MULTIFREQUENCY MICROWAVE MONITORING OF WATER DIFFUSION IN SOIL

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Abstract — Possibilities of the monitoring the water diffusion into soil by data of multifrequency microwave measurements of the dynamics of complex amplitudes of the signal scattered by such an inhomogeneous medium are considered. Measurements have been carried out at 801 frequencies in the range (1.7…7) GHz using the vector network analyzer Agilent E5071B. In the experiment, the initial homogeneous over transversal co-ordinates near-surface water content distribution was prepared by uniformly spilled water, so following diffusion was described by the dynamics of the depth profile of the volume water content in soil. Transformation of multifrequency data to the complex-valued pseudopulse makes it possible to obtain a quality visualization of diffusion. The inverse problem of the retrieval of the depth profile evolution of the water content in soil has been solved by these data using the reduction of the problem to a one-dimensional Fredholm integral equation of the 1st kind with the kernel function that has been obtained experimentally.

МНОГОЧАСТОТНЫЙ СВЧ МОНИТОРИНГ ПРОЦЕССА ДИФФУЗИИ ВОДЫ В ГРУНТ

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Аннотация — Рассмотрены возможности контроля просачивания воды в грунт по данным многочастотных СВЧ измерений динамики комплексной амплитуды сигнала, рассеянного такой неоднородной средой. Измерения выполнялись на 801 частоте в диапазоне (1,7…7) ГГц с помощью векторного анализатора цепей Agilent E5071B. В эксперименте путем равномерного разлива воды создавалось начальное, однородное по поперечным координатам распределение увлажненности на поверхности грунта, так что процесс диффузии описывался динамикой глубинного профиля объемного содержания воды. Трансформация многочастотных данных в комплексный псевдоимпульс позволила получить качественную визуализацию процесса диффузии. Обратная задача восстановления динамики глубинного профиля влагосодержания грунта решалась по этим данным путем сведения задачи к одномерному интегральному уравнению Фредгольма 1-го рода, ядро которого было получено экспериментально.

I. Introduction

Inverse problems of physical diagnostics are widely used in various methods of non-destructive testing and tomography of media parameters [1]. In this paper, we apply the method of near-field microwave tomography of subsurface dielectric inhomogeneities, developed by us in [2—4], to monitoring of water diffusion in the sandy soil.

II. Theory

The tomography [4], i.e. retrieval of 3D distribution of the subsurface inhomogeneity of complex permittivity $\varepsilon_1(\mathbf{r})$ in the medium with $\varepsilon(\mathbf{r})=\varepsilon_0+\varepsilon_1(\mathbf{r})$, was based on measurements of signal complex amplitudes for 801 frequencies in the range (1.7…7.0) GHz obtained by 2D lateral scanning. The source-receiver system based on the vector network analyzer Agilent E5071B includes two identical transmitting and receiving planar bow-tie antennas in bistatic configuration. They were scanning together in the rectangle *x*-*y* area above buried targets. In this case, variations of complex amplitudes of the received signal *s* are expressed by the convolution of the instrument function of the receiver and the scattered field that leads in the Born approximation to expression:

$$s(\mathbf{r}_r,\omega)=\int \varepsilon_1(\mathbf{r}')K(x_r-x',y_r-y',z_r,z',\omega)dx'dy'dz' , \quad (1)$$

where $\mathbf{r}_r$ is the vector determining the receiver position.

In the considered here case of water diffusion monitoring, the water distribution, homogeneous in the plane above the soil surface, has been prepared, poured out, and measurements begin. At such initial conditions we deal with one-dimensional inhomogeneities, and (1) is reduced to

$$s(\omega)=\int \varepsilon_1(z')K_\omega(\omega,z')dz', \quad (2)$$

where $K_\omega(\omega,z')=\iint K(X,Y,\omega,z')dXdY$. Subsurface inhomogeneities with the complex-valued distribution of permittivity can be obtained from this Fredholm integral equation of the 1st kind (2) using the algorithm based on the generalized discrepancy principle in the complex Hilbert space W_2^1 [3]. The kernel function in (1) obtained from calibration measurements [4] can be used to obtain that in (2), and this experimental kernel is valid to some extent beyond the Born approximation [3, 4].

Because in our case inhomogeneities are related to variations of water content in soil, it is suitable, using the

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De Loor formula [5], represent $\varepsilon_1(z)$ in (2) as $\varepsilon_1(z) = f_1(z)F(\omega)$, where f_1 corresponds to variations of the water volume fraction and $F(\omega)$ is a known complex-valued function determined by permittivities of mixture components. Then, (2) is expressed as

$$s(\omega) = \int f_1(z')\tilde{K}_\omega(\omega, z')dz', \tag{3}$$

where $\tilde{K}_\omega(\omega, z') = F(\omega)K_\omega(\omega, z')$. Here, like in [4], we use the possibility to transform the multifrequency problem (3) to that in time domain using the inverse Fourier transformation of multifrequency data to the synthesized pseudopulse $s(t) = \int_0^\infty s(\omega)\exp(i\omega t)d\omega$ that can be represented in dependence on the effective depth parameter z_s according $s(z_s) = s(t = -2z_s \operatorname{Re}\sqrt{\varepsilon_0}/c)$ (taking into account the light velocity in a medium and signal path to and from a scattering element). At that, we obtain the equation to be solved:

$$s(z_s) = \int f_1(z')K_f(z_s, z')dz', \tag{4}$$

$$K_f(z_s, z') = \int_0^\infty \tilde{K}(\omega, z')\exp(-i\omega z_s 2\operatorname{Re}\sqrt{\varepsilon_0}/c)d\omega .$$

Like in [4], the kernel function in (4) has maxima (instead of exponential kernel in (3)), that much simplifies the solution of inverse problems. The range of subsurface inhomogeneities is clearly seen in the visualization of $|s(z_s, \Delta t)|$, where Δt is counted from the beginning of diffusion of spilled water. This function has maxima at a value of z_s that marks the position of surface, and values of z_s are counted from this point.

III. Experiment

In our experiment, the initial water content, homogeneous over transversal co-ordinates, was prepared by uniform water spilling under source-receiver antennas — totally about 1 g/cm^2. After its absorption into the soil near-surface layer, measurements begin. In Fig. 1, one can see dynamics of pseudopulse, synthesized by multifrequency data, related to water diffusion.

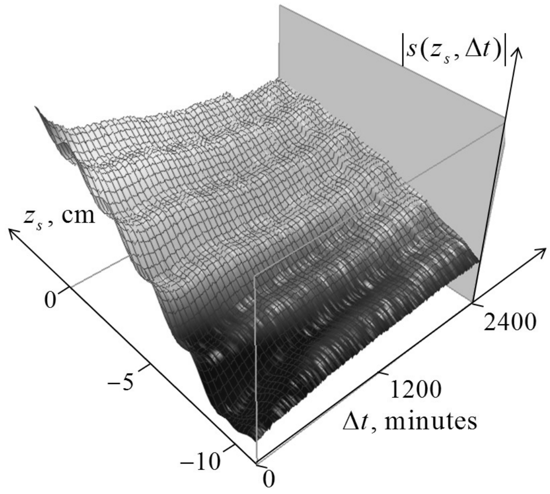

Fig. 1. Dynamics of pseudopulse, synthesized by multifrequency data, related to water diffusion in soil.

Рис. 1. Динамика псевдоимпульса, синтезированного по многочастотным данным, связанная с диффузией воды в грунт

It is possible to see that the scattering at large values of effective depth z_s grows with time. In fig. 2, corresponding evolution of the water volume content related to the water diffusion in soil retrieved from the solution of the Fredholm integral equation of the 1st kind (4) is shown.

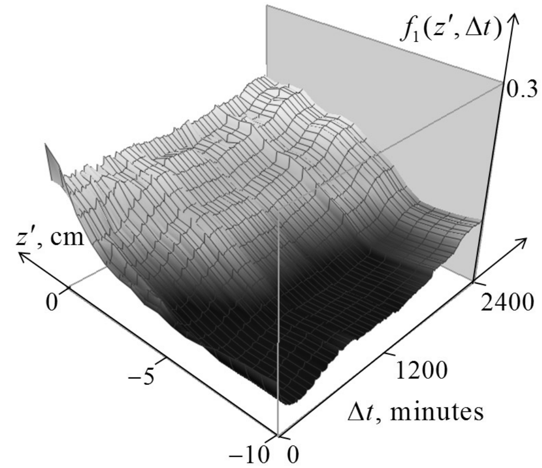

Fig. 2. Evolution of the water volume content at its diffusion in soil retrieved from the solution of (4).

Рис. 2. Эволюция объемного содержания воды при ее диффузии в грунт, восстановленная из (4)

As it is seen in Fig. 2, the retrieved process of water diffusion in soil looks very reasonable. Of course, it is hardly possible to expect a good quantitative agreement between retrieved and real water content values. However, it could be used as a good first guess for a more complicated and rigorous analysis based on the dual regularization method — a new approach in the theory of non-linear ill-posed problems that has been successfully applied in [6].

IV. Conclusion

The theory and experiment demonstrating the feasibility of the monitoring of the water diffusion in soil by data of multifrequency microwave measurements have been presented in this paper.

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