Advances in Military Technology
Vol. 20, No. 1, 2025, pp. 263-275
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01962

Calculation of Frequency-Territorial Separation Norms for Decimeter Radio-Electronic Means

V. Pozdniak[1], O. Vysotskyi[1], S. Makarov[1], P. Open'ko[2*], V. Bondar[2] and V. Horbenko[2]

[1] *Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine*
[2] *National Defence University of Ukraine, Kyiv, Ukraine*

The manuscript was received on 31 January 2025 and was accepted after revision for publication as a case study on 3 June 2025.

Abstract:

The paper considers the main models of radio wave propagation used in the calculation of radio lines in the line-of-sight area. It has been shown that to calculate the frequency-territorial separation norms, the Vvedensky reflective model is advisable. The methodology for calculating the frequency-territorial separation norms and the peculiarities of its application for radio-electronic means operating in the decimeter-wave range are determined. Failure to take into account the attenuation multiplier during radio wave propagation within the scope of the Vvedensky formula leads to an error in the calculation of the interference power at the input of the interference receiver-receptor and to an erroneous increase in frequency separation during the development of frequency-territorial separation norms for decimeter radio-electronic means.

Keywords:

electromagnetic compatibility, frequency separation, territorial separation, multiplier, attenuation

1 Introduction

The constant increase in the density of radio-electronic means (REMs) with a limited frequency resource leads to a rise in mutual interference, affecting their intended functioning.

1.1 Problem Formulation

The problem of mutual interference is mainly observed where REMs are combined into complexes that should be located in a limited area. A large number of studies have

* *Corresponding author: Institute of Aviation and Air Defence, National Defence University of Ukraine, Air Force Avenue 28, 03049 Kyiv, Ukraine. Phone: +38066 764 59 20, E-mail: pavel.openko@ukr.net. ORCID 0000-0001-7777-5101.*

been devoted to the research of methods and algorithms for calculating the frequency-territorial separation (FTS) of REM and determining the conditions of electromagnetic compatibility (EMC) of REM located at the same position [1-22]. The rapid development of the latest technologies and standards (norms) of information transmission and their implementation in modern electronic communications and radio engineering causes an increase in the density of REM placed in local groupings. Therefore, the study of the problem of ensuring the intra-object electromagnetic compatibility of REMs is relevant.

2 Statement of Research Problem

In [23], the authors obtained relations that can be considered a system of criteria for ensuring the EMC of a group of independent REMs located in a limited area. However, the methodology for determining the individual parameters included in these ratios is not given. Paper [24] presents a methodology for analyzing the object EMC of communication means, which can be used exclusively to assess the interference effect on the receiver due to blocking and intermodulation. Paper [25] provides a general methodology and algorithm for calculating the EMC of REM, which does not provide for the development of FTS norms of REM [26]. Papers [26, 27] consider the peculiarities of assessing the mutual influence of exclusive radar means placed in a common position. The analysis of publications [23-28] indicates an insufficient level of research on the problem of ensuring intra-site electromagnetic compatibility of REM with the calculation of the FTS norms, on the basis of which recommendations are determined to ensure the EMC conditions of REM.

The most complete basic methods for analyzing and ensuring the EMC of REM located at the same facility are considered in [26], where, in particular, it is determined that the analysis and calculation of the EMC of REM located at the same facility includes the following main stages:

- frequency analysis of the object’s REM,
- energy analysis of the facility's REM:
  - calculation of the power of radio interference affecting the radio receiver (RR), reduced to its input,
  - calculation of the permissible power of unintentional radio interference at the input of the RR,
  - determination of the degree of EMC protection of the REM,
  - auxiliary calculations:
    - calculation of frequencies and levels of intermodulation radiation of radio transmitters (RT),
    - calculation of out-of-band characteristics of antennas,
    - calculation of the decoupling between antennas located close to each other.

To ensure in-situ EMC, in addition to the frequency, time and spatial separation of REM, the following methods are used [26]:

- reduction of interference caused by out-of-band and sideband radiation of the RT, as well as interference from side reception channels by using additional special filters at the output of the RT to reduce the level of radiation outside the main frequency band occupied by the transmitted signal,
- increasing the decoupling between antennas and feeders of radio frequency equipment located at the same facility,

ensuring the EMC of REM located at the same facility by using electromagnetic shields.

However, in [26], several aspects related to the analysis and assurance of EMC for REM are not explored in sufficient depth, necessitating further clarification and refinement to reach a design-level specification.

The purpose of the article is to consider the peculiarities of calculating the FTS norms for REM located in a joint, limited area position and operating in the decimeter wave (DW) range. This range is widely used in radar, radio navigation and radio communication.

3 Selecting a Radio Wave Propagation Model for Calculating FTS Norms

It is known [29] that radio frequency energy during signal transmission on any radio line is determined by the so-called basic equation of radio transmission:

$$P_2(r) = P_1 G_1 \eta_1 G_2 \eta_2 \left(\frac{\lambda}{4\pi r} \right)^2 W_\mathrm{r} \tag{1}$$

where P_1 – the power of RT – sources of interference,
G_1 – the transmitting antenna gain,
G_2 – the receiving antenna gain,
η_1 – the efficiency of the transmitting antenna feeder,
η_2 – the efficiency of the receiving antenna feeder,
λ – the average wavelength of the operating range of the RR – interference receptor,
$\left(\frac{\lambda}{4\pi r} \right)^2 = W_0$ – the signal attenuation multiplier in the free space between the non-directional antennas. In this case, the attenuation occurs only due to a decrease in the energy flux density due to an increase in the wave front area with distance,
W_r – the signal attenuation multiplier during radio wave propagation on a real route.

W_r shows how many times the signal power decreases when it propagates on a real route compared to the power in free space at the same distance from the transmitting antenna. The main problem when calculating any radio link is always the calculation of this particular multiplier.

In the DW range, all antennas are ‘elevated’, i.e., those whose suspension height above the ground is many times greater than the wavelength. With elevated antennas, the field at the receiving point in the line-of-sight is formed as a superposition of the direct wave and the wave reflected from the ground surface. When operating beyond the line of sight, the field is calculated using diffraction relations or relations describing the tropospheric scattering of radio waves. However, the area of direct line of sight is of the greatest interest for EMC assessment, since operation of the REM beyond it requires a completely different and much higher energy potential of the radio line.

Currently, the most widely used approaches for solving practical problems of signal level prediction in line-of-sight areas include interference (reflective) formulas and their simplified version known as the Vvedensky model, the Okumura-Hata model, and the ITU-R Recommendation R.1546 methodology, which is considered the standard reference [2].

The results of calculations of radio lines by different models differ significantly, which does not contradict the physical understanding of the specifics of each of them.

It should be noted that none of the existing models provides absolute accuracy in calculations. This is primarily due to the fact that radio waves in the ultra-short-wave range propagate in the troposphere, the physical parameters of which are temperature, pressure and relative humidity, as well as the law of their change with height. It is clear that these parameters are constantly changing. Therefore, the concept of the so-called normal troposphere with average physical parameters is used for calculations.

According to the ITU-R R.1546 recommendation, the field strength at the receiving point is obtained from radio wave propagation curves that reflect the functional dependence of the field strength on the communication range under certain radio line parameters:

$$E = F\left(R, P, f, h_{1e}, h_{2e}\right) \tag{2}$$

where R – the length of the route, km,
P – the radiated power,
f – the operating frequency (frequency range), MHz,
h_{1e}, h_{2e} – the effective height of the RT and RR antennas, m.

The radio propagation curves (RPCs) in ITU-R P.1546 are constructed for the median value of the field strength at a location and different values of the probability of time fluctuations of 50, 10 and 1 %. In addition, the ITU-R P.1546 recommendation provides families of radio wave propagation curves for frequencies of 100, 600, 2 000 MHz. The propagation curves are constructed for a transmitter power of 1 kW using a half-wave dipole as an antenna. The curves are given for different heights of the transmitting antenna and at the height of the receiving antenna of only 10 m. For the heights of the RT and RR antennas, which differ from the received ones, a linear approximation of the curves is used. In addition, the curves are constructed for land routes in medium-rough terrain with an elevation difference $\Delta h = 50$ m. If the values of operating frequencies in the 30 to 3 000 MHz bands differ from the values used in the construction of graphs (radio wave propagation curves), appropriate correction coefficients are used, which are determined by interpolating or extrapolating the field strength values for the curves at the frequencies given in the recommendation.

Despite the fact that this model [2] is considered basic, it has one fundamental drawback: the absence of any calculation ratios, which significantly complicates the calculations, requires numerous interpolations and extrapolations, and worsens the accuracy of calculations.

The Okumura-Hata model [30-32] provides calculations under the following restrictions:
the signal frequency $f = 100,\cdots, 1\,500$ MHz,
the communication range $R = 1,\cdots, 100$ km,
the height of the RT antenna $h_1 = 20,\cdots, 200$ m,
the height of the RR antenna $h_2 = 1,\cdots,10$ m.

The Okumura-Hata model is intended for use in the design of cellular networks. Therefore, it has significant limitations on the height of the RT and RR antennas. In addition, REMs in local groups are mutually intermixed at distances, usually less than 1 km.

The two-beam (reflective) model of radio wave propagation [29] is most convenient for calculating line-of-sight radio lines, where the field at the receiving point is calculated using interference (reflective) formulas. In this case, the signal attenuation multiplier during radio wave propagation (interference multiplier) W_r is calculated using the formula [29]:

$$W_{\mathrm{r}} = \sqrt{1 + |R|^2 + 2|R|\cos\left(k\Delta r + \psi\right)} \tag{3}$$

where $\Delta r = r_2 - r_1$ – the difference between the travel time of the direct and reflected waves,
$|R|$, ψ – the modulus and phase of the reflection coefficient,
$k = 2\pi/\lambda$ – the wave number.

According to Eq. (3), when the location of the RT and RR antennas and/or the wavelength changes, the phase shift between the direct and reflected waves changes, too. The field strength (interference multiplier) changes periodically, passing through a series of maximum and minimum values. The field strength and the interference multiplier reach their highest values when the direct and reflected waves arrive at the point of reception in phase, and the lowest – when they arrive out of phase. At the same time, the field strength at the receiving point can almost double in the case of an in-phase arrival compared to the case when only a direct wave acts, and in the case of an out-of-phase arrival, it drops to almost zero. For the same reason, the antenna radiation pattern (ARP) raised above the ground will also have a multi-lobe (interference) character. The advantage of interference formulas lies in their unrestricted applicability; however, their use is complicated by the need to account for the magnitude and phase of the complex reflection coefficient, which, in turn, depends on the incidence (or grazing) angle and the electrical properties of the ground in the area significant for radio wave reflection.

However, at small slip angles, when the direction to the receiving point is within the lower slope of the lower interference lobe of the ARP of RT, the interference formula can be simplified. It is transformed into the quadratic Vvedensky formula [29], where the multiplier W_{r} is calculated by the formula:

$$W_{\mathrm{r}} = \left(\frac{4\pi h_1 h_2}{\lambda r}\right)^2 \tag{4}$$

To take into account the sphericity of the earth, instead of the true heights h_1 and h_2, it is necessary to substitute the equivalent heights of the RT and RR antennas in formula (4), which are found by Eq. (5):

$$h_{1\mathrm{e}}, h_{2\mathrm{e}} = h_1, h_2 \left(1 - \frac{r^2}{r_{\mathrm{dl}}^2}\right) \tag{5}$$

where $r_{\mathrm{dl\,[km]}} = 4.12\left(\sqrt{h_{1[\mathrm{m}]}} + \sqrt{h_{2[\mathrm{m}]}}\right)$ – the direct line of sight distance.

In addition, when using the Vvedensky formula, it is necessary to take into account the condition for its application, which is as follows:

$$18\frac{h_{1\mathrm{e}} h_{2\mathrm{e}}}{\lambda} < r \tag{6}$$

The mechanism of field attenuation within the application of the Vvedensky formula is that the reflected wave, nearly equal in amplitude to the direct wave, arrives at the receiving point almost in antiphase with the direct wave. The greater the distance, the smaller the difference in the travel time of the direct and reflected waves and the more the resulting field is weakened. Therefore, the condition for using the Vvedensky formula is as follows:

$$18\frac{h_{1e}h_{2e}}{\lambda} < r < 0.8r_{dl} \tag{7}$$

However, to calculate the intra-object EMC, it is necessary to know the value of the attenuation multiplier W_r at ($r \leq 18h_{1e}h_{2e}/\lambda$), at which the Vvedensky formula does not work according to Eq. (7). To address this issue, we will analyze separately how the multipliers W_r and W_0 depend on the distance between the RT and RR antennas. The graphs of the dependences of the signal attenuation multiplier W_r during radio wave propagation and the signal attenuation multiplier in free space W_0 on the distance r, calculated by Eqs (4) and (1), respectively, are shown in Fig. 1. Calculations were carried out using the following initial data: $h_1 = 6$ m, $h_2 = 20$ m, $\lambda = 0.23$ m.

The analysis of the dependencies shown in Fig. 1 shows that the values of the interference power attenuation multipliers W_r and W_0 differ by several orders of magnitude. If $W_0 \approx 10^{-8},\cdots,10^{-12}$ (blue curve), then $W_r \approx 1,\cdots,10^{-7}$ when it is calculated using Vvedensky formula (red curve), i.e. at short ranges, the multiplier W_r is close to 1.

If we calculate the multiplier W_r using the interference Eq. (3), which has no restrictions on its application, we can see that ($r \leq 18h_{1e}h_{2e}/\lambda$) 'hesitates' near unity. At the same time, the maximum value W_r does not exceed 2, which, in comparison with the attenuation multiplier $W_0 \approx 10^{-8},\cdots,10^{-12}$, makes the influence of the attenuation multiplier W_r negligible, i.e., at such ranges ($r \leq 18h_{1e}h_{2e}/\lambda$) can be disregarded when calculating the FTS norms for REM operating in the DW range. Therefore, at short ranges and if ($r \leq 18h_{1e}h_{2e}/\lambda$), it is advisable to take into account only the attenuation multiplier W_0, since at these ranges $W_r \approx 1$ (see Fig. 1).

If condition (7) is met, the resulting attenuation multiplier $W_\Sigma = W_0W_r$ must be considered. A fragment of a Mathcad document designed to calculate the resulting attenuation multiplier W_Σ is shown in Fig. 2.

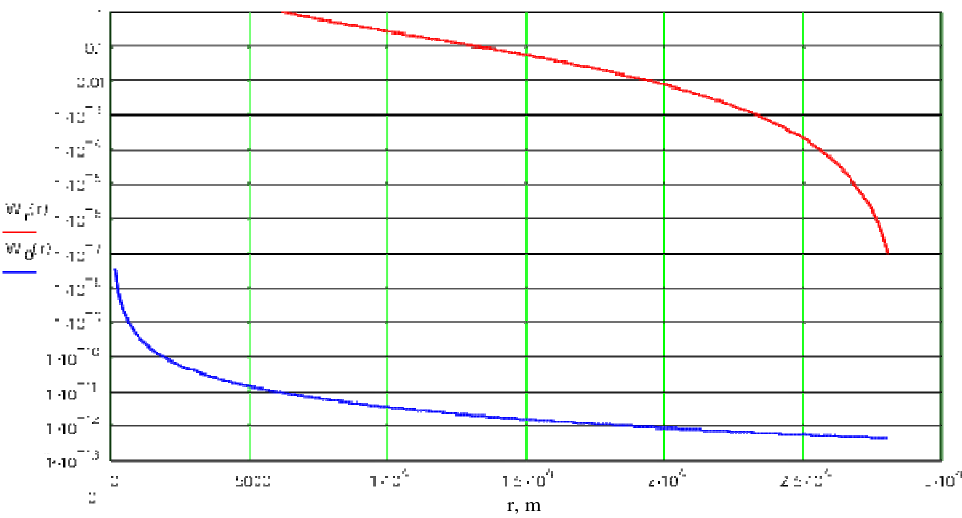

Fig. 1 Graphs of dependences W_r *and* W_0 *on distance r*

$$W_{\Sigma}(r) := \begin{cases} W_{0}(r) & \text{if } r \le 18\cdot\dfrac{h_{1e}\cdot h_{2e}}{\lambda} \\ \left(W_{0}(r)\cdot W_{r}(r)\right) & \text{if } r > 18\cdot\dfrac{h_{1e}\cdot h_{2e}}{\lambda} \end{cases}$$

Fig. 2 A fragment of a Mathcad document for calculating the attenuation multiplier W_{Σ}

The graphs of the dependences of the attenuation multipliers W_r, W_0 and W_{Σ} on the distance r, calculated by Eqs (4) and (1) and Fig. 2, respectively, are shown in Fig. 3.

Analysis of the dependencies W_r, W_0 and W_{Σ} (Fig. 3) shows that the multiplier has a much smaller contribution to the resulting attenuation W_{Σ} than the multiplier W_0, but this contribution is really present and at relatively long ranges it must be taken into account when calculating the FTS norms for REM operating in the DW range. However, the resulting attenuation of the interference at the RR input characterizes exclusively the value of the multiplier W_{Σ} used in the calculations. At the same time, the dependence graph $W_{\Sigma}(r)$ is quite smooth, without breaks, i.e. the proposal with the logical addition of two RPCs models in the calculation W_{Σ} for calculating the intra-object EMC is justified.

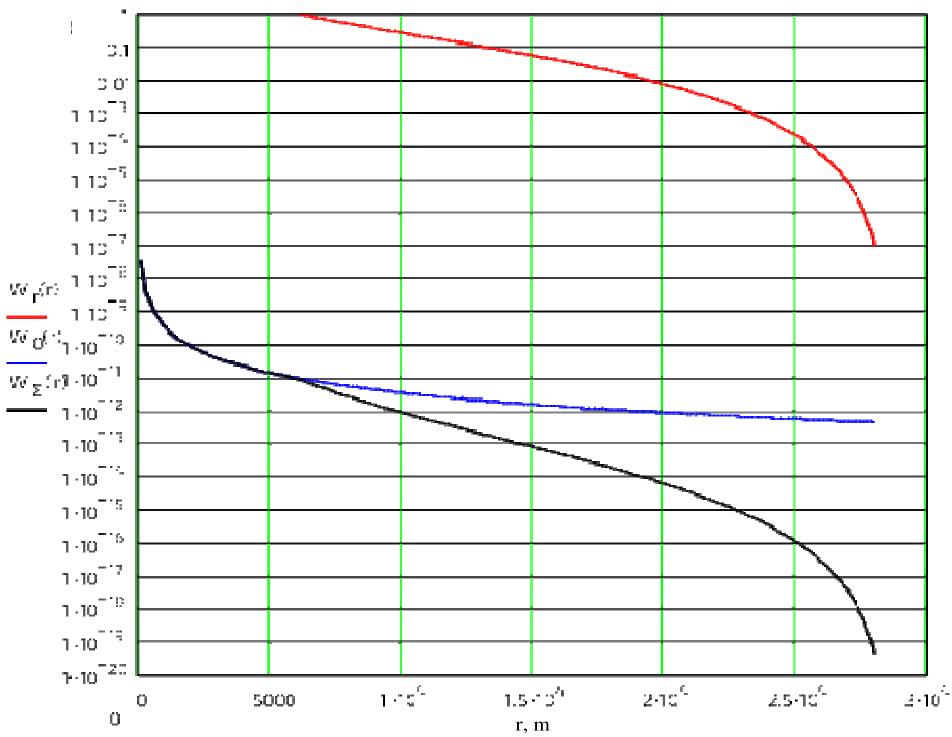

Fig. 3 Graphs of dependences of W_r, W_0 *and* W_{Σ} *on distance r*

4 Methodology for Calculating the FTS Norms for REM Operating in the DW Range

Phase 1. Frequency analysis is performed to determine possible channels of interference penetration [26].

Phase 2. For each possible channel of interference penetration, an energy analysis is performed and simultaneously the FTS norms are calculated as follows:

Subphase 2.1. The permissible value of the interference power $P_{\text{intrfr perm}}$ at the input of the interference receiver is found. It is determined through the protective signal-to-noise ratio k_{prot} and the power value of the useful received signal P_{s}:

$$P_{\text{intrfr perm}} = \frac{P_{\text{s}}}{k_{\text{prot}}} \tag{8}$$

When calculating the FTS norms of REM $P_{\text{intrfr perm}}$, the minimum value of the payload signal power corresponding $P_{\text{s min}}$ to the sensitivity of the interference receiver should be used for determination. If there is reliable information about the actual power level of the useful signal P_{s}, which exceeds the sensitivity level of the useful signal $P_{\text{s min}}$, it is permissible to use a known value P_{s} for calculating the FTS norms.

Subphase 2.2. The power of unacceptable interference at the receiver's input is calculated $P_2(r)$ by Eq. (1).

Subphase 2.3. Calculate the territorial spread of the REM at zero detuning [26] in the following sequence:

- a graph of the dependence of the interference power at the receiver input $P_2(r)$ is plotted,
- in the created coordinate system of the graph $P_2(r)$, a horizontal line is drawn corresponding to $P_{\text{intrfr perm}}$,
- the value of the territorial separation at zero detuning is determined (abscissa of the intersection point, $P_2(r) = P_{\text{intrfr perm}}$). If the line corresponding to $P_{\text{intrfr perm}}$ passes below the dependence graph $P_2(r)$ and does not intersect with it, then the dependence graph $P_2(r)$ should be ‘extended’ to the diffraction region and ‘stitched’ with the graph for the line of sight.

Subphase 2.4. The influence of frequency diversity Δf is considered by calculating the power of unacceptable radio interference P_{2RR} reduced to the input of the RR:

$$P_{\text{2RR}}\left(r\right) = P_2\left(r\right) \cdot k_{12}\left(\Delta f_{\text{tn}}\right) \cdot k_{13} \tag{9}$$

where $k_{12}(\Delta f_{\text{tn}})$ – the coefficient of radio interference attenuation due to frequency tuning,
k_{13} – the coefficient of attenuation of the radio interference effect due to its penetration through the side reception channel.

The calculation methodology $k_{12}(\Delta f_{\text{tn}})$ is described in detail in [26] and is acceptable for calculating the FTS norms for radio electronic means operating in the DW range. The initial data for the calculation $k_{12}(\Delta f_{\text{tn}})$ is as follows:

Δf_{tn} – the frequency detuning, which is set in accordance with the known tuning step of the RT,
Δf_j – the width of the radiation spectrum of the RT at the level of minus 3 dB,
Δf_i – the bandwidth of the amplitude-frequency response (AFR) of the RR at the level of minus 3 dB,
$k_{i\text{RR}}$ – the squareness coefficient of the AFR of the RR when it is read at a given level.

Subphase 2.5 The FTS norms are calculated considering the frequency detuning Δf_{tn} in the following sequence:

- a graph of the dependence of the power of unacceptable radio interference reduced to the RR input $P_{2\text{RR}}(r)$ at a given frequency detuning is plotted,
- a horizontal line is drawn in the created coordinate system of the graph $P_{2\text{RR}}(r)$, which corresponds to $P_{\text{intrfr perm}}$,
- the abscissa of the intersection point of these graphs determines the amount of territorial separation at a given frequency detuning. And then again, if the line corresponding to the level of $P_{\text{intrfr perm}}$, passes below the dependence graph $P_{2\text{RR}}(r)$ and does not intersect with it, then the dependence graph $P_{2\text{RR}}(r)$ must be 'extended' into the diffraction region,
- sets the next value of the frequency tuning and repeats all the previous steps in subphase 2.4-2.5 of this methodology.

The results of calculating the FTS norms are presented in the form of graphs, i.e., the dependencies of the required frequency separation Δf on the distance between the REM of radio interference source (RT) and REM of radio interference receptor (RR), which are determined on the condition that they are EMC compliant. The following notations are used (Fig. 4):

r – the distance between the antennas of the RT and the RR, km,

Δf – the frequency separation between the operating frequency of the transmitting device (interference source) and the operating frequency of the receiving device of the identified REM (interference receptor), MHz.

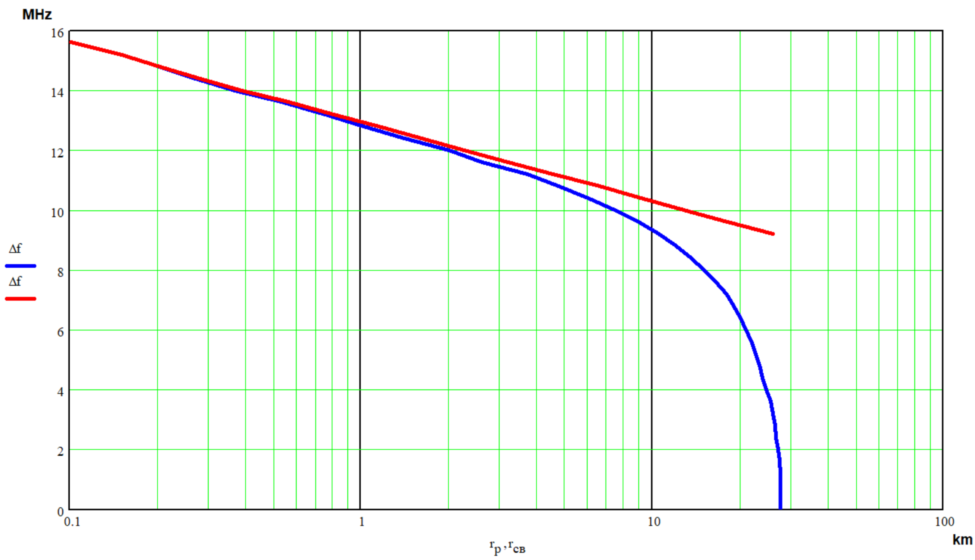

Fig. 4 Graphs of FTS norms

In Fig. 4 shows a graph of FTS norms (blue) calculated using the developed methodology for REM located in a joint, limited area position and a graph of FTS norms of REM (red), which is calculated using the same initial data as the previous one, assuming that there is no reflected wave from the ground, i.e., the interference signal attenuation multiplier W_r during radio wave propagation at any range is equal to 1, which is an erroneous statement defined in sources [33]. For example, source

[33] states that "... in cases where it is difficult or impossible to estimate losses due to the transmission medium, the communication range can be calculated at least for the case of free space with further refinement at the stage of operation", source [34] states that "... in practice, the ground surface for most land routes is not smooth, which causes diffuse scattering of radio waves and their significant attenuation when reflected from the earth's surface. Therefore, when the receiver is in the line of sight ($r \leq r_{\mathrm{dl}}$) relative to the transmitter, due to the diffuse reflection of radio waves from the ground, it can be assumed that $W_{\mathrm{r}} = 0\mathrm{dB}$". However, it is known [29] that in the range of DW under consideration, the modulus of the reflection coefficient at small slip angles can be considered equal: for the water surface of rivers and lakes, its value is from 0.95 to 0.9; for flat areas and meadows, from 0.8 to 0.7; for forested areas, from 0.7 to 0.6; for medium-rough forested areas, from 0.5 to 0.4. The reflective capability of the Earth's surface with respect to electromagnetic waves is characterized by the Rayleigh criterion [29]. A practical confirmation of ground-reflected waves is the use of glide path beacons in aircraft landing instrument systems, whose operation relies on the presence of such reflections.

The analysis of the attenuation multipliers given above shows that their values do indeed differ sharply in magnitude. However, this does not mean that there is no wave reflected from the ground, and attenuation multipliers W_{r} can be ignored at all at any range.

Thus, at short ranges, the signal attenuation multiplier during radio wave propagation W_{r} can indeed be omitted from the calculations of the FTS norms. For long ranges, this must be taken into account. Failure to comply with this rule leads to an error in the calculation of the frequency separation value when developing the FTS norms, as illustrated in the red graph in Fig. 4. Moreover, the greater the distance between the REM, the higher the calculation error Δf.

5 Conclusions

The methodology for calculating the frequency-territorial dispersion norms in the analysis of intra-objective EMC is considered in detail (step by step), and the peculiarities of its application for REM operating in the DW range are determined.

The main models of radio-wave propagation used in the calculation of radio lines in the line-of-sight area are considered. It has been shown that for such calculations it is advisable to use the Vvedensky reflective model within the scope of its application. The reliability of the calculation results when using the Vvedensky model was confirmed during field tests within the implementation of fourth-generation LTE mobile communication networks in Ukraine with the participation of the authors of this scientific work. When calculating the interference power at distances beyond line of sight, it is necessary to use diffraction calculation relations or relations describing the tropospheric scattering of radio waves.

It has been determined that at short distances, where the Vvedensky formula does not work, it is quite acceptable to assume that the attenuation multiplier during radio wave propagation $W_{\mathrm{r}} \approx 1$, i.e., can be ignored when calculating the FTS norms. However, within the scope of the Vvedensky formula, it must be considered without failure. Failure to comply with this rule leads to an error in the calculation of the interference power value (its overestimation) and to an overestimation of the calculated values of the frequency separation of REM when developing the FTS norms for REM operating in the decimeter range.

References

[1] CHRISTOPOULOS, C. *Principles and Techniques of Electromagnetic Compatibility*. 3rd ed. Boca Raton: CRC Press, 2022. ISBN 0-367-53361-8.

[2] Recommendation ITU-R P.1546-6. *Method for Point-to-Area Predictions for Terrestrial Services in the Frequency Range 30 MHz to 4 000 MHz*. Geneva: ITU, 2019.

[3] Recommendation ITU-R P.370. *VHF and UHF Propagation Curves for the Frequency Range 30 MHz to 1 000 MHz*. Geneva: ITU, 1991.

[4] Recommendation ITU-R P.529-3. *Prediction Methods for the Terrestrial Land Mobile Service in the VHF and UHF Bands*. Geneva: ITU, 1999.

[5] Recommendation ITU-R P.1406-2. *Propagation Effects Relating to Terrestrial Land Mobile Service in the VHF and UHF Bands*. Geneva: ITU, 2015.

[6] Recommendation ITU-R SM.337-6. *Frequency and Distance Separations*. Geneva: ITU, 2019.

[7] Recommendation ITU-R P.1057-7. *Probability Distributions Relevant to Radiowave Propagation Modelling*. Geneva: ITU, 2022.

[8] Recommendation ITU-R P.525-5. *Calculation of Free-Space Attenuation*. Geneva: ITU, 2024.

[9] Recommendation ITU-R P.452-18. *Prediction Procedure for the Evaluation of Interference Between Stations on the Surface of the Earth at Frequencies Above About 100 MHz*. Geneva: ITU, 2023.

[10] GOROBETS, N.N. Using Polarization Effects to Improve the Electromagnetic Compatibility of Radio Electronic Equipment. *Telecommunications and Radio Engineering*, 1997, **51**(1), pp. 89-96. DOI 10.1615/ TelecomRadEng.v51.i1.90.

[11] BALDWIN, T.E. and G.T. CAPRARO. Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP). *IEEE Transactions on Electromagnetic Compatibility*, 1980, **22**(4), pp. 224-228. DOI 10.1109/TEMC.1980.303859.

[12] ZHAO, Y., W. YAN, J. SUN, M. ZHOU and Z. MENG. *Electromagnetic Compatibility: Principles and Applications*. Singapore: Springer, 2021. ISBN 978-981-16-6451-9.

[13] WILLIAMS, T. *EMC for Product Designers.* 3rd ed. Oxford: Newnes, 2001. ISBN 0-7506-4930-5.

[14] KUNZ, K.S. Finite Element/Finite Difference Modelling in Electromagnetic Compatibility. In*: Proceedings of the 10th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*. Zurich: IEEE, 1993. DOI 10.23919/EMC.1993.10781226.

[15] MA, M.T. and G.H. KOEPKE. A Method to Quantify the Radiation Characteristics of an Unknown Interference Source. Gaithersburg: National Bureau of Standards, 1982.

[16] TESCHE, M., M. IANOZ and T. KARLSSON. *EMC Analysis Methods and Computational Models.* New York: Wiley, 1996. ISBN 0-471-15573-X.

[17] BOOTON, R.C. *Computational Methods for Electromagnetics and Microwaves.* New York: Wiley, 1992. ISBN 0-471-52804-8.

[18] SADIKU, M.N.O. *Numerical Techniques in Electromagnetics*. 2nd ed. Boca Raton: CRC Press, 2000. ISBN 0-429-19608-3.

[19] KUBINA, S.J. Numerical Analysis and Modelling Techniques. In: P.S. CROVETTI, ed. *Electromagnetic Interference and Electromagnetic Compatibility*. Loughton: AGARD, 1991, pp. 3.1-3.18. ISBN 92-835-0620-0.

[20] PEREZ, R. Solution of EMC Problems via Analysis Methods: A Review. In: *Proceedings of the 1992 IEEE Regional Symposium on Electromagnetic Compatibility*. Tel Aviv: IEEE, 1992. DOI 10.1109/ISEMC.1992.257532.

[21] HUBING, T. and M. ALI. EMC Applications of EMAP-2: a 3D Finite Element Modeling Code. In: *Proceedings of the 1993 International Symposium on Electromagnetic Compatibility*. Dallas: IEEE, 1993. DOI 10.1109/ISEMC.1993.473730.

[22] TSYANENKA, D.A., E.V. SINKEVICH, Y.Y. ARLOU and S.V. MALY. Computationally-Effective Worst-Case Estimation of Currents in Transmission Lines for EMC Diagnostics of Big Systems. In: *Proceedings of the EMC 2015 Joint IEEE International Symposium on EMC and EMC Europe*. Dresden: IEEE, 2015. DOI 10.1109/ISEMC.2015.7256334.

[23] IVANOV, V.O., L.V. SIBRUK and O.V. KULENKO. Conditions for Ensuring Electromagnetic Compatibility in the Grouping of Radio Electronic Systems. *Electronics and Control Systems* (in Ukrainian), 2009, **1**(19), pp. 76-81. DOI 10.18372/1990-5548.19.666.

[24] KOVALENKO, I., S. BRIGADIR and Y. MAZNICHENKO. Methods of Electromagnetic Compatibility Telecommunication Means of Special Purpose. *Collection of Scientific Papers of the Military Institute of Telecommunications and Informatization* (in Ukrainian) [online], 2016, **1**, pp. 71-80 [viewed 2024-11-15]. Available from: http://nbuv.gov.ua/UJRN/Znpviti_2016_1_11

[25] KOVALENKO, I.G., V.V. MALYKH and V.I. MAKARCHUK. General Methodology and Algorithm for Calculating the Electromagnetic Compatibility of Radioelectronic Devices. *Collection of Scientific Works of the Military Institute of Telecommunications and Informatization* (in Ukrainian) [online], 2020, **2**, pp. 17-27 [viewed 2024-11-12]. Available from: https://hups.mil.gov.ua/assets/uploads/ library/nadhodzhennya/ zhovten-gruden-2020/pdf/27.pdf

[26] FEOKTISTOV, Y.A., V.V. MATASOV, L.I. BATURIN and V.I. SELEZNEV. *Theory and Methods for Assessing Electromagnetic Compatibility of Radio Electronic Equipment* (in Russian). Moscow: Radio and Communications, 1988. ISBN 978-5-256-00026-4.

[27] KAMALTYNOV, G., V. POZDNIAK and K. SHUTKO. Features of Assessment of Electromagnetic Compatibility of Radio Location Devices Located at a Common Position (in Ukrainian). *Scientific Works of Kharkiv National Air Force University*, 2024, **2**(80). pp. 106-112. DOI 10.30748/zhups.2024.80.14.

[28] QIANG, Z., H. YAGUO, W. LU, L. KAI and Y. YUAN. Research on Electromagnetic Compatibility Technology Based on Airborne Electronic Equipment. *Proceedings of the 10th Chinese Society of Aeronautics and Astronautics Youth Forum*. Singapore: Springer, 2023. ISBN 978-981-19-7651-3.

[29] NARYSHKIN, E.M., and V.P. SERKOV. *Wave Service and Antenna Devices. Part 1: Theory of Electromagnetic Field and Radio Wave Propagation* (in Russian). Moscow: Ministry of Defense of the USSR, 1982.

[30] HATA, M. Empirical Formula for Propagation Loss in Land Mobile Radio Services. *IEEE Transactions on Vehicular Technology*, 1980, **29**(3). pp. 317-325. DOI 10.1109/T-VT.1980.23859.

[31] YUVRAJ, S. Comparison of Okumura, Hata and COST-231 Models on the Basis of Path Loss and Signal Strength. *International Journal of Computer Applications*, 2012, **59**(11), pp. 37-41. DOI 10.5120/9594-4216.

[32] MARDENI, R. and K.F. KWAN. Optimization of Hata Propagation Prediction Model in Suburban Area in Malaysia. *Progress in Electromagnetics Research*, 2010, **13**, pp. 91-106. DOI 10.2528/PIERC10011804.

[33] HURSKYI, T., E. STEPANENKO and A. SHISHATSKYI. Evaluation of Boundary Communication Range of Modern Radio and Radio Relay Links. *Collection of Scientific Papers of the Military Institute of Telecommunications and Informatization* (in Ukrainian) [online], 2019, **1**, pp. 6-17 [viewed 2024-11-18]. Available from: http://nbuv.gov.ua/UJRN/Znpviti_2019_1_3

[34] SAAKIAN, A. *Radio Wave Propagation Fundamentals*. 2nd ed. Boston: Artech House, 2020. ISBN 1-63081-844-5.