THERMAL SOUNDING OF THE ATMOSPHERIC BOUNDARY LAYER IN THE CENTER OF AN OXYGEN ABSORPTION LINE

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A radiometric method is proposed and checked experimentally for remote sensing of the atmospheric boundary layer in the absorption maximum of the 60-GHz oxygen line. The algorithm for solving the inverse problem is based on the Tikhonov method. By means of it, the temperature profile of the boundary layer up to a height of 500 m can be reconstructed with an accuracy ~0.5 K.

The atmospheric boundary layer situated between the underlying surface and the free atmosphere has, depending on various factors, a height of from 100 to 1000 meters. The boundary layer plays an important role in the interaction of the atmosphere with the earth's surface, the nearness of which causes exceptional diversity in the air-temperature profile T(h). To obtain information about the high-altitude temperature distribution in the boundary layer is, however, very difficult. Using aerological sounding, because of the high rate of climb of the radiosonde, only two or three values of the boundary-layer temperature can be obtained, spaced at heights of usually more than 300 m. This is clearly insufficient for determining the high-altitude temperature distribution of the boundary layer.

Statement of the Problem. In radiometeorology there are well-known methods for the remote sensing of the temperature profile of the troposphere by radiometric measurements of the atmosphere's own radiation, on the slope of the oxygen absorption band $\nu = 53 + 56$ GHz [1-3]. But to achieve a sufficiently high resolution in the boundary layer at these frequencies, it is necessary to make measurements at very small angles, which presupposes the use of large antennas with narrow radiation patterns. The accuracy of absolute measurements is then reduced, while for thermal sensing of the boundary layer very high precision measurements are required (not worse than 0.1 K), since variations in the intensity of the radiofrequency emission of the boundary layer are slight. In reconstructing the temperature profile T(h) in the boundary layer, the difficulties of solving the inverse problem also arise. Methods of statistical regularization developed in [1, 2] propose the use of information in the form of covariation interlevel coupling of T(h). For the boundary layer, the use of this method is made difficult, since the spatial and temporal diversity of the T(h) profiles is too great, and it is not possible nor justified in practice to select some representative statistical ensemble with stable covariance couplings.

The physical basis of thermal sensing of the boundary layer is the use of the atmosphere's own thermal radiofrequency emission in the absorption maximum of the oyxgen band $\nu = 60$ GHz [4], where the effective thickness of the layer forming the emission (skin-depth thickness) is ~300 m. As usual, by the thickness of the layer forming the emission is understood the height H_B from the surface of the earth in which the absorption $\tau(H_B) = \frac{1}{\cos\theta}\int_0^{H_B} \gamma_\nu(h)\,dh = 1$. For the boundary layer, we may consider that, with a sufficient degree of accuracy, the absorption coefficient $\gamma_\nu(h) = \text{const} = \gamma_\nu(0)$, and $H_B = [\cos\theta/\gamma_\nu(\theta)] \approx 300\cos\theta$(M), where θ is the zenith angle of the sounding. And so, thermal sounding of the boundary layer is by the reception of radiofrequency radiation of the atmosphere at various zenith angles in the range $\theta = 0 + 90°$. With this, the thickness of the layer forming the emission changes in the limits $H_B \approx 0 + 300$ m.

As an initial value for obtaining physical information about the atmosphere in the radiofrequency range, it is usual to use the brightness temperature value T_B, the expression of

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which is in our case

$$T_B(\theta) = \frac{1}{\cos\theta}\int_0^H T(h)\gamma(h,T)\exp\left(-\frac{1}{\cos\theta}\int_0^h \gamma(h',T)dh'\right)dh = \int_0^H T(h)K(h,\theta)dh, \quad (1)$$

where H ≈ 2 km, the upper limit above which the atmosphere's contribution to the radio emission can be neglected; K is the kernel.

Equation (1) is the Fredholm equation of the first kind, the solution of which is, as is well known, not a well-behaved problem. The choice of inversion algorithm (1) depends on the type of a priori information used. The Tikhonov method of generalized discrepancy was used for solving the problem by inversion of (1).

Method of Solving the Inverse Problem. Let us rewrite (1) in operator form

$$KT = T_B^\delta, \qquad KT = \int_0^H T(h)K(h,\theta)dh, \quad (2)$$

where $T_B{}^\delta$ is the measured brightness temperature, with error in $T_B{}^\delta$, which satisfies the condition

$$(\delta T_B)^2 \le \|KT - T_B^\delta\|^2_{L_2}, \quad (3)$$

where $T_B(\theta)$ corresponds to the exact solution T(h).

In solving (3) we have to deal with not the exact kernel K, but with the approximate kernel K_z, a measure of the error z of which is evaluated from

$$z \ge \sup \frac{\|KT - K_z T\|}{\|T\|}. \quad (4)$$

This occurs both from digitization of the problem in its numerical solution, and from some nonlinearity (temperature dependence) of the kernel K, caused by the dependence of the radiowave absorption coefficient on temperature.

The solution of (2), as is well known, is not a well-behaved problem, i.e., during the solution of (2) without the use of sufficient additional a priori information about the distribution T(h), small values of the error δ correspond to an error in the determination of T(h), which can be any amount larger. The possibility of the Tikhonov method, which uses information of the quadratic summability and/or smoothness of the exact solution [5], for sounding the layer near to the earth is shown in [6].

From [5], in order to find an approximate solution of (2), it is necessary to minimize in the corresponding set the functional

$$M^\alpha(T) = \|K_z T - T_B^\delta\|^2_{L_2} + \alpha\|T\|^2_{W_2^1} = \int_{\theta_1}^{\theta_2}\left[\int_0^\infty K_z(\theta,h)\,T(h)dh - T_B^\delta(\theta)\right]^2 d\theta + \alpha\int_0^\infty \left[T^2(h) + \left(\frac{dT}{dh}(h)\right)^2\right]dh.$$

$\|x\|$ denotes the norm x as an element of the space L_2 or $W_2{}^1$ (for definition, see [5]). Then if the regularization parameter α is matched with the measurement error, so that it is determined as the root of the one-dimensional nonlinear equation for the generalized discrepancy

$$\rho(\alpha) = \|K_z T^\alpha - T_B^\delta\|^2_{L_2} - (\delta + z\|T^\alpha\|_{W_2^1})^2 = 0, \quad (6)$$

then as $\delta \to 0$, the approximate solution T^α converges uniformly to the exact solution T(h), which constitutes a great advantage of this method compared with others, the convergence of which it is usually not possible to prove. We note that if in (5), (6), the norm T appears in space L_2, then the convergence of the solution will also be in L_2. Minimization of the convex functional (5) is accomplished by gradient methods (for example, the method of conjugate directions). A measure of the error of the kernel z is determined by a numerical experiment. In the case considered, the value of z is determined mainly by a nonlinear equation associated with the temperature dependence of the kernel K, and the value of the corresponding error $z\|T\| \le 0.03$ K.

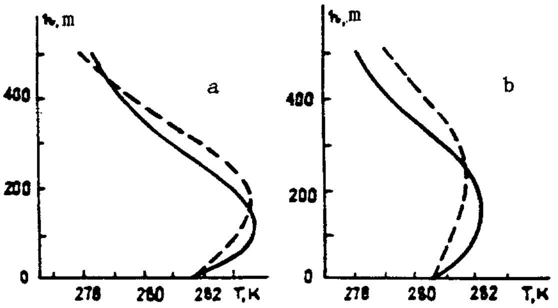

Fig. 1

The method enables flexible use to be made of additional information of the exact solution T(h) in the form of limits, if, for example, it is known that the exact solution is obviously bigger (or smaller) than some function. For this, it is necessary to minmize (5) in the set of absolutely defined functions, and, moreover, in place of T(h), to use the deviation of T(h) from the limit function. Minimization in this case is achieved by means of the method of projection of conjugate directions.

In solving the not-well-behaved problem, a valid relationship cannot be established in all cases between the measurement error and that of the reconstruction. A closed system numerical experiment is needed which will make it possible to judge the quality of the reconstruction for the class of exact solutions considered, and for the type of error considered, and also to choose the optimal measuring parameters (choice of angles).

An example of a numerical experiment is given in Fig. 1 (where the broken lines denote theoretical values, and the solid lines, the reconstructions). It may be seen that with the measuring accuracies $\delta T_B \approx 0.05$ K realized in present-day radiometry, good quality reconstructions of the T(h) profiles are achieved. Not only the presence of the ground temperature inversion of $\Delta T = 2$ K, but also a change in its height by $\Delta h = 50$ m is certainly detected. Numerical experiments carried out for different modeled profiles with various dispersion values δT_B^2 modeled by random normally distributed error, and also with various step sizes in the angle measurements made it possible to establish the following: The reconstruction at $\delta T_B \approx 0.05$ K is effective to a height of ~0.5 km, and the mean accuracy of the reconstruction is 0.1-0.2 K for smooth profiles, and 0.3-0.6 K for profiles with inversion (usually, the stronger and more abrupt the inversion, the larger the error). The number of independent measurements at different angles in the range 0-85° is not more than six, for the given error $\delta T_B = 0.05$ K. For more complex T(h) profiles, the number of independent measurements is larger than for simpler ones. With reduction in the measuring accuracy, that of the reconstruction is also reduced, but relatively slowly. These results are of interest in particular also because in an actual experiment it is rather difficult to get for comparison directly measured temperature data in the boundary layer, especially with an accuracy of some tenths of a degree; therefore, it is difficult to make general deductions about the effectiveness of the reconstruction.

Methods of Measurement. For the implementation of thermal sounding of the boundary layer, a high sensitivity superheterodyne radiometer at $\nu = 60$ GHz was developed and built at the Institute of Space Research, Academy of Sciences of the USSR. The radiometer sensitivity was $\delta T_B = 0.06$ K with integration time constant of the signal $\tau = 1$ sec. The receiving antenna was a scalar horn type with radiation pattern ~6°. Such an antenna has a low scattering coefficient outside the main lobe $\beta \approx 1\%$, causing an insignificant effect of the side and minor lobes of the radiation pattern on the measuring accuracy during angle scanning.

Calibration of the received radiofrequency radiation is by means of two "black" standard radiators, situated in the far field of the antenna, at D ~ 1 m, and having the temperature of either the surrounding air T_0, or of boiling nitrogen [3]. The brightness temperature of the nitrogen standard is calculated from the relationships for thermal radiation of stratified media. In calibration by this method, the expression for the measured brightness temperature takes the form

$$T_B = T_0 - (m/m_k)\ (T_0 - T_{N_B}), \tag{7}$$

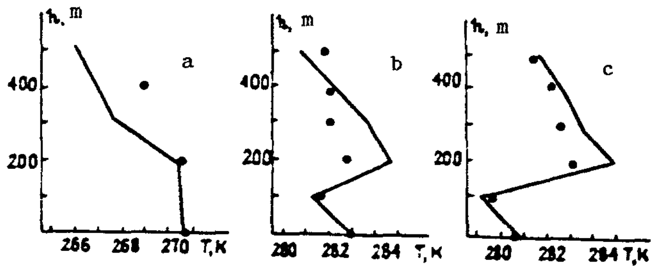

Fig. 2

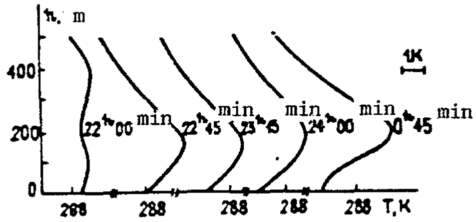

Fig. 3

where m is the difference in the readings of the recording instrument during reception of the radiofrequency radiation from the atmosphere and from the standard; m_k is the difference in the readings during reception from the standards at T_S and T_{N_B}.

Let us consider in more detail errors in measuring T_B when sounding at the maximum of the O_2 absorption band, ν = 60 GHz, a knowledge of which is necessary for solving the inverse problem of reconstructing the temperature profile. Differentiating (7):

$$\delta T_B = \delta T_0 + (m/m_k)(\delta T_0 + \delta T_{N_B}) + (T_0 - T_{N_B})\,\delta(m/m_k). \tag{8}$$

In Eq. (8), the first term is the error in measuring the ground temperature $\delta T_0 \approx 0.2$ K, which is connected only with the accuracy of the measuring thermometer and is statistical in character. It brings a constant additive contribution to the brightness temperature at all angles of sounding. This does not lead to distortion in the shape nor the function $T_B(\theta)$, nor the reconstructed function $T(h)$, but only shifts them parallel to themselves by the value of the thermometer error. In investigating the effectiveness of the remote method in comparison with a contact method, the thermometer error may be neglected, since it occurs in both methods with equal weight.

The precision in determining the brightness temperature of the nitrogen standard is $\delta T_{N_B} \leq 1.5$ K [7]. The third term in (8) is the reading fluctuation error, measured experimentally, and equal to ~0.03 K for a radiometer sensitivity $\delta T_B = 0.06$ K, and integration time of the signal $\tau = 10$ sec. Substituting the numerical values in (8), and taking into account that $m = (T_0 - T_B)\alpha = 3\alpha$ and $m_k = (T_0 - T_{N_B})\alpha = 200\alpha$, where α is the radiometer transfer coefficient, we find that the value of the random error is $\delta T_B \approx 0.06$ K.

An important favorable circumstance in thermal sounding in a region of very high absorption is that in which the measurements of the brightness temperature take place as if in a "black box," with temperature approximately equal to the ground temperature T_0 (the contrast of the brightness temperature of the atmosphere relative to T_0 is ~3 K). As a consequence, the temperature background T_G averaged over the side and minor lobes differs from T_B by less than 3 K, and changes in T_G during angle scanning may be neglected. In fact, the expression for the measured antenna temperature T_A reduced to the input of the horn takes the form

$$T_N = T_B - \beta(T_G - T_B). \tag{9}$$

Evaluations of the values T_B, T_G, and β (see above) show that the contribution of the second term in (9) does not exceed 0.03 K. Naturally, its change during angle scanning is even smaller (practically the situation is realized in which $T_A = T_B$).

Thus, use of a high-sensitivity radiometer, special antenna, and specific experimental conditions ($T_G \approx T_B$) makes it possible to realize such a high measurement accuracy.

Experimental Results. Thermal sounding of the boundary layer was made in autumn 1989-1990 on the TsAO testing ground in Ryl'sk, using a radiometer at ν = 60 GHz, and the methods described above. Measurements were carried out at six zenith angles θ = 0, 40, 60, 70, 80, and 85°. Then the thicknesses of the layers forming the radiation were $H_B \approx$ 300, 225, 150, 100, 50, and 25 m. Reconstructions of the quantity T(h) were compared with data from contact measurements made with a captive balloon. Examples of the reconstructions of different types of profile T(h) of the boundary layer are given in Fig. 2, from which it is seen that the stratification of T(h) is certainly recovered from radiometric measurements. Divergence between the contact (points) and remote (solid lines) results of the sounding in defining the amplitude of the inversion may be explained by the fact that ocntact measurements with the balloon "overlooked" the inversion maximum since the step size of the measurement was 100 m.

An important advantage of the radiometric method is the possibility of continuously tracking the temperature of the boundary layer. In Fig. 3 is shown a series of T(h) reconstructions during the development of the night inversion. In the initial stage, under cloudless conditions, radiation cooling of the layer occurred, and radiometric measurements clearly detected the transformation of the isothermal distribution T(h) in the earth-adjacent inversion. In the end stages there began to be formed in the earth-adjacent layer radiation fog, which slowed the cooling of the earth-adjacent layer and led to the formation of the slightly raised inversion. This is also recorded in the remote measurements at 0 h 45 min.

We note that in distinction to thermal sounding of the troposphere [1-3], cloud and fog do not affect the results of sounding the boundary layer, since the oxygen absorption at ν = 60 GHz is ten times larger than the absorption in even dense clouds. So, for example, the contribution of dense cloud with water content W = 2 kg/m^2 and lower boundary 200 m makes up only ΔT_B = 0.08 K in the radio radiation. The T(h) reconstructions shown in Fig. 2b, c were made in a dense fog, of thickness $\Delta h \approx$ 150 m.

The radiometric method of temperature sounding the boundary layer of the atmosphere makes possible:

thermal sounding of the boundary layer to a height of h ≈ 500 m with vertical resolution ~50 m in the height range h ≈ 0 + 200 m, or 100 m, in the range h ≈ 200 + 500 m;

reconstruction of the T(h) profile with an accuracy of 0.5°C;

detection with confidence of the main features of the temperature profile (isothermality, earth adjacent and raised inversion, etc.), and in follow-up studies;

measurements in the presence of any type of cloud cover.

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