Comparative Analysis of Methods for Calculating the Energy Flux Density used in Assessing the Permissible Level of Environmental Pollution by Electromagnetic Radiation

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Abstract **– In this article, the results of measurements and calculations of the power flux density in the frequency range 670 MHz-766 MHz (46th and 57th television channels) of digital broadcasting of the DVB-T2 standard were presented. Experimental data on the power flux density were obtained by the selective electromagnetic field meters NARDA SRM-3000 with an isotropic antenna. The radiating system consists of 16 panel antennas (four-storey panel antennas) with a circular radiation pattern in the horizontal plane. Calculations were carried out in the ПК АЭМО (Software package for electromagnetic environment analysis) and MMANA programs. The data obtained were compared with the permissible exposure limit (PEL) of energy flux density (EFD) set by health and safety rules and standards (2.1.8/2.2.4.1383-03), which operate on the territory of Russia.**

The values obtained are significantly less than the acceptable levels. In the USA, Japan, European countries, Canada, China, and the PEL of energy flux density in the frequency range 300 MHz – 300 GHz are higher than in Russia.

Keywords **– electromagnetic field high frequency, environmental pollution, high-frequency. electromagnetic radiation, computational methods in antenna theory, wire antenna, electromagnetic compatibility.**

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1. Introduction

With the development of wireless technologies, new devices and instrumentation, this in turn leads to an increase in the level of the general electromagnetic background. New technologies often require the transmission of a large amount of information and the associated use of high frequencies. To control the radiation of high-frequency devices, it is required to periodically measure the level of electromagnetic fields. High-frequency electromagnetic oscillations can adversely affect living organisms, mainly due to the heating of tissues under the influence of radiation [1]. Different countries have different requirements for the permissible level of electromagnetic radiation [2], but in any case, monitoring the state of the general electromagnetic background is necessary. The problem of electromagnetic air pollution by high-frequency electromagnetic radiation is now the most acute due to the rapid development of wireless digital communication [3]. On the one hand, the development of new technologies that allow us to transmit more information is good, but on the other hand, it requires more energy resources. The general background of electromagnetic radiation increases, in addition, a large amount of interference occurs and the electromagnetic compatibility of radio-electronic devices deteriorates. This is especially noticeable in large cities [4]. The electromagnetic situation can be predicted by modeling radiation sources and the environment – this reduces the cost of monitoring electromagnetic radiation [5]. The relevance of the study lies in the experimental determination of the reliability of the results of methods for calculating the experimental situation on the ground.

2. Research Methods

At the first stages, the method of calculating prediction of the electric field strength of radiating technical devices of very high frequency (VHF) and ultra-high frequency (UHF) was based on the use of the method proposed by B. A. Vvedensky. The basis of this method is the interference formula

$$E = \frac{\sqrt{30PGL}}{r} K_f F(\alpha) F(\varphi) \quad (1)$$

where P – power at the input of the antenna-feeder path; G – the gain of the antenna relative to the isotropic source, determined in the direction of peak radiation; $L = L_0 L_T$ – the loss coefficient in the antenna-feeder path; L_0– reflection losses due to insufficient alignment of the antenna with the feeder; L_T– the efficiency of the feeder, determined by heat losses; r – distance from the geometric center of the antenna to the observation point; $F(\alpha)$ – normalized antenna pattern in the vertical plane; $F(\varphi)$ – normalized antenna pattern in the horizontal plane; $K_f = 1.15 \ldots 1.3$ – attenuation multiplier, it takes into account frequency properties and the higher the frequency, the greater the attenuation multiplier.

Expression (1) is true only when the observation point is in the far zone, and calculations will be very inaccurate near the installation site of the radio engineering object. By introducing an attenuation multiplier, a margin was provided for the level of electric field strength.

This approach to finding the distribution of the electromagnetic field intensity is used in some computer programs that analyze the electromagnetic situation and calculate the electromagnetic monitoring of transmitting radio engineering objects in strict accordance with the current regulatory and methodological documentation of the Russian Federation. For example, such a program as ПК АЭМО is released by a Samara branch of Federal State Unitary Enterprise Radio Research Institute ("ФГУП НИИР – СОНИИР").

In more modern methods, it is recommended to calculate the levels of the electromagnetic field by currents in the antenna. The calculation is performed in two stages: first, the current distribution in the antenna conductors is calculated, and then the levels of the electromagnetic field are calculated. The current distribution is calculated based on the solution of the electrodynamic problem by the method of integral equations in the thin-wire approximation. At the same time, the actual antenna design is represented as a system of electrical thin cylindrical conductors.

When analyzing antennas, the task is divided into two: internal and external. The internal task is to find the distribution function of high-frequency currents in the radiating system. In the external problem, the electromagnetic field of the antenna radiation and other numerical characteristics are determined.

The calculation of antennas made of thin conductors, as a rule, boils down to the transformation of Maxwell's equations to integro-differential or integral equations for the distribution of surface current on the conductor. To date, three basic equations are known: the Pocklington and Harrington integro-differential equations, as well as the Gallen integral equation.

In the regions containing electric and magnetic sources, Maxwell's equations have the form

$$rot\dot{\vec{E}} = -j\omega\dot{\mu}_a\dot{\vec{H}} - \dot{\vec{J}}^m, \quad (2)$$

$$rot\dot{\vec{H}} = -j\omega\dot{\varepsilon}_a\dot{\vec{E}} - \dot{\vec{J}}^e, \quad (3)$$

where $\dot{\vec{E}}$ – vector of the complex amplitude of the electric field strength; $\dot{\vec{H}}$ – vector of the complex amplitude of the magnetic field strength; $\dot{\vec{J}}^e$, $\dot{\vec{J}}^m$– the densities of third-party complex electric and magnetic currents, respectively; $\dot{\varepsilon}_a$ – complex absolute permittivity of the medium, $\dot{\varepsilon}_a = \varepsilon\left(1 - j\frac{\sigma}{\omega\varepsilon}\right)$; $\dot{\mu}_a$ – complex absolute magnetic permeability of the medium.

To solve Maxwell's equations, two auxiliary vector fields are usually introduced: the vector potential of electric currents $\dot{\vec{A}}^e$ and the vector potential of magnetic currents $\dot{\vec{A}}^m$. Electromagnetic fields vectors $\dot{\vec{E}}$ and $\dot{\vec{H}}$ are determined through auxiliary potentials as follows:

$$\dot{\vec{E}} = -j\omega\dot{\mu}_a\dot{\vec{A}}^e + \frac{1}{j\omega\dot{\varepsilon}_a} graddiv\dot{\vec{A}}^e - rot\dot{\vec{A}}^m; \quad (4)$$

$$\dot{\vec{H}} = -j\omega\dot{\varepsilon}_a\dot{\vec{A}}^m + \frac{1}{j\omega\dot{\mu}_a} graddiv\dot{\vec{A}}^m - rot\dot{\vec{A}}^e, \quad (5)$$

where

$$\dot{\vec{A}}^{e,m} = \frac{1}{4\pi}\int_V \dot{\vec{J}}^{e,m}(x', y', z')\frac{e^{-jkr}}{r}dV, \quad (6)$$

r – distance between the observation point (x, y, z) and the point where the source is located (x', y', z'):

$$r = \sqrt{(x - x')(x - x')^2 + (y - y')^2 + (z - z')^2}, \quad (7)$$

Richmond used essentially a Pocklington type integral equation, but applied a slightly different method of derivation [6]. Let there be an arbitrary volume distribution of sources (Figure 1).

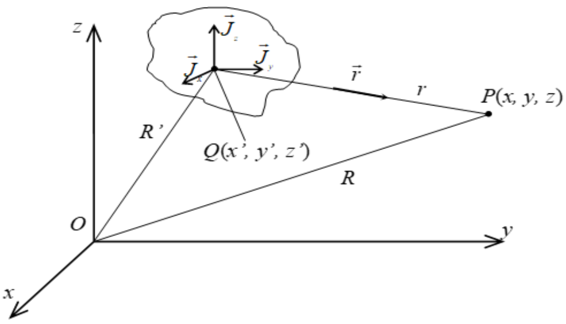

Figure 1. Arbitrary volume distribution of sources

Expressing the field in terms of the vector potential, we have

$$\dot{\vec{H}} = \frac{1}{\mu} rot\vec{A}, \quad (8)$$

$$\dot{\vec{H}}(x,y,z) = -\frac{1}{4\pi\mu}\int_V (\vec{r}_1,\vec{J})\frac{1+jkr}{r^2}e^{-ikr}dV', \quad (9)$$

where $\vec{r}_1$ is a unit vector directed from the source point to the observation point.

Applying the rotor operation to both parts of this equality, we obtain expressions for the components of the electric field intensity vector in a rectangular coordinate system excited by an electric current source:

$$\dot{E}_x = \frac{\sqrt{\mu_0/\dot{\varepsilon}_a}}{4\pi jk}\int_V \Big[F_1(r)J_x + (x-x')F_2(r)\big[(x-x')J_x + (y-y')J_y + (z-z')J_z\big]\Big]dV' \quad (10)$$

$$\dot{E}_y = \frac{\sqrt{\mu_0/\dot{\varepsilon}_a}}{4\pi jk}\int_V \Big[F_1(r)J_y + (y-y')F_2(r)\big[(x-x')J_x + (y-y')J_y + (z-z')J_z\big]\Big]dV' \quad (11)$$

$$\dot{E}_z = \frac{\sqrt{\mu_0/\dot{\varepsilon}_a}}{4\pi jk}\int_V \Big[F_1(r)J_z + (z-z')F_2(r)\big[(x-x')J_x + (y-y')J_y + (z-z')J_z\big]\Big]dV' \quad (12)$$

where

$$F_1(r) = \frac{-1-jkr+k^2r^2}{r^3}e^{-ikr};$$

$$F_2(r) = \frac{3+3jkr+k^2r^2}{r^5}e^{-ikr}. \quad (13)$$

In the study of wire antennas, one can proceed from both the Pocklington or Harrington equation and the Gallen's equation and use these equations to find the current distribution function, and then calculate the electrodynamic parameters. In the works of scientists of the Samara school [7] and in the guidelines for determining voltage levels the guidelines «Determination of the levels of the electromagnetic field created by the transmitting technical devices of television, FM radio broadcasting and base stations of mobile terrestrial radio communication» (4.3.1677-03) in Russia, the Harrington's equation is used. But Pocklington's equation turns out to be more general in a certain sense. In fact, the right side of the Pocklington's integral equation includes a quantity that determines the field generated by the source. The source may be, for example, the opening of a coaxial line exciting the antenna on a grounded plane. Or, for example, in the case of a slit antenna on a metal body, a slit can be considered as a source, and the metal surface can be characterized or modeled by passive antenna elements or wire segments. At the same time, the Gallen integral equation uses exclusively a voltage generator applied to an infinitely narrow gap to describe the excitation, which does not give the desired flexibility in choosing different sources of excitation. In addition, although the infinitely narrow gap approximation is very useful, it is much worse than models with finite sources, describes the real physical picture and can lead to difficulties in calculating the imaginary part of the input impedance with great accuracy [8]. Integral equations are solved by the well-known method of moments [9], [10] or some new combined methods [11]. Other numerical methods are also used, for example the method Finite Difference Time Domain [12].

A slightly modified approach is possible. For example, this is an exact representation of the kernel of the Green's function instead of the kernel of the approximation of a thin wire for solving arbitrary wire antennas and reflectors with a moderately thick radius by the method of moments [13].

The disadvantage of the Pocklington's and Harrington's equations is that in addition to the current function, its derivative is explicitly included in them, this circumstance causes computational difficulties. At the same time, the Pocklington's equation can be transformed into the Mei's equation, where there is no derivative. As an integral equation for determining the current distribution in a wire antenna, you can choose the Mei's equation, for the following reasons:

1. The equation is successfully solved by the computationally economical method of colocation;
2. Good convergence of the solution is observed, almost regardless of the type of basis functions;
3. The right side of the equation is a piecewise smooth function even with concentrated excitation.

This approach is used when calculating the electromagnetic field in the well-known MMANA program.

There is a slightly different approach to calculating the current in a thin electric vibrator, described in [14], [15]. This approach is based directly on Maxwell's equations written in a cylindrical coordinate system, which make it possible to reduce the problem not to an integro-differential, but to an integral equation. In these works, the mathematical apparatus of the theory of singular integral equations is used. The problem was reduced to solving singular integral equations with respect to the longitudinal coordinate derivative of the surface current density on the vibrator.

The main advantage of the presented approach of calculating the current distribution in comparison with other known methods is the possibility of mathematically correct solution of singular integral equations. The disadvantage is the limitation of the application of this theory to curved conductors.

3. Results of the Research

The authors conducted a comparative analysis of electromagnetic field modeling in the ПК АЭМО, MMANA and experimentally measured.

Consider an object on which four floors of panel antennas are installed in four directions with a gain of 13.15 dBi of the entire antenna as a whole, the width of the radiation patterns in the vertical plane is 5.5°, in the horizontal plane the radiation pattern is circular. The height of the antenna phase center is 74 m above the ground. Broadcasting digital terrestrial TV of DVB-T2 standard on 46th and 57th television channels, the power of transmitters of 500 watts. As a result of attenuation on the feeder, the radiated power of the antenna is 708 watts.

When calculating in the ПК АЭМО program, the distribution of the safety criterion – the ratio of the found power flow density to the maximum permissible level of power flow density (Figure 2). If the value of the safety criterion is less than 1, then the electromagnetic environment is safe for the population, if it exceeds, then it is not safe for people to be in this place. In ПК АЭМО expression

$$\sum_{j=1}^{m}\left(\frac{E_{sum\,j}}{E_{PEL\,j}}\right)^2+\sum_{k=1}^{q}\left(\frac{EFD_{sum\,k}}{EFD_{PEL\,k}}\right) \quad (14)$$

defined as a security criterion. In this formula $E_{sum\,j}$ – the total electric field strength generated by EMF sources of the j-th normalized range. $E_{PEL\,j}$ – PEL electric field strength of the j-th normalized range; $EFD_{sum\,k}$ – total EFD, generated by electromagnetic field sources k-th normalized range; $EFD_{PEL\,k}$ – PEL of EFD of the k-th normalized range; m – the number of ranges for which is normalized E; q – the number of ranges for which is normalized EFD. In our case, the maximum EFD will be 0,5 $\mu W/cm^2$. In a simplified calculation, an antenna radiation pattern is used, in this case a circular radiation pattern, so the distribution of EFD in other directions will have the same appearance.

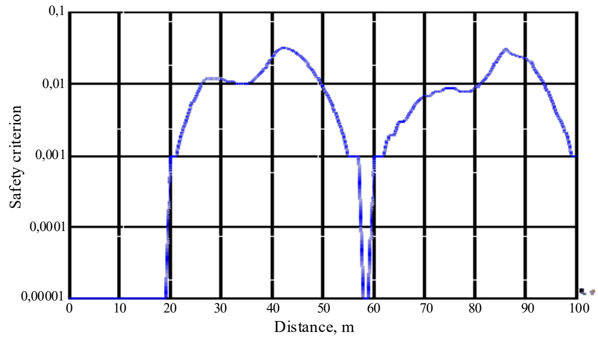

Figure 2. Distribution of the safety criterion at a height of 2 m from the ground

When calculating the power flux density in the MMANA program, it has a distribution according to Figure 3.

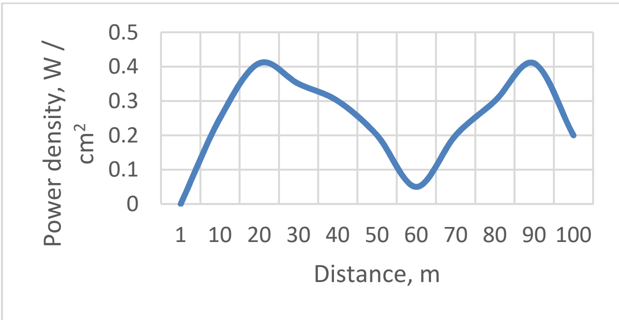

Figure 3. Distribution of the power flux density at a height of 2 m from the ground

Power flux density measurements were experimentally carried out using a selective electromagnetic field meter Narda SRM-3006 in the village of Izederkino (Figure 4) of the Chuvash Republic (Russia). The measurement results are influenced by external electromagnetic interference that occurs during the operation of electrical appliances, electrical equipment, power supply systems, etc. and their own noise. The terrain (Figure 5) also affects the measurement results, the incident electromagnetic wave is reflected from the earth's surface and superimposed on a direct wave. The influence of the terrain can be clearly seen both on the simulation results and on the experimental results in the form of dips at a distance of approximately 60 meters.

Figure 4. Location of the antenna

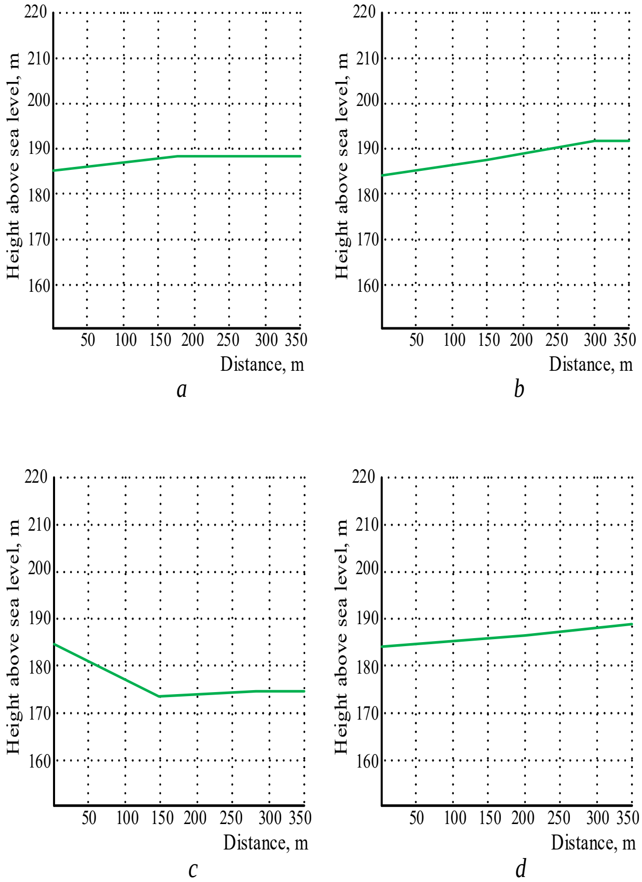

Figure 5. Terrain in directions relative to the north: a) in the direction of 0 ° b) in the direction 90 ° c) in the direction 180 ° d) in the direction 270 °

The measurements were carried out under the conditions of operation of the transmitters at the maximum permitted power. The preparation of the equipment for measurements and the measurement process itself were carried out in accordance with the operating instructions of the devices used. The measurement of power flux density levels in the far zone of the transmitting radio equipment was carried out by a selective device with a non-directional reception antenna at a height of 0.5 to 2 m from ground level with the orientation of the measuring antenna to the maximum reception. The measurements were carried out taking into account the summation of the power flux density generated by individual sources that are part of the broadcasting system. The measurement results are shown in Figure 6. Two digital television transmitters of the *DVB-T2* standard *Harris UAX*-500 *DV*(670 MHz-678 MHz) and *Maxiva UAX*-500 T2 (758 MHz-766MHz) are placed on the transmitting facility, each with output power 500 W.

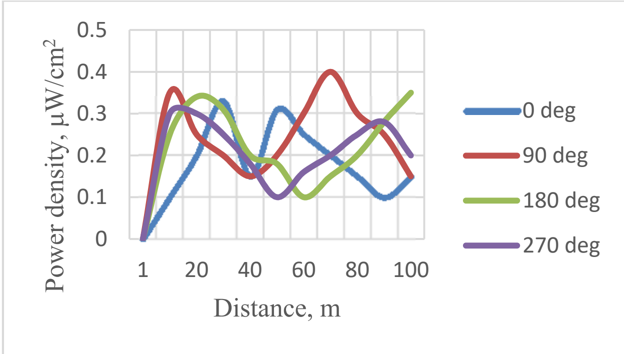

Figure 6. Distribution of the electromagnetic field power flux density at a height of 2 m from the ground in the direction of 0 °, 90 °, 180 ° and 270 °

In accordance with the health and safety rules and standards (2.1.8/2.2.4.1383-03) the assessment of the impact of the electromagnetic field on the population is carried out in the frequency range of 300 MHz-300 GHz – according to the average values of the power flux density and up to 10 $\mu W/cm^2$ is acceptable. The comparison of deviations between the maximum calculated values (Figures 2, 3) and the measured values (Figure 6) is no more than 10%. The comparison of calculated and measured values of the power flux density at 46th and 57th television channels was also carried out in the village of Poshnary of the Yadrinsky district, the village of Raskildino of the Alikovsky district and the village of Kanash of the Yadrinsky district (Russia). The results of these experiments are similar to those obtained above. Therefore, the calculations allows us to correctly estimate the level of power flux density created by the transmitting equipment.

4. Conclusion

The paper presents the results of measurements of the power flux density at high frequency and parallel calculations in the programs ПК АЭМО and MMANA. The values obtained do not exceed the permissible level of power flux density established in Russia of 10 $\mu W/cm^2$ in the range from 300 MHz to 3GHz for the population. The maximum measured energy flux density is 0.41 $\mu W/cm^2$, which is more than 24 times less than the permissible level. The considered programs for calculating electromagnetic fields use different algorithms, but a comparison of the results of measurements and calculations of the power flux density indicate that the existing programs for modeling electromagnetic radiation sources correctly calculate the density distribution of the high-frequency electromagnetic field and allow assessing the pollution from electromagnetic radiation at high frequency. This makes it possible to assess the adverse effects on living organisms and electromagnetic compatibility of radio-electronic devices.

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