Thermal Sounding of the Atmospheric Boundary Layer in the Oxygen Absorption Band Center at 60 GHz

Arkady V. Troitsky, Konstantin P. Gajkovich, Vladimir D. Gromov, Eugeni N. Kadygrov, and Alexander S. Kosov

Abstract—**A sensitive radiometer has been developed, which allows the measurement of the radiobrightness temperature with an error not greater than $\delta T_b \approx 0.06$ K. It provides the facility for the remote temperature sensing of the boundary layer. According to numerical experiments, the accuracy of the temperature profile recovery is about 0.2 K in the case of a simple profile, and about 0.5 K in the case of a profile with an inversion. Field experiments were conducted with the radiometer in elevation angle scanning mode. *In situ* temperature measurements were carried out simultaneously with the remote sensing.**

I. INTRODUCTION

THE boundary atmospheric layer is between the Earth surface and the free atmosphere. Depending on various factors it has a thickness varying from about 100 to 1000 m. The boundary layer plays an important role in the interactions between the atmosphere and the Earth surface. There are extremely wide variety of possible temperature profiles $T(h)$. However, acquisition of $T(h)$ is not a simple problem. Radiosonde soundings, due to high speed of the sounder at low altitudes, supply only a few points, under 300–500 m and do not determine in some cases main features of the temperature distribution of a boundary layer $T(h)$.

There are some methods of remote troposphere temperature sensing, using the wing of the oxygen absorption band at frequencies $f = 53 - 56$ GHz [1]–[3]. But, to achieve high vertical resolution in the boundary layer it is necessary to conduct measurements at very low elevation angles, which require a large size antenna with a narrow beam. The variations in radiation intensity of a boundary layer are small and the sensitivity of a radiometer must be very high (better than 0.1 K). And for this purpose the microwave radiometric measurement accuracy at low elevation angles become insufficient due to sidelobe effects. Also there are some difficulties in obtaining $T(h)$ when solving the retrieval problem. Methods of statistical regularization [1], [2] uses *a priori* information by covariational relationships between temperatures at different altitudes. It is difficult to use this method for most boundary layer problems, due to extraordinary spatial and time variety of $T(h)$ from which it is not possible practically to extract any representative statistical ensemble with a stable covariational bindings.

II. THE PROBLEM

The technique that we use for microwave remote sensing of the boundary layer temperature is based on measuring thermal radiation of atmosphere in the center of the oxygen absorption band near 60 GHz, where the skin depth is about 300 m. By definition the skin depth is equal to the height H_b where optical depth

$$\tau(H_b) = \frac{1}{\cos\theta} \int_o^{H_b} k_f(h)\, dh = 1.$$

For the boundary layer with a good accuracy may be put absorption coefficient $k_f(h) = \text{const} = k_f(0)$ and $H_b(h) = \cos\theta / k_f(0) \approx \cos\theta \cdot 300\,\text{m}$ where θ — sensing zenith angle. Thus, remote temperature sensing of the boundary layer is conducted by measurements of the radiobrightness temperature at different zenith angles $\theta = 0°$ to $90°$. In this case the depth of the contributing radiation layer changes in a range 0 to 300 m.

The expression for the radiobrightness temperature T_b has the form:

$$\begin{aligned} T_b(\theta) = \frac{1}{\cos\theta} \int_o^H T(h)\, k_f(h,T) \\ \cdot \exp\left[-\frac{1}{\cos\theta} \int_o^h k_f(h',T)\, dh' \right] dh \\ = \int_o^H T(h)\, K(h,\theta)\, dh \qquad (1) \end{aligned}$$

where K is the kernel; $H \approx 2$ km - upper limit of integration. The layers of an atmosphere, which are higher than 2 km, do not influence T_b.

Equation (1) is the type 1 Fredholm equation, the solution of which is, as known, an ill-conditioned problem. The choice of an inversion algorithm for (1) depends upon the form of *a priori* information used. The Tikhonov method in form of a generalized variation is used for solving (1).

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III. METHOD FOR SOLUTION OF THE INVERSE PROBLEM

Let's rewrite (1) in operator form.

$$K\,T = T_b^\delta \tag{2}$$

where $K\ T = \int_o^H T(h)\ K(h,\theta)\ dh$, T_b^δ — the measured brightness temperature realization, with the variation δT_b, which obeys the equation:

$$(\delta T_b)^2 = \left\|KT - T_b^\delta\right\|_{L_2}^2 = \int_{\theta_2}^{\theta_1} \left[T_b(\theta) - T_b^\delta(\theta)\right]^2 d\theta \tag{3}$$

where $T_b(\theta)$ — correspond to an exact solution of $T(h)$. In practice the kernel K employed for solving (1) is not exact, but has an approximation K_η which has the variance η, which is evaluated from

$$\eta = \sup \frac{\|KT - K_\eta T\|}{\|T\|}. \tag{4}$$

This results from both the discreteness of the problem, which arises from a numerical solution, and any nonlinearity of the kernel K, which is due to a temperature dependence of the absorption coefficient.

The solution of (2) is an ill-conditioned problem and it is requires some additional *a priori* information about $T(h)$ for correctly solving (2); otherwise any small variation in $T_b(\theta)$ may cause great variations in $T(h)$. The theoretical foundation of the application of the Tikhonov method to the problem of the boundary layer remote sensing was developed in [6].

For approximate solution (2), according to [5], it is necessary to minimize the functional

$$M^\alpha = \left\|K_\eta T^\alpha - T_b^\delta\right\|_{L_2}^2 + \alpha\|T\|_{w_2^1}^2 \tag{5}$$

on an appropriate manifold. Here $\|X\|$ is the norm of X as an element of the space L_2 or W_2^1 (there is the definition in [5]). The regularization parameter α is determined by variance of the measured values as a root of one dimensional equation for generalized variation

$$r(\alpha) = \left\|K_\eta T^\alpha - T_b^\delta\right\|_{L_2}^2 - \left(\delta T_b + \eta\|T^\alpha\|_{W_2^1}\right)^2 = 0. \tag{6}$$

In this case if $\delta T_b \to 0$ then the estimated solution uniformly approaches the exact solution $T(h)$. This is the great advantage of this method with respect to others, convergence of which is not proved as a rule. Note, that if the norm $\|T\|$ in (5), (6) is taken in the space L_2, then the convergence of the solution would be in L_2 too. Minimization of the convex functional (5) was produced by the gradient method (the conjugated directions method, for example). The measure of the kernel variance η was determined by the numerical experiment. In our case the value η is determined mainly by nonlinearity, which is due to the temperature dependence of the kernel K, and the appropriate variance is $\eta\|T\| < 0.03$ K.

By this method the additional information about the exact solution $T(h)$ in a form of restrictions can be flexibly used. For example, it may be known that the exact solution is obviously greater (or less) then some function. For this purpose instead of $T(h)$ the deviation from the restriction function can be minimized on the manifold of positively determined functions.

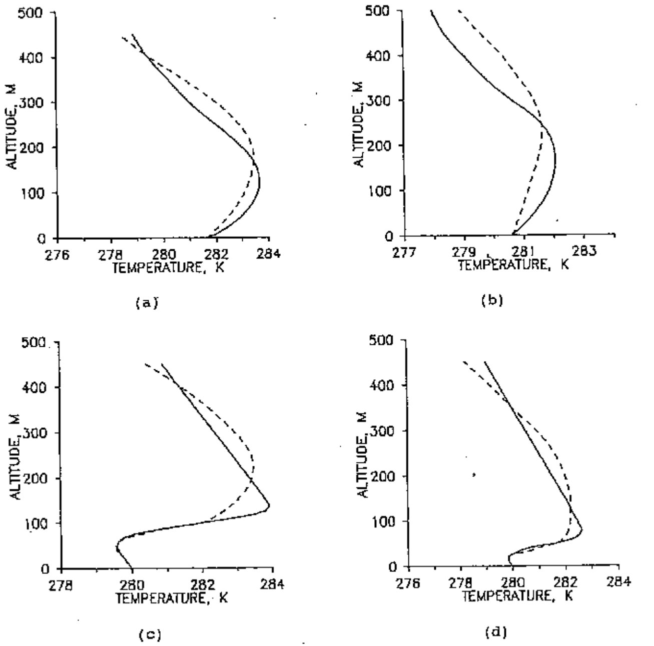

Fig. 1. Temperature profiles of the boundary layer retrieved in the model simulation (solid line), and the initial model data (dashed line); (a), (b) — profiles with inversion; (c), (d) — elevated inversion.

A numerical experiment was conducted for checking the accuracy of the solution. It also was used to find the optimal measurement parameters (set of angles). An example of the numerical experiment is shown in Fig. 1. It may be seen that a good accuracy of solution $T(h)$ can be obtained if the accuracy of the measurements $\delta T_b \approx 0.05$ K. Not only the fact of inversion or elevated inversion is firmly detected, but also change in inversion parameters (see Fig. 1). (a) and (b) correspond to inversion with thickness 120 m (a) and 175 m (b). (c) and (d) correspond to elevated inversions with base 50 m (c) and 25 m (d).The following results were found from the numerical experiments with different modeling profiles having different dispersion values δT_b^2 with normal distribution and with different set of angles. The solution of the problem under $\delta T_b \approx 0.05$ K is effective to the height ~ 0.5 km and the average accuracy of the solution is 0.1–0.2 K for flat profiles, and 0.3–0.6 K for profiles with temperature inversion (the greater and sharper the inversion — the worse the accuracy, as a rule). The number of an angle independent measurements in the range 0–85° is not greater than 6 in the case of $\delta T_b \approx 0.05$ K. For more complex profiles $T(h)$ the number of angles must be increased. With a decrease of the noise level δT_b, the accuracy of the solution is improved, but slowly.

The conclusions given here have particular interest because of the advantages of the numerical experiment with respect to the real experiment. The numerical experiment can be conducted in a much greater variety of conditions, and the accuracy of data in the numerical experiment is greater than that of the real one. It is difficult to acquire accurate data for comparative analysis in direct measurements of atmospheric temperature distributions, particularity with an accuracy of tenth degrees, what is necessary for main conclusions on the efficiency of retrieving procedures.

IV. THE MEASUREMENT METHOD

The high-sensitivity radiometer for the remote sensing of the boundary layer temperature at the frequency 60 GHz was developed in the Space Research Institute (Moscow) as by-product of the Relict-2 mission [8]. The sensitivity of this radiometer is $\delta T_b = 0.06$ K with an integration time $t = 1$ s. The antenna is a scalar horn with beamwidth of about 4°. The radiometer is an all solid state superheterodyne receiver. The input circuit of the radiometer consists of a waveguide isolator, reference noise source, and the DSB Schottky diode mixer with loss of 3 dB and noise temperature of 300 K. The local oscillator is an original InP Gunn effect oscillator with a frequency of about 60 GHz, low power consumption of 0.8 W and relatively high efficiency of 3%. The transistor IF amplifier has a power gain of 45 dB, a noise temperature at 200 K and a bandwidth about 2 GHz. The total equivalent noise temperature of the receiver doesn't exceed 800 K.

The antenna has a small scattering coefficient outside the main lobe, $\beta \approx 1\%$. It means small influence of the parasitic lobes on the measurement accuracy during the angular scanning. The calibration of the received radiation was conducted by means of two "black body" targets, placed in far field antenna zone $D \sim 1$ m [3]. One target was at the ambient temperature T_o, another was cooled to liquid nitrogen temperature. Radiobrightness temperature of nitrogen reference load T_{nb} was calculated by means of relations for radiation of multilayer medium. In this case the relation for the measured radiobrightness temperature is

$$T_b = T_o - (T_o - T_{nb})\, m/m_k \tag{7}$$

where m_k is the difference in recorded data in cases of atmosphere and T_o reference load radiation; m - the difference in recorded data in cases of reference loads radiation at T_o and T_{nb} temperatures.

For retrieval of the temperature profile, $T(h)$, the errors of the T_b measurements must be known. Let us take the differential of (7)

$$\delta T_b = \delta T_o + (\delta T_o - \delta T_{nb})\,(m/m_k) + (T_o - T_{nb})\,\delta(m/m_k). \tag{8}$$

In the expression (8) the first term is the error of the near surface temperature measurement $\delta T_o \approx 0.2$ K, which is the error of the thermometer and it is an additive error. This error has the same value at all angles θ . The error δT_o does not distort the form of the profile $T_b(\theta)$ and $T(h)$, but results in additive displacement. The δT_o in remote sensing has the same value as in the *in situ* methods.

The error of nitrogen reference load radiobrightness temperature $\delta T_{nb} < 1.5$ K [7]. The third term in (8) was determined experimentally and is near ~ 0.03 K at radiometer sensitivity $\delta T_o \approx 0.6$ K and integration time $t = 10$ s. Using data above and (8) it can be obtained that for $m = G_a(T_o - T_b) \approx 3G_a$, where G_a is the radiometer gain. So, the final error is about $\delta T_b \approx 0.06$ K .

In field measurements a secondary calibration was conducted by means of an internal reference noise source. This noise source produces a stable reference temperature step T_s calibrated by means of two "black body" targets as discussed above. The step T_s determines the scale of the instrument. For the absolute radiobrightness temperature measurements the radiation temperature in the horizontal direction was used. It was believed that it is equal to the air temperature near the Earth surface T_o.

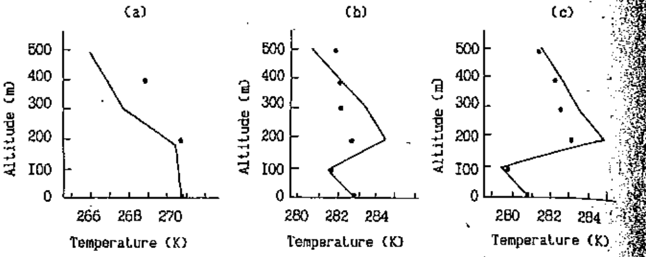

Fig. 2. Boundary layer temperature profiles of various types retrieved from observation data (solid line), and measured with *in situ* thermometer (filled circles).

Remote sensing of temperature at frequency near 60 GHz has one essential advantage. Due to the large absorption by the atmosphere, the temperature contrast in all directions of sensing is relatively small, about 3 K. As a consequence, the signal received through the parasitic lobes of the antenna has temperature difference with respect to the main beam of not greater than 3 K. As a result the error produced by parasitic lobes can be neglected. Actually, the expression of the antenna temperature is

$$T_a = T_b + \beta(T_{\text{back}} - T_b) \tag{9}$$

where T_{back} — the background temperature. As can be seen the value of the second term of (9) is less than 0.03 K and its variation under the angle scanning is essentially lower. Therefore, with the combination of the sensitive radiometer, the antenna with low sidelobes and the fact $T_b \approx T_{\text{back}}$, the accuracy of the measurements may be very high.

V. THE EXPERIMENTAL RESULTS

Experiments was conducted in the summers of 1989 and 1990 near the town of Rylsk. The *in situ* measurements were carried out simultaneously with the radiometric measurements to check the method. The binding balloon was used for the *in situ* measurements. The height of lifting was about 700 m, and the temperature was measured by the thermometer every 100 m. The radiobrightness temperature was measured at zenith angles (angles with respect to a vertical direction) 0, 40, 60, 70, 80, 85, 90°. The radiation forming layer altitudes $H_b(\theta)$ was $\approx$ 300, 225, 150, 100, 50, 25 m respectively. Examples of different retrieved boundary layer temperature profiles $T(h)$ are shown in Fig. 2. From Fig. 2 it can be seen that the retrieval of different types of profiles is achieved reliably from the radiometric measurements. Some discrepancy between *in situ* and remote sensing measurements can be explained by roughness of the *in situ* measurements with a 100 m measurement increment.

One of the advantages of the radiometric method measurements is its continuity. Fig. 3 shows the creation and development of the nocturnal temperature inversion. It can

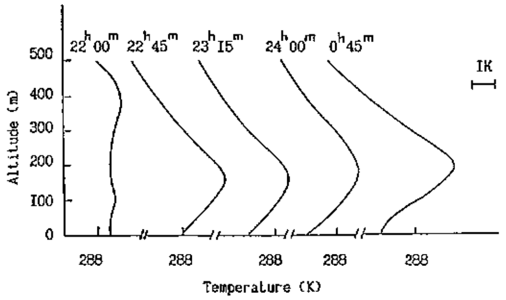

Fig. 3. Dynamics of the boundary layer temperature profiles retrieved from radiometric observations.

be seen that isothermal $T(h)$ is transformed into inversion temperature distribution $T(h)$.

It must be pointed out that in contrast to remote temperature sensing in troposphere [1]–[3] the boundary layer temperature remote sensing at frequency 60 GHz isn't influenced by clouds and fog. This is due to high attenuation of radiation near 60 GHz, which is ten times greater than the attenuation in the dense clouds without rainfall. For example, the signal change due to the cloud with $W = 2$ kg/m^2 water accumulation and 200 m bottom boundary is only 0.08 K. The temperature retrieval $T(h)$ on Figs. 2 (b), and (c) was done under conditions of strong fog with height $\sim$ 150 m.

VI. CONCLUSIONS

Radiometric method of boundary layer temperature sounding allows us:

- to carry out boundary layer temperature sounding up to $h \approx 500$ m with vertical resolution $\sim$ 50 m in interval $h = 0$–200 m and $\sim$ 100 m in interval $h = 200$–500 m;
- to achieve a retrieval error of $T(h)$ which is not greater than 0.5 K;
- to record reliably the main features of temperature profiles (isothermal, inversion) and their dynamics;
- to carry out measurements in all weather conditions excluding strong rain.

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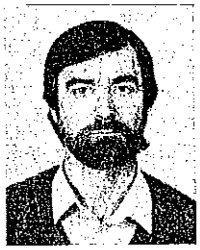

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