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RADIO-WAVES REFLECTION AT REMOTE SENSING OF UNDERLYING COVERS

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Monitoring technologies are rapidly developing at present and allow to extract and use non-coordinate information about objects. Non-coordinate information is the information about the type and properties of an object under study. Remote sensing is the main method of solving monitoring problems where special positioning belongs to the radar methods, based on space-time processing of signals and, in particular, on methods of radio polarimetry. It is necessary to have information about the surface in order to solve the monitoring task. The slightest changes in the electrical and physical properties of such areas as salinity, humidity, soil composition, etc. will lead to a change in the basic electrodynamics of the surface, notably its complex dielectric permittivity. The article demonstrates the precise solutions to the problems of radio-waves reflection from a layered surface with various laws of changes of the complex permittivity ε in depth. Media with exponential and quadratic laws of variation ε for arbitrary angles of incidence of the radio wave on the surface are considered. Precise decision is obtained for layered media with the law of change in the complex permittivity the polynomial and linear characteristics. A similar problem for the parabolic layer is considered separately. The detailed analysis of radio waves reflection from the medium with a matching layer is carried out. The nature of the electromagnetic field inside the transition layer is studied in detail. The article is illustrated by the graphs showing the dependences of an electromagnetic wave reflection coefficient on the layered medium with linear and exponential laws of variation of the complex dielectric constant over depth.

Key words: polarization, scattering matrix, underlying surface, complex dielectric permittivity, scanning, remote sensing.

1. INTRODUCTION

In order to solve the remote sensing issues, it is very important to know polarization patterns of radio waves reflected from underlying surfaces. We initially need the information on elements of the scattering matrix of illuminated areas on the surface. It is clear that variations of electrical-and-physical properties (salinity, moisture, soil composition, etc.) of such areas will cause variations in the main electrodynamic characteristics of the surface, notably its complex permittivity ε. Complex permittivity variation results in variation of reflecting characteristics of the underlying surface (i.e. characteristics of its elements in the scattering matrix).

2. GENERAL RELATIONS

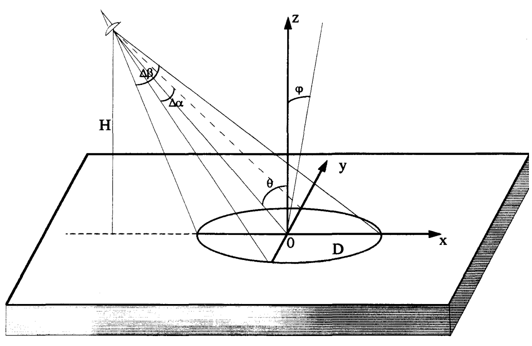

Fig. 1. To statement of a problem

In radiolocation, the scanning of underlying surfaces is carried out from top to bottom (from the aircraft board, satellite, stationary tower, etc.). Thus, the dimensions of an illuminated area of the underlying surface are determined by the height (H) from which scanning is carried out, the scanning angle (α), the antenna beam width [2, 4, 9, 15] (in two mutually perpendicular planes $\Delta\alpha$ and $\Delta\beta$ Fig. 1).

The wave radiated by the antenna induces (on the surface D) currents which are the sources of Ha scattered field [13, 14]. In general, the energy is scattered omnidirectionally and, in particular, in the direction of the antenna.

We shall consider a medium which fills the half-space $z < 0$. Electric-and-physical properties of this medium depend only on the distance to the medium surface.

Suppose that a plane electromagnetic wave is incident on a boundary (medium surface) at the angle. The electric vector of this wave is perpendicular to the plane of incidence (horizontal polarization). The field in the upper half-space will be included into the incident and reflected waves [2]. The electric vector of the reflected wave should meet the differential equation: $\Delta E(x,z)+k^2\varepsilon(z)E(x,z)=0$. This equation after substitution of $E(x,z)=g(z)\exp\{ikx\sin\theta\}$ will be reduced to the following differential equation:

$$g''_{zz}+k^2\left[\varepsilon(z)-\sin^2\theta\right]g(z)=0. \tag{1}$$

It is possible to derive the formula for the reflection coefficient on the horizontal polarization by using standard conditions of the continuity of tangential components of the vectors $\vec{E}$ and $\vec{H}$:

$$R_{HP}(\theta)=\left[ikg(0)\cos\theta+g'_z(0)\right]/\left[ikg(0)\cos\theta-g'_z(0)\right]. \tag{2}$$

The magnetic vector for a vertical polarization may be represented by the following form:

$$H(x,z)=n(z)v(z)\exp(-ikx\sin\theta), \tag{3}$$

where $n(z)=\sqrt{\varepsilon(z)}$, the function $v(z)$ is the solution for the differential equation:

$$\left[n(z)\nu(z)\right]''_{zz}+k^2\left[n^2(z)-\sin^2\theta\right]n(z)v(z)=0.$$

It is possible to derive the formula for the reflection coefficient by using standard conditions of the continuity of tangential components of the vectors $\vec{E}$ and $\vec{H}$:

$$R_{VP}=\left[g'_z(0)+ikg(0)\varepsilon(0)\cos\theta\right]/\left[g'_z(0)-ikg(0)\varepsilon(0)\cos\theta\right]. \tag{4}$$

3. EXPONENTIAL LAYER

The complex permittivity varies according to the exponential law $\varepsilon(z)=\beta\cdot\exp\{2\alpha\cdot z\}=(\beta_1+i\beta_2)\exp\{2\alpha\cdot z\}$; $\operatorname{Im}\alpha=0$. The function $g(z)$ will be the solution for the equation (1):

$$g(z)=H_\xi^{(2)}\left(\frac{k}{\alpha}\sqrt{\beta}\cdot\exp\{\alpha\cdot z\}\right), \tag{5}$$

where $H_\xi^{(2)}$ is the Hankel function of the second kind. The order of this function is $\xi=\frac{k}{\alpha}\sin\theta.$

In case we use the formula for the Hankel function derivative we get:

$$R_{HP}=\left[iH_\xi^{(2)}\left(\frac{k}{\alpha}\sqrt{\beta}\right)e^{-i\theta}-\sqrt{\beta}H_{\xi+1}^{(2)}\left(\frac{k}{\alpha}\sqrt{\beta}\right)\right]/\left[iH_\xi^{(2)}\left(\frac{k}{\alpha}\sqrt{\beta}\right)e^{-i\theta}+\sqrt{\beta}H_{\xi+1}^{(2)}\left(\frac{k}{\alpha}\sqrt{\beta}\right)\right]. \tag{6}$$

4. QUADRATIC LAYER

The complex permittivity varies according to the quadratic law: $\varepsilon(z) = (\alpha z + \beta)^2$. For such a medium it is impossible to express the solution (1) with the use of the known functions. The following solution may be derived with small α, :

$$g(z) = \frac{1}{\sqrt[4]{(\alpha z + \beta)^2 - \sin^2\theta}} \exp\left\{ -ik \int_0^z \sqrt{(\alpha z + \beta)^2 - \sin^2 z dz} \right\}. \quad (7)$$

5. VERTICAL SCANNING

Vertical scanning is quite often used when solving remote sensing issues. In this case there is no difference between vertical and horizontal polarizations and the scattering matrix becomes the identity matrix. However, the reflected-wave power depends to a great extent on the behavior of dielectric properties of the surfaces under study [7, 12, 14, 15, 16, 17, 18]. Let us consider how such reflection for several laws of the complex permittivity changes with depth.

5.1. Polynomial layer

The law of the complex permittivity change is described by relation: $\varepsilon(z) = (az + b)^m$. The formula will be the solution of (2) which satisfies the condition of infinity [15]:

$$g(z) = \sqrt{az + b} \cdot J_{\frac{1}{m+2}} \left[\frac{2}{m+2} \left(\frac{k}{a} \right)^{\frac{m+2}{4}} (az + b)^{\frac{m+2}{2}} \right]. \quad (8)$$

5.2. Linear layer

The law of the complex permittivity change is described by the relation: $\varepsilon(z) = az + b$. It results in the relation [2, 18]:

$$R = \left[H_{1/3}^{(2)}\left(\frac{2k}{3a}\right) - i\sqrt{b} \cdot H_{-2/3}^{(2)}\left(\frac{2k}{3a}\right) \right] / \left[H_{1/3}^{(2)}\left(\frac{2k}{3a}\right) + i\sqrt{b} \cdot H_{-2/3}^{(2)}\left(\frac{2k}{3a}\right) \right]. \quad (9)$$

Analysis of this expression with arbitrary complex values a and b results in awkward, hardly soluble expressions. Let us consider only extreme cases of small and large $|\alpha|$ and also the relations between $|R|$ and $|\alpha|$ for several typical and practically important cases.

With small $|\alpha|$ (when the complex permittivity modulus slowly varies in depth), we derive:

$$R = \left[1 - b^{0,5} + ib^{-1,5} \frac{a}{k} \left(0,104 + 0,146 b^{0,5} \right) \right] / \left[1 + b^{0,5} + ib^{-1,5} \frac{a}{k} \left(0,104 - 0,146 b^{0,5} \right) \right]. \quad (10)$$

When a sharp boundary is absent (i.e. $b = 1$), we have: $R = 0{,}004 |a|^2 \lambda^2$. In this case there is almost no reflection.

Another extreme case is when the complex permittivity increases with a high speed, i.e. $|a|$ is large. In this case we derive:

$R = -1 + 1{,}58\left(\frac{2kb\sqrt{b}}{3a}\right)^{1/3}(1 - i \cdot 1{,}73)$. This formula shows that the reflection coefficient is close to 1 for large values of $|\alpha|$. With a further increase of $|\alpha|$ and λ it tends to 1.

The above mentioned behavior of *R* remains mainly for other kinds of the polynomial dependence. Fig. 2. shows the dependence of the reflection coefficient $|R|^2$ on the parameter $|\alpha|$ for a linear layer.

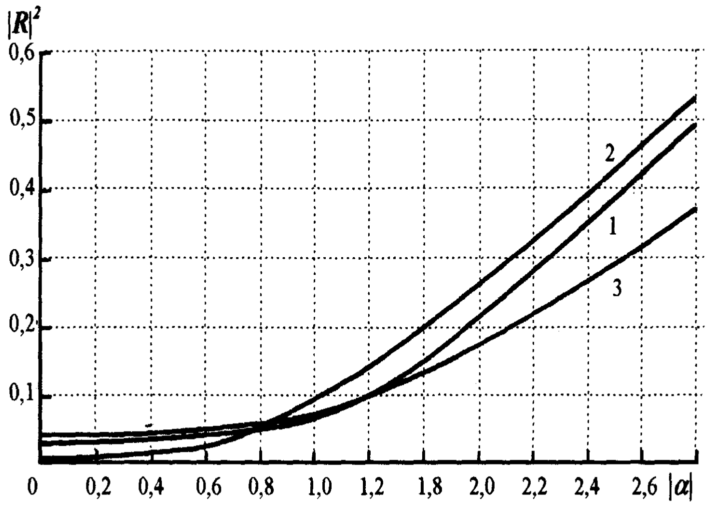

Fig. 2. Dependence $|R|^2$ upon $|\alpha|$ cm^{-1} for a liner layer. $\lambda = 3cm$.
1. $\varepsilon(z) = 2 + i|\alpha|z$; 2. $\varepsilon(z) = 1 + i|\alpha|z$; 3. $\varepsilon(z) = 2 + 0{,}5\sqrt{2}(1+i)|\alpha|z$

5.3. Parabolic layer

Let us introduce the following notation: $\varepsilon(z) = (az+b)^2 = \left[(a_1 + ia_2)z + (b_1 + b_2)\right]^2$. In this case:

$$R = \left[H^{(2)}_{0,25}(w) - ibH^{(2)}_{-0,75}(w)\right] / \left[H^{(2)}_{0,25}(w) + ibH^{(2)}_{-0,75}(w)\right], \quad (11)$$

where $w = \frac{kb^2}{2a}$.

When $|a|1 << b$, i.e. $|\rho| >> 1$, we have

$$R = \left[(1-b)kw + i(0{,}0094 + 0{,}156b)\right] / \left[(1+b)kw + i(0{,}0094 - 0{,}156b)\right]. \quad (12)$$

When a sharp boundary is absent (*b* = 1): $R = 0{,}016|a|^2\lambda^2$. In another extreme case when $|\rho| << 1$, we have: $R = -1 + \frac{5{,}1(1-i)}{\sqrt{|a|\lambda}}$.

5.4. Matching layer

In a number of extreme cases a thin intermediate layer is formed on the medium-atmosphere boundary. In this layer, the complex permittivity smoothly varies from 1 (atmosphere) to its value in the depth of the medium and the curve which represents this dependence has no kinks. The presence of such a layer in a number of cases results in a substantial decrease of the reflection coefficient due to the decrease in reflections that take place on the boundary.

Let us discuss the reflection of the following structure: a region of the space z is filled with a medium with the complex permittivity ε_k. A "matching" layer is located within *h*. The complex permittivity ε_S of this layer varies according to the law: $\varepsilon_S = \frac{1+\varepsilon_k}{2} + \frac{1-\varepsilon_k}{2}\cos\pi\frac{z}{h}$. This relation shows that when z = 0 the complex permittivity is $\varepsilon_S = 1$, when $z = h$ – $\varepsilon = \varepsilon_S$ and $\varepsilon'_S(0) = \varepsilon'_S(h) = 0$, i.e. the matching over the derivative takes place on boundaries of the layer. The wave equation for the matching layer is reduced by means of substitution of an independent variable into the Mathieu equation.

Fig. 3. shows the results of calculation of the reflection coefficient with different values of the complex permittivity

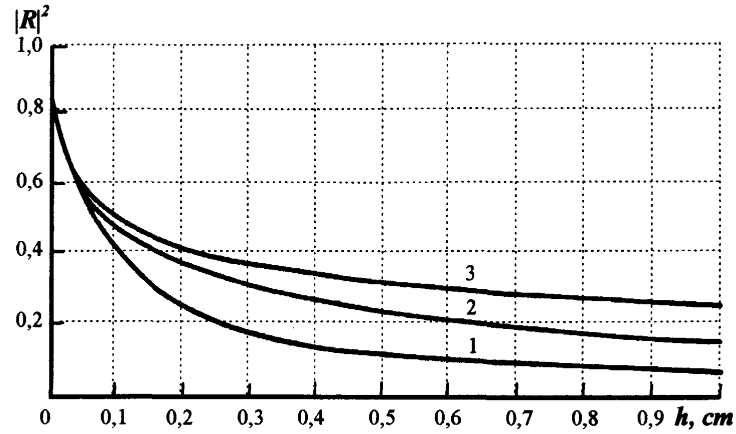

Fig. 3. Dependence of $\varepsilon(z)$ upon the thickness of an intermediate layer – *h*.
In an intermediate layer ε(z) changes from ε = 1 up to ε = 65−40*i*
according to the linear (1), harmonical (2) and exponent (3) laws. λ = 3*cm*

This figure shows that the reflection coefficient varies from $\left|\left(1-\sqrt{\varepsilon}\right)/\left(1+\sqrt{\varepsilon}\right)\right|^2$ to zero. The figure demonstrates the comparison of the similar curves for the matching layer with a linear dependence (without the matching over the derivative). The figure reveals that a decrease in the reflection coefficient for the linear layer is faster than for the matching "cosinusoidal" layer. For a thick layer ($h\to\infty$) $R = 0{,}002\left|1-\varepsilon_k\right|^2\left(\frac{\lambda}{h}\right)^2$; for a thin layer ($h\to 0$) $R = \frac{20{,}4}{\sqrt{\left|1-\varepsilon_k\right|}}\sqrt{\frac{h}{\lambda}}$.

5.5. Intermediate layer

The law of the complex permittivity change, determined by (3), corresponds to an intermediate layer. In this case the formulae in 3 remain valid. For a medium with small α we have:

$$R = \frac{1-\sqrt{|\beta|}e^{i\delta/2}+0{,}125\frac{i}{\rho_0}\left(1+3\sqrt{|\beta|}e^{-i\delta/2}\right)}{1+\sqrt{|\beta|}e^{-i\delta/2}+0{,}125\frac{i}{\rho_0}\left(1-3\sqrt{|\beta|}e^{-i\delta/2}\right)}, \quad (13)$$

where $\rho_0 = k\frac{\sqrt{|\beta|}}{\alpha}e^{-i\delta/2}$, δ is the angle of losses. This formula shows that the reflection coefficient is determined first and foremost by the complex permittivity on the boundary. In particular, for a medium with a very small permittivity (sweet water) we derive: $R = \frac{1-\sqrt{|\beta|}}{1+\sqrt{|\beta|}}\left(1-\frac{0{,}14\alpha\lambda}{|\beta|^2-1}\right)$. In another case when α is large we derive: $R \approx -1+2N_0(\rho_0)/\left[N_0\left(\rho_0+2i\sqrt{\beta}e^{i\delta/2}/\pi\rho_0\right)\right]$. Fig. 4 shows a number of dependencies of the reflection coefficient upon α with different values [5, 6, 8, 17] of β and δ.

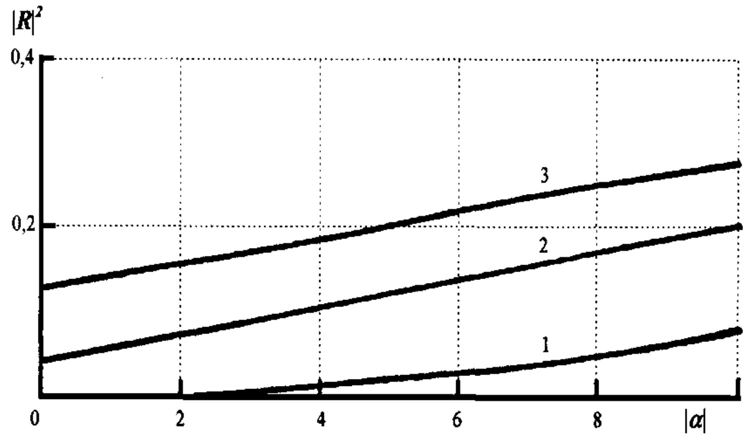

Fig. 4. Dependence $|R|^2$ upon $|\alpha|$ cm^{-1} for an exponent medium.
1. $\varepsilon(z) = \exp(1 + i0{,}1\alpha z)$; 2. $\varepsilon(z) = (1 + i)\exp(\alpha z)$; 3. $\varepsilon(z) = (3{,}5 + 2i)\exp(\alpha z)$

It is important to mention that, regardless of the law of variation of the complex dielectric constant from depth, there is almost a linear dependence of the reflection coefficient on the determining parameter.

CONCLUSION

The paper deals with the problem of reflection of electromagnetic waves from electrically layered inhomogeneous media. Most natural formations belong to the class of such media. The corresponding problems of reflection of radio waves always arise during remote sensing of natural objects under observation. The purpose of the relevant monitoring is to remotely determine the physical characteristics of the underlying surfaces (humidity, hardness, temperature, etc.). The listed properties are determined by the electrophysical characteristics of the surface: dielectric permittivity and conductivity, which, as it is known, are combined into a complex permittivity ε.

Layered structures in which the laws of variation of the complex permittivity in terms of depth were exponential, polynomial, parabolic and linear were considered as models of remote sensing objects. The field inside each of the matching and transition layer was considered separately.

Knowledge of the reflection coefficients dependence in such media opens the way to unambiguous definition of the complex dielectric permittivity, and, consequently, of the physical characteristics of the probed surfaces.

Unfortunately, it is impossible to express the value of the complex dielectric constant explicitly as the function of the reflection coefficient and the viewing angle by means of the obtained strict dependences of the reflection coefficient on the parameters of the laws of the change in the complex dielectric constant. However, this problem is solved quite easily by numerical methods, which, in the final analysis, make it possible to determine the desired physical characteristics.

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ОТРАЖЕНИЕ РАДИОВОЛН ПРИ ДИСТАНЦИОННОМ ЗОНДИРОВАНИИ ПОДСТИЛАЮЩИХ ПОКРОВОВ

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В настоящее время активно развиваются технологии мониторинга, которые позволяют извлекать и использовать некоординатную информацию об объектах. Некоординатная информация – это информация о типе и свойствах исследуемого объекта. Основным методом решения задач мониторинга является дистанционное зондирование, где особое место принадлежит радиолокационным методам, опирающимся на пространственно-временную обработку сигналов, и в частности на методы радиополяриметрии. Для решения задачи мониторинга необходимо иметь информацию о поверхности. Поскольку даже небольшие изменения электрических и физических свойств (солености, влажности, состава почвы и т. д.) таких зон приведут к изменению основной электрофизической характеристики поверхности – комплексной диэлектрической проницаемости. В статье приводятся строгие решения задач отражения радиоволн от слоистой поверхности с различными законами изменения комплексной диэлектрической проницаемости – ε по глубине. Рассматриваются среды с экспоненциальным и квадратичным законами изменения ε при произвольных углах падения радиоволны на поверхность ε. Для слоистых сред с законами изменения комплексной диэлектрической проницаемости, носящими полиномиальный и линейный характер, строгое решение получено для случая вертикального визирования. Отдельно рассматривается аналогичная задача для параболического слоя. Проводится детальный анализ отражения радиоволн от среды с согласующим слоем. Подробно исследуется характер электромагнитного поля внутри переходного слоя. Статья иллюстрируется графическими зависимостями коэффициентов отражения электромагнитной волны от слоистой среды с линейным и экспоненциальным законами изменения комплексной диэлектрической проницаемости по глубине.

Ключевые слова: поляризация, матрица рассеяния, подстилающая поверхность, комплексная диэлектрическая проницаемость, сканирование, дистанционное зондирование.

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