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RADIOMETRY OF DYNAMICS OF WATER-MEDIUM TEMPERATURE PROFILE BY INTERNAL-WAVE TRANSMISSION

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Measurements of thermal radio emission at wavelengths of 3, 9, and 30 cm are used to determine the temperature-distribution variations in the surface layer of a water medium by the excitation of internal waves *in it.*

Multi-frequency radiometric measurements allow the subsurface temperature profiles *T(z)* of various media to be determined [1-7]. The possibilities of radiometric monitoring of the temperature stratification of a water medium have been studied [3]. It has been shown that in fresh water the temperature distribution in a layer with a depth of up to 5-10 cm can be reconstructed from the brightness temperatures of the radio emission observed in the centimeter and decimeter bands. For simple distributions *T(z),* a reconstruction of better quality (with an error of not more than 10-20% of the total temperature differential) is obtained with the use of three or four wavelengths selected such that the corresponding skin-layer thicknesses cover the reconstruction depth interval. The effectiveness of the method has been studied in numerical experiments as well as on the basis of real measurements by comparing the reconstructed profiles *T(z)* with the data of contact measurements. Temperature-dynamics measurements were performed in the surface layer of an artificially stratified water medium at a depth of up to several centimeters; also measured were temperature differentials of 0.5-1 K of the natural thermal films produced in the unperturbed layer with a thickness of several millimeters at the water-air interface as well as the dependence of their parameters on the state of the surface (the presence or absence of wind).

One of the processes resulting in temperature-profile variations in the surface layer of a water medium is. for example, internal-wave propagation. A non-uniform temperature profile in a water medium causes a non-uniform density distribution, which creates conditions for internal-wave propagation as well. An internal wave causes periodic variations of the initial temperature distribution, and these variations can be determined by radiometry. An advantage of this method is non-invasiveness, i.e., the measuring device does not affect the process under observation.

The possibility of internal-wave monitoring is important for laboratory studies of internal waves in a temperature-stratified medium, such as the ocean. A considerable temperature differential - on the scale of the skin layer — can be created for successful implementation of the method under laboratory conditions (as distinct from natural conditions. The skin layer is considerably thicker in fresh water than in salt water; therefore, fresh water should be used in a laboratory experiment.

1. Measurement Procedure and Solution of Inverse Problem. Measurements were performed under laboratory conditions for an artificially stratified surface layer of water 1-3 cm thick with a temperature differential of 10-40 K (hot water over cold). The measurements were performed at wavelengths of 3, 9, and 30 cm, which provided a sounding depth on the order of 5 cm. A system of contact antennas [4, 8] with an overall linear dimension of -5 cm was used to eliminate the effect of reflection from the surface and to achieve the required space resolution. Control temperature measurements were performed at a depth of 1 cm using a contact gauge. The measurement setup is shown in Fig. 1(1- container with water, *2* - antenna system, 3 - contact temperature gauge). The first results of periodic measurements of brightness temperatures with internal-wave excitation were presented earlier [9].

The fluctuation sensitivity threshold of the radiometers was at least 0.1 K for a time constant of 1 sec. The studied water medium itself was used a calibration standard in the measurements, which practically eliminated the main sources of error that usually accompany absolute radiometric measurements. Brightness-temperature measurements for two temperature values of uniformly heated water in the container were used for calibration. One of these calibration measurements was performed before the creation of a heated surface layer at a water temperature of 20°C; the other, after

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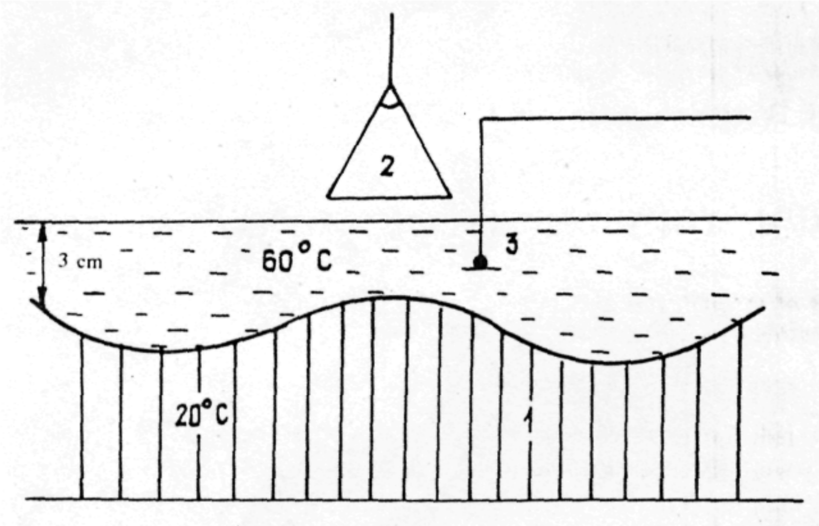

Fig. 1

measurement of the wave process, when the hot and cold water had been mixed. The temperature difference of the two calibration measurements was ΔT = 2 K. In the brightness-temperature range of 20-22°C, the measurement accuracy with allowance for the sensitivity of the radiometers is δT_{b0} = 0.1-0.15 K. However, the brightness-temperature values to be measures extend far beyond the calibration interval, so the error in this case rises in proportion to the deviation and can be estimated as $\delta T_b = [(T_b - 20)/\Delta T]\delta T_{b0}$, which is 2-3 K for λ = 3 cm, 1.5-2 K for λ = 9 cm, and about 1 K for λ = 30 cm at the initial moments. At the end of the measurements, when the amplitude of the T_b oscillations and the T_b values themselves have decreased, the measurement error is reduced proportionally.

The brightness temperature $T_b(\lambda)$ of thermal radio emission at wavelength λ is expressed in terms of the depth profile *T(z)* as

$$T_b(\lambda) = \int_{-\infty}^{0} T(z)\gamma(\lambda, T(z)) \exp\left[-\int_{z}^{0} \gamma(\lambda, T(z'))dz'\right]dz, \tag{1}$$

where $\gamma(\lambda)$ is the absorption coefficient.

Equation (1) is an equation of the first kind, and additional information on the desired function *I\z)* must be used to solve it. We employed a method based on Tikhonov's principle of the generalized discrepancy [10] using information on the quadratic summability or smoothness of $T(z)$ and also on its positive definiteness. The method has been studied thoroughly for the case of sounding of a water medium [3].

In the case in question, specifically, the temperature differentials are great and result, through the temperature dependence $\gamma(\lambda)$, in nonlinearity of Eq. (1).

The following iteration algorithm was therefore used to solve (1):

$$T_b(\lambda) = \int_{-\infty}^{0} T^{i}(z)\gamma(\lambda, T^{i-1}(z)) \exp\left[-\int_{z}^{0} \gamma(\lambda, T^{i-1}(z'))dz'\right]dz, \tag{2}$$

where, for calculation of the first approximation $T^1(z)$, the depth temperature, i.e., $T_0(z) = T(-\infty)$, was substituted into the kernel of Eq. (2). The solution was sought as the deviation of $T^i(z)$ from $T(-\infty)$ using *a priori* information on the positive definiteness of this value [10].

The effectiveness of the method was studied by a numerical experiment with a closed scheme. The initial profile $T(z)$ was specified, the $T_b(\lambda)$ values were calculated, the random error was added to the standard deviation δT_b, inverse problem (2) was solved, and the reconstructed profile was compared with the original. It was established that a second approximation in the iteration process was sufficient for the examined class of distributions *T(z)*. For the realized measurement accuracy, the reconstruction error is ~ 20% of the temperature differential (as compared with the depth temperature).

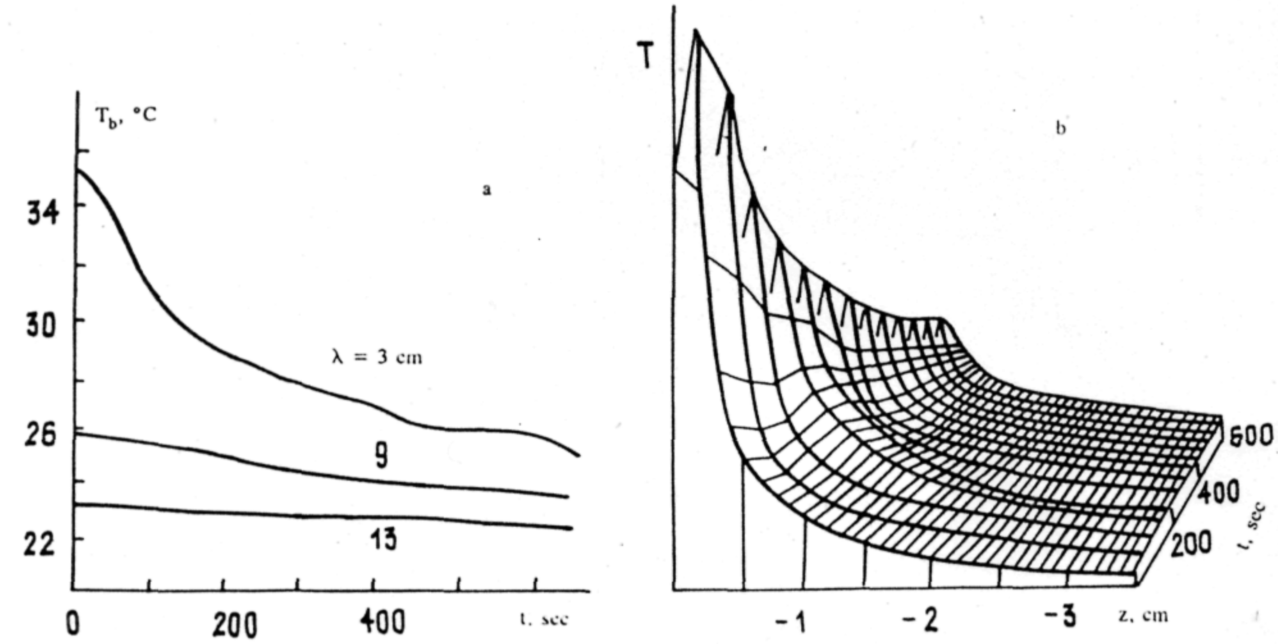

Fig. 2

2. Reconstruction of Internal-Wave Temperature Structure. Ii should be noted that temperature oscillations caused by internal-wave transmission are not the only process in a layer with pronounced artificial temperature stratification. This process takes place against a background of cooling of the heated surface layer and diffusion of the heat into deeper layers. The temperature dynamics of these processes was investigated earlier [3]. We used the obtained experimental data to construct the three-dimensional structure of this process. The dynamics of $T_b(t)$ at the three wavelengths is shown in Fig. 2a, and the corresponding dynamics of the reconstructed temperature profile $T(z,t)$ over a period of 10 min is depicted in Fig. 2b. Since the time-variable grid has more dimensions than earlier [3], it is apparent that this process is not entirely monotonic, which is evidently due to lowering of the thermal curve from the cooling surface at $t = 200$ sec.

The example shows that the processes associated with cooling of the stratified layer are considerably slower than the wave processes. Figure 3a shows the quasi-periodic variations $T_b(t)$ after movement of the wave producer at time $t = 0$ in a stratified layer ~3 cm thick. The variation period $\tau = 10\text{-}15$ sec, and the variation amplitude varies from ~ 10 K (~3 K at $\lambda = 30$ cm), gradually decreasing with a characteristic time scale $\tau_d = 30\text{-}40$ sec.

It is known that the internal-wave period must satisfy the condition $\tau > \tau_B$, where τ_B is the period corresponding to the Brunt-Vaisala frequency

$$\omega_B = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}}\,. \tag{3}$$

g is the acceleration due to gravity, and ρ is the density of the medium. Estimates show that $\tau_B = 3\text{-}5$ sec, i.e., the observed process satisfies the necessary condition. It can be seen that the oscillation period increases gradually, which is explained by the gradual decrease in the density gradient with temperature equalization.

The dynamics of the temperature profile $T(z,t)$ with internal-wave transmission, which was reconstructed from solution (2) and the data of Fig. 3a. is presented in Fig. 3b. The structure of the temperature wave is such that the amplitude maximum is reached at depth $z = -0.2$ cm. This can be explained by the effect of the surface, but the artifact cannot be eliminated. The set of wavelengths should include $\lambda = 0.5\text{-}1$ cm for a more thorough study ot the wave structure for thicknesses that are typical of natural thermal films and for reliable recording of the corresponding characteristics.

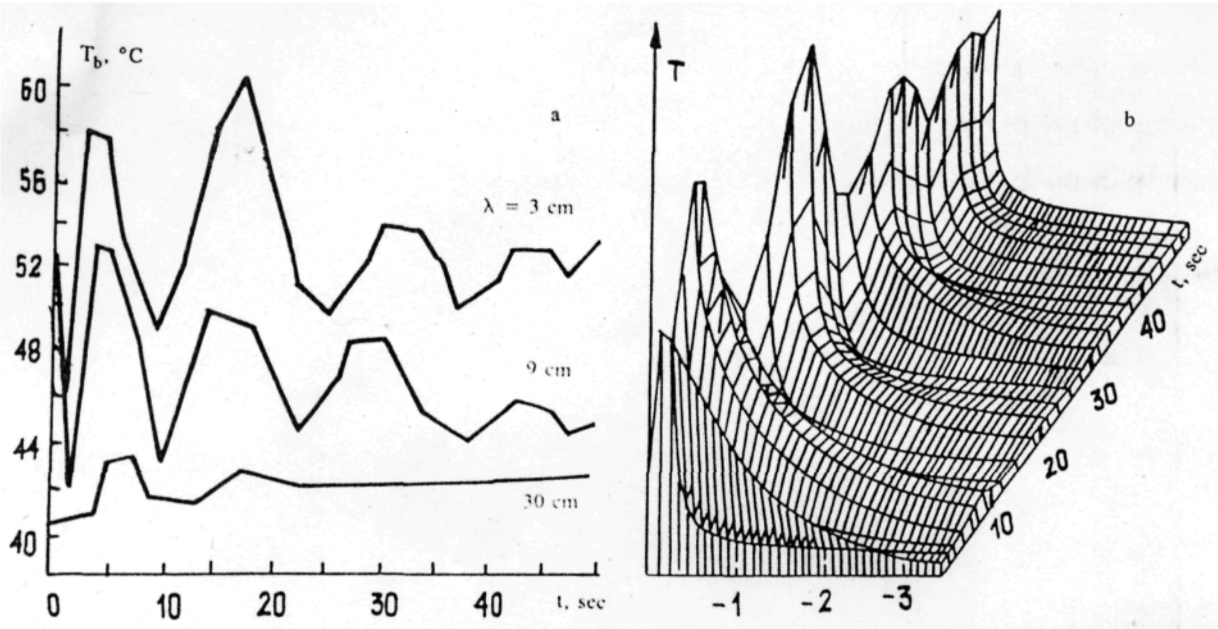

Fig. 3

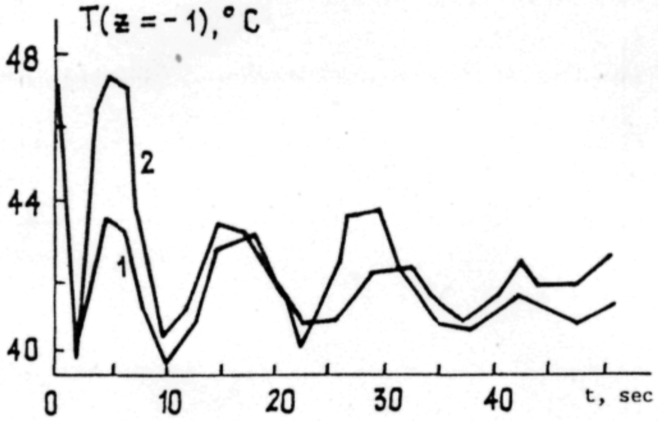

Fig. 4

The temperature at depth z = - 1 cm was measured by means of a contact gauge simultaneously with the measurements of T_b. For comparison, Fig. 4 provides temperature $T(z$ = - 1 cm) as reconstructed from solution (2) (curve 1) and measured by the gauge (curve 2). The contact-measurement error was ±0.1 K. It can be concluded that the deep wave structure is reconstructed fairly well. The greatest discrepancies occur near the initial moment, which can be explained by errors of T_b measurement as well as by the inertia of the contact gauge. The depth of the layer that encompassed by the wave process in Fig. 3b corresponds to the depth of the stratified layer (3 cm). Reconstruction of the internal-wave temperature structure also allows the structure of the wave perturbations of the water-medium density to be determined.

The possibility of radiometric monitoring of the temperature structure of a stratified water medium by internal-wave transmission has been demonstrated. This noninvasive method offers new possibilities for research in hydrophysics applications. For example, the study of convection and other dynamic processes in a thermally heterogeneous liquid that result in variations of surface-layer temperature is promising.

It should be noted that in natural media, especially in sea water, the recording of subsurface waves is highly problematic, due to the small temperature gradient and measurement difficulties in the presence of wave action, which modulates the reflection coefficient Of interest, however, are attempts at radiometric detection of the effect of internal waves on the parameters of a thermal film in a thin unperturbed surface layer of water, where the temperature gradient rises sharply. At the same time, considering that the potential effect cannot exceed a fraction of a degree, this problem should be solved at first in the laboratory, where radiometric monitoring of the temperature profile in thermal films has been accomplished [3].

LITERATURE CITED

1 . T. V. Tikhonov and V. S. Troitskii, Izv. Vyssh. Uchebn. Zaved., Radiofiz., **13**, No. 9, 1273 (1970).

2. K. Ya. Kondrat'ev and V. M. Shul'gina, Dokl. Akad. Nauk SSSR, **200**, No. 1, 88 (1971).

3. K. P. Gaikovich, A. N. Reznik, M. 1. Sumin, and R. V. Troitskii, Izv. Akad. Nauk SSSR, Ser. FAO, **23**, No. 7, 761 (1987).

4. K. P. Gaikovich, M. I. Sumin, and R. V. Troitskii, Izv. Vyssh. Uchebn. Zaved., Radiofiz., **31**, No. 9, 1104 (1988).

5. K. P. Gaikovich and A. N. Reznik, Izv. Vyssh. Uchebn. Zaved.. Radiofiz., **32**, No. 11, 1343 (1989).

6. K. P. Gaikovich, A. N. Reznik, and R. V. Troitskii, Izv. Vyssh. Uchebn. Zaved., Radiofiz., No. 12, 1467 (1989).

7. K. P. Gaikovich, Issled. Zemli Kosmosa, No. 6, 71 (1990).

8. V. S. Troitskii, V. A. Aranzhereev, A. V. Gustov, et al., Izv. Vyssh. Uchebn. Zaved., Radiofiz., **29**, No. 1, 62 (1986).

9. K. P. Gaikovich, A. N. Reznik. and R. V. Troitskii, in; Abstracts of Proceedings of Third All-Union School-Seminar "Methods of Hydrophysics Research" [in Russian], Part 2, Kaliningrad (1989), p. 27.

10. A. N. Tikhonov, A. V. Goncharskii, V. V. Stepanov, and A. G. Yagola, Regularizing Algorithms and *A Priori* Information [in Russian], Nauka, Moscow (1983).