MICROWAVE SUBSURFACE PROFILE THERMOMETRY

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ABSTRACT

This paper refers to the inversion of radiometric data in 0.8 – 3O cm rang. Some new theoretical and experimental approaches in subsurface radiometry have been proposed. Using special measurement method for eliminating of boundary reflection influence the sounding of water and soils have been carried out. Evolution of thermal stratification, wind influence, internal waves, natural thermal films in water have been investigated as well as diurnal temperature variations and frozen depth in soils. The thermal evolution equations have been derived and on the base of these equations the problem of one-frequency subsurface temperature profile monitoring ana thermal history retrieval have been solved.

I. INTRODUCTION

Subsurface radiothermometry is based on the fact that thermal radio emission is formed in a layer with the thickness which depends on the wavelength. The sub-surface penetration depth (skin-depth) depends also on dielectric parameters of the medium and ordinary increases with decreasing frequency of operation. Therefore, the measurements of brightness temperatures $T_B(\nu_i)$ at a number of different frequencies contain the information about surface temperature profile $T(z)$. That information can be used in very different applications, such as medical [1-2] , remote sensing of Earth [3-5], hydrophysics [7-8], planet radio astronomy [9-10]. The subsurface sounding has three main difficulties. First, there is the boundary reflection influence on the values and spectral dependence $T_B(\nu)$. This effect is negligible when reflection is small, ordinary when material does' t include water. Such a situation have a place in planet radio astronomy. In other case there is a need in compensation methods. In sounding of living tissues contact antennas nave been used [11]. For remote sensing applications we have proposed another method with the nadir-looking antenna under reflecting (metallic) screen [7].

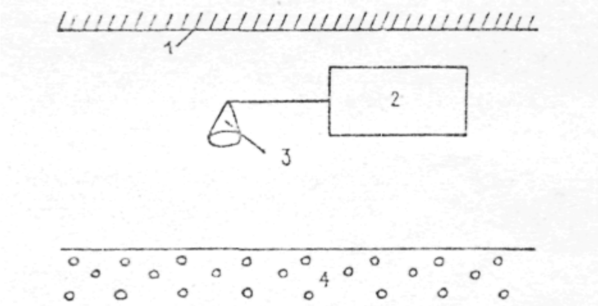

Fig.I. I- metall screen, 2- radiometer, 3- antenna, 4- medium

In this case brightness temperatures are not disturbed by emulating factors of reflection and defined by subsurface profile onlv:

$$T_Б(\lambda) = \int_{-\infty}^{0} T(z)\exp(-\gamma z)\,dz , \qquad (I)$$

where $\gamma(\lambda)$ - absorption coefficient. The second difficulty of subsurface sounding is the incorrect nature of equation (1) which is an example of Fredholm's integral equation of the 1-st kind. We chose Tikhonov's method in the form of generalized discrepancy principle, where *a priori* properties of exact solution (smoothness, boundness) are used [12]. It is the most mathematically consistent method. The retrieval accuracy in incorrect problems depends not only on measurements errors but also on $T(z)$ distribution, and on additional restrictions (if there is any), and on the set of frequencies.

Therefore, there is a need in numerical simulation to investigate the inversion quality.

Third, in real situation one has often strong lossy media (water, living tissue) or layered materials where ordinary radiative transfer theory is not consistent. The strong lossy medium was examined on the base of electrical field correlation function[7] and the main result is that (1) is correct if $\gamma = 2\pi / \lambda \,\mathrm{Im}(\sqrt{\varepsilon})$ (ε is complex dielectric permittivity). The layered materials have been investigated in [13] where result was derived in the form of linear equation familiar to (1) but with more complicated kernel.

1. SOUNDING OF WATER MEDIA

It is known that in thin surface layer (0.1 – 1 cm) appears non-uniform temperature distribution (thermal films") [14] with temperature decrease about $\delta T \sim 0.5 – 2$ K. The thermal films play the most important role in heat exchange between atmosphere and ocean.

It is possible to make artificial temperature stratification in water medium with greater temperature and thickness intervals. This provides the possibility of different hydrophysical investigations. One can observe and retrieve the evolution of temperature distribution due to thermal conductivity or by propagation of internal waves. The numerical simulation has shown [7] that for simple monotonous $T(z)$ it is suffice to use only 3 different properly chosen wavelengths. For profiles with one maximum it needs about 10 wavelengths. For retrieval with accuracy ~ 20% it needs accuracy of $T_B(\lambda)$ about 5 – 10% comparing with $T(z)$ variation (for natural thermal films $\delta T_B \sim 0.1 - 0.2$ K). One can get such nigh accuracy by calibration with water at two different temperatures. Another conditions are unchanged. In the cases of artificial distributions when $\Delta T \sim 5 – 10$ K the measurement error can be $\delta T_B \approx 1$ K.

We used the 3- cannel radiometric systems (0.8, 3 and 9 cm) to investigate the natural thermal films in laboratory. Fig.2 shows the influence of water-air temperature difference and of wind conditions on $T(z)$. It is clear that the influence of wind is much stronger.

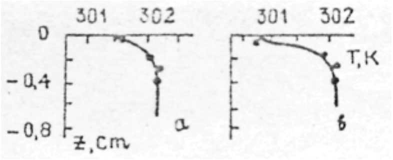

Fig.2. Retrieval of natural thermal film in water. Points - contact measurements, solid line - retrieval. a - without wind, b- in presence of wind

Another cannels (3, 9 and 13cm) have been used for investigation of artificially stratified water. Results on the Fig.3,4 show evolution $T(z)$ by cooling and diffusion from initial state with large value of ΔT. The retrieval results are in good agreement with contact measurements of T.

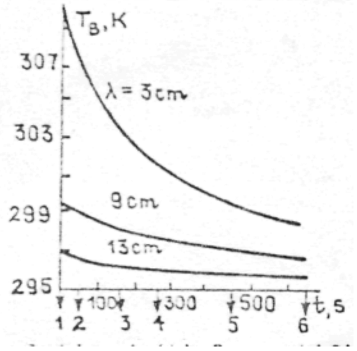

Fig.3. Evolution $T_B(t)$ for artificial water stratification.

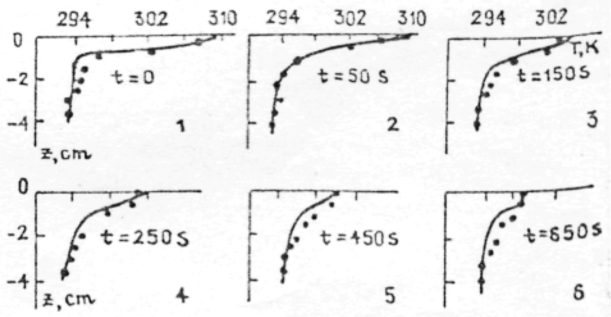

Fig.4-. Solid $-T(z)$ retrievals for moments marked with arrows on Fig.3. Points - contact -measurements

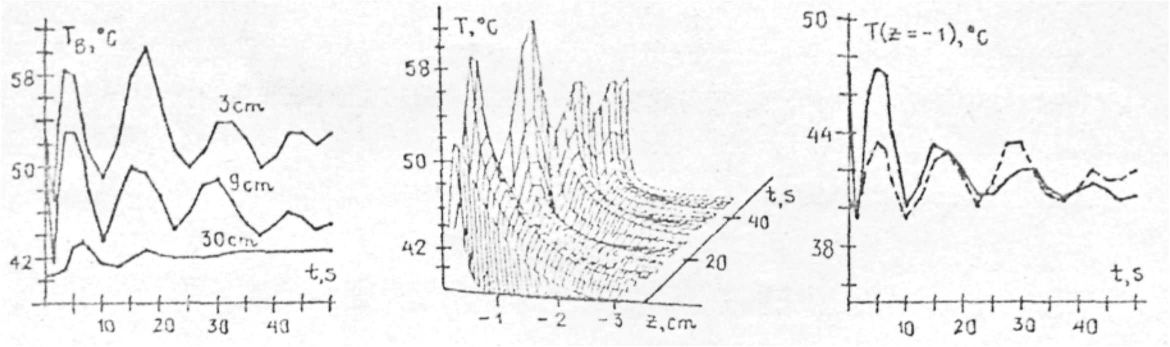

Fig.5. Thermal structure of internal wave retrieval, a – $T_B(t)$ dependence at λ = 3, 9 and 30cm; b - thermal structure of wave $T(z,t)$ in water; c -retrieved dependence (solid) $T(t)$ at z = -1 cm and contact measurement (dashed)

In stratified water medium the internal saves can exist and propagate. They lead to strong variations of $T(z)$and hence to variations T_B which firstly were observed in [8]. Here we present; the retrieval of wave thermal structure (see Fig.5)

2. RETRIEVAL OF SOIL SUBSURFACE PROFILES AND DETERMINATION OF FROZEN DEPTH

The radiometric measurements have been carried out in summer and in winter conditions [4,5]. The dielectric parameters of soil had uniform distribution and have been determined according [15]. It should be mentioned that in winter snow cover smoothes the influence of diurnal temperature variations and $T(z)$ profile is close to linear forts. In that case the reconstructed profile is given by:

$$T(z) = TB(d), \qquad (2)$$

where skin-depth d =1/γ(λ). Therefore, it is easy to determine frozen soil depth on the basis of one or two-cannel sounding

$$\tilde{z}^* = \frac{d}{T_B/T_0 - 1}, \; z^* = \frac{(T_{B_1}/T_{B_2})d_2 - d_1}{1-(T_{B_1}/T_{B_2})} \qquad (3)$$

where $\tilde{z}^*$ is estimation of soil depth z^*, T_0 is the surface temperature,T_0, T_B, T_{B1}, T_{B2} (^{0}C). The Fig.6 show the retrieved profiles and corresponding values of $T_B(d)$for two moments of diurnal temperature circle in summer conditions. First moment presents cooling, the second one – beginning of sun heating.

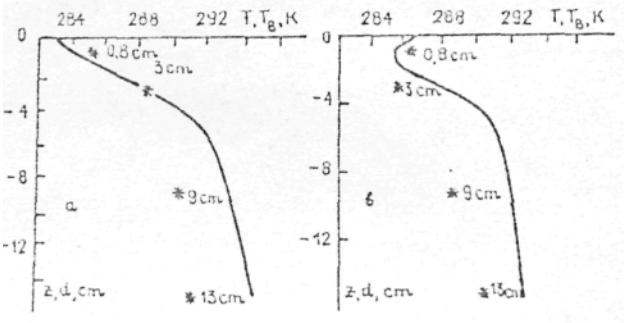

Fig.6. Retrieval of $T(z)$ -solid. Stars -$T_B(d)$ at λ = 0.8, 3, 9 and 13 cm.
a – 7^h30^m; b – 12^h20^m.

On the Fig.7 one can see results for two days in winter conditions.

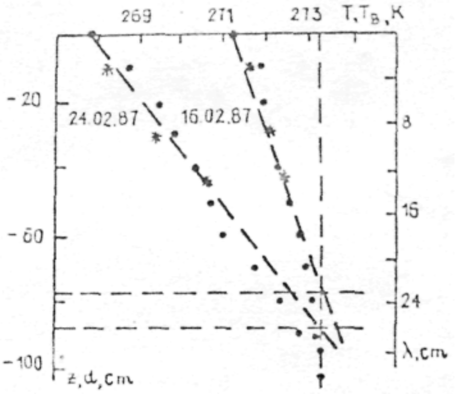

Fig.7. Sounding of frozen soil. Points -contact measurements of $T(z)$, stars - retrieved $T(z) = T_B(d)$ at λ = 3 , 9 and 13 cm according (2); dashed -estimation of z^*according (3) by T_B(λ=13 cm)

3. TERMAL EVOLUTION EQUATION AND RADIOMETRIC SOUNDING

The mutual solution (1) and equation

$$\frac{\partial T}{\partial t}(z,t)=a^2\frac{\partial^2 T}{\partial z^2}(z,t) \qquad (4)$$

have been obtained in [4,7] and have been called 1-st thermal evolution equation for boundary condition $T(0,t)=T_0(t)$:

$$T_B=\int_{-\infty}^{t}T_0(\tau)\left[\frac{\gamma a}{\sqrt{\pi(t-\tau)}}-(\gamma a)^2\operatorname{erfc}(\gamma a\sqrt{t-\tau})\,e^{(\gamma a)^2(t-\tau)}\right]d\tau \qquad (5)$$

and 2-nd thermal evolution equation for boundary condition $dT/dz(0,t)=-(1/k)J_0(t)$:

$$T_B=\int_{-\infty}^{t}J_0(\tau)\left[-\frac{a^2\gamma}{k}e^{(\gamma a)^2(t-\tau)}\operatorname{erfc}(\gamma a\sqrt{t-\tau})\right]d\tau \qquad (6)$$

If one has spectra $T_B(\lambda)$at moment t, (5,б) are Fredholm equations and $T_0(\tau)$, $J_0(\tau)$ are evolution of temperature and heat flax in past ("thermal history"). If one considers (5,6) with upper limit as variable, (5,6) are Volterra's equations and these equations provide the possibility of one-cannel monitoring of $T_0(t)$, J_0(t) and hence, using the known solution of (4) subsurface profile monitoring.

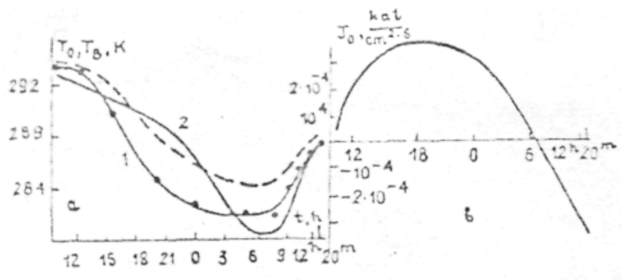

Fig.8. a) 1 - monitoring $T_0(t)$ by $T_B(t)$ at λ = 9 cm (dashed); 2 - retrieval $T_0(t)$ as thermal history by $T_B(\lambda)$ at $t = 12^h20^m$ (see Fig.6) , points -contact measurements of $T_0(t)$. b) thermal flux monitoring by $T_B(t)$at λ = 9 cm (dashed line in Fig 8a)

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