Studying the Influence of Material Physical Parameters on the Transformation Error of Super-High-Frequency Moisture Meters

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Abstract. This article presents generalized theoretical studies of errors in converting material moisture into informative parameters of the superhigh frequency field. Errors of ultra-high-frequency primary measuring transducers associated with the conversion of moisture into dielectric characteristics of the material and the conversion of dielectric characteristics into informative parameters of the ultra-high-frequency field are investigated. These errors are inherent in all the above-mentioned converters and can be considered as a result of the influence of the informative parameters of the material on the measured characteristics of the superhigh frequency field. Such informative parameters of the material are the heterogeneity of the material structure, the uneven distribution of moisture throughout the volume, and the scattering of ultra-high-frequency energy when passing through the material. The influence of electromagnetic energy scattering on material inhomogeneity was theoretically investigated. A generalized mathematical model of a heterogeneous material has been developed, on which the influence of heterogeneities during measurements in free space has been investigated.

INTRODUCTION

Ultra-high frequency UHF) methods for measuring the moisture content of solid materials and liquids are based on the interaction of UHF radio waves with a moisture-bearing material, and the informative parameter serves as the integral characteristics of various properties of primary measuring transducers PMT). The ultra-high frequency UHF) range includes radio waves with wavelengths from 1 m to 1 mm; in humidity measurement, mainly centimeter waves are used, less commonly decimeter and millimeter waves [1]. In this frequency range, primary measuring transducers are electromagnetic systems with distributed parameters, and although the basis of ultra-high frequency moisture meters is the dielectric method, the principles of their construction differ significantly from the principles of constructing high-frequency long, medium, and short-wave moisture meters, in which primary transducers can be considered as systems with concentrated parameters.

Based on the given definition, it is impossible to classify as microwave moisture meters devices in which the microwave field energy is used to remove moisture from the material being studied, for example, thermogravimetric moisture meters [2].

EXPERIMENTAL RESEARCH

The transition from dielectric humidity measurements in the 0.5 - 50 MHz range to the microwave range was driven by the desire to improve the characteristics of dielectric humidity meters by increasing their operating frequency. In particular, this refers to increasing the accuracy of moisture meters due to the reduction of the influence of chemical composition and some other parameters on the moisture measurement result.

The preference given in ultra-high frequency UHF)- moisture metering to the centimeter range is due to a number of reasons: firstly, the dispersion region of the dielectric properties of polar liquids. As already indicated in [3], for water, the frequency corresponding to the relaxation time of the dipole orientation in the electric field, i.e., the maximum absorption of energy, is in the centimeter range. The consequence of this is the high sensitivity of the centimeter range of microwave moisture meters. Secondly, the prevalence and availability of waveguide tract elements, regulating and other devices necessary for constructing microwave humidity meters in the so-called "X-band," i.e., for frequencies close to 3.2 cm, played a certain role.

We investigated the errors associated with the conversion of moisture to dielectric characteristics of the material $\varepsilon = fW$) and the conversion of dielectric characteristics to informative parameters of the microwave field *A, φ, ω R*). These errors are inherent in all existing microwave converters [4,5] and can be considered as a result of the influence of informative material parameters on the measured characteristics of the microwave field. These errors are inherent in all existing microwave converters and can be considered as a result of the influence of informative material parameters on the measured characteristics of superhigh-frequency fields. Such informative parameters of the material are the heterogeneity of the material structure, the uneven distribution of moisture across the volume, and the scattering of ultra-high-frequency energy when passing through the material, etc.

RESEARCH RESULTS

Investigation of the error of primary measuring transducers caused by the scattering of superhigh-frequency energy. The heterogeneity of the material can be due to its structural structure or the uneven distribution of moisture throughout the volume. If the heterogeneities are due to the structure of the material itself and represent approximately identical particles, for example, in bulk materials such as grain, granulated feed, and cotton seeds, then the error from heterogeneities can be investigated using the theory of electromagnetic energy scattering on heterogeneities comparable to wavelengths of [6].

The intensity of scattered energy on a single particle non-uniformity) is determined by the parameter

$$\rho = \frac{2\pi a}{\lambda} \qquad 1)$$

where: a - is the particle size,

λ - radiation wavelength in our case, considering the experience of creating ultra-high-frequency moisture meters for various materials, as well as the availability of a well-equipped base for research, λ- is taken to be 3.2 cm. It should be noted that the search experiments for one centimeter wavelength yielded negative results, which are not considered in this work).

Consequently, the error due to scattering depends on the particle sizes, the frequency of the microwave field, and the number of such particles per unit volume of the material. The investigated error is characteristic of all types of transducers based on measuring the amplitude of the microwave wave. Using the methodology discussed below, it is possible to estimate the error from this fact for any range of superhigh frequency waves, as well as for various types and sizes of heterogeneities.

Let's consider the scattering scattering of superhigh-frequency energy on particles in the form of a rotational ellipsoid. Note that depending on the value of the eccentricity, a particle in particular cases can be represented by a sphere or a thin thread elongated ellipsoid).

To estimate the relative error caused by scattering, we can use the expression obtained earlier in work [7]

$$\frac{\Delta b}{\Delta b_0} = \frac{10^{1-0.1^{ba}}}{10^{-0.1h} h b_y (\Pi^0 - \Pi^a)} \left[\frac{\partial \Pi^a (a,N)}{\partial N} \Delta N + \frac{\partial \Pi^a (a,N)}{\partial a} \Delta a \right] \qquad 2)$$

where: b_0 - *total attenuation of electromagnetic energy in the material;*

h - *material layer thickness;*

b_y - *weakening of electromagnetic energy per unit thickness of the material layer;*

Δa, ΔN - *corresponding limit changes in the size and number of particles from sample to sample;*

Π^0, Π^a - *respectively, falling and scattered electromagnetic energy flows on particles;*

b_a - weakening due to the scattering of electromagnetic energy on particles:

$$b_a = 10\ell g \frac{b_y}{b_y - 4{,}34 K_p N\left[1 - \exp(-0{,}23 в_y h)\right]} \qquad 3)$$

The total flux of electromagnetic energy scattered by particles in all directions is equal to

$$\Pi^a = N\vartheta_{cp} \oint \Pi_r^a r^2 d\Omega = N\vartheta_{cp} J \; K_p \qquad 4)$$

where: *N - number of particles per unit volume;*
d Ω - body angle element;
r^2 d Ω - area element on the sphere;
J - intensity of radiation incident on the particle;
K_p - scattering coefficient;
v_{cp} - the volume of the medium containing inclusions.

If we take into account that particles lying at a depth of *h* are irradiated by a stream of intensity

$$J_h = J_0 \exp\left(-\frac{byh}{10 \lg e}\right) \qquad 5)$$

then, at the cross-sectional area of the sample in the planeperpendicular to the direction of wave propagation *S*

$$\Pi^a = \frac{10 \lg e}{by} \int_0^h KpNSJ_0 \exp\left(-\frac{byh}{10 \lg e}\right) \cdot dh \qquad 6)$$

so that after integrating and substituting the limits gives thefollowing expression for the scattered flow

$$\Pi^a = \frac{10 \lg e}{by} \int_0^h KpNSJ_0 \exp\left[1 - \exp\left(\frac{byh}{10 \lg e}\right)\right] \qquad 7)$$

The components of formulas (2) and (3) bγ b_y *N, Δ N, h, a, Δ* a are known parameters of the particle and measuring device. Thus, the problem reduces to determining the scattering coefficient K_p using the known particle parameters and the wavelength of the radiation λ. If a monochromatic linearly polarized wave $\vec{E}_0$, falls on a particle at an angle of Δ to its major axis, then the scattered field [8,9] in some direction $\vec{R}_0$ is determined by the formula

$$\vec{E}_p = a_0 \vec{E}_0 \exp(-ikr) v * F(\Delta_2 \beta) \qquad 8)$$

here v - is *volume of the ellipsoid;*
r - distance to the observation point;
k - wave vector:

$$F \cdot (\Delta, \beta) = \frac{3}{q^3}\left[\frac{1-\varepsilon^3}{1-\varepsilon^2+(1-a^2)\varepsilon^4}\right]^{3/2} \cdot \left\{\left[1+q^2 \frac{a^2(1-a^2)\varepsilon^4}{2(1-\varepsilon^2)}\right]\sin q - q\cos q\right\} \qquad 9)$$

where; ε - *ellipsoid eccentricity*;

$$q = \frac{4\pi b}{\lambda} \cdot \frac{1}{\sqrt{1-a^2 \varepsilon^e}} \sin\frac{\beta}{2}; \qquad 10)$$

β - *the angle between the direction of incident of the polarized wave and the direction in which the scattering is observed;*

$$a = \frac{Cos\Delta - Cos\gamma}{2Sin\beta / 2}$$

γ - *angle between the scattering direction* $\vec{R}_0$ *and the X* axis.

Since we are interested in the scattering indicatrix of the group of chaotically oriented ellipsoids, then according to 8) it is necessary to average the expression.

$$F^2 = \frac{\left(1 + \frac{3}{2} \cdot \frac{a^2(1-a^2)\varepsilon^4}{1-\varepsilon^2}\right)^2}{\left(1 + \frac{a^2(1-a^2)\varepsilon^4}{1-\varepsilon}\right)^3}, \qquad 11)$$

that is

$$F^2 = \frac{1}{2}\int_{-\pi}^{\pi} \frac{(1 + \frac{3}{2}\lambda cos^2\theta \sin^2\theta)^2}{\left(1 + \lambda \cos^2\theta Sin^2\theta\right)^3} \sin\theta d\theta = \varphi(\lambda) \qquad 12)$$

here

$$\lambda = \frac{\varepsilon^4}{1-\varepsilon^2}$$

θ - the angle between the ellipsoid's axis and the direction lying in the plane of vectors $\vec{R}_0$ and $\vec{K}$ and perpendicular to the bisector of the angle between them.

After calculating the integral for (φλ) the following expression was obtained:

$$\varphi(\lambda) = \frac{1}{32(\lambda+4)^2}\left\{-\left(43\lambda + 148\right) + \frac{1}{2\sqrt{\lambda^2 + 4\lambda}}\left(A_\lambda - C_2^2 B_\lambda\right) \cdot \right. \qquad 13)$$

$$\left. \frac{2}{C_2} arctg \frac{1}{C_2} + \left(A_{\lambda 1} + C^2 B_\lambda\right)\frac{1}{C_1} \ln \frac{C_2 + C_1}{C_1 - 1}\right\}$$

where:

$$A_\lambda = 41\lambda^3 + 363\lambda + 660;$$

$$B_\lambda = 21\lambda^2 + 72\lambda;$$

$$C_1^2 = \frac{\sqrt{\lambda+4} + \sqrt{\lambda}}{2\sqrt{\lambda}};$$

$$C_2^2 = \frac{\sqrt{\lambda+4} - \sqrt{\lambda}}{2\sqrt{\lambda}}.$$

In the case under consideration, the diffracted flux is represented as the sum of individual partial waves, and the solution for *Kp* is represented as a series.

Considering the estimated nature of our calculations for *Kp,* we can limit ourselves to considering only the first term.

Then

$$K_p = \pi a^2 \ /\alpha/^2 F Z).$$

here

$$\alpha = \frac{3}{4\pi}\left[\frac{m^2 - 1}{m^2 + 2}\right].$$

$$F(Z) = \frac{2\pi^2}{Z^2}\left[\frac{Z^4}{4} + 5Z^2 + (4Z^2 - 16)(CiZ - \ln Z - C) - 2ZSinZ + 14(\cos Z - 1)\right] \quad 14)$$

where

$$Z = \frac{8\pi a}{\lambda_o};$$

a - "effective radius" of the particle;
C – Euler constant equal to 0.577;
Ci Z - integral cosine from Z
m - relative refractive index of the material;
λ_0 - electromagnetic wavelength

Thus, it seems possible to estimate the relative error caused by the energy dissipation on ellipsoidal particles when measuring humidity using the ultra-high frequency method. The obtained expressions describe the scattering of electromagnetic energy in ellipsoid-type inhomogeneities. When considering limiting cases - spheres and elongated ellipsoids in the form of rod-shaped particles, it should be taken into account that for a rod-shaped particle, the scattering indicatrix, averaged along its various orientations, coincides with the sphere's indicatrix, the volume of which

$$\vartheta^* = \sqrt{\varphi(\varepsilon)}\vartheta, \quad 15)$$

where ϑ - the volume of material consisting of rod-shaped particles;
($\varphi\,\varepsilon$) - tabulated function.

Our calculations for wheat grain in the 5-20% humidity range showed that with a deviation of grain sizes from the average values by 25%, the considered error does not exceed 0.5% relative), i.e., is negligibly small compared to other components of the conversion error of ultra-high-frequency primary measuring transducers PMT) [10].

Similar calculations were carried out for peas and cotton fiber. At a sample layer thickness of 10 cm peas) and a 30% change in peas diameter, the error from the scattering of ultra-high-frequency energy dissipation was 0.8% relative), and for fiber, at a layer thickness of 15 cm and deviations in their length and thickness by an average of 30% in the 3-18% humidity range, it did not exceed 0.1% relative error). Thus, when the size of particles changes within real limits, the error due to the scattering of microwave energy can be neglected. However, in each specific case, it is necessary to evaluate this component of the error using the methodology described above and the calculated formulas.

Investigation of the influence of inhomogeneities during measurements in free space. Inhomogeneities affect the parameters of the superhigh frequency wave both in free space and in sewer systems. However, the solution of the wave equations for these cases is different due to different boundary conditions. In this section, we will consider the propagation of a superhigh-frequency microwavewave in heterogeneous materials of finite thickness, assuming that the transverse and longitudinal dimensions are much larger than the dimensions of the antennas exciting the field.

Let's represent a generalized model of a heterogeneous material in a Cartesian coordinate system, as shown in Figure 1. Let's assume a plane wave is incident on a material in the direction of - z. The heterogeneity of a material with a weakening coefficient a_2 and a phase β_2 is represented as a volume bounded by a surface $Z = f\,x, y)$. The rest of the material has parameters a_1, β_1. The intensity vector of the flow passing through the material can be represented as the sum

$$E_Z = E_o \exp\{-\alpha_2\,[\ell - f\,x,y)] -_1 f\,x,y) + j\,[\beta_2\,[\ell - f\,x,y)] + \beta_1\ \ f x,y)]\} + E_0 \exp\ \{-\alpha_2[\ell - f\,x,y)] + j\beta_2\,[\ell - f\,x,y)]\} \quad 16)$$

The component of the wave reflected from the air-material interface is not included in this expression. This assumption is valid, as to assess the investigated error, this factor can be considered a second-order small value. In addition, the influence of the reflected wave from the front boundary of the material is taken into account when graduating the primary measuring transducer PMT). In 16), the factor determining the time factor is also omitted. The second term in expression 16) determines the intensity vector of the reflected wave. Considering that at the interface of the media

$$E_1 e^{\alpha 2\ell - f\,x.y))} = \Gamma_{12} E_0 e^{-\alpha 2\ \ell - f\,x,y))} \quad 17)$$

let's write

$$E_z = E_0\, e^{-\alpha 2\,[\ell - f\,x,y)] - \alpha 1 f\,x,\,y) + j\,\{\beta_2[\ell - f\,x,y)] + \beta_1 f\,x,y)\,\}} + \Gamma_{12}\, E_0\, e^{-\alpha 2[\ell - f\,x,\,y) + j\beta_2[\ell - f\,x,y)]} \tag{18)}$$

or

$$E_z = E_0 e^{-\alpha 2[\,\ell - f_2\,x,\,y) + j\beta_2[\ell - f\,x,y)]]} + [e^{-\alpha 1[\,\ell - f\,x,\,y) + j\beta_1[\ell - f\,x,y)]} + \Gamma_{12}], \tag{19)}$$

where:

$$\Gamma_{12}\,\frac{(x_1 - x_2)^2 + (\beta_1 - \beta_2)^2}{(a_1 + a_2)^2 + (\beta_1 - \beta_2)^2}\,. \tag{20)}$$

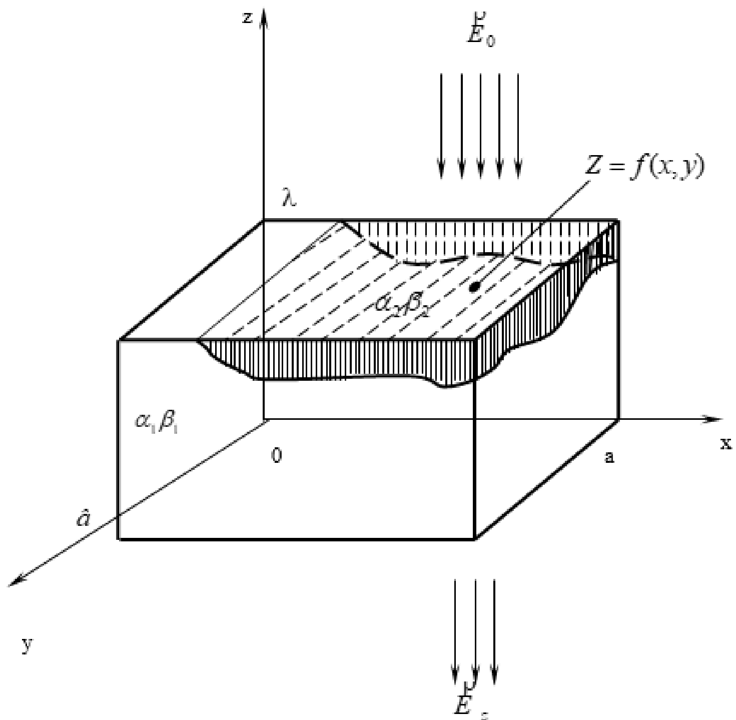

FIGURE 1. Generalized model of a heterogeneous material

where, the amplitude and phase ratios of the material

□□ - phase coefficient of vacuum

E_0 - electric field strength of the incident wave

l, S - geometric parameters of the stages.

The flow passing through a heterogeneous material is determined from the expression

$$\vec{P} = \int_0^a \int_0^в \vec{E}\,dxdy \tag{21)}$$

The attenuation of the passing wave is determined by the formula

$$A = 20\,\ell g\,\frac{|P|}{|Po|} \tag{22)}$$

and phase

$$\varphi = arctg\,\frac{J_m P}{R_i P_o} \tag{23)}$$

where J_m - intensity of radiation incident on the particle;

Let's analyze the obtained model of a heterogeneous material. In the simplest case, when $f x,y) = \ell$, that is

$$\alpha_1 = \alpha_2, \beta_1 = \beta_2$$

we have a model of a plane-parallel layer of homogeneous material. In this case, from 19) taking into account 20) we have

$$E_z = E_0 e^{-\alpha_1 \ell + j\beta_1 \ell}$$

and we obtain from (22) and (23)

$$A = -8.68\, \alpha_1 \ell, \quad \varphi = \beta_1 \ell \qquad 24)$$

These expressions are derived for the case where a superhigh-frequency wave passes through a plane-parallel layer of material of infinite length.

In the case

$$f(x,y) = \begin{cases} \ell \quad at \quad x \le \dfrac{a}{2} \\ -\Delta\ell - i \quad at \quad x > \dfrac{a}{2} \end{cases}$$

and at α_2=0, β_2=0, we obtain the "step" type homogeneity model, which was previously considered in work [11].

In the given particular cases, the non-uniformities associated with sample formation are considered, i.e., these are the non-uniformities of the sample's geometric dimensions. Since in primary measuring transducers, samples have constant dimensions, the case when the heterogeneity is due to the difference in dielectric characteristics i.e., α and β)) in some partial volume of the sample, i.e., the case when $\alpha_1 \neq \alpha_2 \neq 0$, $\beta_1 \neq \beta_2 \neq \beta_0$.

The influence of material heterogeneity on thickness was investigated using the physico-mathematical models of heterogeneous material shown in Figure 2. The physical meaning of the model in the form of two flat parallel steps, with thicknesses $\ell - \Delta\ell$) and $\ell + \Delta\ell$), where the dimensions of both steps are equal and significantly exceed the wavelength, is the limiting case of changes in the thickness of the material layer, for example, cotton on the conveyor belt.

Let's consider the simplest case of heterogeneity Fig.2.) when,

$$f x,y) = \ell \qquad \text{at} \qquad x \le \frac{a}{2}, \alpha_1 \neq \alpha_2, \beta_1 \neq \beta_2$$

$$f x,y) = \ell - \Delta\ell \qquad \text{at} \qquad x > \frac{a}{2}.$$

For evaluation calculations, let's assume $\Gamma_{12} \approx$ O.

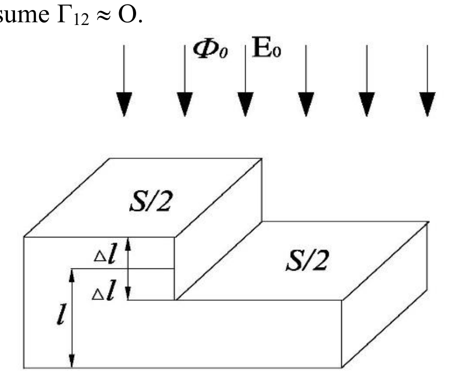

FIGURE 2. Model of a primary transducer in the form of two steps

Flow passing through the material

$$P = \frac{E_0 a_b}{2} = \left\{ \left[e^{-a_2 \Delta\iota - a_2 1(\iota - \Delta\iota) + j\beta_2 \Delta\iota + \beta_1 (\iota - \Delta\iota)} \right] + \left[e^{-a_1 \iota + j\beta_1 \iota} \right] \right\} \quad 25)$$

Passed flow modulus

$$|P| = \frac{E_0 a_b}{2} \cdot \sqrt{e^{-2a1i} + e^{-2a1i(a1-a2)\Delta\iota} + 2e^{-2a1i+(a1-a2)\Delta\iota} \cdot \cos[(\beta_1 - \beta_2)\Delta\ell]} \quad 26)$$

Then from (22)

$$\Delta = 8{,}68 a_1 \ell + 4{,}34 \ln \frac{1}{4} \left\{ 1 + e^{2(a_1 - a_2)\Delta\ell} + 2e^{(a_1 - a_2)\Delta\ell} \cdot \cos[(\beta_1 - \beta_2)\Delta\ell] \right\}. \quad 27)$$

Let us analyze expression (27). The first term in this expression does not depend on the dimensions of the heterogeneous section and its dielectric parameters and characterizes the attenuation in a homogeneous material with a thickness ℓ and attenuation coefficient of α_1.

The second component does not depend on the material thickness but is fully determined by the size of the heterogeneity and the difference in the attenuation coefficients and phase of the homogeneous and heterogeneous parts of the material. Indeed, at $\alpha_1 = \alpha_2$ и $\beta_1 = \beta_2$ expression (27) determines the attenuation in a homogeneous material according to (24).

The amplitude error of the ultra-high-frequency primary measuring transducers, caused by the heterogeneity of the material, is determined from (27)

$$\Delta W_A = 4{,}34 \frac{1}{S_{W_F}} \ln \frac{1}{4} \left\{ e^{2(a1-a2)\Delta\iota} + 1 + 2e^{(a_1 - a_2)\Delta\ell} \cdot \cos[(\beta_1 - \beta_2)\Delta\ell] \right\} \quad 28)$$

where: S_{WA} - method sensitivity to moisture.

At $\alpha_1 \neq \alpha_2$, $\beta_1 \neq \beta_2$ ΔW_A becomes zero. In the presence of inhomogeneities, i.e., $\alpha_1 \neq \alpha_2$, $\beta_1 \neq \beta_2$ the value of ΔW_A depends on the dimensions of the inhomogeneities, i.e., on $\Delta\ell$ and also tends to $\Delta\ell \to 0$.

Similarly, the error of the phase method due to the heterogeneity of the material is determined.

$$\Delta W\varphi = \frac{1}{S_{W\varphi}} arctg \left[\frac{1 - e^{(a1-a2)\Delta\iota}}{1 + e^{(a1-a2)\Delta\iota}} tg(\beta_1 - \beta_2)\Delta\iota \right] \quad 29)$$

where S_{WA} - is the sensitivity of the phase method to moisture.

For a homogeneous material, i.e., $\alpha_1 = \alpha_2$ и $\beta_1 = \beta_2$, to $\Delta W\varphi = 0$. In the presence of inhomogeneities, the value of $\Delta W\varphi$ depends on their dimensions, i.e., on $\Delta\ell$.

The sensitivities of the S_{WA} and $\Delta W\varphi$ methods are higher the greater the material thickness ℓ, therefore, to reduce the error due to heterogeneity, under other equal conditions, it is necessary to increase ℓ.

Using formulas 28) and 29), the values of ΔW_A and $\Delta W\varphi$ for the hypothetical material at different values of $\Delta\ell/\lambda$ и α_2 were calculated for the cases $\alpha_1 = \alpha_{min}$ и $\beta_1 = \beta_{min}$, $\alpha_1 = \alpha_{nom}$ и $\beta_1 = \beta_{nom}$, $\alpha_1 = \alpha_{max}$ и $\beta_1 = \beta_{max}$ λ -wavelength).

The dependencies of ΔW_A and $\Delta W\varphi$ on α_2 and $\Delta\ell / \lambda$ are graphically shown in Figures 3 and 4. Analysis of the results shows that the error of the phase method due to heterogeneity is on average 1.5-2 times less than that of the amplitude method.

At a ratio of $\Delta\ell / \lambda$ less than 0.3, the error due to non-uniformity is insignificant - 1% relative), even with differences in dielectric characteristics reaching (20%. At $\Delta\ell/\lambda > 0{,}3$), the error from the specified factor increases sharply.

Let us now consider the case when

$$f(x, y) = (c - x) tg \frac{\iota}{c} = (c - x) tg\theta$$

at $\alpha_1 \neq \alpha_2 \neq 0$, $\beta_1 \neq \beta_2 \neq \beta_0$, $\Gamma_{12} \cong 0$, $c \geq a$ - non-uniformity parameter.

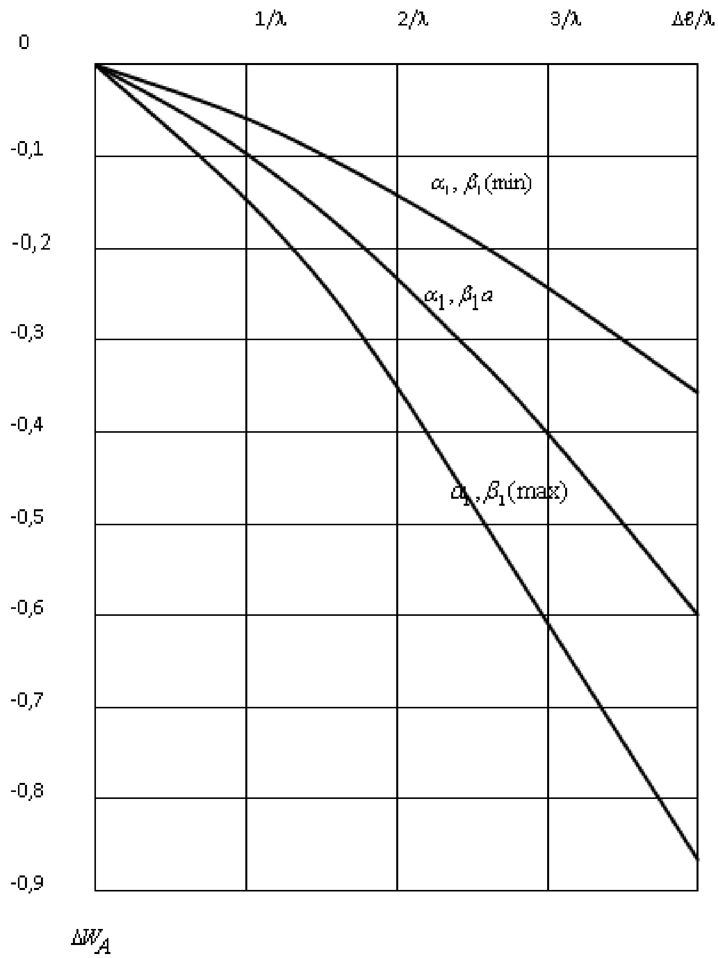

FIGURE 3. Dependence ΔW_A on $\Delta\ell / \lambda$

According to (19), we write

$$E_Z = E_0 e^{-a_2[1-(c-x)tg\theta} \frac{a_1(c-x)tg}{\cos\phi} + j\beta_2\left[l-(c+x)tg\theta\right] + \beta_1 \frac{(c-x)tg\theta}{\cos\phi} \tag{30}$$

where: ϕ - refraction angle of the superhigh-frequency wave at the interface of two media.
Considering that the thickness of the material is $\ell = c\ tg\ \theta$, we have:

$$E_Z = E_0 - a2^{xtg\theta} - \frac{a_1(c-x)tg\theta}{\cos\phi} + j\left[\beta_2 xtg + \beta_1 \frac{(\cos - x)tg\theta}{\cos\phi}\right]. \tag{31}$$

Substituting (31) into (21) and integrating the resulting expression, we determine the value of the flow

$$b = \frac{a_1 - a_2 cos\phi}{\cos\phi}; \tag{32}$$

$$d = \frac{\beta_2 \cos\phi - \beta_1}{\cos\phi}. \tag{33}$$

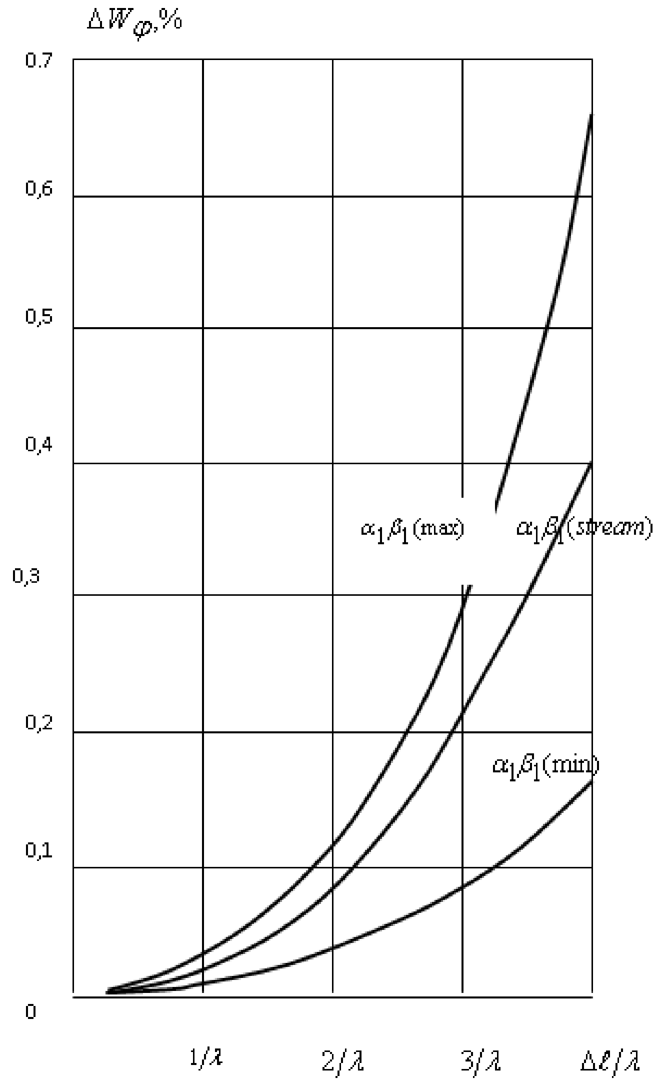

FIGURE 4. Dependence

Passing flow phase ΔW_{φ} on $\Delta\ell/\lambda$ 34)

where: $$k = \frac{c \cdot tg\theta}{\cos\phi}.$$

$$\gamma = [\beta a + \beta 1(c-a)]tg\theta.$$

Calculations of the conversion error using formulas (33) and (34) showed that when changing from θ to 6 degrees, the material thickness is 10 cm and *a*=0.1c corresponds to the ratio $\Delta\ell_m/\lambda < 0{,}3$, the specified errors do not exceed 1% relative). At large values, the specified error increases sharply.

Consequently, the investigated error is determined by the dimensions of the non-homogeneities, and their shape does not significantly affect the transformation error with the same dimensions).

Calculations according to (33) and (34) also showed that the error of the phase primary measuring transducer is less than that of the amplitude transducer.

Thus, for heterogeneous materials, the phase method is preferable.

However, as previously conducted studies have shown, the phase method has a 3-5 times greater error than the amplitude method with a constant mass.

The bulk density natural weight) of most moisture-bearing materials varies widely up to (25%). In these cases, it is necessary to use the amplitude superhigh frequency method. At the same time, it is necessary to strive to reduce the size of heterogeneities when preparing controlled samples, for example, by grinding crushing) coarsely dispersed materials, preliminary crushing of component materials.

On the developed model, any forms of heterogeneity can be investigated. For example, for spherical inclusion:

$$f(x,y) = \sqrt{R^2 - (x-A)^2 - (y-B)^2} \qquad 35)$$

where R - radius of the sphere;

A, B - displacement of the center of the sphere relative to the origin of coordinates.

For cylindrical connection

$$f(x,y)\sqrt{\left[1+\frac{y^2}{b^2}\right]}.$$

Substituting these functions into 19) according to the methodology above, we can calculate the value of the investigated error. However, in some cases, finding the integral from 21) can present significant difficulties. In such cases, it is possible to determine the dimensions of the non-uniformity using the given function *fx,y)* and estimate the error using Figures 3 and 4, since the error, as mentioned above, is determined by the relations $\Delta\ell/\lambda$, α_1/α_2 *u* β_1/β_2.

CONCLUSION

1. The influence of electromagnetic energy scattering on material heterogeneity was theoretically investigated, and it was shown that for bulk materials with particle sizes less than 8 mm, the size deviation from scattering error does not exceed 0.5-0.8% relative), for fibrous materials - 0.1% relative).

The proposed method allows us to calculate the specified error for any material.

2. A generalized mathematical model of a heterogeneous material has been developed, on which the influence of heterogeneities during measurements in free space has been investigated. It has been shown that at non-uniform dimensions $\Delta\ell<0,3\lambda$, the error from non-uniformities is insignificant 1%relative), even with differences in dielectric characteristics reaching 20%.

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