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Modeling of electromagnetic wave reflection from wet soil taken into account of dispersion, heterogeneity and surface roughness

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Abstract – **Background.** Taking into account temperature, soil composition, surface roughness and the dependence of effective dielectric constant on frequency allows a more accurate assessment of soil moisture and other important parameters, which can be used in various fields such as agriculture, geology, ecology and hydrology. **Aim.** In this work, we calculate the reflection of a linearly polarized electromagnetic wave from wet soil, taking into account such physical factors as heterogeneity of soil structure, surface roughness and dispersion. **Methods.** Based on a heterogeneous mathematical model of wet soil, taking into account the dispersion of the dielectric constant of water and surface roughness, expressions are derived for the complex reflection coefficients of electromagnetic waves of vertical and horizontal polarization. **Results.** The model of loose wet soil with the standard deviation of roughness on the surface was chosen as the object of study. An analysis of the frequency and angular characteristics of the modules of the reflection coefficients was carried out at a fixed level of soil moisture. **Conclusion.** The data obtained as a result of the calculations is a valuable tool for further improving methods of remote sensing of the Earth and contributes to the development of new technologies for monitoring soil parameters using unmanned aerial vehicles, which opens up prospects for more accurate and efficient analysis of the state of land resources and ecosystems.

Keywords – metamaterial; electromagnetic wave; soil moisture; reflection coefficient; heterogeneous model; Earth remote sensing; surface roughness; dispersion.

Introduction

Due to the accelerated growth of technological production processes in the agricultural industry, there is a need to measure soil moisture remotely in real time [1; 2]. Existing methods for determining soil moisture are mainly contact methods and have different labor intensity and error [3]. Synthetic aperture radar data are widely used for remote estimates of soil moisture content [4; 5]. However, such estimates may face difficulties due to various factors such as heterogeneous soil composition, temperature and vegetation cover effects. To improve the accuracy and precision of soil moisture estimates, a new approach based on a mathematical model of moist soil using the concept of artificial metamaterials is proposed [6–8]. This paper considers the adaptation of the metamaterial model to moist soil, where dry soil acts as a container and inclusions act as regions of unknown moisture content. The purpose of constructing such a mathematical model is to analyze the reflection of electromagnetic wave from moist soil, taking into account dispersion and surface roughness. For this purpose, the heterogeneous Maxwell-Garnett model [9], which takes into account the dispersion of the dielectric constant of water in the soil, has been applied. The use of such mathematical models can greatly improve the performance of remote sensing of soil moisture and provide more accurate data for agricultural processes.

1. Heterogeneous mathematical model of complex dielectric permittivity of moist soil with regard to dispersion

Moist soil is considered as a heterogeneous medium consisting of a solid matrix (dry soil) with water filled pores (Fig. 1). The complex dielectric constant (CDC) of dry soil ε_c can be considered as the permeability of a solid matrix, which is constant for a certain type of soil. The CDC of pure water ε_w, however, depends on both the frequency *f* and the temperature *T*.

The equation for the effective CDC of moist soil based on the heterogeneous Maxwell-Garnett model can be written in the following form:

$$\varepsilon_{эфф}(f,T,W) = \varepsilon_c \frac{1+2\alpha(W)\varepsilon_x(f,T)}{1-\alpha(W)\varepsilon_x(f,T)}; \quad (1)$$

$$\varepsilon_x(f,T) = \frac{\varepsilon_w(f,T)-\varepsilon_c}{\varepsilon_w(f,T)+2\varepsilon_c},$$

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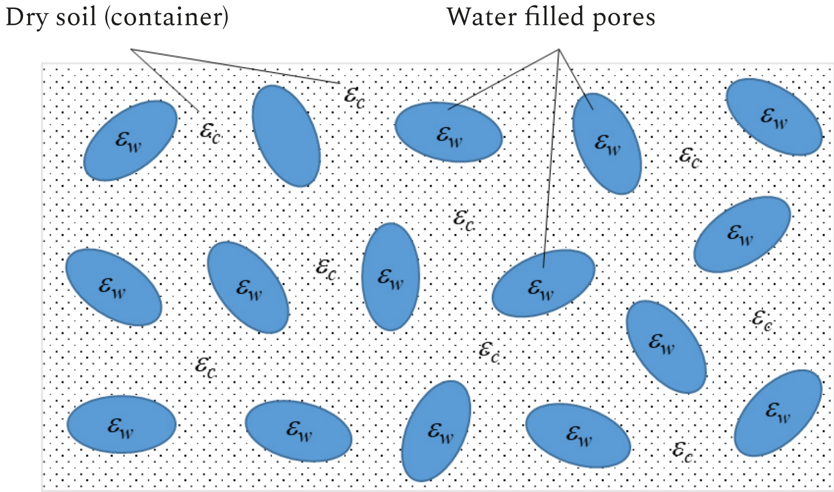

Fig. 1. Wet soil as a two-component heterogeneous system
Рис. 1. Влажная почва как двухкомпонентная гетерогенная система

where $\alpha = W\rho_{dw}$ is the concentration of moist components in soil; W is the soil moisture; ρ_{dw} is the normalized dry soil density.

The pure water CDC is described in general by the following equation:

$$\varepsilon_w(f,T) = \varepsilon'_w(f,T) - j\varepsilon''_w(f,T), \tag{2}$$

where $\varepsilon'_w(f,T)$ is the real part of the CDC of water; $\varepsilon''_w(f,T)$ is the imaginary part of the CDC of water; j is the imaginary unit.

Further, for the compactness of writing formulas, we will use simplified designations of the real and imaginary parts of the CDC, assuming their dependence on frequency and temperature: ε'_w, ε''_w.

The explicit form of expressions for the real and imaginary parts of the pure water CDC are given in the ITU recommendations [10] and are written in the following form:

$$\varepsilon'_w = \frac{\varepsilon_s - \varepsilon_1}{1+\Omega_1^2} + \frac{\varepsilon_1 - \varepsilon_\infty}{1+\Omega_2^2} + \varepsilon_\infty; \tag{3}$$

$$\varepsilon'_w = \frac{\Omega_1(\varepsilon_s - \varepsilon_1)}{1+\Omega_1^2} + \frac{\Omega_2(\varepsilon_1 - \varepsilon_\infty)}{1+\Omega_2^2}, \tag{4}$$

where

$\Omega_1 = f/f_1$; $\Omega_2 = f/f_2$; $\varepsilon_s = 77{,}66 + 103{,}3\beta$;

$\varepsilon_1 = = 0{,}0671\varepsilon_s$; $\varepsilon_\infty = 3{,}52 - 7{,}52\beta$;

$\beta = 300/(T + 273{,}15) - 1$,

f_1 and f_2 are the Debye relaxation frequencies, GHz:

$$f_1 = 20{,}20 - 146{,}4\beta + 316\beta^2; \quad f_2 = 39{,}8 f_1. \tag{5}$$

2. Reflection of a plane electromagnetic wave from the air-soil interface when surface roughness is taken into account

We shall consider the problem of oblique incidence of a plane electromagnetic wave of linear polarization on the air-soil interface taking into account the surface roughness. The geometry of the problem is shown in Fig. 2. The wave falls on the interface at an angle of θ. Region 1 is a vacuum with permeabilities: $\varepsilon_1 = 1$, $\mu_1 = 1$. Moist soil (Region 2) is described by the material parameters $\varepsilon_{эфф}(f,T,W)$ and $\mu_2 = 1$. For simplicity, we denote the effective dielectric constant of moist soil as $\varepsilon_{эфф}$.

To take into account the roughness of the soil surface, we used the model proposed in [11], according to which the reflection coefficients for waves of horizontal R_e and vertical R_h polarization are determined as:

$$R_e = \frac{\cos\theta - \sqrt{\varepsilon_{эфф} - \sin^2(\theta)}}{\cos\theta + \sqrt{\varepsilon_{эфф} - \sin^2(\theta)}}\Psi(h,\theta); \tag{6}$$

$$R_h = \frac{\varepsilon_{эфф}\cos\theta - \sqrt{\varepsilon_{эфф} - \sin^2(\theta)}}{\varepsilon_{эфф}\cos\theta + \sqrt{\varepsilon_{эфф} - \sin^2(\theta)}}\Psi(h,\theta), \tag{7}$$

where $\Psi(h,\theta) = \exp\left(-\frac{1}{2}h\cos^2\theta\right)$.

In formulas (6) and (7), h is the roughness parameter, which is defined as follows:

$$h = 4\sigma^2\left(\frac{2\pi}{\lambda}\right)^2, \tag{8}$$

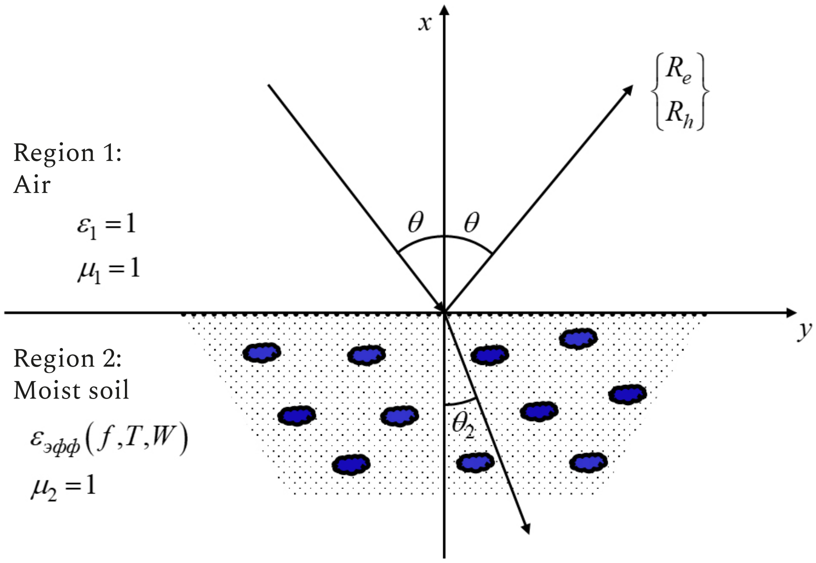

Fig. 2. Geometry of the problem
Рис. 2. Геометрия задачи

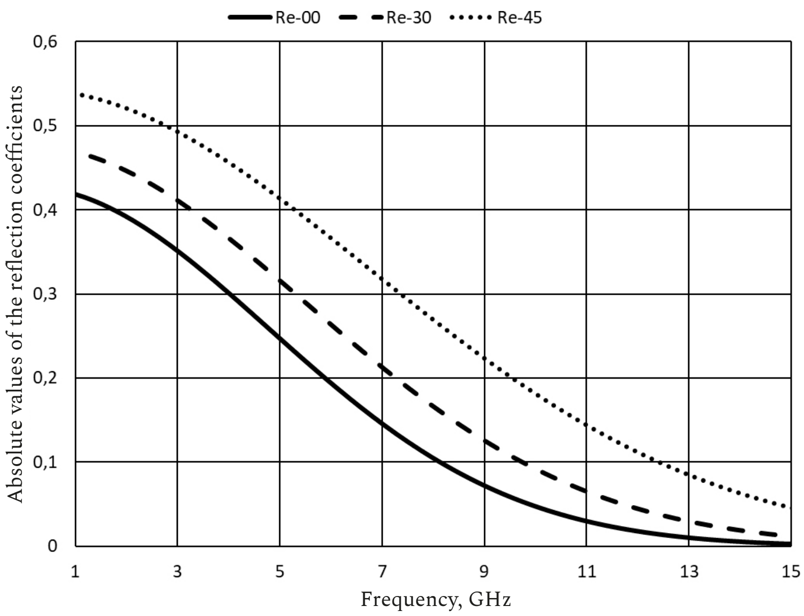

Fig. 3. Dependences of the absolute values of the reflection coefficients of an electromagnetic wave of horizontal polarization on frequency at different angles of incidence
Рис. 3. Зависимости модулей коэффициентов отражения электромагнитной волны горизонтальной поляризации от частоты при различных углах падения

where λ is the electromagnetic wavelength; σ is the standard deviation of roughness on the soil surface.

According to [12], the following is accepted: for a slightly rough surface $\sigma < 0,2$ cm, for a surface with an average roughness of 0,2 cm $\leq \sigma \leq$ 1 cm, and for a strongly rough surface $\sigma > 1$ cm. The values of the electromagnetic wave reflection coefficients calculated by formulas (6) and (7) from the soil were compared with the experimental results given in [13; 14]. There is a steady correspondence between theoretical dependences and experimental values of reflection coefficients of moist and frozen soils at different frequencies, at different soil moisture contents.

3. Calculation results

During the calculations, a model of loose soil $\rho_{dw} = 1,5$ (silty loam) with a standard deviation of roughness on the soil surface $\sigma > 0,5$ cm and a temperature $T = 20$ °C. CDC permeability of dry soil $\varepsilon_c = 3,556 - j0,361$ is considered. Figs. 3 and 4 show graphs of calculations of the reflection coefficients of a plane electromagnetic wave of horizontal and

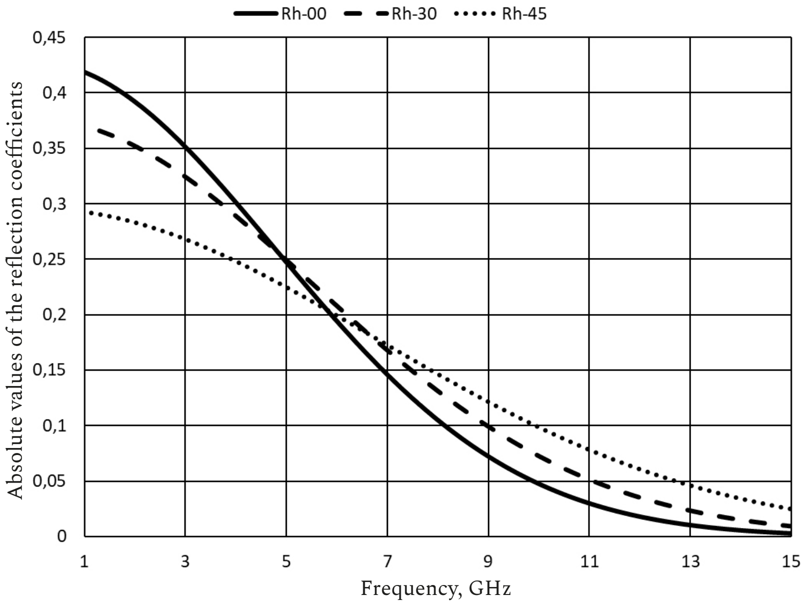

Fig. 4. Dependences of the modules of the reflection coefficients of an electromagnetic wave of vertical polarization on frequency at different angles of incidence

Рис. 4. Зависимости модулей коэффициентов отражения электромагнитной волны вертикальной поляризации от частоты при различных углах падения

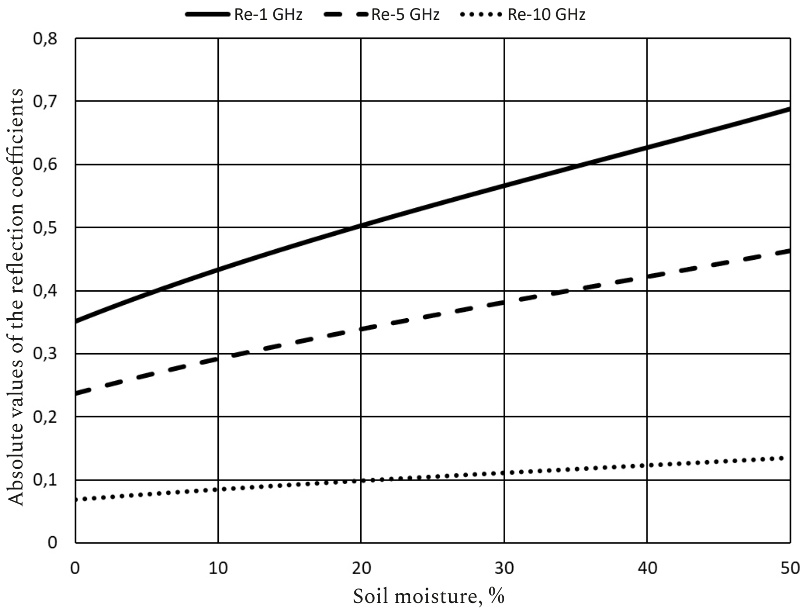

Fig. 5. Dependences of the modules of the reflection coefficients of an electromagnetic wave of horizontal polarization on soil moisture at various frequencies

Рис. 5. Зависимости модулей коэффициентов отражения электромагнитной волны горизонтальной поляризации от влажности почвы на различных частотах

vertical polarization depending on the frequency of probing radiation at a fixed value of soil moisture $W = 15$ % and the following angles of incidence: $\theta = 0°$ is depicted as a solid line, $\theta = 30°$ as a dashed line, and $\theta = 45°$ as a dotted line. The calculations were performed in the frequency range from 1 GHz to 15 GHz.

From the graph in Fig. 3, it can be seen that the reflection level in the case of horizontal polarization increases with increasing angle of incidence. However, for the case of vertical polarization in the frequency range of interest from 1 to 6 GHz, the reflection level decreases with increasing incidence angle.

Figs. 5 and 6 are plots of calculations of the reflection coefficient moduli of a plane electromagnetic wave of horizontal and vertical polarization as a function of soil moisture at a fixed value of the angle of incidence $\theta = 30°$ and the following frequencies: 1 GHz

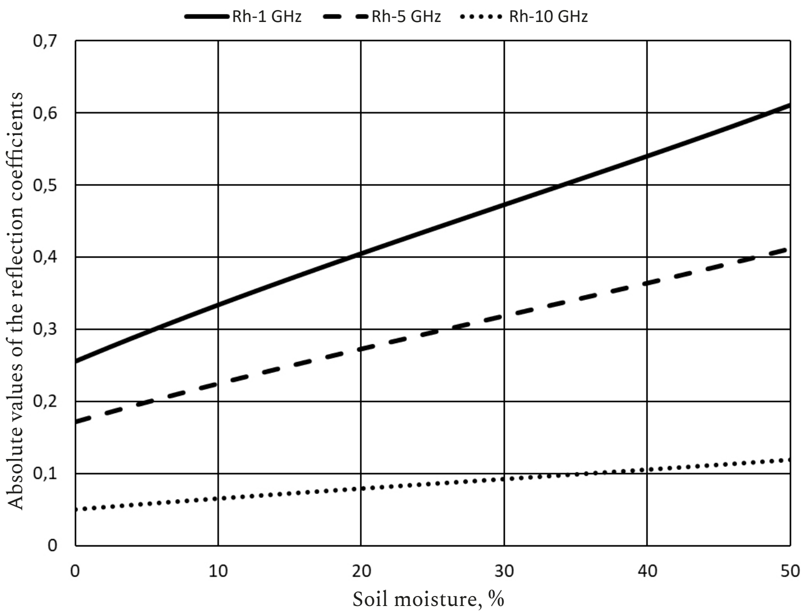

Fig. 6. Dependences of the modules of the reflection coefficients of an electromagnetic wave of vertical polarization on soil moisture at various frequencies

Рис. 6. Зависимости модулей коэффициентов отражения электромагнитной волны вертикальной поляризации от влажности почвы на различных частотах

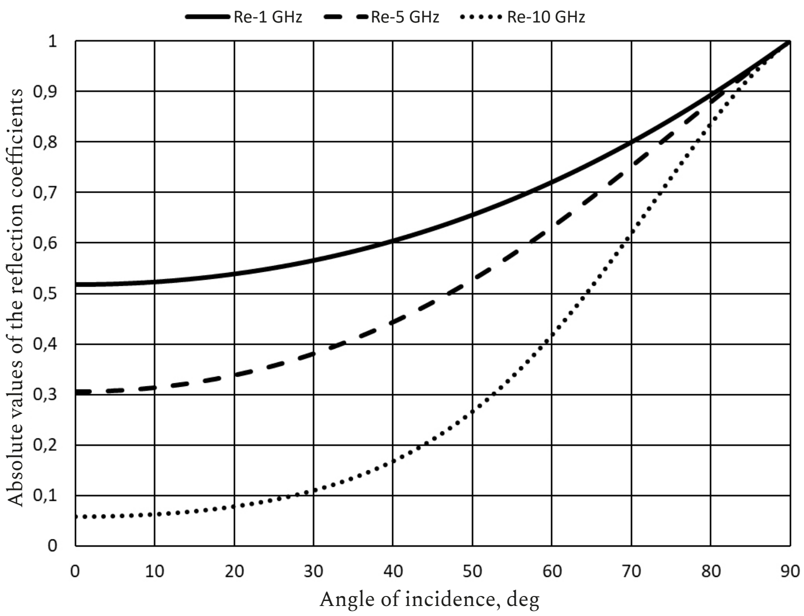

Fig. 7. Dependences of the absolute values of the reflection coefficients of an electromagnetic wave of horizontal polarization on the angle of incidence at various frequencies

Рис. 7. Зависимости модулей коэффициентов отражения электромагнитной волны горизонтальной поляризации от угла падения на различных частотах

is depicted as a solid line, 5 GHz as a dashed line, 10 GHz as a dotted line.

Calculations were carried out in the range of soil moisture variation up to 50 %. From the graphs presented in Figs. 5, 6, it can be seen that with increasing soil moisture the level of reflection smoothly increases.

Figs. 7 and 8 are plots of calculations of the reflection coefficient moduli of a plane electromagnetic wave of horizontal and vertical polarization as a function of the angle of incidence at a fixed value of soil moisture $W = 30$ % and the following frequencies: 1 GHz is depicted as a solid line, 5 GHz as a dashed line, 10 GHz as a dotted line.

From the graphs presented in Figs. 7, 8, it can be seen that in the case of horizontal polarization with increasing angle of incidence there is an increase in the level of reflection of the electromagnetic wave,

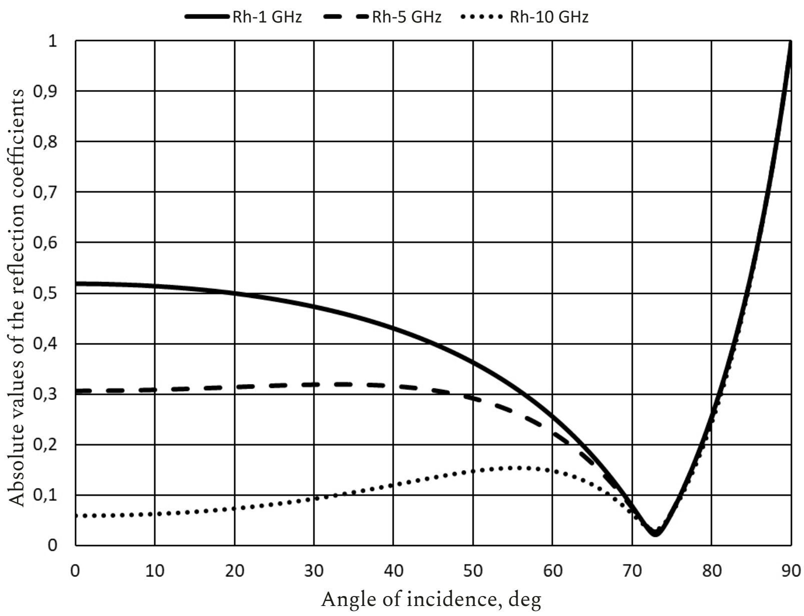

Fig. 8. Dependences of the modules of the reflection coefficients of an electromagnetic wave of vertical polarization on the angle of incidence at various frequencies
Рис. 8. Зависимости модулей коэффициентов отражения электромагнитной волны вертикальной поляризации от угла падения на различных частотах

and in the case of vertical polarization the Brewster phenomenon is clearly manifested at an angle of incidence of 74°.

Conclusion

The results of calculations of electromagnetic wave reflection coefficients from moist soil obtained in this work are valuable information for various fields of science and industry. They can be used to determine the optimal plant watering regime, to control water drainage systems, and to develop systems for automated control of soil moisture in greenhouse farming. In addition, these data can be useful for ecologists when studying the effects of soil moisture on vegetation and animal life, and for geologists when studying soil composition and structure. The results of the calculations can also be used for remote sensing of the earth's surface by Unmanned Aerial Vehicles (UAVs). This opens up new opportunities for monitoring studies of soils and land moisture, as well as for assessing the state of ecosystems.

References

1. Z.-L. Li et al., "Soil moisture retrieval from remote sensing measurements: Current knowledge and directions for the future," *Earth-Science Reviews*, vol. 218, p. 103673, 2021, doi: https://doi.org/10.1016/j.earscirev.2021.103673.
2. S. Sadri et al., "A global near-real-time soil moisture index monitor for food security using integrated SMOS and SMAP," *Remote Sensing of Environment*, vol. 246, p. 111864, 2020, doi: https://doi.org/10.1016/j.rse.2020.111864.
3. J. P. Walker, G. R. Willgoose, and J. D. Kalma, "In situ measurement of soil moisture: a comparison of techniques," *Journal of Hydrology*, vol. 293, no. 1, pp. 85–99, 2004, doi: https://doi.org/10.1016/j.jhydrol.2004.01.008.
4. N. Chen et al., "Surface soil moisture estimation at high spatial resolution by fusing synthetic aperture radar and optical remote sensing data," *Journal of Applied Remote Sensing*, vol. 14, no. 2, p. 024508, 2020, doi: https://doi.org/10.1117/1.JRS.14.024508.
5. J. Wang et al., "Saline soil moisture mapping using Sentinel-1A synthetic aperture radar data and machine learning algorithms in humid region of China's east coast," *Catena*, vol. 213, p. 106189, 2022, doi: https://doi.org/10.1016/j.catena.2022.106189.
6. D. N. Panin, O. V. Osipov, and K. O. Bezlyudnikov, "The calculation of reflections of linear polarization plane electromagnetic wave from the boundary of the «air – wet soil» based on heterogeneous Maxwell Garnett and Brughehman models," *Physics of Wave Processes and Radio Systems*, vol. 25, no. 2, pp. 22–27, 2022, doi: https://doi.org/10.18469/1810-3189.2022.25.2.22-27. (In Russ.)
7. I. Yu. Buchnev et al., "Development of a mathematical model of a chiral metamaterial based on a cylindrical helical elements accounting for the dispersion and concentration of elements," *Physics of Wave Processes and Radio Systems*, vol. 26, no. 2, pp. 36–47, 2023, doi: https://doi.org/10.18469/1810-3189.2023.26.2.36-47. (In Russ.)
8. A. N. Bespalov et al., "Research of antenna complexes using chiral metamaterials and fractal geometry of radiators for MIMO systems," *Physics of Wave Processes and Radio Systems*, vol. 23, no. 4, pp. 97–110, 2020, doi: https://doi.org/10.18469/1810-3189.2020.23.4.97-110. (In Russ.)

9. F. Guerin et al., “Scattering of electromagnetic waves by helices and application to the modelling of chiral composites. II. Maxwell Garnett treatment,” *Journal of Physics D: Applied Physics*, vol. 28, no. 4, p. 643, 1995, doi: https://doi.org/10.1088/0022-3727/28/4/005.
10. Recommendation ITU-R P.527-4 dated 06/2017. Electrical characteristics of the earth’s surface. Series R. Radio wave propagation, 2017. (In Russ.)
11. B. J. Choudhury et al., “Effect of surface roughness on the microwave emission from soils,” *Journal of Geophysical Research: Oceans*, vol. 84, no. C9, pp. 5699–5706, 1979, doi: https://doi.org/10.1029/JC084iC09p05699.
12. T. J. Schmugge, “Effect of texture on microwave emission from soils,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-18, no. 4, pp. 353–361, 1980, doi: https://doi.org/10.1109/TGRS.1980.350313.
13. T. J. Jackson and P. E. O’neill, “Salinity effects on the microwave emission of soils,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-25, no. 2, pp. 214–220, 1987, doi: https://doi.org/10.1109/TGRS.1987.289820.
14. S. A. Komarov et al., “The influence of humidity and salinity on radio emission of frozen soils in the microwave range,” *Issledovanie Zemli iz kosmosa*, no. 2, pp. 22–30, 1995, url: https://www.elibrary.ru/item.asp?id=12753101. (In Russ.)

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Физика волновых процессов и радиотехнические системы
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Оригинальное исследование

Дата поступления 1 марта 2024
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Дата публикации 29 июня 2024

Моделирование отражения электромагнитной волны от влажной почвы с учетом дисперсии, гетерогенности и шероховатости поверхности

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Аннотация – **Обоснование.** Учет температуры, состава почвы, шероховатости поверхности и зависимость эффективной диэлектрической проницаемости от частоты позволяет более точно оценивать влажность почвы и другие важные параметры, что может быть использовано в различных областях, таких как сельское хозяйство, геология, экология и гидрология. **Цель.** В данной работе проводится расчет отражения электромагнитной волны линейной поляризации от влажной почвы с учетом физических факторов: гетерогенности структуры почвы, шероховатости поверхности и дисперсии. **Методы.** На основе гетерогенной математической модели влажной почвы, учитывающей дисперсию диэлектрической проницаемости воды и шероховатость поверхности, выводятся выражения для комплексных коэффициентов отражения электромагнитной волны вертикальной и горизонтальной поляризации. **Результаты.** В качестве объекта исследования выбрана модель рыхлой влажной почвы со среднеквадратичным отклонением шероховатостей на поверхности. Проведен анализ частотных, угловых характеристик модулей коэффициентов отражения при фиксированном уровне влажности почвы. **Заключение.** Полученные в результате расчетов данные являются ценным инструментом для дальнейшего улучшения методов дистанционного зондирования Земли и способствуют развитию новых технологий мониторинга почвенных параметров с использованием беспилотных летательных аппаратов, что открывает перспективы для более точного и эффективного анализа состояния земельных ресурсов и экосистем.

Ключевые слова – метаматериал; электромагнитная волна; влажность почвы; коэффициент отражения; гетерогенная модель; дистанционное зондирование Земли; шероховатость поверхности; дисперсия.

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Список литературы

1. Soil moisture retrieval from remote sensing measurements: Current knowledge and directions for the future / Z.-L. Li [et al.] // Earth-Science Reviews. 2021. Vol. 218. P. 103673. DOI: https://doi.org/10.1016/j.earscirev.2021.103673
2. A global near-real-time soil moisture index monitor for food security using integrated SMOS and SMAP / S. Sadri [et al.] // Remote Sensing of Environment. 2020. Vol. 246. P. 111864. DOI: https://doi.org/10.1016/j.rse.2020.111864
3. Walker J.P., Willgoose G.R., Kalma J.D. In situ measurement of soil moisture: a comparison of techniques // Journal of Hydrology. 2004. Vol. 293, no. 1. P. 85–99. DOI: https://doi.org/10.1016/j.jhydrol.2004.01.008
4. Surface soil moisture estimation at high spatial resolution by fusing synthetic aperture radar and optical remote sensing data / N. Chen [et al.] // Journal of Applied Remote Sensing. 2020. Vol. 14, no. 2. P. 024508. DOI: https://doi.org/10.1117/1.JRS.14.024508
5. Saline soil moisture mapping using Sentinel-1A synthetic aperture radar data and machine learning algorithms in humid region of China's east coast / J. Wang [et al.] // Catena. 2022. Vol. 213. P. 106189. DOI: https://doi.org/10.1016/j.catena.2022.106189
6. Панин Д.Н., Осипов О.В., Безлюдников К.О. Расчет отражений плоской электромагнитной волны линейной поляризации от границы раздела «воздух – влажная почва» на основе гетерогенных моделей Максвелла-Гарнетта и Бруггемана // Физика волновых процессов и радиотехнические системы. 2022. Т. 25, № 2. С. 22–27. DOI: https://doi.org/10.18469/1810-3189.2022.25.2.22-27
7. Разработка математической модели кирального метаматериала на основе цилиндрических спиральных элементов с учетом дисперсии и концентрации / И.Ю. Бучнев [и др.] // Физика волновых процессов и радиотехнические системы. 2023. Т. 26, № 2. С. 36–47. DOI: https://doi.org/10.18469/1810-3189.2023.26.2.36-47
8. Исследование антенных комплексов с использованием киральных метаматериалов и фрактальной геометрии излучателей для систем MIMO / А.Н. Беспалов [и др.] // Физика волновых процессов и радиотехнические системы. 2020. Т. 23, № 4. С. 97–110. DOI: https://doi.org/10.18469/1810-3189.2020.23.4.97-110
9. Scattering of electromagnetic waves by helices and application to the modelling of chiral composites. II. Maxwell Garnett treatment / F. Guerin [et al.] // Journal of Physics D: Applied Physics. 1995. Vol. 28, no. 4. P. 643. DOI: https://doi.org/10.1088/0022-3727/28/4/005
10. Рекомендация МСЭ-R P.527-4 от 06/2017. Электрические характеристики земной поверхности. Серия P. Распространение радиоволн. 2017.
11. Effect of surface roughness on the microwave emission from soils / B.J. Choudhury [et al.] // Journal of Geophysical Research: Oceans. 1979. Vol. 84, no. C9. P. 5699–5706. DOI: https://doi.org/10.1029/JC084iC09p05699
12. Schmugge T.J. Effect of texture on microwave emission from soils // IEEE Transactions on Geoscience and Remote Sensing. 1980. Vol. GE-18, no. 4. P. 353–361. DOI: https://doi.org/10.1109/TGRS.1980.350313
13. Jackson T.J., O'neill P.E. Salinity effects on the microwave emission of soils // IEEE Transactions on Geoscience and Remote Sensing. 1987. Vol. GE-25, no. 2. P. 214–220. DOI: https://doi.org/10.1109/TGRS.1987.289820
14. Влияние влажности и засоленности на радиоизлучение мерзлых почв в СВЧ-диапазоне / С.А. Комаров [и др.] // Исследование Земли из космоса. 1995. № 2. С. 22–30. URL: https://www.elibrary.ru/item.asp?id=12753101

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