THERMAL SOUNDING OF ATMOSPHERIC BOUNDARY LAYER IN THE OXYGEN ABSORPTION BAND CENTER AT 60 GHZ.

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Abstract. The sensitive radiometer is developed, which allow to measure the radiobrightness temperature with the error not greater than dT = 0.06 K. It provides the facility for the remote temperature sensing of the boundary layer. According to numerical experiment the accuracy of the temperature profile recovery is about0.2 K in the case of a simple profile, and about 0.5 K in the case of a profile with inversion. The field experiment was conducted with the radiometer in elevation angle scanning mode. The contact temperature measurements was carried out simultaneously with the remote sensing.

I. INTRODUCTION.

The boundary atmospheric layer is placed between Earth surface and the free atmosphere. It has thickness between 100 and 1000 meters, depending on various factors. The boundary layer plays an important role in interaction between an atmosphere and Earth surface. There are extremely wide variety of temperature dependence T(h). However, acquisition T(h) is not a simple problem. Radiosonde sounding, due to high speed of the sounder at low altitudes, supply only a few points, as a rule higher then 300 m and does not determine the temperature distribution of a boundary layer T(h).

There are some methods of remote troposphere temperature sensing, using the wing of Oxygen absorption band at frequencies f = 53 - 66 GHz [1-3]. But, in this case for high vertical resolution in the boundary layer it is necessary to conduct measurements on very low elevation angles, which needs 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 sidelobes effects. Also there are some difficulties in obtaining T(h) by solving of 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 boundary layer problem, due to extraordinary spatial and time variety of T(h) from which it is not possible practically extract any representative statistical ensemble with a stable covariational bindings.

II. THE PROBLEM.

Microwave remote sensing of a boundary layer temperature is based on a thermal radiation of atmosphere in a center of Oxygen absorption band near 60 GHz, where a skin depth is about 300 m. By definition the skin depth is equal to the height H where:

$$t(H_b) = \frac{1}{\cos y}\int_0^{H_B} g_n(h)\,dh = 1$$

For the boundary layer with a good accuracy may be put $g_n(h)$ = const = $g_n(0)$ and

$$H_B = \frac{\cos(y)}{g_n(0)} \approx \cos(y)\cdot 300m,$$

where y - sensing zenith angle. Thus, remote temperature sensing of the boundary layer is conducted by means of measurements of a radiobrightness temperature at different zenith angles yt=t0t÷t90. In this case the depth of the forming radiation layer changes in a range 0 ÷ 300 m.

As a prime information for obtaining the physical characteristics of the atmosphere the value of radiobrightness temperature T is used, the expression of which has a form:

$$T_B(y) = \frac{1}{\cos(y)}\int_0^H T(H)g(h,T)\exp(-\frac{1}{\cos(y)}\int_0^H g(h',T)dh')dh = \int_0^H T(h)K(h,y)dh \tag{1}$$

where K is a core; H = 2 km - upper limit of integration. The layers of an atmosphere, which are higher than 2 km, is believed do not influenced on T_B.

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

III. THE INVERSE PROBLEM SOLVING METHOD.

Let's rewrite the equation (1) in operator form.

$$KT = T_B^d \tag{2}$$

where

$$KT = \int_0^H T(h)K(h,y)dh,$$

T_B^d - the measured temperature realization, with the variation dT_B , which obeys the equation:

$$(dT_B)^2 \le \left\|KT - T_B^d\right\|_{L2}^2 = \int_{y1}^{y2}[T_B(y) - T_B^d(y)]^2 dy \tag{3}$$

where $T_B(y)$ - corresponds to an exact solution of T(h).

In practice the core K employed for solving (1) is not an accurate, but the approximate K_h have the variance h , which is evaluated from:

$$h = \sup\frac{\left\|KT - K_h T\right\|}{\left\|T\right\|} \tag{4}$$

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

The solution of (2) is ill-conditioned problem and it is required some additional *a priori* information about T(h) for correct solving (2), otherwise any small variation in T_B (y) may cause to great variations in T(h). The theoretical foundation of the application of the Tikhonov method to the problem of the boundary layer remote sensing in case of the existence of an information about the squared summing and/or about the flatness of an accurate solution [5] was developed in [6].

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

$$M^a = \left\|K_h T - T_B^d\right\|_{L2}^2 + a\left\|T\right\|_{W_2^1}^2 \tag{5}$$

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 a is determined by variance of the measured values as a root of one dimensional equation for generalized variation:

$$r(a)=\left\|K_h T^a - T_B^d\right\|_{L_2}^2 - (d+h\left\|T^a\right\|_{W_2^1})^2 = 0 \qquad (6)$$

In this case if d -→ 0 then the estimated solution uniformly approach to the exact solution T(h). This is the great advantage of our 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 core variance h was determined by the numerical experiment.

In our case the value h is determined mainly by an equation nonlinearity, which is due to the temperature dependence of the core K, and the appropriate variance is h T < 0.03 K.

By this method the additional information about the exact solution T(h) can be used in a form of any restrictions. For example, if it is known that the exact solution 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.

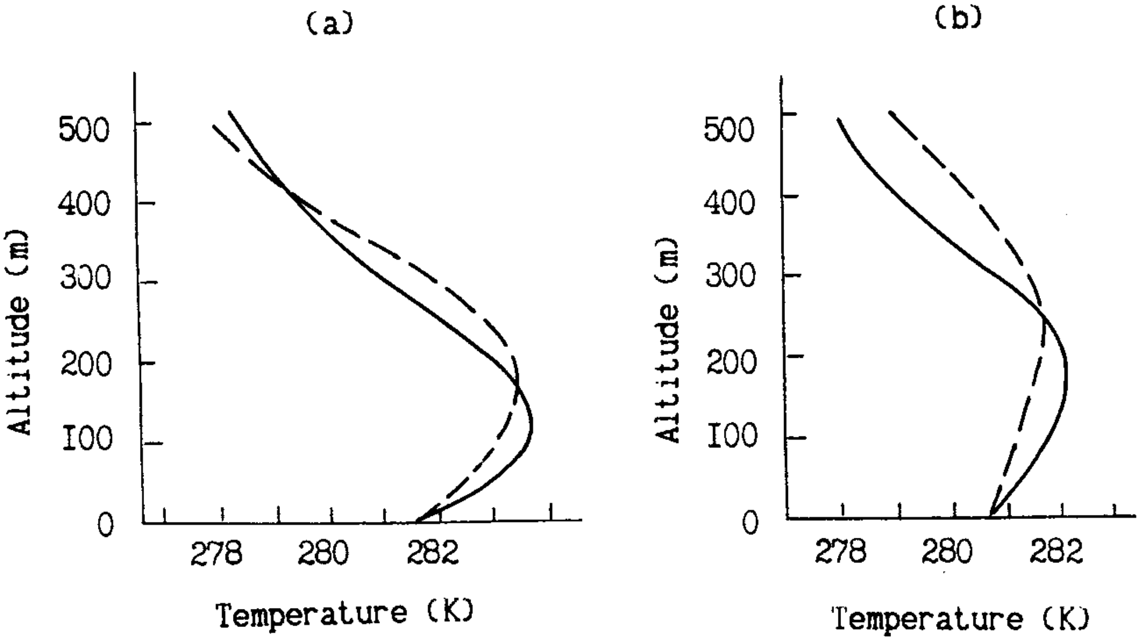

Fig.1, The example of the numerical experiment.

The numerical experiment was conducted to check the accuracy of the solution. It also was used to find the optimal measurement parameters (set of angles). The example of the numerical experiment is shown on Fig.1. It may be seen that a good accuracy of solution T(h) can be obtained if the accuracy of the measurements $dT_B \cong 0.05$ K. The following results was found from the numerical experiments with the different modeling profiles having the different dispersion values dT with normal distribution and with different set of angles. The solution of the problem under $dT_B \cong 0.05$ K is effective to the height ~0.5 km and the average accuracy of the solution is 0.1-0.2 K for a flat profiles, and 0.3-0.6 K for profiles with temperature inversion (the greater and sharper inversion - the worse accuracy, as a rule). The number of an angle independent measurements in the range $0\text{-}85^{O}$ is not greater than 6 in the case of $dT_B \cong 0.05$ K. For more complex profiles T(h) the number of angles must be increased. Under the decrease of dT_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 real experiment. The numerical experiment can be conducted in much greater variety of conditions, and the accuracy of data in numerical experiment is greater than that of real one. It is difficult to acquire accurate data for comparative analysis in direct measurements of atmospheric temperature distributions, particularity with 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 Space Research Institute (Russian Academy of Sciences). The sensitivity of this radiometer is $dT_B \cong 0.06$ K with the integration time t = 1 s. An antenna is the scalar horn with beam width about 4 degrees. The radiometer is all solid state superheterodyne receiver. The input circuit of the radiometer consist of isolator, Faradey effect chopper, reference noise source, and Schottky diode mixer. The local oscillator is InP Gunn effect oscillator with frequency about 60 GHz. The transistor IF amplifier has the bandwidth about 2 GHz.

The antenna has a small scattering coefficient outside the main lobe, b ≅ 1%. It means small influence of the parasitic lobes on the measurements 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 ~ 1 m [3]. One target was at the ambient temperature T , 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

$$T_B = T_0 - \frac{m}{m_K}(T_0 - T_{NB}) \tag{7}$$

where m is the difference in recorded data in cases of atmosphere and T_0 reference load radiation; m_K - the difference in recorded data in cases of reference loads radiation at T_0 and T_{NB} temperatures.

For retrieval the temperature profile T(h) the errors of T_B measurements must be known. Let us to obtain the differential of (7)

$$dT_B = dT_0 + (dT_0 + dT_{NB})(m/m_K) + (dT_0 - dT_{NB})d(m/m_K) \tag{8}$$

In the expression (8) the first term is the error of the near surface temperature measurement $dT_0 \cong 0.2$ K, which is the error of the thermometer and it is the additive error. This error have the same value at all angles y. The error dT_0 do not distort the form of the profile $T_B(y)$ and T(h), but results in addi -tive displacement. The dT_0 in remote sensing has the same value as in the contact methods.

The error of nitrogen reference load radiobrightness temperature $dT_{NB} \leq 1.5$ K [7]. The third term in (8) was determined experimentally and is near ~ 0.03 K at radiometer sensitivity $dT_B \cong 0.06$ K and integration time t = 10 s. Using data above and (8) it can be obtained that for $m = a(T_0\text{-}T_B) \cong 3a$, $m_K = a(T_0\text{-}T_B) \cong 200a$, where a is the radiometer gain. So, the final error is about $dT_B \cong 0.06$ K.

In field measurements the secondary calibration was conducted by means of internal reference noise source. This noise source produces a stable reference temperature step DT calibrated by means of two "black body" targets as discussed above. The step DT_r determines the scale of the instrument. For the absolute radiobrightness temperature measurements the radiation temperature at horizontal direction was used. It was believed that it is equal to the air temperature near the Earth surface T_0.

The temperature remote sensing at frequency near 60 GHz has one essential advantage. Due to the large absorption of an atmosphere the temperature contrast in all direction of sensing is relatively small, about 3 K. As a consequence of this fact the signal received through the parasitic lobes of the antenna has the temperature difference with respect to the main beam 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

$$T_A = T_B + b(T_{Back} - T_B) \qquad (9)$$

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. So, the application of the sensitive radiometer, the antenna with low sidelobes and under the fact $T_B \cong T_{Back}$ the accuracy of the measurements may be very high.

V. THE EXPERIMENTAL RESULTS.

The experiments was conducted in summers 1989-1990 near the town Rylsk. The contact measurements was carried out simultaneously with the radiometric measurements to check the method. The binding balloon was used in contact 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 $H_B(y)$ was ≈ 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 con-ducted reliably from the radiometric measurements. Some discrepancy between contact and remote sensing measurements can be explained by roughness of the contact measurements with 100 m discrete.

One of the advantages of the radiometric method measurements is in its continuousity. In Fig.3 is shown the creation and development of the night temperature inversion. It can 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 doesn't influenced by clouds and fog. This is due to high attenuation of radiation near 60tGHz, which is ten times greater than the attenuation in the power clouds. For example, the signal change due to the cloud with $W = 2\text{kg/m}^2$ water accumulation and 200 m bottom boundary is only $DT_B = 0.08$ K. The temperature retrieval T(h) on Fig. 2 b,c was done under conditions of strong fog with height h ≈ 150 m.

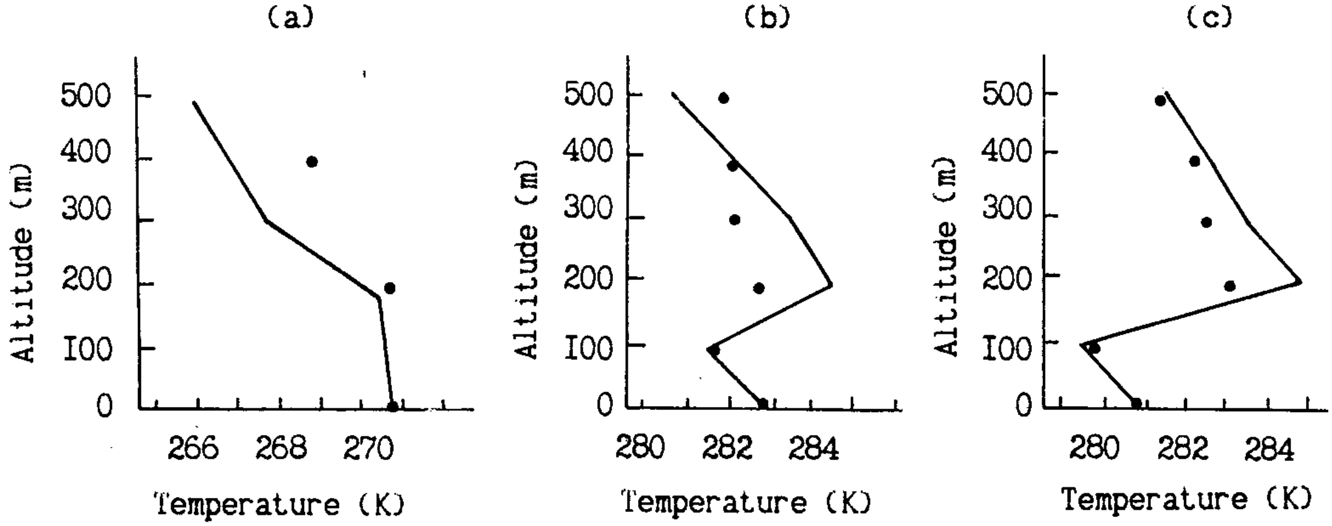

Fig. 2. Examples of different retrieved boundary layer temperature profiles T(h).

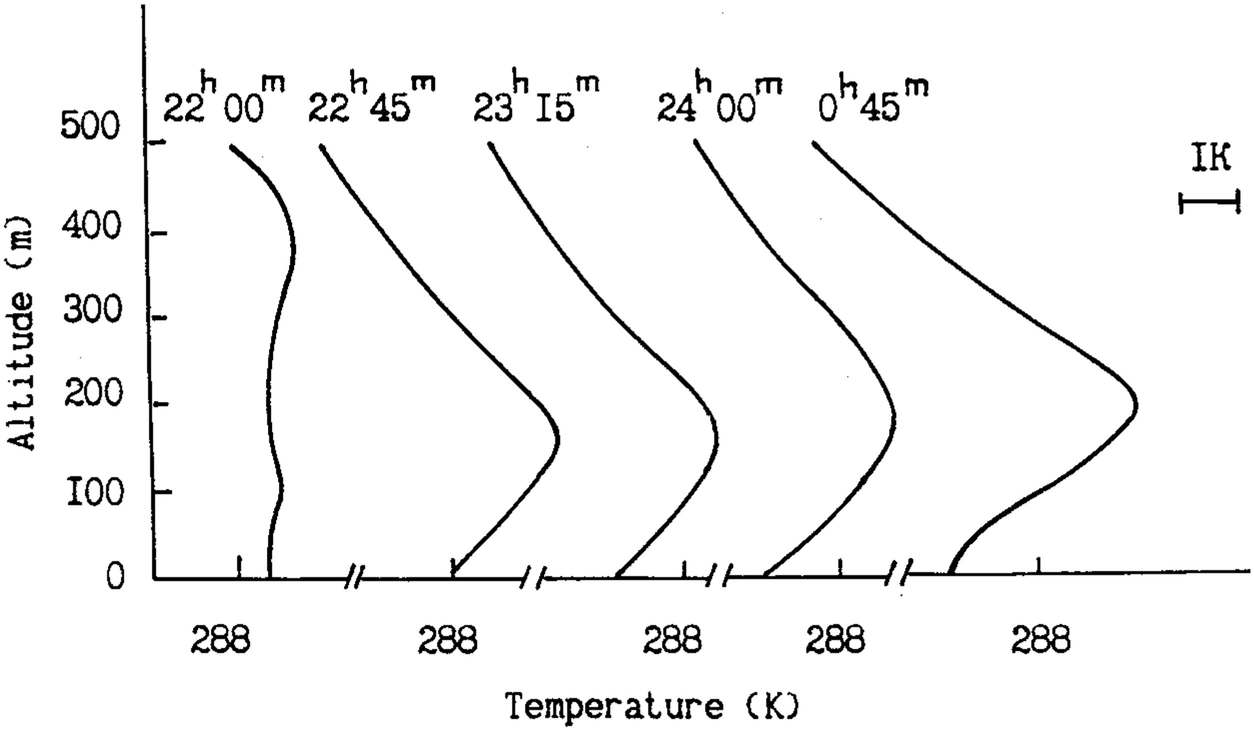

Fig.3. The creation and development of the night temperature inversion.

VI. CONCLUSIONS.

Radiometric method of boundary layer temperature sounding allows:

- to carry out boundary layer temperature sounding up to h ¸ 500 m with vertical resolution ~ 50 m in interval h = 0-200 m and ~ 100 m in interval h = 200-500 m;
- to realize the retrieval error of T(h) not greater than 0.5 K;
- to record reliably the main features of temperature profiles (isothermal, inversion) and its dynamics;
- to carry out measurements at all weather conditions.

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