The influence of a layered-inhomogeneous underlying surface on the antenna pattern

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Abstract. The results of works aimed at studying the influence of a flat-layered heterogeneous medium on the type of directional pattern of elementary wave emitter are presented. It was found that a change in the thickness of the frozen soil layer leads to a change in the directional characteristics of elementary emitter. The largest changes in the type of radiation pattern are observed when the thickness of the frozen / thawed layer is a quarter of the wavelength in this medium. It is shown that a change in the type of radiation pattern is also associated with the radiophysical characteristics of the underlying surface on which the antenna is located. The obtained results can be used in the process of optimizing the operation of antenna-feeder devices in conditions of changing the state of the underlying surface.

1. Introduction
The state of the underlying surface is one of the main factors that influence the features of the processes: the propagation of the ground electromagnetic wave, the reflection of space electromagnetic waves from the underlying surface, the radiation of waves by the antenna feeder device, etc [1, 2]. Quantitatively, the state of the underlying surface is described by a set of parameter called radiophysical characteristics. The main radiophysical characteristics of substances and materials include dielectric and magnetic permeability, as well as quantities associated with them. Since the values of the magnetic permeability of natural media differ little from unity, the propagation of electromagnetic waves in natural conditions is determine by the values of the complex dielectric permittivity (CDP) of the underlying surface medium. The underlying surface for areas of land surface free of vegetation is a layer of soil and/or ground with a thickness of units to tens of meters.

Soil and ground can be considered as a combination of solid, liquid and gaseous components that do not enter into a chemical reaction with each other. The gaseous component is close in composition to atmospheric air. The solid component is represented matrix of minerals, organic matter, and, at low temperatures, ice. The liquid component is water and organic matter dissolved in it. The value of the CDP of soils and grounds is a function of many variables, the main of which are: the volumetric moisture content and air content, thermodynamic temperature of soil, and soil’s particle size distribution of soil [3].

The moisture content and temperature of the underlying surface are constantly changing. The changes in the CDP of soils caused by diurnal variations in soil moisture and thermodynamic temperature are small. The rainfall leads to a significant increase in soil moisture and, as a consequence, an increase in soil CDP. The soil moisture changes during infiltration of water occur in the toplayer with a characteristic thickness from a few centimetres (for moist soils) to dozens of centimetres (for extremely dry). This values have close values to the thicknesses of the soil layer, which makes the main contribution to the reflective and absorption characteristics of the underlying surface at the frequency range of $10^7$-$10^9$ Hz (hereinafter, the soil layer that makes the main contribution to the reflective and absorption characteristics of the surface will be called the skin.
depth). For this reason, a change in soil moisture caused by precipitation of atmosphere meteors leads to a noticeable change in the nature of the interaction of electromagnetic waves with the underlying surface at frequencies above $10^8$ Hz. The skin depth of moist soil in the HF band ranges from several decimetre (for very wet soils) to several meters (for extremely dry). A significant change in the integral moisture content within the skin depth of soils is observe during of seasonal processes of movement and infiltration soil water. An example of such processes is snowmelt, transpiration and evapotranspiration of soil moisture in summer.

However, a sharp change in the CDP values of soils and grounds is also observe during soil freezing, which is explained by a significant difference in the CDP of liquid water and ice. So, the values of the real part of CDP of the water and ice at frequencies corresponding to the HF band are 81 and 3.15, respectively. Since the values of CDP of the soil in the dry state and frozen soil with high moisture content are close to each other, the soil freezing process significantly changes the nature of the interaction of electromagnetic waves with soil surface. At the same time, a decrease in the soil CDP values with an increase in the thickness of the frozen layer leads to antireflective effect of waves reflected from the boundaries of the “frozen soil – air” and “frozen soil – unfrozen soil” boundary. At the same time, an increase in the thickness of the frozen layer leads to antireflective effect of waves reflected from the boundaries of the “frozen soil – air” and “frozen soil – unfrozen soil”.

A review of the public literary sources showed that now there are no studies aimed to influence of a layered-inhomogeneous underlying surface on the directional properties of radiating systems. This fact determines the relevance of the studies carried out by the authors.

2. The choice of modelling technique
At the base of any software product designed for numerical modeling of physical processes is one or more methods of solving differential or integral equations of mathematical physics: the Finite Difference Time Domain method, the Finite Element Method, the Method of Moments, etc. [4, 5, 6]. The feature of the problem being solved during the modeling process determines the choice of this or that method. Currently, a number of commercial software products for numerical electrodynamic modeling known: ANSYS HFSS, FEKO, CST, COMSOL, etc. These software products distinguished by rich functionality and user-friendly interface; however, the result of modelling of the antenna's directional properties and the radiophysics characteristics of device at HF band, a number of difficulties arise. Hereinafter, we are analyses of the ANSYS functionality. However, they are largely true for most programs of numerical electrodynamic modeling. So, numerical simulation in these software products is carried out within a finite area of space. For simulate the presence of a solitary antenna in free space, the modelling region is limited the absorbing boundaries [7]. In this case, the view of directional pattern obtained in the modeling process will be close to the results obtained empirically in an anechoic chamber. A similar approach is suitable for modelling of antennas with a relatively high directivity located high altitude above the underlying surface. However, antennas for the HF band are located near to the underlying surface; the toplayer of soil with a thickness comparable to the skin depth influence on the process of emission of electromagnetic waves. After the model space restriction will be carried out, the view of model this radiating system will be the form shown in Figure 1.
It can be seen from the figure the model of the emitting system is an antenna located at a certain height under the surface of the dielectric mat with finite size and thickness. The CDP value of dielectric mat similar to CDP of the underlying surface at the corresponding frequency. Wherein, the simulate region with finite volume is limited the absorbing boundaries i.e. formally, the antenna and dielectric of finite size are in vacuum. As was shown earlier, the result obtained in the simulation process is largely determined by the size of the region within which the antenna and dielectric are located [8]. For estimate the view of radiation pattern in semi-infinite space (with the dimensions of the underlying surface rushing to infinity), the results obtained during the simulation are recalculated. In the finally iteration of modelling process is assumpted that the surface of the dielectric mat covered infinite conducting plane. This approach to modeling process significantly distorts the results of simulate. It can be argued that the largest error in the values of the gain of the radiation pattern will be observed for directions close to sliding angles (see Figure 2).

3. Description of used models
In the process of numerical simulation, the radiation patterns of horizontal half-wave vibrator were obtained. The directed characteristics of the dipole were obtained in the plane perpendicular to its axis.
and passing through the geometric centre. In this plane, the radiation of the dipole is isotropic. When calculating the radiation pattern by mirror image method, the influence of the underlying surface is taken into account as a result of the interference of waves emitted by two sources: real and virtual (see Figure 3).

Figure 3. The method of mirror images; h is the height at which the source is located, φ is the zenith angle, Δ is the path difference of the direct and reflected wave.

The interference minimum and maximum in this case correspond to expression (1a) respectively (1b):

$$\Delta = 2 \cdot h \cdot \sin \varphi = (2n + 1) \cdot \lambda / 2 \quad (1a)$$
$$\Delta = 2 \cdot h \cdot \sin \varphi = n \lambda \quad (1b)$$

where Δ is the path difference of the wave, h is the height at which the emitter is located, φ is the zenith angle, $n$ is any integer (0, 1, 2...). In the simplest case, the underlying surface is a perfect conductive surface. In this case, the real and virtual emitters are identical to each other. For media with finite conductivity (for example, soil), the power of a virtual emitter is less than the power of a real emitter by a value determined by the reflection coefficient.

If the underlying surface is a homogeneous dielectric, the reflection coefficient is calculated using Fresnel formulas. The reflection coefficient from a flat-layered medium, which is a freezing/thawing soil, is calculated using an expression of the form [9]:

$$R_p = |r_p|^2 = \left| r_0 + r_1 \exp(-2jk_1 \Delta Z_1) \right|^2 / \left| 1 + r_0 r_1 \exp(-2jk_1 \Delta Z_1) \right|; \quad (2)$$

where $r_p$ is the complex reflection coefficient in amplitude, $r_0$ is the Fresnel reflection coefficient at the upper boundary, $r_1$ is the reflection coefficient from a multilayer medium lying below the first layer, determined by a similar formula; $k_1 = k_0 (\varepsilon_1 \sin^2 \theta)^{1/2}, \Delta Z_1, \varepsilon_1$ — are the characteristics of the first layer — the projection of the wave number on the vertical axis, the thickness and the CDP of the first layer, respectively; $k_0 = 2\pi/\lambda$ wave number in vacuum; θ is the sounding angle. The view of the plane-layered structure for which the expression was used is shown in Figure 4. The values of the CDP of the soils used in the modeling process are shown in table 1 and table 2.
Figure 4. Schematic view of a flat-layered medium.

Table 1. The CRP values of sandy soil.

| Frequency, MHz | Temperature | +1 °C | -7 °C |
|---------------|-------------|-------|-------|
|               | Real part of CDP | Image part of CDP | Real part of CDP | Image part of CDP |
| 3             | 25.4        | -108.2 | 3.9   | -2.3  |
| 30            | 24.7        | -12.8  | 4.4   | -1.2  |

Table 2. The CRP values of loamy soil.

| Frequency, MHz | Temperature | +1 °C | -7 °C |
|---------------|-------------|-------|-------|
|               | Real part of CDP | Image part of CDP | Real part of CDP | Image part of CDP |
| 3             | 47.3        | -251.1 | 29.6  | -70.4 |
| 30            | 29.4        | -30.3  | 14.3  | -12.3 |

4. The results of simulation
As a result of the calculation, a series of radiation patterns of a half-wave dipole at several frequencies in the HF band were obtained at different freezing depths of two types of soils with different particle size distribution. As can be seen from the above data, the change of the frozen depth layer (see Figure 5-6) leads to a change in the appearance of the radiation pattern. The change in the view of radiation patterns is due to a nonlinear change in the reflectivity from the surface of a plane-layered medium with increase in the thickness of the upper frozen layer. The typical dependence of the reflection coefficient by the thickness of frozen layer is shown in Figure 7-8.
**Figure 5.** The view of the radiation pattern at a frequency of 3-30 MHz at different thicknesses of the frozen layer sandy soil. The numerical values are antenna gain.

**Figure 6.** The view of the radiation pattern at a frequency of 3-30 MHz at different thicknesses of the frozen layer loamy soil. The numerical values are antenna gain.

**Figure 7.** The variation of the reflectivity value with increase of frozen layer thickness, sandy soil.
Figure 8. The variation of the reflectivity value with increase of frozen layer thickness, loamy soil.

In the modelling process the values of CDP corresponding to high soil moisture were taken. In this case, the change in CDP during freezing of the soil reaches significant values. If the humidity of the surface layer is less than that used in the simulation, the view of the radiation pattern during freezing will change to a lesser extent.

5. Conclusion
As a result of the calculations, an assessment was carry out of the effect of a flat-layered underlying surface on the directional characteristics of elementary emitter in the HF band. It was revealed that with increase of thickness of the frozen layer the directional characteristics of elementary emitters are change. The obtained results will find application in the process of optimizing the operation of antenna-feeder devices under conditions of a change in the state of the underlying surface.

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