Calibration of Volna-3 sodar

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The method and results of calibration of the transmitting/receiving system of an acoustic meteorological radar (sodar) are discussed. The calibration is intended for measurement of the absolute value of the temperature structure characteristic C_T^2. Examples of C_T^2 measured under conditions of stable and unstable stratification of the atmospheric boundary layer are presented.

The modern set of the methods for remote acoustic diagnostics of the atmospheric boundary layer (ABL) should provide for the capability of estimating the intensity of random pulsations of temperature field by measuring its structure characteristic C_T^2. Toward this end, absolute calibration of the transmitting/receiving system of a sodar is quite necessary. The full-scale calibration is too a laborious procedure. It has to include measurements of the amplitude of the emitted sonic signals in the far zone of free space (or in a specialized large-size chamber with sound-absorbing walls), as well as measurement of voltages at the output of the sodar electronic system at different angles of arrival of plane sonic waves with the controlled pressure.

However, in practice, simpler calibration techniques are used. In one technique, the data of independent measurements of C_T^2 at some height are involved and compared with the values of acoustic signals scattered at this height and recorded with a sodar. As a result, the coefficient of transition from the square amplitude u^2 of the voltage at the output of the sodar electronic system to C_T^2 is determined: $C_T^2 \approx k_c u^2$ (from here on, C_T^2 is in $K^2 \cdot m^{-2/3}$). As an example of realization of such an approach, we can mention Ref. 1, which describes in detail the technique and result of calibration – the coefficient $k_c = 3.8 \cdot 10^{-3}\ K^2 \cdot m^{-2/3} \cdot V^{-2}$. This coefficient, naturally, is only applicable to a particular sodar. Similar approach to measuring the C_T^2 was used in some other papers (see, for example, Refs. 2–4).

For calibration of a Volna-3 sodar designed and manufactured at the Institute of Atmospheric Optics SB RAS, we used a simplified instrumental approach. It is based on the determination of the efficiency of electric-to-acoustic signal transformation, that is, on the estimation of the efficiency of the transmitting/receiving system. Similar approach to calibration of sodars for C_T^2 measurements was used, for example, in Refs. 5–7. The technology of C_T^2 measurements in this case is based on the widely known monostatic acoustic lidar equation, which establishes the relation between the mean power P_a of the signal received by the sodar (signal scattered at the height H by temperature pulsations with the effective backscattering cross section σ) and the power P_0 of the emitted sensing pulse with the duration τ, carrier frequency f, and the sound speed c in the atmosphere:

$$P_a = 0.5\, c\tau P_0 S L \sigma H^{-2}. \quad (1)$$

Signals are received by an antenna with the effective area S. Absorption of sound along the sensing path is taken into account by introducing the extinction function L into this equation.

If we use the representations with $\sigma = 0.00753\, c^{-1/3} f^{1/3} C_T^2 T^{-2}$ (Ref. 8) and $c \approx 20.05\sqrt{T}$ (Ref. 9), then the lidar equation can be written as

$$P_a = \kappa_s P_0 S \tau L f^{1/3} H^{-2}\, T^{-5/3} C_T^2. \quad (2)$$

Here P is the power, in W; $\kappa_s = 0.0278$ is the dimensional coefficient.

In formulating Eq. (2), it was assumed that sonic signals are emitted and received by the same antenna. The directional pattern (DP) of the antenna is shaped as a round cone with the solid angle Ω. The distribution of the sonic wave intensity over the cone cross section is assumed constant. The angle Ω is estimated from the half-power level of the major lobe of the actual directional pattern. Besides this approximation, other assumptions (rectangular shape of the sensing pulse, smallness of the scattered pulse as compared with the emitted one, the absence of refraction, etc.) were involved in the process of derivation of Eq. (2).

In connection with formulation of the Eq. (2), there is no need in any detailed study of the antenna DP and full-scale calibration of sodar for reconstruction of C_T^2. We can restrict ourselves to minimum information about the main parameters of the antenna and the transmitting/receiving system.

If the antenna DP is presented as the following function[10]:

$$R(\psi, \alpha) = p(\psi, \alpha)/p_m, \quad (3)$$

where $p(\psi, \alpha)$ is the distribution of the acoustic pressure field in the far zone at the distance r_0 as a function of the angular coordinates ψ and α (from here on, the sonic pressure is measured in Pa), p_m is the

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sonic pressure on the DP axis at the distance r_0, then the power of the emitted signal P_0 (in W) can be estimated by the equation

$$P_0 = I_m \iint R^2(\psi, \alpha)\, ds = $$

$$= r_0^2 I_m \int_0^{2\pi} d\alpha \int_0^{\pi} R^2(\psi, \alpha) \sin\psi d\psi, \quad (4)$$

and in the case of the axial symmetry inherent, for example, in antennas of Volna-3 sodars:

$$P_0 = 2\pi r_0^2 I_m \int_0^{\pi} R_\psi^2 \sin\psi d\psi. \quad (5)$$

Here $I_m = p_m^2/2\rho c$ is the sound intensity on the DP axis at the distance r_0 from the antenna, in W/m^2, ρ is the air density, in kg/m^3, and c is the speed of sound, in m/s.

According to the DP approximation used at formulation of Eq. (2), we have

$$R_\psi = \begin{cases} 1, & \psi \le \Omega/2, \\ 0, & \psi > \Omega/2, \end{cases} \quad (6)$$

what (at a small Ω angle) reduces Eq. (5) to the form

$$P_0 \approx \pi\, r_0^2 \Omega^2 p_m^2 / 2\rho c. \quad (7)$$

Thus, one of the steps in achieving absolute sodar calibration by the simplified technique is the determination of Ω and p_m. This provides for estimation of the emitted power P_0.

In addition to the sodar calibration for emission of a signal, we should establish the relation between the pressure amplitude p_i of the scattered sonic signal coming to the antenna and the amplitude u_e of the signal at the output of the bandpass amplifier of the receiving part, that is, determine the coefficient γ (in V/Pa) in the equation

$$u_e = \gamma p_i. \quad (8)$$

In fact, the coefficient γ is the product of the coefficient of transformation of transmitting/receiving elements γ_a and the gain factor of the electronic system γ_e: $\gamma = \gamma_a \gamma_e$. The factor γ_e is dimensionless.

For a convenient automated processing of measurement data, the calibration procedure should involve the coefficient of digitization of the voltage u_e at the output of an analog-to-digital converter (ADC):

$$u_d = \gamma_d u_e = \gamma_d \gamma_a \gamma_e p_i, \quad (9)$$

where u_d is the voltage, in ADC units; γ_d is the digitization coefficient, in ADC units/V.

In the process of calibration of Volna-3 sodar operated with a 12-bit ADC, we have united the calibration of the electronic and digital systems, that is, we have estimated $\gamma_d \gamma_e$ as $113.4 \cdot 10^6$ ADC units/V.

To determine the coefficient γ_a, the antenna was exposed to a sonic wave from a remote external source. The sonic pressure p_i in the antenna aperture plane was measured, as well as the voltage amplitude u_p at the pre-amplifier output with the gain factor k_p. As a result, we have obtained the coefficient $\gamma_a = u_p/(k_p p_i) \approx 0.146$ V/Pa. From this it follows that the sonic pressure p_i at the output of the acoustic part of the receiving system and its digital representation for the Volna-3 sodar are related as follows:

$$u_d = 16.556 \cdot 10^6 p_i. \quad (10)$$

At sodar calibration for signal transmission, the measuring microphone was at the distance r_0 from the antenna in the plane of its possible rotation. The sodar emitted short sonic pulses with a stuffing at the frequency of 1700.68 Hz. The sonic pressure was measured at different angles of antenna inclination. Figure 1 depicts a part of DP needed for sodar calibration. It was found that the DP full width at half power is $\Omega \approx 8°$. In this case, the amplitude of sonic pressure p_m at the distance $r_0 \approx 11.1$ m is roughly equal to 21.2 Pa. After substituting these values into Eq. (7), we obtain the estimate of the power emitted within the solid angle Ω: $P_0 \approx 3.85$ W.

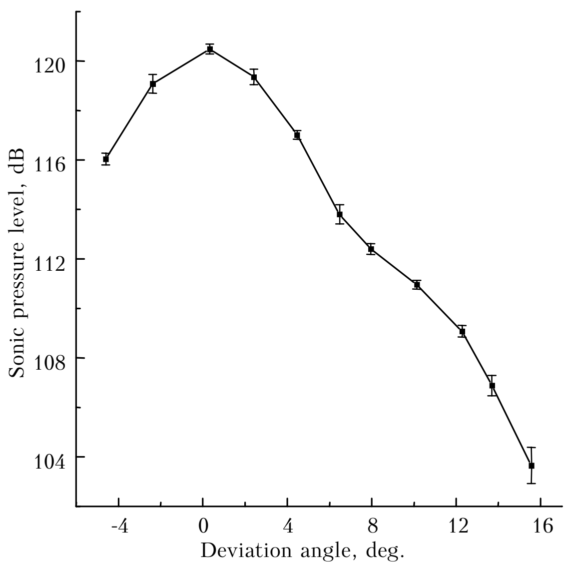

Fig. 1. Level of sonic pressure vs. the angle of deviation of the antenna DP of Volna-3 sodar from the direction to the measuring microphone. Vertical bars show the standard errors.

Thus, Eq. (2) can be transformed into the following form:

$$u_d^2 = 1.444 \cdot 10^{15}\, \tau L f^{1/3} H^{-2} T^{-7/6} C_T^2 \quad (11)$$

provided that $\rho = 1.293$ kg/m^3.

Thus, the instrumental calibration of the Volna-3 sodar allows estimating the absolute values of the structure characteristic of temperature pulsations C_T^2 by the equation

$$C_T^2 = 6.925 \cdot 10^{-16}\, u_d^2 H^2 T^{7/6} (\tau L f^{1/3})^{-1}. \quad (12)$$

In this equation, the given parameters are the length of the sensing pulse τ and the carrier frequency f. The value of u_d^2 is measured directly in the experiment. The sound absorption function L depends on the temperature, humidity, air pressure, and the distance to the scattering volume. It can be calculated, for example, with the use of equations from Ref. 9. The distance H to the scattering volume can be determined as

$$H = 0.5\ (t - t_0)c \approx 10.025\ T^{1/2}(t - t_0),$$

where t is the time of recording the amplitude u_d; t_0 is the initial time of emission of the sonic pulse. For details on the technique of sodar signal processing and the algorithm of C_T^2 reconstruction, as well as estimated errors, see Ref. 11. It should be noted that the errors of C_T^2 reconstruction that are connected with the problem of correct allowance for meteorological parameters entering into the extinction function L can be from several units to hundreds percent depending on the meteorological conditions. The situation is most favorable at negative temperatures, when even significant errors in the air temperature and humidity give the errors no larger than 20–30% in the estimates of C_T^2.

Figure 2 depicts, as an example, the result of one experiment. The upper panel shows the initial record of the signal amplitude u_d, and the lower one demonstrates the height-time distribution of C_T^2 as a smoothed contour map obtained with the use of Eq. (12). The scale of C_T^2 values is given in the bottom. This figure corresponds to the case of a broken nighttime (radiative) temperature inversion and transition to the convective conditions of the atmospheric boundary layer in summer time (July 5 of 2000, Tomsk). The temperature of the near-ground air increased from 22°C at 09:00 to 30°C at 14:00. The relative humidity decreased for this period from 70 to 40%. The values of C_T^2 are obviously typical for the considered case of daytime convection.

One more example of C_T^2 reconstruction, but for winter conditions (January 4–5 of 2000, Tomsk) multilayer temperature inversion in the atmospheric boundary layer is shown in Fig. 3. The temperature and relative humidity of the near-ground layer were practically the same for the considered period (−34.6 ± 0.8)°C and (77 ± 1)%, respectively.

Since this paper is devoted to the technique we used for simplified instrumental calibration of the sodar, we restrict our consideration only to few illustrations. The detailed analysis of C_T^2 fields in different thermodynamic situations should be a subject for a separate study.

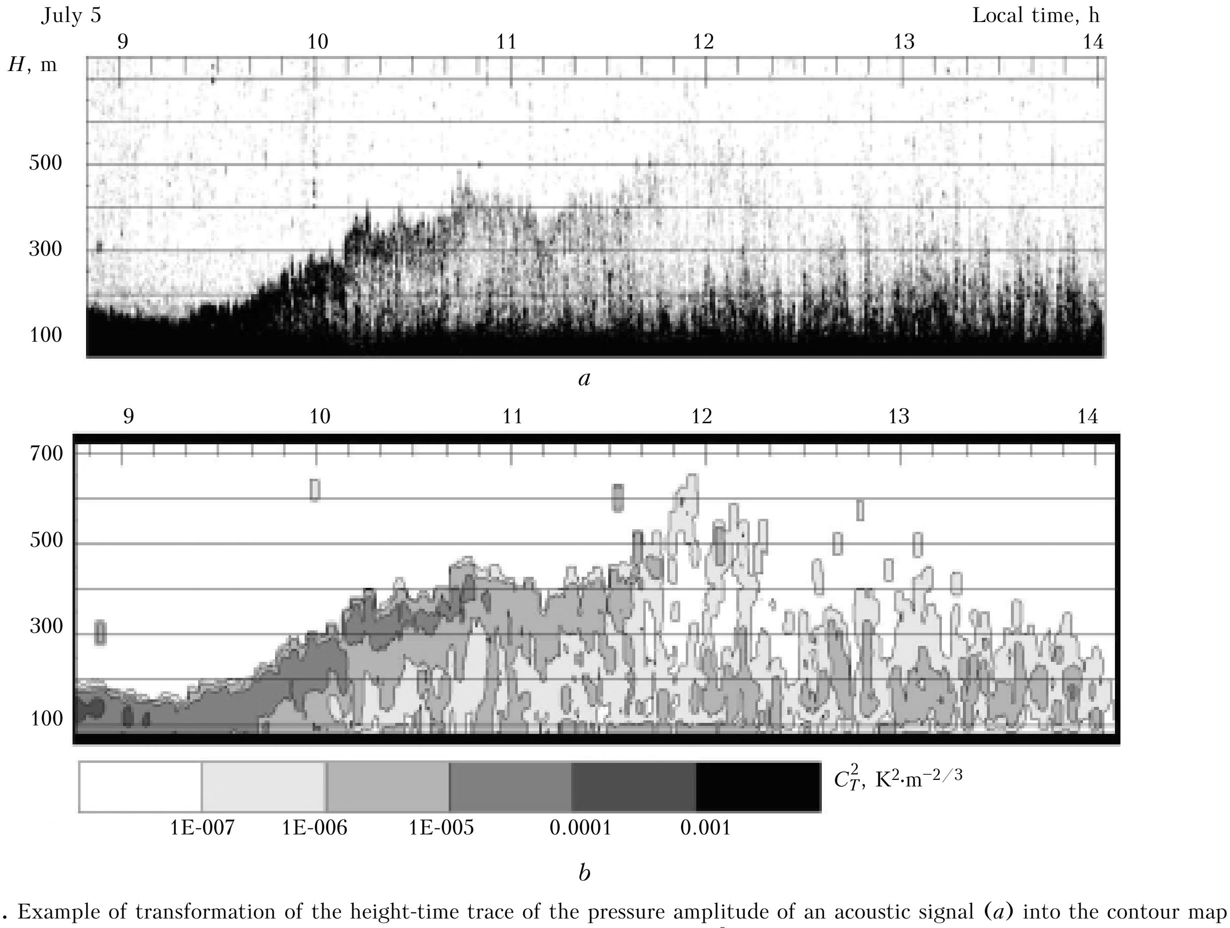

Fig. 2. Example of transformation of the height-time trace of the pressure amplitude of an acoustic signal (*a*) into the contour map of smoothed absolute values of the temperature structure characteristic C_T^2 (*b*). The case of broken nighttime (radiative) temperature inversion and transition to the convective conditions in the ABL.

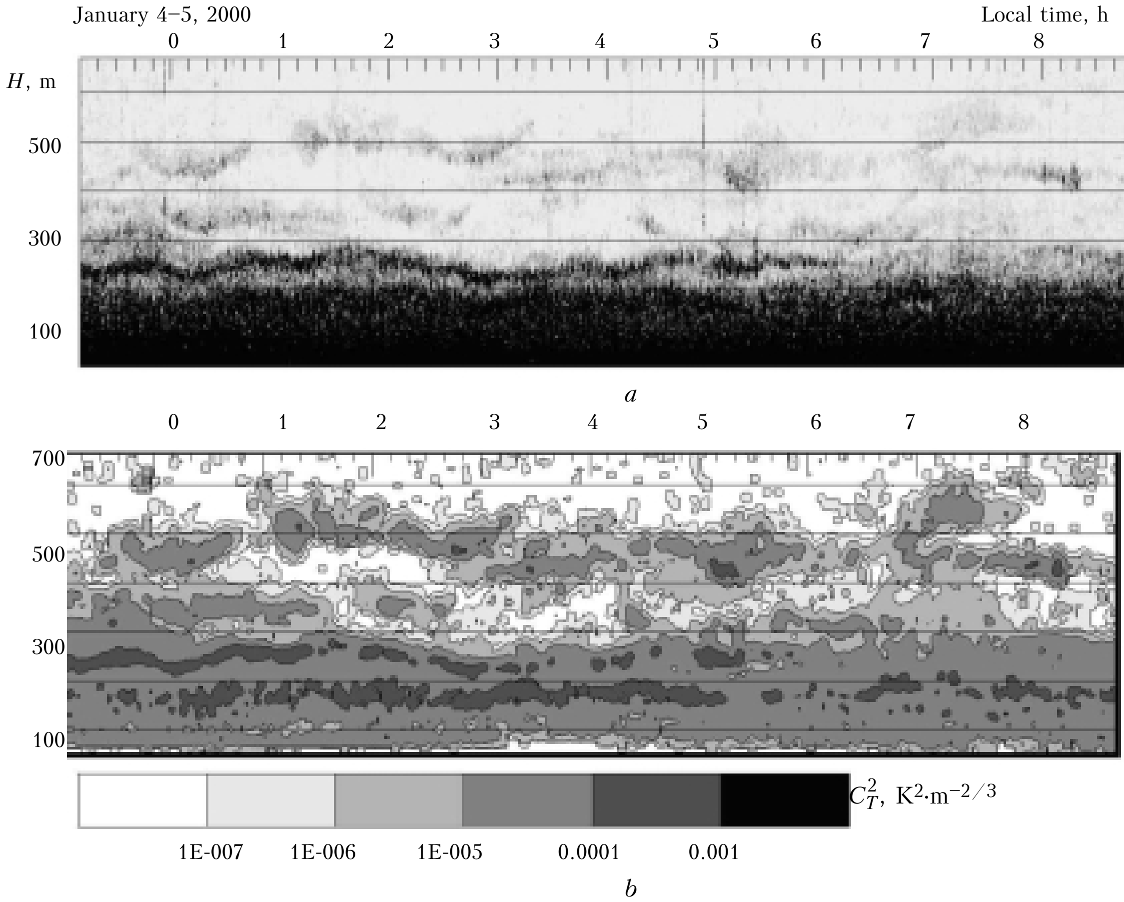

Fig. 3. Example of transformation of the height-time trace of the pressure amplitude of an acoustic signal (*a*) into the contour map of smoothed absolute values of the temperature structure characteristic C_T^2 (*b*). The case of stable stratification in winter.

Measurements of C_T^2 with the sodar calibrated in this way are certainly to be checked against the data obtained with independent measurement tools, for example, with high-sensitivity contact temperature sensors installed on a meteorological mast or on a tethered balloon. However, now we have no such a possibility.

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