Near- Field Subsurface Radiothermometry

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Abstract - New methods of subsurface temperature profile retrieval based on measurements of thermal radio emission of homogeneous lossy dielectric half-space (such as living tissues, water, soils) in the near-field zone (in contact or at small distance above the surface). The first method uses the radiobrightness dependence on the height of the antenna above the surface, the second - the dependence of radiobrightness on the antenna size.

I. Introduction

Radiometric methods have been widely applied for remote sensing of living tissues, water and soils. The best surface resolution is achieved in contact radiometry [1]. The temperature profile could be retrieved by multi-channel measurements using the frequency dependence of the radiobrightness (T_b) on the basis of the solution of emission transfer equation for the half-space z ≤ 0 [2]:

$$T_b(\lambda) = (1-R)\int_{-\infty}^{0} T(z)\gamma(\lambda)\exp(\gamma z)dz\,, \quad (1)$$

where λ is the wavelength, *R* is the reflection coefficient, *T*(*z*) is the temperature profile in dependence on depth *z*, γ is the absorption coefficient.

It is a difficult problem both from mathematical and measurement point of view. Mathematically, the equation (1) is an ill-posed Fredholm integral equation of the first kind, and for its solution it is necessary to apply regularization methods which use additional *a priori* information about the exact solution. For multi-channel measurements there is also a number of technical difficulties related with calibration, adjusting different antennas for the same place one after one, high expenses, etc.

In the paper [3] it was shown, that in general the equation (1) can be inapplicable for the contact measurements because of the quasi-stationary field influence, especially in the cases of strong absorption in medium (where for real and imagery parts of permittivity ε it takes place $\varepsilon_1 \approx \varepsilon_2$) and for small (relative to wavelength in medium) antenna sizes. The solution of this problem has been obtained in [3] on the base of wave approach, and the expression for antenna temperature at given wavelength λ could be written in compact form as:

$$T_a(h,D) = \int_{-\infty}^{0} T(z)K(h,D,z)dz, \quad (2)$$

where *h* is the height of antenna above the surface of the half-space, *D* is the effective antenna diameter. It is possible to represent the kernel *K* of (2) as a sum of quasi-stationary field and wave field parts. The quasi-stationary component dominates, if *D* << λ and *h* << λ. In this case the depth of layer which gives the main contribution in the value of measured thermal emission in (2) is much less then the skin-depth $d_s = 1/\gamma$ for wave field component which dominates, if *D* ≥ λ and *h* ≥ λ.

Thus, it appeared possible to propose two new methods of measurements of the thermal emission in dependence on the depth of its formation in the medium. The first of them is based on measurements of $T_a(h)$ in the range 0 ≤ *h* ≤ λ at *D* << λ, the second on measurements of $T_a(D)$ in the range 0 < *D* ≤ λ at *h* chosen in 0 ≤ *h* << λ. It is also possible to combine both methods as well as to combine each one of them with multi-channel method.

II. Numerical Simulation

Let us consider the homogeneous medium with ε = 40 + *i* 13 (the same as in [3]). Suppose the field distribution on antenna aperture as:

$$E_s(r) = \exp(-4r^2 / D^2)\,. \quad (3)$$

It is possible to express the kernel *K* in (2) as:

$$K(z) = \frac{K_1(z)+K_2(z)}{\int_{-\infty}^{0}(K_1(z)+K_2(z))dz}, \quad (4)$$

where K_1 represents the contribution of wave field and K_2 - of quasi-stationary field. The normalization is chosen so that at *T*(*z*) = *const* = T_0, $T_a = T_0$. The values in (4) can be written :

$$K_1 = \int_0^{\pi/2} \sin\theta(1+\cos^2\theta)\left(1-\frac{|R_E(\theta)|^2+|R_H(\theta)|^2}{2}\right)\times$$
$$\times\gamma_1(\theta)\exp(\gamma_1 z)\left|E_s^1(\theta)\right|^2 d\theta,$$

$$K_2 = \int_0^{\infty} sh\theta\, ch\theta\,(1+sh^2\theta)(A(\theta)+B(\theta))\times$$
$$\times\exp[\gamma_2(\theta)z - 2k_0 h\sqrt{ch^2\theta-1}]\left|E_s^2(\theta)\right|^2 d\theta,$$

$$\gamma_1 = 2k_0\,\mathrm{Im}(\sqrt{\varepsilon-\sin^2\theta}, \gamma_2 = 2k_0\,\mathrm{Im}(\sqrt{\varepsilon-ch^2\theta},$$

$$R_E = \frac{\cos\theta-\sqrt{\varepsilon-\sin^2\theta}}{\cos\theta+\sqrt{\varepsilon-\sin^2\theta}},$$

$$R_E = \frac{\sqrt{\varepsilon - \sin^2\theta} - \varepsilon\cos\theta}{\sqrt{\varepsilon - \sin^2\theta} + \varepsilon\cos\theta},$$

$$A = \frac{4}{sh^2\theta + \left|\sqrt{\varepsilon - ch^2\theta}\right|^2},$$

$$B = \frac{4(ch^2\theta + \left|\sqrt{\varepsilon - ch^2\theta}\right|^2)}{|\varepsilon|^2 sh^2\theta + \left|\sqrt{\varepsilon - ch^2\theta}\right|^2},$$

$$E_s^1 = \exp[-(1/4k_0 D\sin\theta)^2],$$

$$E_s^2 = \exp[-(1/4k_0 D ch\theta)^2],$$

where $k_0 = 2\pi/\lambda$.

For the first method, when we have measured the dependence $T_a(h)$ at given wavelength λ and at fixed antenna diameter D, it is possible to retrieve the temperature profile $T(z)$ from the solution of (2). The corresponding inverse problem has been solved on the basis of Tikhonov's method of generalized discrepancy which has been used early for the solution of the multi-channel inverse problem [2]. In Fig.1 it is possible to see results of numerical simulation of temperature profile retrieval by measurements given in Fig.2 at D = 1cm.

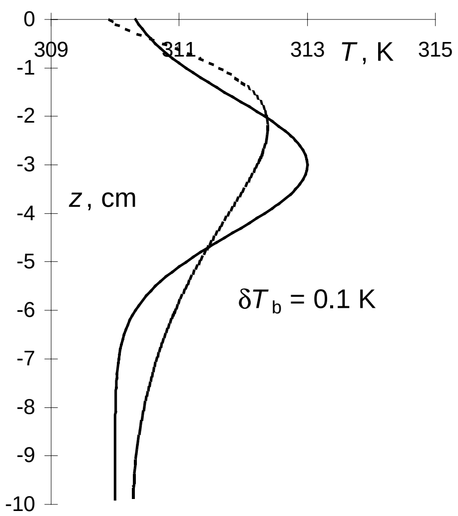

Fig.1. Retrieval of $T(z)$ by $T_a(h)$ (dashed line). Solid line is the initial profile $T(z)$.

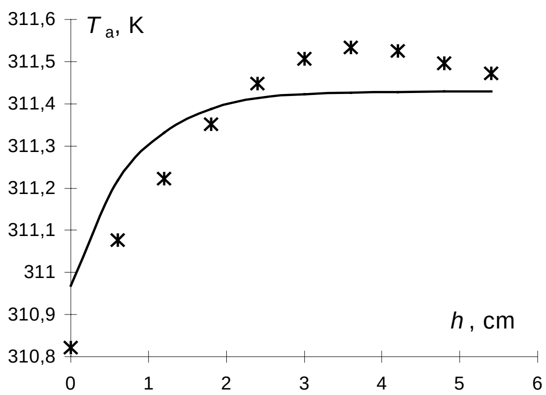

Fig.2. "Measurement data" (points) used for retrieval at rms of random error δT_a = 0.1 K and $T_a(z)$ for initial profile (solid line).

For the second method, when the dependence $T_a(D)$ is measured at fixed h = 0.1 cm, corresponding results are given in Fig.3,4.

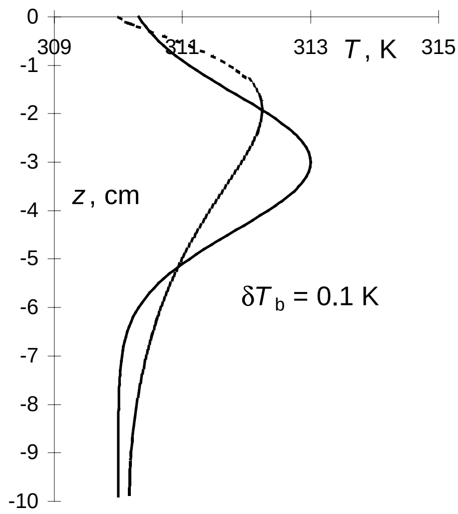

Fig.3. Retrieval of $T(z)$ by $T_a(D)$.

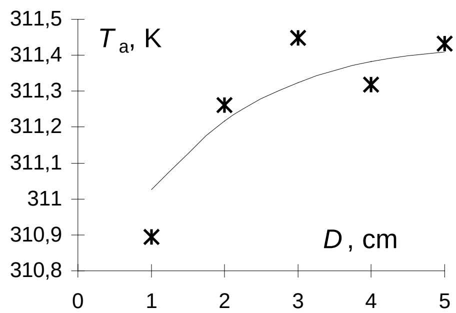

Fig.4. "Measurement data" used for retrieval (points) in Fig.3. Solid line is $T_a(z)$ for initial profile in Fig.3.

III. Conclusion

One can see that the results for both methods are similar and they show the real possibility to retrieve the temperature subsurface profile. It is clear also that from the practical point of view it is more easy to realize the measurements $T_a(h)$ than $T_a(D)$. The main difficulty in both methods is related with the necessity to use small (electrically short) antennas because of the sharp fall of the efficiency for such antennas. But now it is possible to solve this problem using high temperature supercoductive (HTSC) antennas [4].

IV. References

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