EFFECT OF ATMOSPHERIC TURBULENCE ON THE ACCURACY OF THE DETERMINATION OF HUMIDITY BY THE AMPLITUDE RADIOACOUSTIC METHOD

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Received March 26, 1990

The results of numerical estimates of the absolute error introduced in measurements of the relative humidity by atmospheric turbulence in the case of vertical two-frequency radioacoustic sounding are presented.

The main interfering factors in this case are the decrease in the transverse coherence length in the sound wave and the effect of horizontal atmospheric wind.

The estimates were made for harmonic acoustic frequencies in the band 1–13.6 kHz *while sounding in an atmospheric layer* 50–200 m *under calm conditions and in the presence of a moderate wind. The relative error in the relative humidity of* 10–100% *does not exceed* 10%*: when sounding at frequencies of* 3.4–6.8 *and* 6.8–13.6 kHz *under calm conditions and at frequencies of* 6.8–13.6 kHz *in the presence of wind with velocity* 5 s^{-1}.

Radioacoustic sounding[1] has been used in the last few years not only to measure the air temperature and wind velocity but also for determining the humidity. The method of remote determination of the humidity from values of the absorption coefficient of an acoustic wave in air is best known.[2,3] The method is based on excitation of vibrational degrees of freedom of molecules of polyatomic gases, which results in molecular absorption of the acoustic wave[1] and an increase in the sound absorption coefficient.

Since turbulence in the atmospheric boundary layer is quite strong, it is of interest to find quantitative estimates of the combined effect of turbulence and wind on the accuracy of determination of the humidity by the amplitude method using two-frequency vertical radioacoustic sounding.[3]

It is well known that in radioacoustic sounding a radio wave is focused by an "acoustic mirror."[1] The power of the radio signal P_R at the focal point of the receiving radio antenna in the Fraunhofer diffraction zone $(\lambda_e R / 2) \gg \pi a_e^2$ has the following dependence on the range R up to the region being sounded in a nonturbulent calm atmosphere:[1–3]

$$P_R = \frac{A}{R^2} \exp\left[-\int_0^R \alpha(r)dr \right], \tag{1}$$

where $\alpha(r)$ is the energy coefficient of sound damping; λ_e is the wavelength of the radio wave; a_e is the characteristic linear size of the radio antenna; and, A depends on the parameters of the apparatus.

As shown in a number of works (for example, Ref. 1), the effect of locally homogeneous and isotropic turbulence, including in the presence of horizontal atmospheric wind can be described by the factor $F(R)$, which changes the form of the dependence of the average power $\langle P_R \rangle$ of the received signal (1) on the range R up to the region being sounded.

The altitude dependence of the coefficient of molecular absorption of sound is determined by the altitude distribution of the relative humidity of the atmosphere,[1] if temperature and pressure variations are neglected. When the relative humidity observed in the near-ground layer of the atmosphere is almost constant,[3] the difference of the coefficients of sound damping $\Delta\alpha$ at the frequencies f_1 and f_2 can be reconstructed according to the formula

$$\Delta\alpha = \alpha_2 - \alpha_1 = \frac{1}{R} \ln \frac{\langle P_{R1} \rangle}{\langle P_{R2} \rangle} - \frac{1}{R} \ln \frac{F_1}{F_2} + \frac{1}{R} \ln \frac{A_2}{A_1}, \tag{2}$$

where $\frac{1}{R} \ln \frac{A_2}{A_1}$ does not depend on the meteorological conditions and is the systematic error, while

$$\Delta\alpha - \Delta\alpha_m = \frac{1}{R} \ln \frac{F_1}{F_2} \tag{3}$$

is the shift caused in the sound absorption coefficients by turbulence and atmospheric wind. (Here $\Delta\alpha_m = \frac{1}{R} \ln \frac{\langle P_{R1} \rangle}{\langle P_{R2} \rangle}$ is the difference of the sound molecular absorption coefficients when sounding at frequencies f_1 and f_2 in a nonturbulent calm atmosphere.) The power of the radioacoustic signal in the relation (1) is customarily determined based on the maximum of the signal amplitude at a given altitude when the sound frequency f is tuned to Bragg's condition[1]

$$\kappa = 2k_e - q = 0.$$

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where $k_e = 2\pi/\lambda_e$, $q = 2\pi/\lambda$, and λ is the wavelength of the acoustic wave. To reduce the effect of atmospheric turbulence in the case of sounding at two frequencies, the mode ratio of the amplitude distributions obtained during the averaging period is used. However, since analysis of most amplitude measurements shows that the histograms of amplitude distributions are extremely diverse, in this paper the difference of the sound absorption coefficients, which is calculated from the ratio of the average maximum powers when tuned to the Bragg condition at each altitude, is chosen as the characteristic quantity.

When the effect of fluctuations of the humidity above dry land is weak and the temperature and wind velocity are not correlated the structure constant C_n^2 of the acoustic index of refraction for an acoustic beam whose radius is less than the path length is equal to[4]

$$C_n^2 = \frac{C_T^2}{4T^2} + \frac{C_V^2}{C^2},$$

where C_T^2 and C_V^2 are the structure constants of the temperature and wind velocity; C is the velocity of sound; and, T is the absolute temperature of the air.

We shall derive the turbulence-wind shift in the difference of the coefficients of sound damping for two cases: weak ($C_n^2 \sim 10^{-8}\ \mathrm{m}^{-2/3}$) and strong ($C_n^2 \sim 5 \cdot 10^{-7}\ \mathrm{m}^{-2/3}$) turbulence at altitudes $Z = 100$–200 m. We shall start from specific data on the altitude dependence of the structure constants under conditions close to calm conditions and in the presence of a moderate wind. In Ref. 5 it is suggested that for convective conditions the altitude dependences obtained for atmospheric boundary layer with moderate and strong wind be regarded as typical:

$$C_T^2 = 2.9 \cdot Z^{-4/3} \tag{4a}$$

$$C_V^2 = 0.04 + 0.33 \cdot Z^{-2/3} \tag{4b}$$

Under conditions close to calm conditions, based on data on C_T^2 and C_V^2 above the steppe,[1] the altitude dependence

$$C_n^2 = \frac{C_T^2}{4T^2} = C_{n0}^2\ Z^{-4/3}. \tag{5}$$

can be regarded as typical. In estimating the effect of fluctuations of the Bragg parameter and deformations of the phase front of an acoustic wave on the average intensity of the received radioacoustic signal the effect of deformations of the phase front of the acoustic wave, which are characterized by breakdown of transverse coherence, was found to predominate under normal atmospheric conditions.[6] Using the particular representation of the factor $F(R)$ given in Ref. 1 under conditions when transverse coherence of the acoustic wave breaks down, we obtain the dependence of the turbulence-wind shift in the difference of the coefficients of sound damping (3) on the frequency of the sounding signal f, the range R up to the region being sounded, and the structure constant of the acoustic index of refraction C_n^2 :

$$\Delta\alpha_s = (\Delta\alpha - \Delta\alpha_m)_s = \frac{1}{R} \ln\left[\frac{1 + R_{02}^2/\rho_{c2}^2}{1 + R_{01}^2/\rho_{c1}^2} \right], \tag{6}$$

under almost quiet conditions and

$$\Delta\alpha_{mod} = (\Delta\alpha - \Delta\alpha_m)_{mod} = \frac{1}{R} \ln\left[\frac{1 + R_{02}^2/\rho_{c2}^2}{1 + R_{01}^2/\rho_{c1}^2} \right] - 2\left[\frac{v_\perp}{C}\right] \cdot \frac{R}{d_0^2} \left[\frac{1}{1 + R_{01}^2/\rho_{c1}^2} - \frac{1}{1 + R_{02}^2/\rho_{c2}^2} \right]. \tag{7}$$

in the presence of a moderate transverse wind with velocity $v_\perp$. Here $d_0 = \sqrt{2a^2 + a_e^2}$, a is the characteristic linear size of the acoustic antenna (in what follows, $a = 0.4$ m and $a_e = 0.6$ m),

$$R_0 = \frac{a_e a}{d_0} \sqrt{2(1 + Q_e Q)},$$

is the effective diffraction transverse size of the region of interaction of the radio beam and the acoustic beam[1], $Q_e = R / k_e a_e^2$, and $Q = R/qa^2$ are the wave parameters of the radio beam and the acoustic beam, and ρ_c is the transverse coherence length of the acoustic wave.

The theory of propagation of optical waves in randomly nonuniform media[1,6] in the short-wavelength approximation and under certain restrictions on the magnitude of the turbulent fluctuations[4] has been used many times to estimate the transverse coherence length of the "acoustic mirror" of a radioacoustic system in a turbulent medium. A number of methods have been developed to calculate the transverse coherence length of an optical wave propagating in a turbulent atmosphere in the case of turbulent fluctuations of an arbitrary quantity.[7] We shall start from the fact that an acoustic antenna creates in the plane of the aperture an acoustic wave with a plane phase front.[8] We shall employ the ratio obtained in Ref. 7 for the transverse coherence length of a light wave starting from the solution of the equation for the coherence function under the assumption that the source of light waves with a plane phase front at the output of the optical laser system is Gaussian:

$$\rho_c^2 = \rho_0^2\ \frac{3(1 + \Omega^2) + 4 \cdot k \cdot \Omega}{3 + \Omega^2 + k\ \Omega}, \tag{8}$$

where $\rho_0 = (1.5 C_n^2 q^2 R)^{-3/5}$ is the transverse coherence length of the plane wave, calculated by the method of geometric optics; $\Omega = 1/Q$ is the Fresnel number of the transmitting aperture; and $k = R/qp$ is the wave parameter defined relative to the coherence length ρ_0 of the plane wave.

The formula (8) is applicable when[7]

$$R \gg \rho_c, \quad q\rho_c \gg 1.$$

In addition, it is assumed that the longitudinal correlation length of the fluctuations is small compared with other longitudinal lengths in the problem. The conditions for the parabolic equation for the wave field to be applicable must also be satisfied

$$\frac{\lambda R}{l^2} \ll \left[\frac{l}{\lambda}\right]^2, \quad l \gg \lambda \tag{9}$$

and the backscattering by nonuniformities must be weak.

For acoustic wavelengths $\lambda = 0.025$–0.34 m (the frequencies $f = 1$ kHz – 13 kHz) at altitudes R equal to 50–200 m it can be assumed that the conditions listed above are satisfied, if the characteristic size of the nonuniformities of the distorting phase front of the acoustic wave $l \gtrsim 10\lambda$.

The relation (8) makes it possible to take into account the transition of the acoustic wave to a wave with a spherical wavefront in the zone of sounding, when $\Omega \ll 1$, and strong turbulence (the largest values of the wave parameter k $\approx$ 1.5–22 at heights of 50–200 m correspond to the highest frequency $f = 13.6$ kHz).

Figures 1 and 2 show for a harmonic pair of frequencies in the band $f = 1$–13.6 kHz ($f_1 = 6.8$ and $f_2 = 13.6$ kHz for curve 1, 3.4 and 6.8 for curve 2, 1.7 and 3.4 for curve 3, and 1.0 and 2.0 for curve 4) show the altitude dependence of the turbulence-wind shift in the difference of the sound absorption coefficients $\Delta\alpha_c$ and $\Delta\alpha_m$ at altitudes from 50 to 200 m under almost calm conditions (Fig. 1) and in the presence of a moderate wind of 5 m $\cdot$ s^{-1} (Fig. 2).

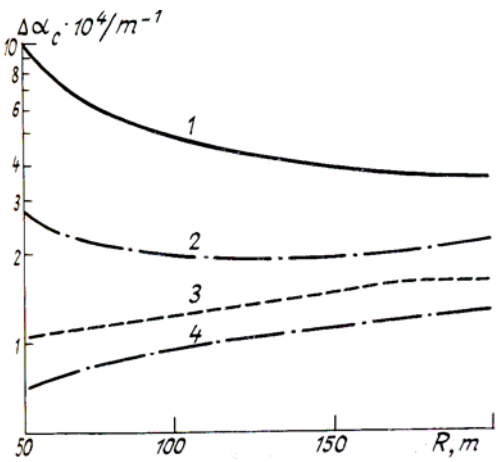

FIG. 1. The turbulent shift in the difference of the sound absorption coefficients under almost calm conditions.

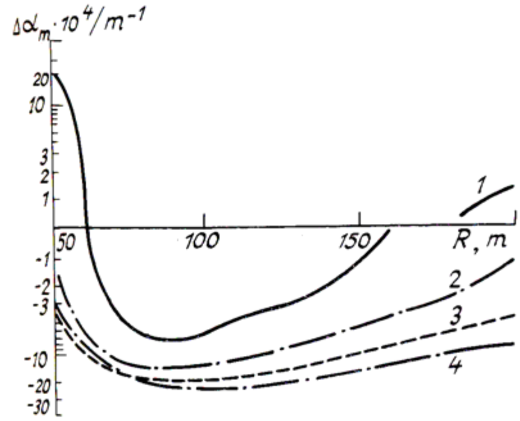

FIG. 2. The turbulence-wind shift in the difference of the sound absorption coefficients with a wind velocity of 5 m $\cdot$ s^{-1}.

In estimating the combined effect of the atmospheric turbulence and wind on the accuracy of determination of the humidity by the radioacoustic method we start from the empirical formulas for the humidity dependence of the molecular sound absorption coefficient, employed for constructing the ANSI S 1.26 = 1978 tables of the standard sound absorption in a calm atmosphere. The atmospheric parameters were set equal to the values for convective conditions: $p = 101.325$ kPa, $T = 293.16$ K (p is the atmospheric pressure).

The linear turbulence and wind induced increment to the difference of the molecular sound absorption coefficients of humid air $\Delta\alpha - \Delta\alpha_m$ (Figs. 1 and 2) determines the absolute error σ in measuring the relative humidity h:

$$|\Delta\alpha - \Delta\alpha_m| = \left|\frac{\partial \Delta\alpha_m}{\partial h}\right| \sigma. \tag{10}$$

where the derivative $\dfrac{\partial \Delta\alpha_m}{\partial h}$ must be calculated for a nonturbulent, calm medium, starting from the dependence[9] of the difference of the molecular sound absorption coefficients on the relative humidity.

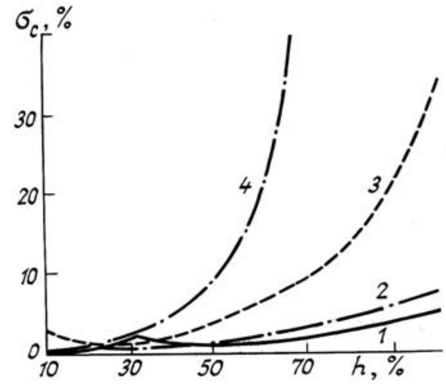

FIG. 3. The absolute error in the measurement of the relative humidity under almost calm conditions (the height is equal to 100 m*).*

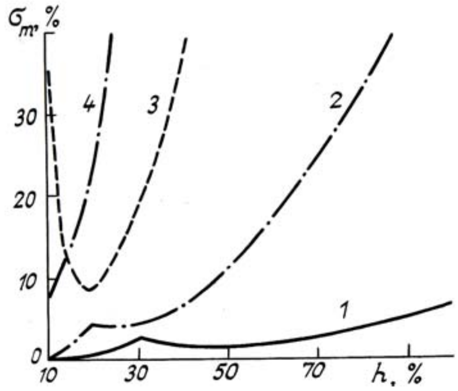

FIG. 4. The absolute error in measuring the relative humidity at a height of 100 m *in the presence of wind with a velocity of* 5 m · s^{-1}.

Figures 3 and 4 (where the same notation is used as in Figs. 1 and 2) show the curves of the absolute error in the determination of the relative humidity under calm conditions σ_c and in the presence of a moderate wind σ_m on the relative humidity at the height Z_0 = 100 m.

The values of σ_c and σ_m at other heights Z in the range 50–200 m can be calculated using the relations

$$\sigma_c(z) = \left|\frac{\Delta\alpha_c(z)}{\Delta\alpha_c(z_0)}\right| \sigma_c(z_0);$$

$$\sigma_m(z) = \left|\frac{\Delta\alpha_m(z)}{\Delta\alpha_m(z_0)}\right| \sigma_m(z_0); \quad (11)$$

which follow from the formula (10).

Starting from the relations (11) and plots of the dependence of $\Delta\alpha_c$ and $\Delta\alpha_m$ on the height Z (Figs. 1 and 2) it can be concluded that when sounding at harmonic frequencies in the range 1–13 kHz the values of σ_c and σ_m at heights of 50–200 m become quite large as the frequencies increase. The increase in the values of the error with increasing relative humidity h is intensified by the effect of the average horizontal wind, with the exception of the frequencies 6.8–13.6 kHz, at which the effect of the average wind is compensated by strong turbulence.[1] It is well known that single-frequency radioacoustic sounding is effective for determining the humidity only in a nonturbulent calm atmosphere.[2] The numerical estimates presented in this paper show the advantage of the two-frequency method: sounding of the turbulent atmosphere using harmonic frequencies above 3.4 kHz determines the relative humidity with a relative accuracy $(\sigma_c/h) \lesssim 10\%$. However, as the velocity of the average horizontal wind increases, right up to 5 m · s^{-1}, the relative error $(\sigma_m/h) \lesssim 10\%$ only at the highest harmonic frequencies of the wave range studied.

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