BACKSCATTER METEOROLOGICAL VISIBILITY RANGE METER INCLUDED IN A LASER BEACON. PART II. EXPERIMENTAL RESULTS

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This paper presents the results of simultaneous measurements of the transparency of a model smoky aerosol medium by a base meteorological visibility range (MVR) meter and a developed backscatter MVR meter that agree to within the limits of a relative error of ~ 20%. The problems regarding the method for calibration and errors in measuring the transparency by the backscatter MVR meter are discussed.

In our previous paper,[1] based on calculation data, we demonstrated the feasibility for a backscatter meteorological visibility range meter, which uses light beams of a beacon itself as a radiation source, to be included in a single–point laser beacon. In addition, practical implementation of the backscatter technique requires the knowledge of the calibration parameters and the estimate of the error in measuring the meteorological visibility range.

This paper presents the estimated accuracy characteristics and the results of calibration of a backscatter meteorological visibility range meter under controllable model conditions obtained during experimental investigations of a prototype of a backscatter meteorological visibility range (MVR) meter compared with the results of measuring the transparency of a model aerosol medium by the base technique (see Ref. 2).*

For experimental investigations the prototype of an autonomous device was produced capable of measuring the backscattered radiation, whose optical–geometric parameters were close to those used for calculations,[1] with variable angle between the optical axes of a source and a receiver of radiation. A base transparency meter was used for comparative measurements. It was capable of measuring the meteorological visibility in the range of 70–1000 m on a path up to 50 m long with sufficient accuracy. Both devices were placed in a big aerosol chamber (BAC) with a volume of 1800 m^3 (26 m long). We carried out simultaneous optical measurements of $S_{\rm m}$ in smoke of different density produced inside the chamber. The results of simultaneous measurements were used to estimate the possible errors of the backscatter MVR meter and to calibrate the prototype.

Backscatter MVR meter

The functional diagram of the backscatter meteorological visibility range meter is shown in Fig. 1. The device operates on a compensation principle according to which two light signals are formed. The first is the main signal proportional to the light flux scattered by the aerosol, and the second is the reference one proportional to the radiation source power. The signals are compared by their difference. The main and reference signals level off by linear displacement of an adjusting element (optical wedge–shaped attenuator) in the reference channel. As a result, the attenuation coefficient of the optical wedge required for compensation and proportional to linear displacement of the wedge is the quantitative characteristic of the meteorological visibility range $S_{\rm m}$.

Really, in the single scattering approximation the backscattered signal can be represented in the form

$$I_{\rm bsc}(\pi) = \kappa_1 P_0 / S_{\rm m} , \quad (1)$$

where P_0 is the radiation source power and κ_1 is the optical–geometric parameter. It should be noted that in Eq. (1) (a) the extinction of radiation along the measurement path is ignored, because the maximum distance from the source to the scattering volume is small (~ 10 m) for the prototype of the device operating in its near field; (b) the backscattering ratio (backscattering phase function) is included into the optical–geometric parameter k_1; and, (c) the above–given relation between the aerosol extinction coefficient and meteorological visibility range is used.

In its turn, the reference signal is

$$I_{\rm ref} = \kappa_2 P_0 \exp [- \tau_{\rm w}(x)] , \quad (2)$$

where κ_2 is the corresponding instrumental constant and $\tau_{\rm w}(x)$ is the optical thickness of the wedge in the linear position x.

From the flux compensation condition $I_{\rm bsc} = I_{\rm ref}$, it is simple to derive

$$\tau_{\rm w}(x) = \ln S_{\rm m}(x) - \ln \kappa , \quad (3)$$

where $k = \kappa_1/\kappa_2$.

Thus we can calibrate the displacement scale of the wedge with linearly varying optical thickness through its length in units of $\ln S_{\rm m}$.

The device is autonomous. It is housed in a one moisture–proof body where optical radiation source, backscattered signal receiver, processing and indicating unit, and power supply unit are enclosed.

*It should be noted that here and in the subsequent text we use the term meteorological visibility range to mean $S_{\rm m}$=3.9/ε(0.5), where ε(0.5) is the extinction coefficient at a wavelength of 0.5 μm. When processing the experimental data on the transparency at λ=0.63 μm, the values ε(0.63) were converted to ε(0.55).

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The device operates as follows (see Fig. 1). The incandescent lamp L emits white light flux periodically chopped by the mechanical modulator M with a frequency of 5 Hz and transported in two directions in antiphase. The first light beam, reflected from the spherical mirror M_1 with the focal length $F = 0.25$ m, enters into the aerosol medium. The second light beam (reference channel), after passage through the adjusting element (wedge–shaped attenuator W) and lightguide, is incident on the photodetector P. The signal scattered by the aerosol is also incident on the photodetector P after reflection from the receiving spherical mirror M_2 with the focal length $F = 0.25$ m. The signal is summed with the reference one in antiphase and then is synchronously detected in the photon counting mode. For predetermined difference between the signals the actuating system AS switches on the electric motor EM that drives the optical wedge–shaped attenuator W, which is linearly displaced thereby moving the pointer relative to the scale of values S_m. The electric sensor of wedge position (slide–wire resistor R) is also mechanically connected with the motor. It generates an analog output signal corresponding to the given position of the wedge, i.e., to the given intensity of light scattered by the aerosol. The analog signal is recorded by the KSP–type recorder.

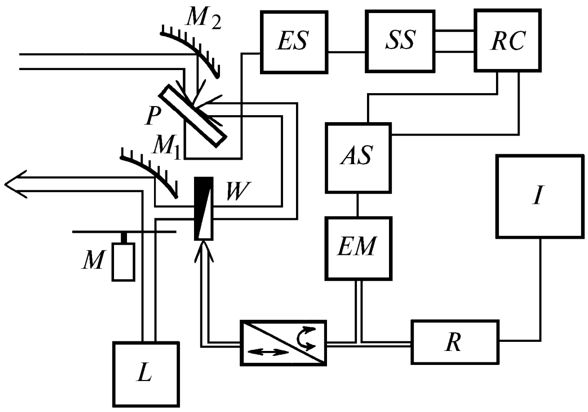

FIG. 1. Functional diagram of the backscatter meteorological visibility range meter, where ES is the electronic system, SS is the synchro switch, and RC is the reversible counter.

The optical–geometric parameters of the backscatter MVR meter are the following: diameters of the source and receiver apertures are $d_s = d_r = 0.16$ m; angular divergence of the source and field of view of the receiver are $2\gamma_s = 2\gamma_r = 0.9°$; distance between their axes is $B = 0.25$ m; and, angle between the optical axes of the source and the receiver is $\varphi = 1.4–2.9°$. In this case, the parameters of the scattering volume for $\varphi = 1.4°$ are: $V_s = 0.1$ m^3, $L_1 = 1.8$ m, and $L_2 = 9$ m, where L_1 and L_2 are the minimum and maximum distances to the scattering volume, respectively.

Base MVR meter

The base MVR meter consists of a radiation source, a system of mirrors placed in the aerosol chamber and capable of varying the path length in the aerosol from 5 to 50 m, a receiver of attenuated radiation, and a recording system. Variation of the path length makes it possible to measure at the aerosol optical thicknesses that ensure small errors. A He–Ne laser with an output power of 20 mW was used as a source of radiation at a wavelength of 0.63 μm. A laser beam enters into an aerosol medium, attenuates on the path of length L, and is recorded by a photometer. A collimator of the photometer, consisting of an objective and a diaphragm placed in the focal plane, determines the field of view of the photometer $2\gamma_p = 5$-$10'$. A system of discrete neutral light filters included into the photometer is capable of attenuating the recorded light flux up to 10^6 times. The FD–24 K photodiode was used as a photodetector. An electric signal from the photodetector was recorded at the frequency of radiation modulation, was amplified by a selective microvoltmeter, and was fed into a digital indicator of the MVR meter. The laser–intensity stability was continuously controlled in the MVR meter.

The device was connected with the Elektronika–60 computer through an interface for data processing in real time and control of the device operation. The data were processed on the computer, loaded in a database, and displayed by a peripheral unit.

The meteorological visibility range S_m was calculated from the measured aerosol extinction coefficient ε by Bouguer's method[2,3] and subsequently converted to

$$S_m = 3.9 / \varepsilon = 3.9\, L / \tau , \quad (4)$$

where $\tau = \varepsilon L = \ln (I_0 / I)$ is the measurable optical thickness of an aerosol medium, I_0 and I are the radiation intensities upon entering and exiting the aerosol medium, respectively.

Analysis of errors in measuring S_m by base and backscatter MVR meters

The errors in measuring S_m by the base MVR meter can be divided into two groups:

1) methodical errors caused by physical conditions of applicability of the Bouguer equation;

2) instrument errors (random and systematic).

Let us analyze the effect of each group of errors on the accuracy of measuring S_m by the base method. It is well known that multiple scattering can make significant contribution to the deviation from Bouguer's law. The portion of the scattered light incident on the receiver depends on τ, $2\gamma_r$, $2\gamma_s$, d_s, and d_r. It is also well known[3] that one can neglect the effect of multiple scattering at $2\gamma_s = 2\gamma_r = 10''–30'$ when the forward scattered radiation is considered up to $\tau < 18$ for atmospheric aerosols of different types. Therefore, in our case when $2\gamma_s = 2\gamma_r = 10'$ we can neglect the contribution of multiple scattering for the extinction coefficient $\varepsilon < 0.36$ m^{-1} (for $L = 50$ m) corresponding to $S_m > 10$ m, i.e., practically in the whole range of S_m under conditions of measurements.

The expression for the random rms error in measuring the extinction coefficient or S_m by the base method has the form[2]

$$\delta = \mathrm{d}S_m / S_m = (\sqrt{1 + \exp (2\tau)}/\tau)\, \mathrm{d}I_0 / I_0 . \quad (5)$$

The rms error caused by instability of the input signal intensity $\mathrm{d}I_0/I_0$ was minimized during measurements due to continuous control of the laser–intensity stability and the sensitivity of the instrument. This error was experimentally estimated to be 3%, on the average.

Figure 2 shows the dependence of the relative error δ on the ratio I_0/I calculated from Eq.(5) for $\tau < 1$. It should be noted that in order to decrease the error, the path length corresponding to $\tau < 1$ was chosen during measurements with the help of the system of mirrors. The scale of values S_m corresponding to $L = 50$ m is also shown in Fig. 2 as an example. As is seen, measurements on such a path make it possible to determine S_m with an error no more than 25% for $S_m < 1000$ m. In this case the error decreases with decreasing S_m, and for $S_m = 200$ m ($\tau < 1$) it is less then 9%.

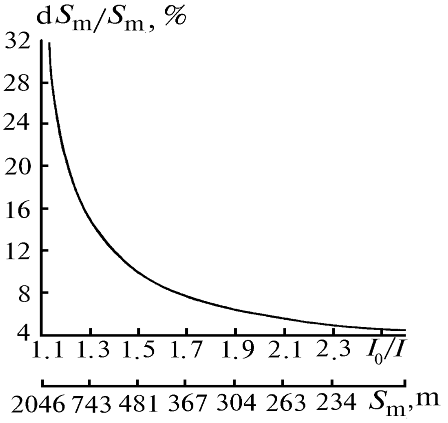

FIG. 2. Relative rms error in measuring S_m by the base method. The scale of S_m is shown for L = 50 m.

Thus we can use the base MVR meter for calibration and estimate of the error of the backscatter MVR meter.

The errors of measuring S_m by the backscatter MVR meter can be of three types: instrument, due to absolute calibrating, and methodical.

In order to estimate the instrument error caused by instability of operation of the instrument for a long time, special measurements were carried out that showed that the average relative error was 2–4%. It was achieved by using the compensation scheme of comparison of a recorded signal in the prototype. Relative error of the device calibration was really determined by the error of measuring S_m by the base MVR meter and was estimated above to be at a level of 20%. The main factors that can lead to the methodical errors are the possible contribution of multiply scattered light to the recorded optical signals and to the spatiotemporal variations of the aerosol optical characteristics. In general, the methodical error of the backscatter MVR meter can be estimated by way of comparison of measurement results with simultaneous data on the transparency of aerosol medium obtained by the base MVR meter. Since such a procedure makes it possible to calibrate simultaneously the scale (readings) of the backscatter MVR meter in absolute units of S_m, the estimate of the methodical error is given below together with the calibration.

Calibration of the backscatter MVR meter was carried out based on the results of simultaneous measurements of transparency by two measuring devices in the smoky aerosol medium with gradually varying density. The smoke was prepared by combustion of a specified amount of wood in an electric furnace. The initial smoke content in the big aerosol chamber varied with the amount of burned wood. Measurement runs started within 1–1.5 hours after the completion of wood burning, when the smoke homogeneously filled the whole chamber volume, and could last one day and more with varying S_m. Choice of such a model medium was caused by the fact that the optical properties of the smoky aerosol, produced by thermal decomposition of wood, are close to that of the atmospheric haze, which is known to be the most often encountered type of atmospheric optical turbidity.

It follows from Eq. (3) that the slope of the operating characteristic of the backscatter MVR meter can be found from two values S_m measured by the base MVR meter. Really, with knowledge of the return signal amplitudes U_1 and U_2 corresponding to two values S_{m1} and S_{m2} obtained by the base MVR meter, according to Eq.(3) we can write

$$\Delta \ln S_m/\Delta\tau = \ln (S_{m2} / S_{m1})/\ln (U_1/U_2) , \tag{6}$$

where $\Delta\tau$ is the corresponding change of the optical thickness of the attenuator. It should be noted that preliminary photometric measurements of the wedge (W in Fig.1) as function of its length showed its linearity with a relative error of 3%, i.e., the equal $\Delta\tau$ correspond to the identical displacements of the wedge Δx.

Any two values S_m can be chosen as calibration ones. From the experimental conditions, we chose the values averaged over ten readings $S_{m1} = 0.25$ km and $S_{m2} = 1.0$ km, that were measured by the base MVR meter on the path of length $L = 50$ m. The average amplitudes of the return signal $U_1 = 16$ mV and $U_2 = 3.5$ mV corresponded to these values of S_m. Substituting the chosen S_m and corresponding U into Eq. (6), we obtain

$$\Delta \ln S_m/\Delta\tau \simeq 1 . \tag{7}$$

The estimated slope of the calibration characteristic is indicative of the applicability of single scattering approximation underlying the developed prototype of the backscatter MVR meter with the given optical–geometric parameters in the considered range of S_m. Hence for this backscatter MVR meter we can ignore the methodical error caused by multiple scattering.

Thus the rms error in measuring S_m by the backscatter MVR meter is about 20%. It should be also noted that a thorough analysis must be made for completed device at the stage of its metrological certification. In our case the order of magnitude of the relative error in measuring S_m was estimated in comparison with the base method.

It follows from Eqs. (6) and (7) that

$$\ln S_{m2} = \ln S_{m1} + \ln (U_1 / U_2) . \tag{8}$$

Equation (8) can be used to calculate the dependence $\ln S_m(U)$ in the given range of S_m if only one calibration point (S_{m1}, U_1) is available.

It follows from Eq. (7) that the linear scale of the wedge $\tau = f(x)$ also remains linear for $\ln S_m$. Substituting the limiting values $U_{max} = 82$ mV and $U_{min} = 0.24$ mV and the calibration point ($U_1 = 3.5$ mV and $S_{m1} = 1$ km) into Eq.(8), we obtain $S_{min} = 0.042$ km and $S_{max} = 14.6$ km.

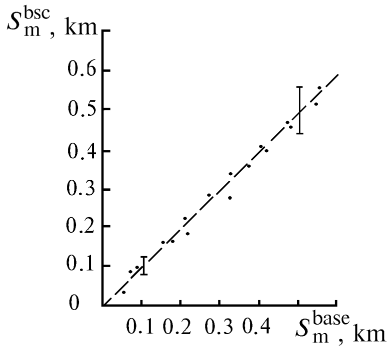

FIG. 3. Results of simultaneous measurements of S_m by the backscatter (y–axis) and base (x–axis) MVR meters.

The results of comparison of simultaneous measurements of S_m by the base and backscatter MVR meters are shown in Fig. 3 for individual realization. It is seen from Fig. 3 that the data on S_m obtained by the backscatter MVR meter agree with the data of base measurements to within a relative rms error of 20%. The figure also illustrates the weak effect of multiple scattering in the S_m range under consideration. This fact makes it possible to extend the proposed technique for calibrating by one calibration point (U, $\ln S_m$) up to S_m = 14.6 km taking into account that $\Delta\tau/\Delta x \simeq$ const.

CONCLUSION

The feasibility of the backscatter MVR meter with selected optical–geometric scheme included in the single–point laser beacon is shown. The total error in measuring S_m is about 20%.

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