Microwave Near-Field Subsurface Radiothermometry[1]

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The near field effect has been discovered in thermal radio emission of lossy media. The effect consist in the fact that the effective depth of the received emission formation layer d_{eff} appears less than the skin-layer depth and depends on the size of receiver antenna and its height above the medium surface h. The dependence d_{eff} (D,h) has been obtained from measurements of the emission of temperature stratified water medium at wavelength 31 cm using a specially developed electrically small antenna. The results of experimental research of antenna parameters are presented. Authors propose to use measurements of received emission dependence on D and h as a new source of information about depth temperature distribution. Methods of the solution of corresponding inverse problems have been developed and the first results of subsurface temperature profile retrieval in the water medium have been obtained.

1. Introduction

Microwave radiometry measurements of thermal emission are widely used for subsurface diagnostics of media. For temperature measurements those methods are superior to other remote (noninvasive) techniques. The intensity of thermal radiation is proportional to the averaged temperature of the layer with thickness d_{eff} where this radiation is formed. Variations of d_{eff} give a possibility to retrieve the subsurface temperature profile $T(z)$. Only the dependence of d_{eff} on the wavelength λ has been used earlier for this purpose, i.e., retrieval of $T(z)$ was performed by measurements of the thermal emission on several wavelengths. Such a technique has been applied in medical and plasma investigations, for diagnostics of water and soils, etc.

It has been shown theoretically in [1] that the near-field (quasi-stationary) component of the thermal radiation tangibly affects a signal intensity measured by a radiometer, if the receiving antenna has a small electric size $D \ll \lambda$ and is situated at height $h \ll \lambda$ over the radiating surface. In this case d_{eff} is determined not only by λ but also by the antenna parameters D, h. So, new possibilities are offered to control d_{eff} by varying parameters D and h. This work is devoted to development of a radiometry system for near-field measurements; investigation of near-field effects in thermal radiation; retrieval of the subsurface temperature profile of medium by the near-field radiometry measurements.

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2. Measurements

The thermal radiation was detected by a radiometer with the operating frequency f_0*=950 GHz*, the frequency band Δf*=200 MHz*, and fluctuation sensitivity threshold $\delta_T = 0{,}05$ K at the integration constant $\tau = 1$ *s*. The key element of the receiving system was an electrically small antenna of size $D = 1$ cm ($D/\lambda = 0.03$) shown in Fig.1. It consisted of two in-phase dipoles connected to a symmetric strip line operating as a matching resonator (a prototype of this system is described in [2]). Water was chosen as the medium for investigation. When the antenna was in close contact with the water surface ($h = 0$), it was matched to the radiometer input so that the reflection coefficient R averaged over the radiometer frequency band Δf did not exceed 0.03 (see Fig.2).

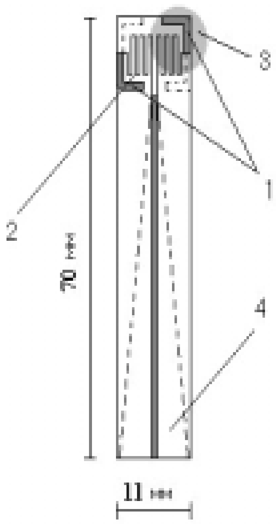

Figure 1. Scheme of the near-field antenna. 1 – electrically-short dipoles; 2 – matching resonator; 3 – dielectric plate for fine tuning; 4 – coaxial to strip-line connector.

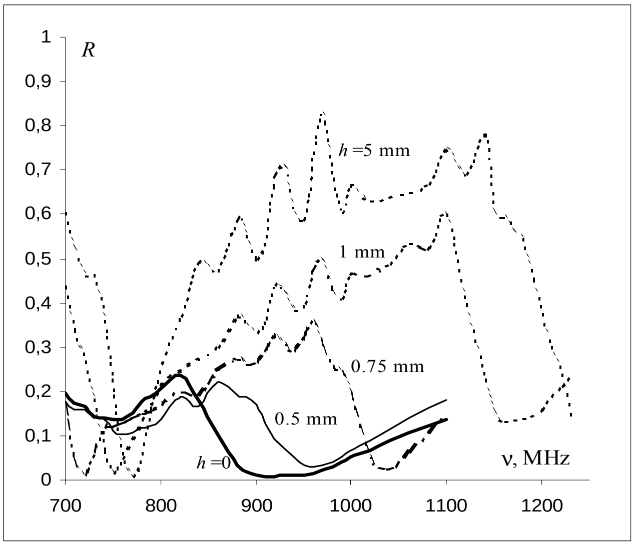

Figure 2. Frequency dependence of antenna reflectivity for different heights above the water surface.

The reflection coefficient, efficiency, and sensitivity of antennas have been studied depending on frequency and the dielectric parameters of the measured medium. The dielectric parameters of water are strongly dependent on temperature and salinity. So, the temperature and salinity dependence of antenna parameters was investigated (see in Fig.3,4). It is clearly seen that the reflectivity of antenna in the radiometer frequency band $f_0 \pm \Delta f$ is practically independent of the temperature and the salinity of water. The antenna in contact with a living tissue has also been investigated (Fig.3). In Fig.5,6 one can see the reflection coefficient R, efficiency η and sensitivity dT_b of radiometer (all parameters are averaged over the radiometer band). The antenna efficiency at $h = 0$ was found to be $\eta = 0{,}85$. An increase in height leads to both the antenna mismatch (increase in R) and a decrease of η. The sensitivity threshold to temperature variations increased from 0.06 K at $h = 0$ to 1 K at a maximum height of measurements $h_{max} = 2.5$ mm. Further decrease in sensitivity at $h > h_{max}$ made measurements at larger heights impossible. Thus, a matched high-efficiency antenna is a fundamental requirement to a near-field radiometric system, in contrast to similar active-location systems, which are usually referred to as near-field microscopes.

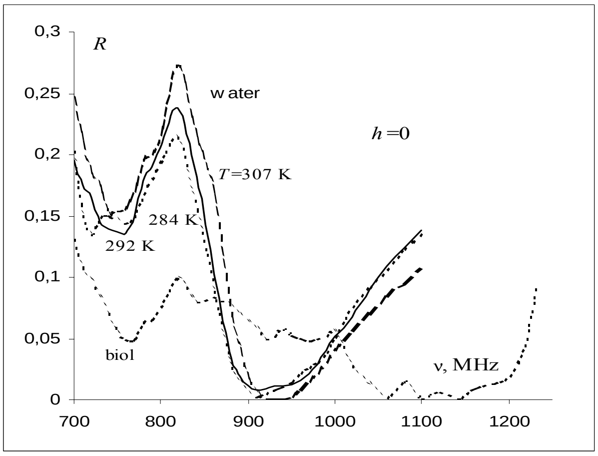

Figure 3. Frequency dependence of the antenna reflectivity at three different temperatures for water medium and for living tissue at 37 C.

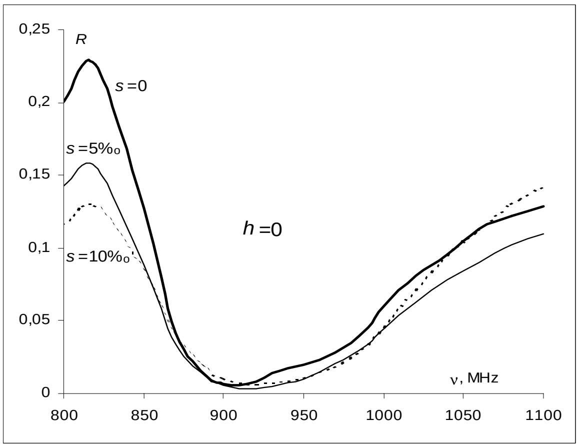

Figure 4. Salinity dependence of the antenna reflectivity at three different values of water salinity.

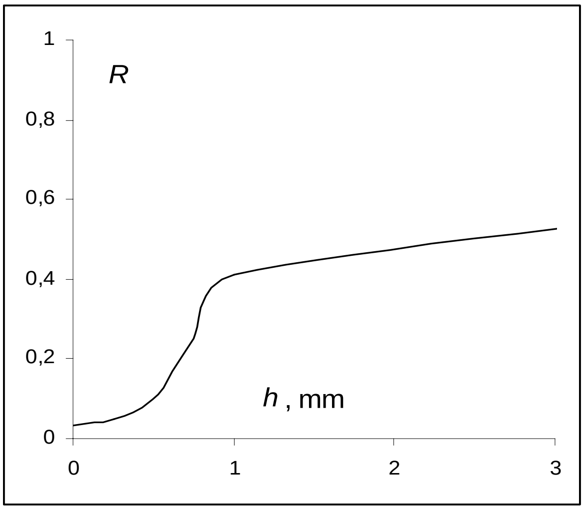

Figure 5. The height dependence of antenna reflectivity in the radiometer frequency band.

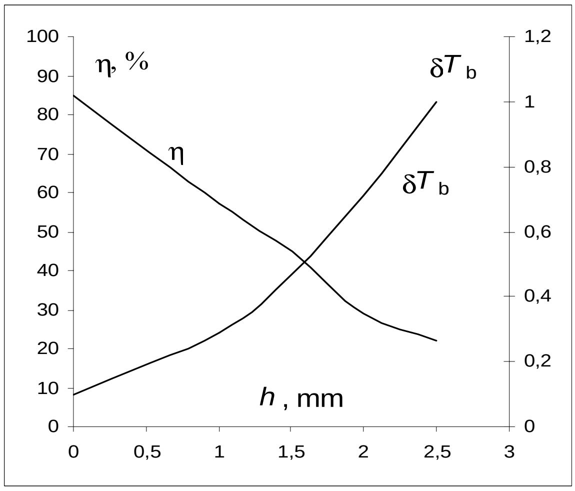

Figure 6. The height dependence of antenna efficiency and radiometer sensitivity in the radiometer band.

3. Near-field effects

For measurements of $d_{\rm eff}$, a stable quasi-linear profile $T(z)$ was formed using a heater near the surface and a cooler near the bottom of a cylindrical vessel (see the measurements scheme in Fig.7 and the temperature profile in Fig.8). The stationary temperature gradient was as large as dT/dz = 2.5 K/cm. For linear $T(z)$ a simple exact expression for the brightness temperature measured by radiometer can be obtained: $T_{\rm b} = T(z{=}d_{\rm eff})$, which was used for determining d_{eff}. Because the dielectric constant of water ε satisfies the condition $|\varepsilon|>>1$, for the wave component of thermal radiation the value of $d_{\rm eff}$ is equal to the skin-depth

$d_{sk} = \lambda / (4\pi \, Im\sqrt{\varepsilon})$ For the near-field component one has $d_{\mathrm{eff}}(D,h)<d_{\mathrm{sk}}$. In our measurements we have obtained $d_{\mathrm{eff}}(D=1\mathrm{cm},h=0)=0{,}5d_{\mathrm{sk}}$.

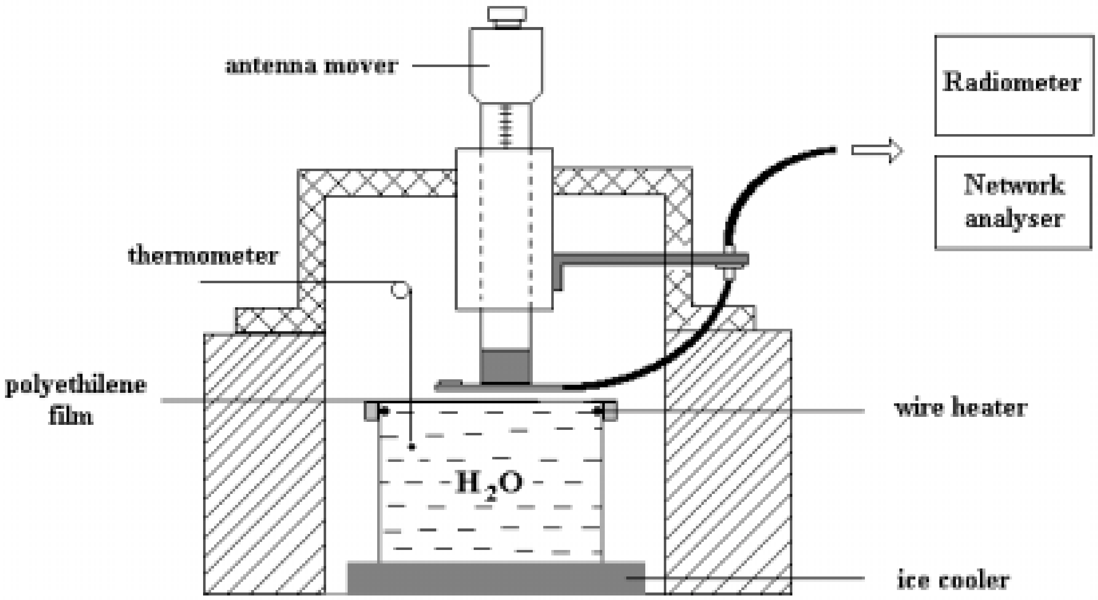

Figure 7. Measurements scheme.

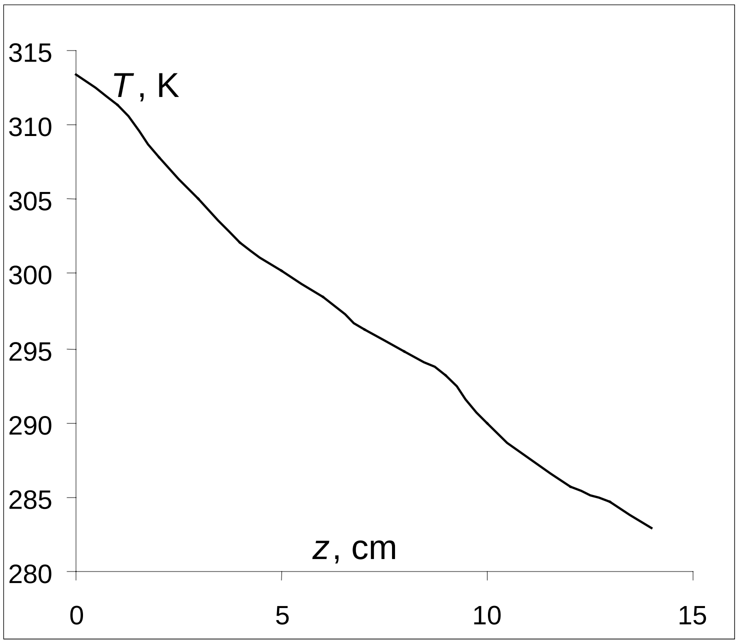

Figure 8. Temperature profile in water.

The expression for the effective radiobrightness temperature at a given wavelength λ could be written in compact form as:

$$T_b(h,D) = \int_{-\infty}^{0} T(z)K(h,D,z)dz, \qquad (1)$$

where h is the height of the antenna above the surface of medium, D is the effective antenna diameter. It is possible to represent the kernel K of (2) as a sum of the quasi-stationary field and the wave field parts. The quasi-stationary component dominates, if $D \ll \lambda$ and $h \ll \lambda$. In this case the depth of the layer which gives the main contribution in the value of measured thermal emission in (1) (the effective depth of radiobrightness formation) $d_{eff} = \left| \int_{-\infty}^{0} zK(h,D,Z)dz \right|$ could be much less than the absorption skin-depth d_{sk}. The wave field component dominates if $D \geq \lambda$ or $h \geq \lambda$, and $d_{eff} \rightarrow d_{sk}$. In any case, for the received radiation including both field components, d_{eff} will be a function of the antenna height and size, i.e., $d_{eff}=d_{eff}(h,D)<d_{sk}$. Integral equation (1) has been applied in [4] for the near-field effect calculations and for the statement and numerical simulation of the inverse problems of the temperature profile retrieval from the known dependence $T_b(D)$ or $T_b(h)$. It is used below for calculations of T_b by the known profile $T(z)$ to compare the obtained values with the experimental results.

Measurements have been carried out on temperature-stratified water at three different values of salinity: $S = 0$, $1.8 \cdot 10^{-3}$ and $5.0 \cdot 10^{-3}$ g/cm^3. At the water salinity $S = 1.8 \cdot 10^{-3}$ g/cm^3 the skin-depth at the given frequency is temperature independent and the medium can be considered as homogeneous. The results for the first two values of salinity are shown in Fig.9,10. The calculation of T_b at $S = 0$ have been done using the theory of a homogeneous medium with the dielectric constant of water at temperature $T(z = -d_{eff})$.

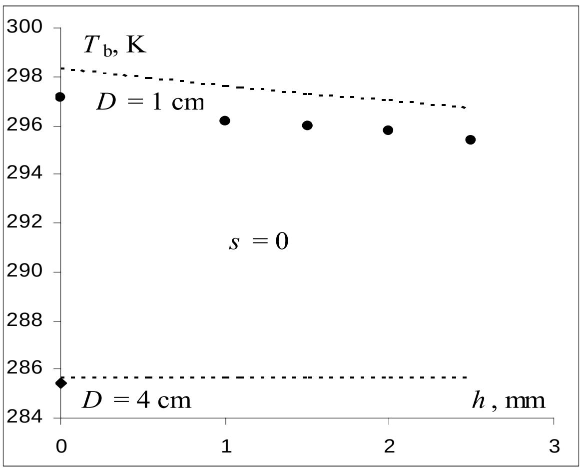

Figure 9. Measured dependence of radiobrightness on the antenna height at antenna sizes D = 1cm and D = 4 cm for the distilled (deionized) water (S=0). Circles-measurements, dashed line – calculation.

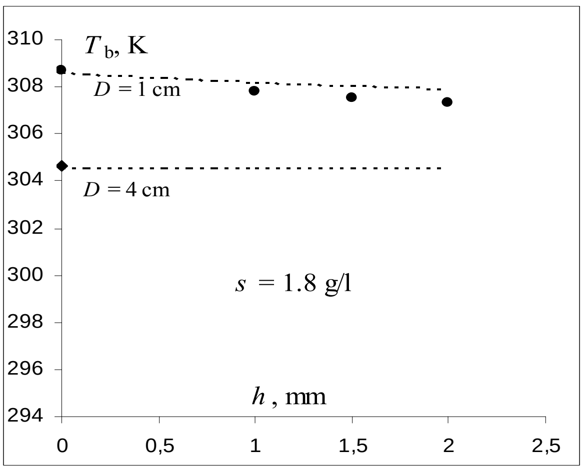

Figure 10. The same as in Fig.9, but at water salinity $S = 1.8 \cdot 10^{-3}$.

One can see in Fig.9,10 that the measurements and the results of calculation of T_b from the integral (1) are in very good agreement. So, the dependencies of radiobrightness on the antenna height and size are successfully detected. For distilled water (Fig.9) stronger effects have been observed, but in this case the dielectric constant of water is temperature-dependent, therefore, the discrepancy between measurements and calculations is higher than for homogeneous water (Fig.10).

The dependence $d_{eff}(D,h)$ was also determined, which appeared to be in a good agreement with the theoretical calculations (see Fig.11). The calculated and the measured dependence of the effective depth d_{eff} on water salinity at contact measurements (h = 0) and the same dependence for the absorption skin-depth d_{sk} are presented in Fig.12. The well-seen difference between d_{eff} and d_{sk} is the most reliable evidence of the near-field effect. These experimental results testify to the presence of the near-field component in the thermal radiation of medium [3].

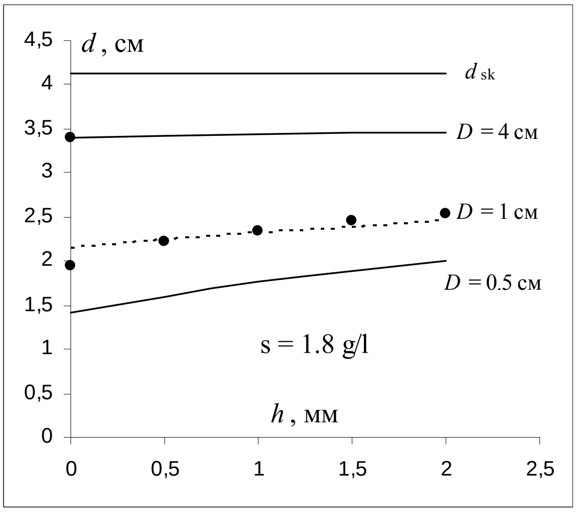

Figure 11. Effective thickness d_{eff} as a function of antenna height for different antenna sizes. Circles – measurements; lines – calculations.

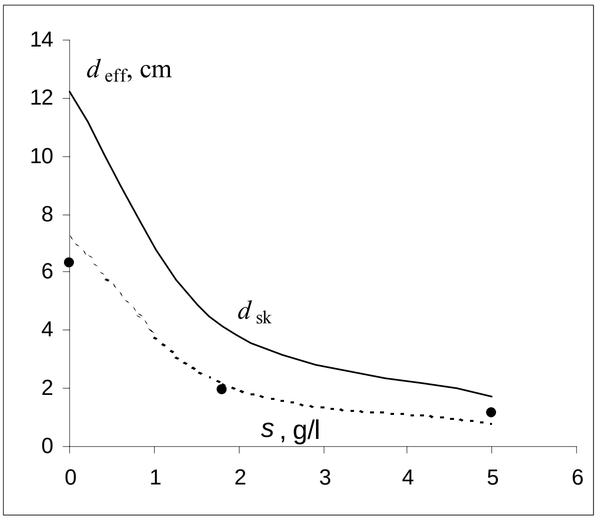

Figure 12. Measured (circles) and calculated (dashed) dependence of the effective depth of radiobrightness formation on water salinity. Solid line – calculated dependence of the absorption skin-depth.

4. Retrieval of subsurface temperature profile

The discovered dependence $d_{eff}(D,h)$ can be used to develop new methods of the radio thermal diagnostics of media. In this study we present first results of a water subsurface temperature profile retrieval using the dependence $d_{eff}(D)$. The brightness temperature of water has been measured using two antennas with D = 1 cm and 4 cm in the process of water surface heating (using the wire heater). Also, direct measurements of surface temperature $T(z=0)$ by a contact thermometer have been used as the third antenna size D = 0 because $T_b(D=0) = T(z=0)$.

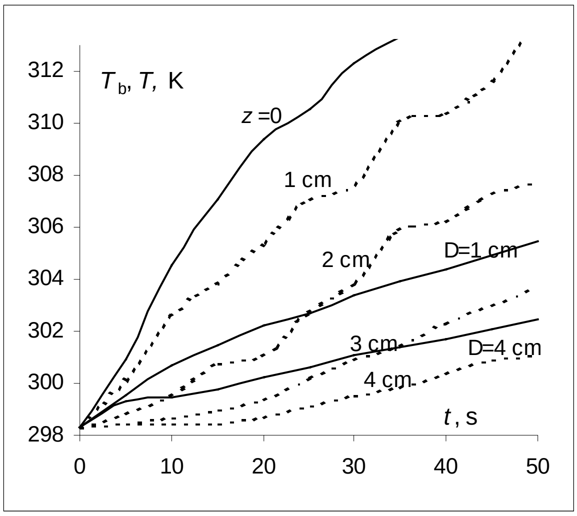

Figure 13. Measurements of the brightness temperature dynamics – solid lines; contact measurements temperature dynamics at different levels inside the water – dashed lines.

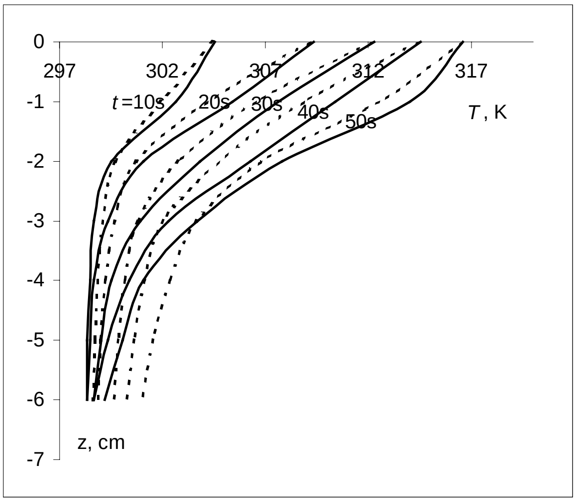

Figure 14. Profiles *T(z)* retrieved in time interval 10 s by measurements of $T_b(D)$ – dashed lines; profiles *T(z)* measured by contact thermometer..

The algorithm and the program for *T(z)* retrieval from the integral equation (1) was developed on the basis of the Tikhonoff method of ill-posed inverse problems solution [4]. The retrieved profiles *T(z)* during the process of heating of a water surface layer are shown in Fig.14 along with the directly measured temperature profiles. One can see that the accuracy of *T(z)* retrieval is about ~(0.5-1) K for $0<z<d_{sk}\approx 4$cm.

5. Conclusion

Further development of the proposed technique may go by increasing the sensitivity of a radiometry system at heights $h>h_{max}$ (in this study, h_{max}=2.5 mm) and decreasing antenna size (in the range D<1 cm). To this end, the antenna should be matched for each height, which is not a difficult problem. At the same time, the efficiency of the electrically small antennas inevitably decreases with increasing h/λ and decreasing D/λ. A possible approach to the solution of this problem might be improving a miniature antenna construction and the use of materials with extremely low ohmic losses, such as high-temperature superconductors. The effectiveness of these materials in terms of miniaturization of antenna devices was examined in [5,6]. Our preliminary calculations show that near-field radiometric measurements are feasible, at least in the height interval $0<h/\lambda<0.1$ and for antenna sizes $D/\lambda>0.01$. In this case, the effective depth of the radiating layer will vary in the range $0.2d_{sk}<d_{eff}<d_{sk}$. This single-wave method may prove simpler for implementation than the known multi-frequency methods [7].

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