY;

б – a fragment of the antenna

During the simulation various turns of wire were considered: from flat to round spiral with step growth along the axis *OZ* (0,01…0,1) λ. It was obtained that flat coils of wire with orthogonal winding directions give the smallest parasitic horizontal field component.

The program interface [4] used for parameters and the antenna geometry input is shown in Fig. 3.

The results of calculations radiation pattern of collinear antenna for underlying surface with parameters $\varepsilon = 9{,}0$ та $\gamma = 0{,}01$ $(\text{ohm*m})^{-1}$ are given in the table.

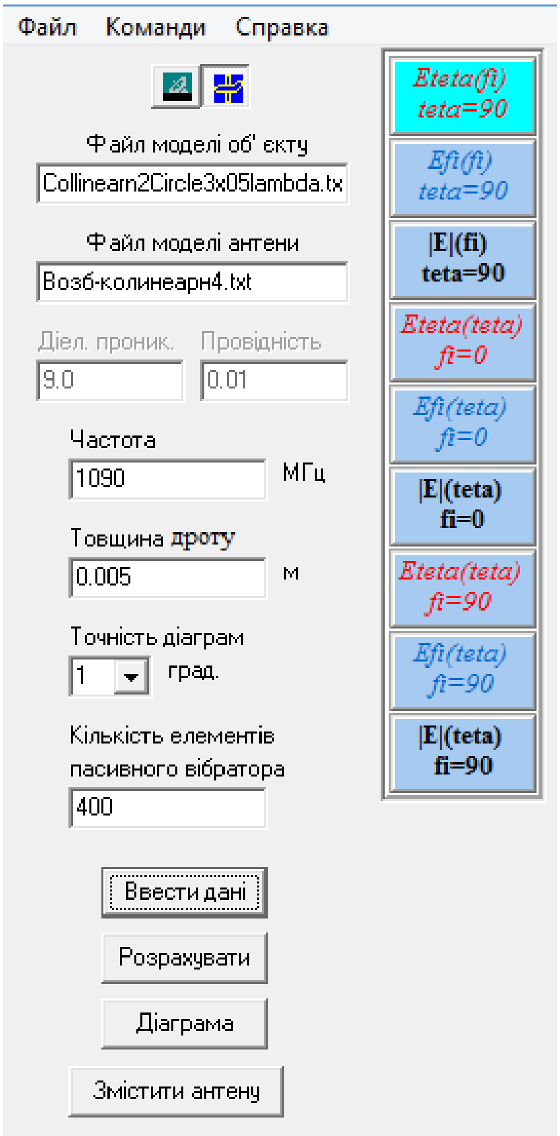


Figure. 3. The program interface [4]

The programs [4] and [5] explore different methods for output data processing. In the program [4] two methods are used for electric field module normalization and the radiation pattern are displayed in a linear scale. In this case, the maximum modulus of the electric field is equal to 1,0 relative units.

In the program [5] a logarithmic method for local electric field module normalization is used. For comparison of results the local normalization mode was used in the program [4].

The change in a radiation pattern during the transition from the ideal to the real conductivity of underlying surface was analyzed with the help of sophisticated graphic interface applications [5]. It can be seen that the radiation pattern is significantly improved by reducing the "failures" (Fig. 4, 5).

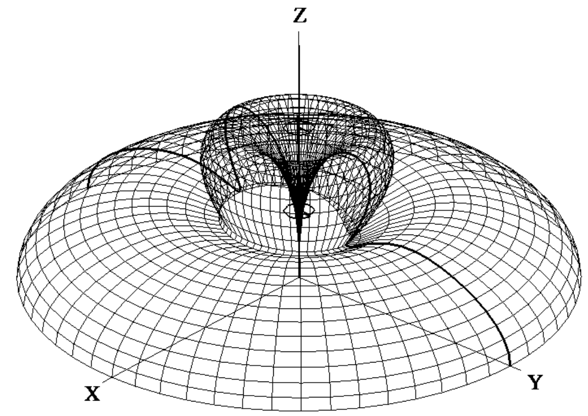


Figure. 4. Three-dimensional radiation pattern for the collinear antenna obtained by the Program MMANA-GAL for perfectly conducting underlying surface

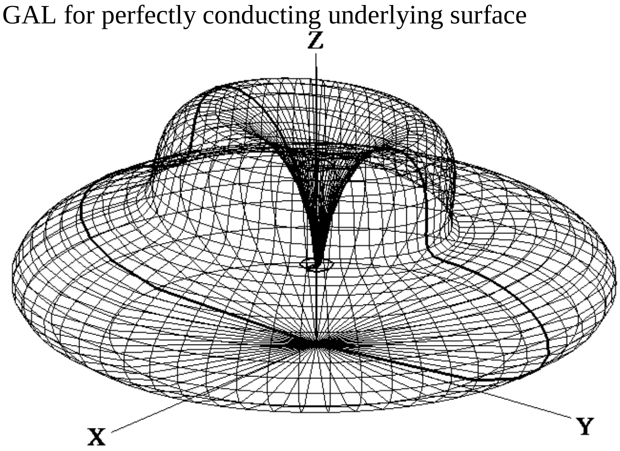


Figure. 5. Three dimensional radiation pattern for the collinear antenna obtained by the Program MMANA-GAL for underlying surface with parameters: $\varepsilon = 9{,}0$ i $\gamma = 0{,}01$ (ohm*m)$^{-1}$

The experimental antenna

On the base of provided calculations the experimental collinear antenna (Fig. 2, *б*) was made from copper wire of a diameter 5 mm. This antenna included phase shift elements (horizontal coils of wire length $\lambda/2$) between half wave elements for inphase power supply. They prevent the formation of currents in the opposite direction of collinear antenna elements. It provides a inphase power supply for vertical antenna elements and forming a desired shape radiation pattern antenna in the vertical plane with a slope of main lobe radiation pattern along the ground. At the elevation angle of 16° an antenna gain is $G_v = 0{,}1$ dB. For the compensation of the horizontal electromagnetic field component right and left turns of wire in first and second phase shift elements were used. This antenna is a narrowband. As shown in Fig. 6 a bandwidth is 67,74 MHz for a standing wave ratio less than 1,5.

Designed collinear antenna has a satisfactory matching on a frequency 1090 MHz and coefficient of input impedance Z = 76,049-j258,117 ohm. It allows receiving signals from the airborne transponder with Mode S Extended Squitter and functioning of ground ADS-B system (Fig. 7).

It was found that the antenna has a small "blind funnel" and allows you to track aircraft "over himself".

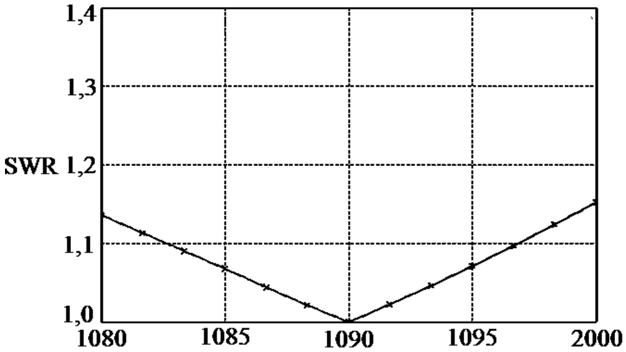


Figure. 6. Dependence of a standing wave ratio on the frequency

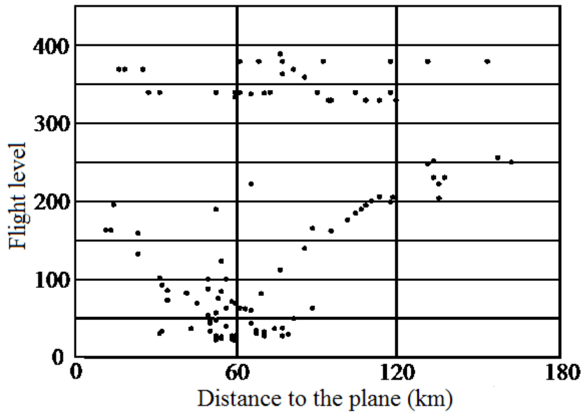
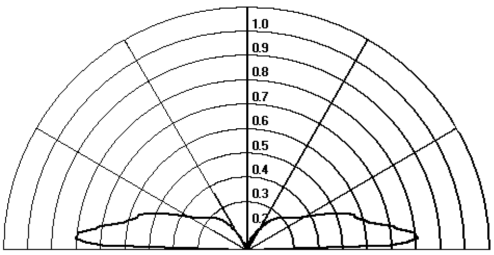
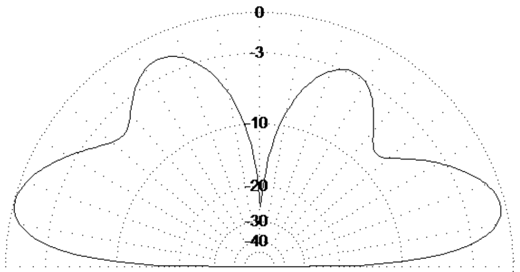
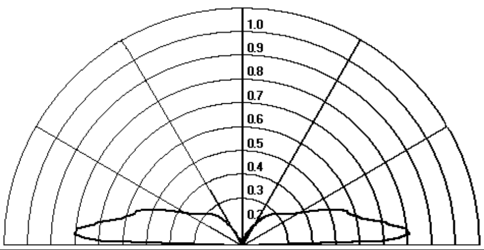
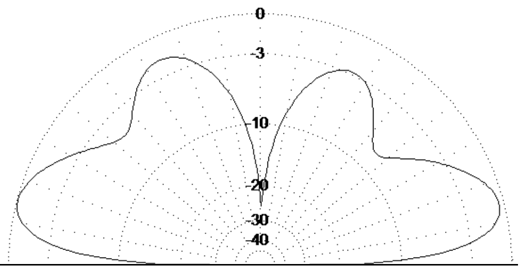


Figure. 7. The dependence of the distance to the aircraft at different flight levels, which was obtained from the experiment

As shown in Fig. 8 designed antenna allowed to receive ADS-B signals from the aircraft at large distances (600 km) from the receiver, which is located in Kyiv on the roof of academic building with a height of 20 meters.

Radiation pattern of collinear antenna

Components of the vector $\bar{E}$	The program NAU (linear scale)	The program MMANA-GAL (logarithmic scale)
The component of the electric field in the vertical plane *XOZ* $E_\theta(\theta)\|_{\varphi=0°}$		
The component of the electric field in the vertical plane *YOZ* $E_\theta(\theta)\|_{\varphi=90°}$		

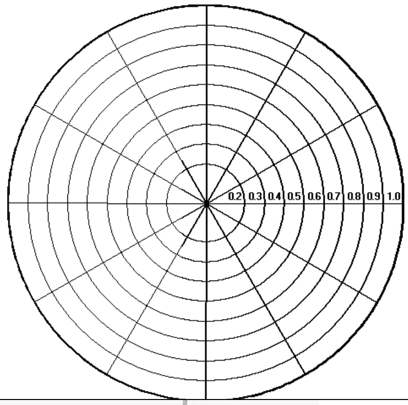
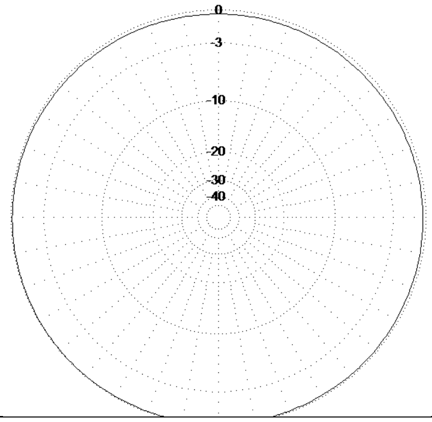
The component of the electric field in the horizontal plane $XOY\ E_{\theta}(\varphi)\|_{\Theta=90^{\circ}}$		

Figure. 8. Result of observations – a piece of air situation mapping

Conclusions

1. The calculations of electromagnetic fields and radiation patterns for the collinear receiving antenna were provided.

2. For calculations of the electric field programs [5] and [6] were used which gave similar results and allowed to do a qualitative analysis of patterns in the vertical plane.

3. Experiments have shown that the created ground ADS-B receiving system provides a significant range of channel "Airborne Transponder – Ground Receiver" for operations in Mode S at a frequency of 1090 MHz.

References

1. CASCADE | EUROCONTROL [electronic resource] – 04.02.2013 – Mode of access: http://www.eurocontrol.int/surveillance/cascade – The name from screen.

2. Calculation methods in electrodynamics [Text] / ed. R. Mitra. – M.: Mir, 1977. – 488 p.

3. *Barabanov Yu.M.* Field whip antenna mounted on the body of the aircraft [Text] / *Yu.M. Barabanov, V.O. Ivanov, O.A. Morhun, I.I. Cherniavskyi* // Electronics and control systems. – 2007. – №3(13). – Page. 88-95.

4. Mathematical modeling of metal structures for measuring antenna characteristics [Text] // Report on research work on NAU № 006-ДБ01-03, 3-rd stage (final) – K.: NAU, 2003. – 86 p.

5. *Goncharenko I.V.* Antenna HF and VHF. Part IV. Directional HF antennas: in-phase and longitudinal radiation [Text] / *I.V. Goncharenko* // – M.: IP RadioSoft, 2007. – 256 p.