Radar tomography

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Received August 18, 2006

The paper describes results of experimental investigations into the radar sounding of inhomogeneous media and objects with the use of both multifrequency scanning in a superwide band (from 0.5 to 17 GHz) and nanosecond and subnanosecond pulses. It is shown that measurements supplemented with angular and spatial scanning with the synthetic-aperture radar (SAR) technologies make it possible to realize 3-D tomography of weakly contrast inhomogeneities with a spatial resolution of 1 cm. Data handling is based on applying physical models of interaction of electromagnetic radiation with the matter, which isolate dominating interaction mechanisms. This enables one to essentially simplify solution of the inverse problems and to use fast algorithms in solving. The radiation focusing is carried out with the use of mirrors, lenses, as well as the methods of 3-D coordinated Wiener filtering with regularization. Examples are given demonstrating the feasibility of the method for contactless tomography of the forest structure, detection and visualization of anti-infantry land mines hidden under a rough surface of sand. The description is given of the experimental installations developed. We have shown that the use of ultrabroadband radiation (UBBR) enables one to increase significantly the measurement accuracy while performing data processing on a real time scale.

Introduction

One of the most promising research areas of the present-day radiowave tomography is associated with the use of a ultrabroadband radiation (UBBR). Such a radiation makes it possible, first, to achieve high depth resolution of sounding and, second, to provide a considerable depth of penetration of radiation into the absorbing media. As a result, this makes it possible to realize high spatiotemporal resolution in a sounding a medium and in fact to provide microwave vision of optically opaque inhomogeneous media and objects.[1] A supplementary application of spatial and angular scanning in sounding system has made it possible to realize the 3-D tomography in the mode of single-ended (radar) access. Such a problem is of current interest, for example, at underground detection and ranging, at non-destructive testing of engineering constructions, in building-up highways, for search of people and machinery in tumblehomes, in geological mining, and in many other cases. In recent years, it has become an urgent task to use methods of sounding using an UBBR in developing counterterrorism measures and facilities.

This paper presents some results of the latest experimental investigations into the radar sensing of inhomogeneous media and objects with the use of both multifrequency scanning in an UBBR (from 0.5 to 17 GHz), and nanosecond and subnanosecond pulses. The objects to be sounded we use the dielectric anti-infantry land mines installed in damp sand and a mean-density forest.

Theoretical models

First, we consider the problem on the subsurface radar tomography. To construct a suitable mathematical model, a series of simplifications can be adopted. It is reasonable to suppose that the Earth's surface is flat, and the inhomogeneities of the medium of the lower half-space V_1 are characterized by a small relative variation of the dielectric constant $\Delta\varepsilon(\mathbf{r})$. We shall explain the main idea of the method in the simplest case of single scattering and we shall consider that the points of emission and reception of radiation coincide and are at the point $\mathbf{r}_0 = (x_0, y_0, h)$, which can move at a height $h = \text{const}$ in the air over the interface between the media.

The horizontal position of this point is described by a two-dimensional vector $\rho_0(x_0, y_0)$. For the complex amplitude of the scattered field (the system transfer function) at a point of reception $\mathbf{r}_0$ we can write the following expression

$$E(\rho_0, f) = k_1^2 \iiint\limits_{V_1} \Delta\varepsilon(\rho_1, z_1) G^2(\rho_1 - \rho_0, z_1)\, \mathrm{d}^2\rho_1 \mathrm{d}z_1, \quad (1)$$

where

$$G(\rho, z) = \int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} \frac{iT(\mathbf{k})\exp\left[i(\mathbf{k}_\perp \rho + k_z h + k_{1z} z)\right]}{2(2\pi)^2 k_z} \mathrm{d}^2\mathbf{k}_\perp \quad (2)$$

is the Green's function describing the field in the lower half-space from a point source located in the upper half-space, $k = 2\pi f/c$ is the wave number in the free space, $T(\mathbf{k})$ is the Fresnel transmission coefficient of the interface of a media for spectral components of plane waves. The values $k_z = \sqrt{k^2 - k_\perp^2}$ and $k_{1z} = \sqrt{k^2 n^2 - k_\perp^2}$ are the vertical components of wave vectors for the incident $\mathbf{k} = (\mathbf{k}_\perp, k_z)$ and refracted $\mathbf{k}_1 = (\mathbf{k}_\perp, k_{1z})$ plane waves for the upper and lower half-spaces, respectively. The position of a running scattering point is determined by the vector

$\mathbf{r}_1 = (x_1, y_1, z_1) \equiv (\rho_1, z_1)$, and its projection on the interface is determined by the vector $\rho_1 = (x_1, y_1)$. In writing Eq. (1) it was assumed that the background refractive index n of the lower medium is known.

Let us assume that multiposition measurements yield the distribution of scattered field $E(\rho_0, f)$ over the surface. To obtain the volume distribution of inhomogeneities, the field (1) is focused at a certain point ρ_F on the interface between the media. It is well known that the focusing operation consists in the co-phased summing of complex amplitudes of the scattered field at a chosen point of focusing ρ_F. The result of the scattered field focusing at a certain surface point ρ_F can be written using the integral of convolution type:

$$F(\rho_F, f) = \iint_S E(\rho_0, f) M(\rho_F - \rho_0, f)\, d^2\rho_0,$$

where

$$M(\rho, f) = \exp\left[-ik_0\left(2\sqrt{\rho^2 + h^2}\right)\right]$$

is the corresponding weighting function of the focusing, and the integration is made over the entire observation plane S, which is the plane of a synthesized aperture.

With the account of Eq. (1) the focused field can be written in the following form

$$F(\rho_F, f) = \iiint_{V_1} \Delta\varepsilon(\rho_1, z_1) Q(\rho_1 - \rho_F, z_1, f)\, d^3\mathbf{r}_1, \quad (3)$$

where

$$Q(\rho_1 - \rho_F, z_1, f) = = k_1^2 \iint_S G^2(\rho_1 - \rho_0, z_1) M(\rho_F - \rho_0, f)\, d^2\rho_0 \quad (4)$$

is the system response to a point scatterer located at a point $\mathbf{r}_1$, i.e., this is the system instrumental function at the frequency f in focusing at a nearsurface point ρ_F. Note that in the case of a larger aperture S we should take into account that the function $Q(\rho_1 - \rho_F, z_1, f)$ depends only on the value of the difference radius-vector $\rho \equiv \rho_F - \rho_1$.

Numerical calculations show that in the medium with a large background refractive index the instrumental function is of the shape of a collimated wave beam propagated practically perpendicularly to the interface between the media. This approximation is the more precise the greater is the refractive index n of the medium studied. In this case, the expression for k_{1z} is simplified:

$$k_{1z} = \sqrt{k^2 n^2 - k_\perp^2} \approx kn = k_1,$$

and the factor from Eq. (2) $\exp(ik_1 z)$ can be removed from the integral sign. As a result, we can write that

$$F(\rho_F, f) = \int_{-\infty}^{0} \exp(i2knz_1) \iint \Delta\varepsilon(\rho_1, z_1) Q_\perp(\rho_F - \rho_1, f)\, d^2\rho_1 dz_1, \quad (5)$$

where

$$Q_\perp(\rho_F - \rho_1, f) = Q(\rho_F - \rho_1, z_1 = 0, f) = = \iint_S M(\rho_F - \rho_0, f) G_\perp^2(\rho_1 - \rho_0)\, d^2\rho_0$$

has the meaning of the transverse instrumental function of the system at the frequency f.

In Eq. (5) we use the Fourier transform at all the measurement frequencies. As a result we can write

$$\tilde{F}(\rho_F, t) \equiv \int F(\rho_F, f) \exp(-i2\pi f t)\, df = = \iiint_{V_1} \Delta\varepsilon(\rho_1, z_1) \tilde{Q}_\perp\left(\rho_F - \rho_1, \frac{ct}{2n} - z_1\right) d^2\rho_1 dz_1, \quad (6)$$

where

$$\tilde{Q}_\perp\left(\rho_F - \rho_1, \frac{ct}{2n} - z_1\right) \equiv \equiv \int Q_\perp(\rho_F - \rho_1, f) \exp\left[-i2\pi f(t - 2nz_1/c)\right] df.$$

In the framework of the presently accepted approximations for restoration of spatial distribution of inhomogeneities $\Delta\varepsilon(\rho_1, z_1)$ we can write the solution of the integral equation in convolutions (6). This is a known problem, which is commonly solved with the use of the Wiener filtering with regularization. However, the established fact of good localization of the system instrumental function enables one, in the first approximation accurate to a constant factor, to consider that

$$\Delta\varepsilon(\rho_F, z_F) \approx \tilde{F}(\rho_F, 2nz_F/c) = = \int_{-\infty}^{\infty} \exp(-i2knz_F) \iint_S E(\rho_0, f) M(\rho_F - \rho_0, f)\, d^2\rho_0 df. \quad (7)$$

The value of the spatial resolution is determined, in this case, by the scale of localization of the system instrumental function.

Taking into account the approximations accepted, the solution of the inverse problem of the subsurface tomography reduces to the radiation focusing at a subsurface point of the medium and the operation of the inverse frequency Fourier transform. The use of an algorithm of the fast Fourier transform enables one to accelerate significantly the processing of measurement data that is especially important, for example, for a search of anti-infantry land mines.

In the case of a beam antenna system or when spatial scanning is difficult to realize, for example, in sounding the forest, it is advantageous to use the scheme of angular scanning and the pulse sounding. In this case the data processing should be carried out in several stages: 1) time compression of a scattered signal based on a matched filtering with the use of a signal reflected from a corner-cube retroreflector as a reference one; 2) separating out of the envelope curve (amplitude) of a reflected signal; as the envelope curve the module is taken of a corresponding analytical signal; 3) the signal correction for transmission based on renormalization with the account of the extinction along the sounding path; and 4) the removal of angular blurring due to the finiteness of angular width of the directional pattern. At the final stage we use the operation of deconvolution with regularization, and as a standard function of directivity a response of radar system to a corner-cube retroreflector is used.

Experimental results

To perform the subsurface sounding a special box, covered inside with a radioabsorber, was manufactured (Fig. 1*a*).

The experiment was carried out using four test dielectric objects inserted at different depth: housings of plastic anti-infantry mines and a stepwise-shaped objects from foam plastic, with the step size of 5 cm. A photograph of objects is presented in Fig. 2*a*.

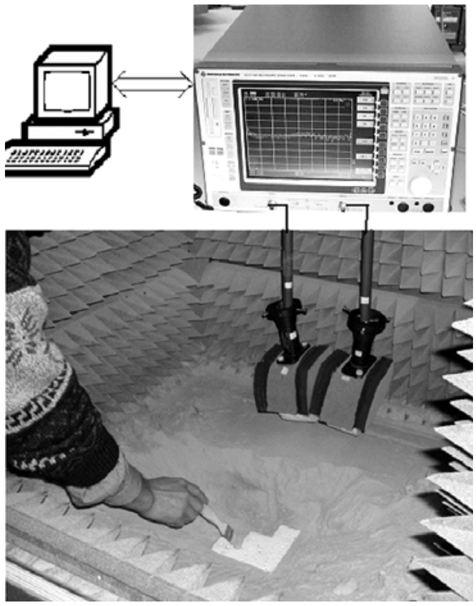
During the measurements the frequency range from 0.5 to 17 GHz was used. The system of the receiving and transmitting antennas, spaced at a distance of 14 cm, moved in a 1-cm step in the horizontal plane over a square of 50×50 cm at a height of 30 cm.

For processing of multifrequency data the above-mentioned algorithm was used. The reconstructed shapes of test objects and the depth of their detection are shown in Fig. 2*b* (see Ref. 2). Note that the time of reconstruction of the total-three-dimensional tomogram at a depth to 50 cm did not exceed 30 s that is approximately two orders of magnitude faster than that obtained in the experiments using a fast 64-bit processor at the Sun Ultra-1 workstation at the United Research Center of the European Commission in Italy (what took about 4 hours to achieve similar task).[3]

The evidence of the spatial resolution obtained, which enables one to speak about really achieved microwave viewing of the objects, is a tomographic section, taken from the total 3-D pattern at the air–ground interface (Fig. 3*b*).

For a comparison Fig. 3 shows a photograph of this interface. On both photographs one can see a track of roughnesses in the form of the "W" letter.

In this connection it should be emphasized that in the proposed scheme of sounding and data processing two unavoidable factors distorting the contactless subsurface detection and ranging of objects, namely, the roughness of terrain and high contrast of the dielectric properties of the media (air and soil) were first used as advantageous ones in decreasing the interfering reflections from the surface thus enabling us to speed up the processing algorithm without the loss of accuracy.



a

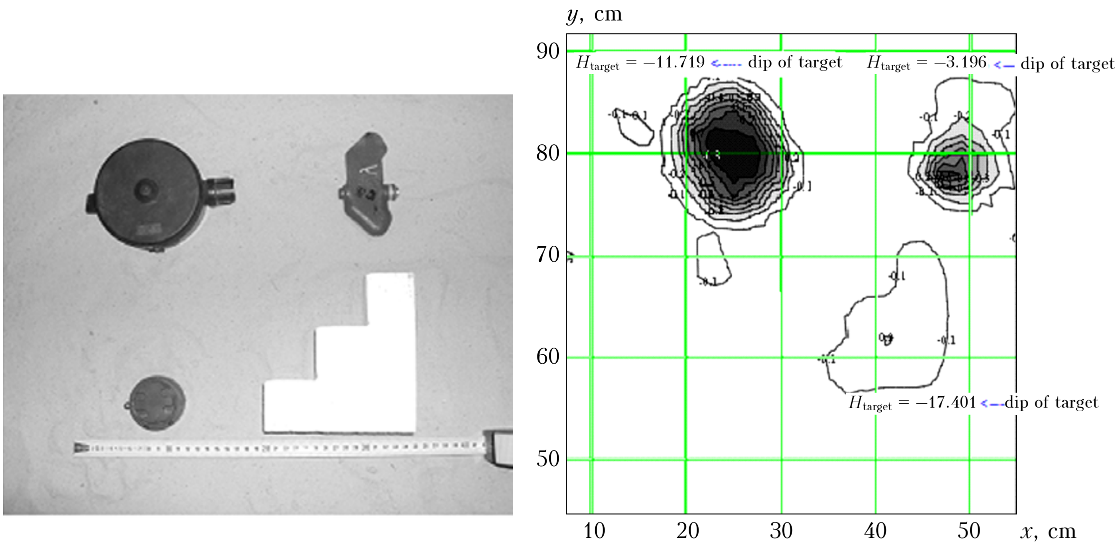
b

Fig. 1. Experimental setups for radar tomography.

The results demonstrated have been obtained primarily because of the use of an ultrabroadband antennas designed by Yu.I. Buyanov (Fig. 4*a*), which differ from the analogs by a very wide band of operating frequencies.

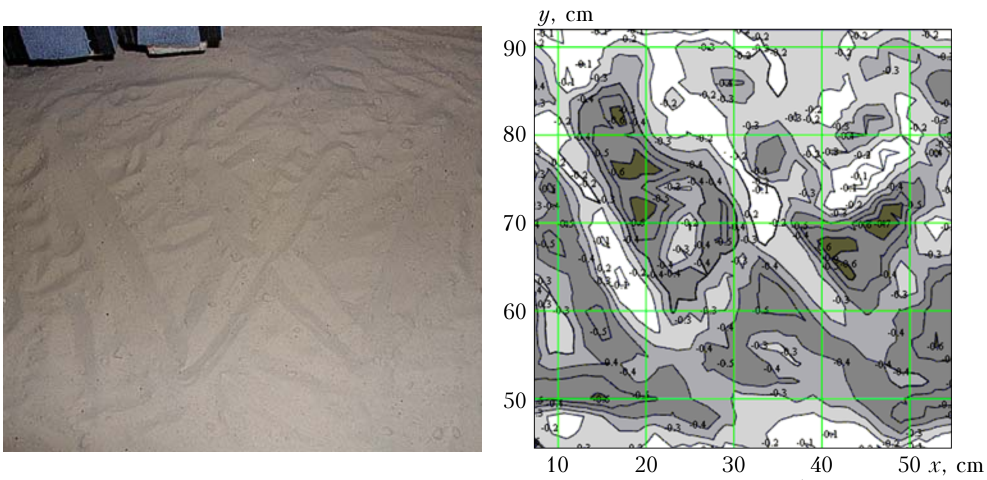
This is confirmed by the measured dependence (Fig. 4*b*) of the Voltage Standing-Wave Ratio (VSWR) for one of the antennas.

One can see from this figure that up to the frequency of 17 GHz this quantity does not exceed 1.5. The same antennas were used as an antenna feed of parabolic mirrors in the forest tomography (Fig. 1*b*).



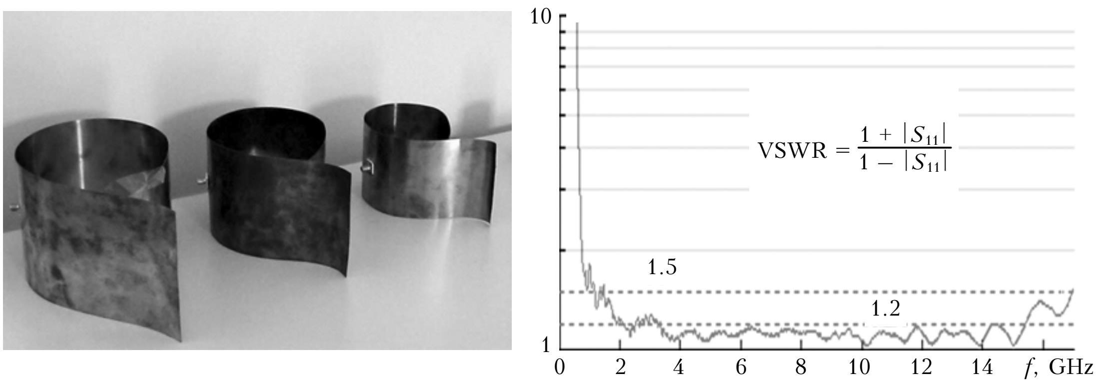
a *b*

Fig. 2. An external view and radiotomogram of the test dielectric objects.



a *b*

Fig. 3. An external view and radioimage of the rough surface of sand.



a *b*

Fig. 4. An external view of UBB antennas designed by Yu.I. Buyanov and their characteristics.

Remote monitoring of standard area of deciduous forest (Fig. 5*a*) was performed at the polygon of the Institute of Forest of KSC SB RAS using two schemes: with the use of a pulsed radar raised over the forest and with the use of a pulsed UBBR radar located inside the forest (Fig. 1*b*).

Based on the data obtained we managed to extend considerably the known ideas about physics of radiowave propagation through the forest.[4–8]

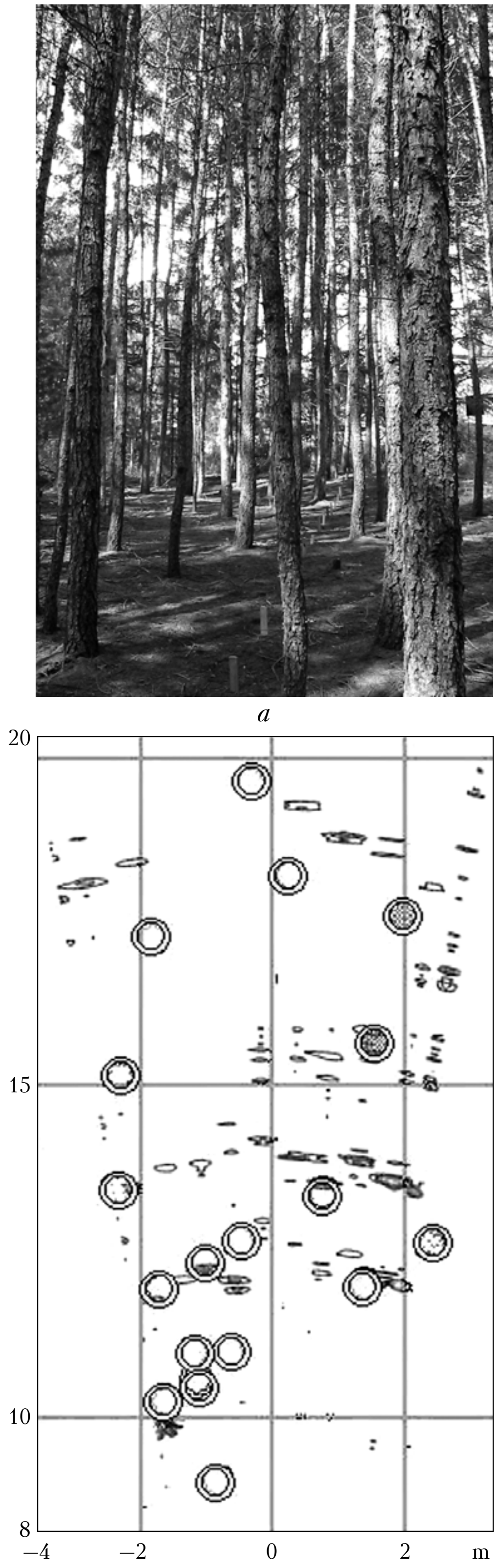


Fig. 5. Deciduous forest and its radiotomogram.

The theory of analytical signal was used to process the reflected unharmonic signals. In accordance with this theory, the amplitude of a UBB signal implied the modulus of a corresponding analytical signal. Averaging is made over all the frequencies of a sounding radiation, i.e., from 500 MHz to 17 GHz. Note that the UBB radar signal can be used to analyze the frequency dispersion of the forest absorption coefficient. For this purpose it is sufficient to make the band filtering of a radar response close to the chosen frequencies and to assess the decrease rate of the frequency components studied with the distance.

The reconstructed tomogram of a standard forest obtained based on the algorithm with matched filtering, described in the theoretical section, renormalization according to an analytical signal and deconvolution, is shown in Fig. 5*b* in the form of gradations of gray color. The location of trees on a landscape plan of the forest is denoted by circles.

Note that a good agreement is observed between the results obtained and the landscape plan as concerning the position of individual trees. This agreement is obtained approximately in 70% of cases. It is evident that on the tomogram except for the trees assigned we can see some additional inhomogeneities, which, most probably, are connected with large branches of the forest canopy, which are not pointed at the landscape plan. Besides, some errors could be made when taking pictures of the landscape plan. It is believed that after performing repeated measurements and more careful data processing the UBB measurements can be used for taking pictures of the landscape plan itself, as well as for detecting strange objects in the forest, for example, camouflaged vehicles, animals or people.

Conclusion

The investigations have shown promise for the radiotomographic sounding method with the use of a UBB radio-frequency radiation. In using the frequency band from 0.5 to 17 GHz we managed to obtain the spatial resolution in sounding inhomogeneities of a medium on the order of 1 cm.

Acknowledgments

The authors would like to thank Prof. A.S. Omar and the Management of the Magdeburg University (Lehrstuhl für Hochfrequenz- und Kommunikationstechnik am Institut für Elektronik, Signalverarbeitung und Kommunikationstechnik der Fakultät für Elektrotechnik und Informationstechnik an der Otto-von-Guericke-Universität Magdeburg) for the possibility of performing high-accuracy measurements using the present-day instrumentation.

The work was supported by the Inter-Ministry Program of the Ministry of Education and the Ministry of Defense of the Russian Federation No. 03.01.028, the grant of the Russian Foundation for Basic Research No. 01–02–17233-a, Federal Task Program "Integration of Science and Higher Education of Russia During 2002–2006," No. I0106.120, grants of the Ministry of Education of the RF No. T00-2.4-2119 and No. E00-12.0-249, grant UR.01.01.395 under the Program "Russian Universities" – and the Task Federal Research and Technology Program (TFRTP) No. 02.438.11.7008 of the Federal Agency of Science and Innovations of the RF during 2005–2006.

References

1. A.Yu. Grinev, ed., *Problems of Subsurface Radiolocation* (Radiotekhnika, Moscow, 2005), 416 pp.
2. V.P. Yakubov, A.S. Omar, V.P. Kutov, N.G. Spiliotis, and D.Y. Sukhanov, in: *Tenth International Conference on Ground Penetrating Radar* (Delft, the Netherlands, 2004), pp. 103–106.
3. J. Fortuny-Guasch, IEEE Transactions on Geosciences and Remote Sensing **40**, No. 2, 443–452 (2002).
4. A.L. Magazinnikova and V.P. Yakubov, Radiotekhn. Elektron. **44**, No. 1, 5–9 (1999).
5. V.P. Yakubov, E.D. Telpukhovskiy, V.L. Mironov, K. Sarabandi, and G.M. Tsepelev, in: *IGARSS* (France, 2003), pp. 4265–4267.
6. V.P. Yakubov, E.D. Telpukhovskiy, and G.M. Tsepelev, Izv. Vyssh. Uchebn. Zaved., Fizika, No. 8, 36–41 (2003).
7. V.P. Yakubov, E.D. Telpukhovskiy, V.L. Mironov, V.M. Tsepelev, and N.A. Moiseenko, in: *IGARSS* (Anchorage, Alaska, 2004), pp. 3471–3473.
8. A.V. Klokov and V.P. Yakubov, Izv. Vyssh. Uchebn. Zaved., Fizika, No. 6, 121–122 (2005).