LASER METER FOR MEASURING RADIATION ATTENUATION COEFFICIENTS AT $\lambda = 10.6$ μm

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The technical requirements which a laser meter for measuring radiation attenuation coefficients must meet in order to increase the accuracy of measurements along paths near the ground are discussed. It is shown that "full interception" of the radiation flux along the path is required in order to reduce the effect of wandering of the beam axis, redistribution of energy over the transverse cross section, and beam expansion in a turbulent atmosphere on the measurement accuracy. The block diagram of the meter at $\lambda = 10.6$ μm is presented. The technical characteristics of the device were studied experimentally. It is shown that for a 0.5 km path the rms error was equal to 6% for measurements of attenuation coefficients in the range 0.06–4.00 km^{-1}. Automatic compensation of the angles of regular refraction is performed in a range of 1′.

To develop the instrumental Ion required for optical radar and communication, optical range finding, and optical tacheometry it is necessary to have light sources which are efficient in the atmospheric channel.[1] Measurement of the atmospheric transmission is an important part of this problem. There are many works, for example, Refs. 2–4, which are devoted to the development of methods and in our opinion little attention is devoted in these works to laser devices which enable measurement of the radiation efficiency directly on the radiation efficiency directly at the radiation line of interest.

In this paper we shall summarize our experience in developing and studying a laser meter for measuring atmospheric attenuation coefficients at the wavelength $\lambda = 10.6$ μm.

Irrespective of the sources employed for measuring the attenuation of radiation in the atmosphere, the effect of the regular geodesic refraction, random wandering of the axis of the beam and beam expansion owing to atmospheric turbulence as well as energy redistribution in the transverse cross section of the beam must be taken into account. The effect of the last factor in the region of strong fluctuations for values of the parameter $\beta_0^2 = 1.23 Cn^2 k^{7/6} L^{11/6} \gg 1$ (Cn^2 is the structure factor of fluctuations of the atmospheric refractive index, L is the path length, and $k = 2\pi/\lambda$ increases owing to interference of separate sections of the wavefront and results in strong fluctuations of the received signal[5] right up to complete fading.

The small, as compared with thermal and other incoherent sources, angular divergence of the laser beam makes it possible to realize "full interception" of the beam, i.e., the condition

$$R \gg a_e, \tag{1}$$

where R is the radius of the receiving aperture of the meter and a_e is the effective beam radius at the end of the atmospheric path, can be satisfied for paths $L \le 1000$ m with acceptable dimensions of the optical receiving system; this makes it possible to reduce significantly the effect of the factors listed above on the accuracy of the measurements of attenuation coefficient[5]. For a Gaussian beam[5]

$$a_e = a_0\left[\left[1-\frac{L}{F}\right]^2 + \Omega^{-2}\left[1+\frac{a_0^2}{\rho_c^2} + \frac{4}{3}\,\frac{a_0^2}{\rho_0^2}\right]\right]^{1/2}, \tag{2}$$

where a_0 is is the initial radius of the beam, F is the radius of curvature of the wavefront at the center of the radiating aperture, $\Omega = ka_0^2/L$ is the Fresnel parameter of the radiating aperture, ρ_c is the coherence length of the field of the source, and $\rho_0 = (1.45k^2 Cn^2 L)^{-3/5}$ is the coherence length of a plane wave. In the case of "full interception" of the beam on the path the turbulence-induced spreading of the energy over the transverse cross section of the beam does not result in fluctuations of the received signal. The intensity fluctuations owing to the statistical screening of the beam by particles are small and are minimized by averaging. Regular refraction for both coherent and incoherent sources must be compensated during the measurements.

The scheme of "full interception" measurements permits calibrating the meter efficiently by placing a mirror which returns the radiation flux into the receiver at the output of the optical-mechanical channel. The calibration error, when the difference of the reflection coefficients of the working and calibration mirrors is taken into account, is determined solely by the instrumental error of the meter.

Satisfaction of these conditions with a low instrumental error will make it possible to measure the attenuation coefficients on short paths even under conditions of high atmospheric transmittance with an error that is no greater than the error introduced in photometric methods on paths several kilometers long without "full interception" of the beam. It is of practical interest to determine the conditions which the instrumental error of such a meter must satisfy in a fixed range of measurements of attenuation coefficients as a function of the path length.

In measurements performed with the help of the most commonly employed basic method the attenuation coefficient is determined from Bouguer's law

$$\alpha = -\frac{1}{L}\ln\frac{P}{P_0}, \tag{3}$$

where P_0 and P are the radiation fluxes corresponding to the traversed path in the atmosphere and transmitted into the path in the atmosphere, and L is the path length. In constructing the meter whose output signal

$$U_{out} = \ln\frac{U_0}{U} = \ln U_0 - \ln U \tag{4}$$

taking into account the calibration, the attenuation coefficient is determined from the formula

$$\alpha = \frac{\gamma(U_{out} - U_{out.c})}{L}, \tag{5}$$

where the coefficient γ is equal to $1V^{-1}$ and is introduced in order to preserve the dimension of a; U_0 and U are the signals in the reference and working channels of the meter, respectively, and are proportional to the power fluxes; U_{out} and $U_{out.c}$ are the respective output signals in measurements on the working path and in calibration of the meter, V.

Differentiating the expression (5) and neglecting the error introduced by the uncertainty in the path length owing to its shortness we obtain the absolute error in the determination of the attenuation coefficients

$$\Delta\alpha = \frac{(\Delta U_{out} - \Delta U_{out.c})\cdot\gamma}{L}. \tag{6}$$

Starting from the given value of $\Delta\alpha$ and the instrumental error ΔU_{out} obtained in the experiments it is possible to select an optimal path length L and the path-dependent dimensions of the receiving optical system of the meter. Thus, for example, to obtain an error of $\Delta a = 0.002$ km^{-1} for a path $L = 0.5$ km, ΔU_{out} must be less than or equal to $5 \cdot 10^{-4}$ V. For a path $L = 0.1$ km, with the same value of ΔU_{out}, $\Delta\alpha = 0.01$ km^{-1}.

Figure 1 shows a block diagram of a laser meter for measuring attenuation coefficients. The meter operates based on the basic photoelectric method in which the reference beam and the beam which has traversed the path in the atmosphere are received on the same pyroelectric bolometer 14 with a sensitive area of 4×4 mm. The working radiation source is an LG-74 power-stabilized single-frequency CO_2 laser with AFC operating on one of three transitions: P(18), P(20), or P(22).

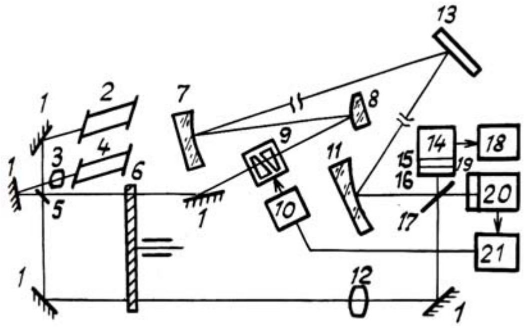

FIG. 1. Block diagram of a laser meter for measuring attenuation coefficients: 1 — mirror; 2 — He-Ne laser; 3 — BaF_2 correcting lens; 4 — CO_2 laser; 5 — half-transmitting BaF_2 plates; 6 — modulator; 7, 8 — off-axis aspherical mirrors of the transmitter; 9 — BaF_2 optical wedges; 10 — drive of the wedge compensator; 11 — off-axis aspherical receiving mirror; 12 — BaF_2 focusing lens; 13 — mirror of the reflector; 14 — pyroelectric bolometer; 15 — dispersion filter; 16, 19 — attenuating filters; 17 — BaF_2 half-transmitting plate; 18 — conversion unit; 20 — 4×4 mm pyroelectric bolometer; 21 — wedge compensator controller.

The beams of the working CO_2 laser and the alignment He-Ne laser are combined on the BaF_2 plate 5 which is half-transmitting for both wavelengths. The disk of the modulator 6 interrupts the combined radiation beam with a frequency of 391±1 Hz and directs the beams into the reference and measuring channels to the detector 14 with a frequency of 16.25±0.04 Hz. The BaF_2 half-transmitting plate 17 divides the beam received from the path into the measured and monitoring beams. The position of the received beam into the measured and monitoring beams. The position of the received beam relative to the optical axis of the receiving mirror is monitored with the help of a 4×4 mm pyroelectric bolometer 20. Automatic compensation of the regular atmospheric refraction in a range of ±1′ is performed with BaF_2 wedges 9 based on the signals indicating deflection along the X and Y axes. For large angles of refraction the compensation is performed by remote control of the reflector drive 13 with a mirror 500 mm in diameter. The mirrors 7 and 8 of the transmitter and the receiving mirror 11 (F = 780 mm, 250 mm diameter) are aspherical, off-axis mirrors. From the pyroelectric bolometer 14 the signal is fed to the input of the converter 18, (Ref. 6), which puts out the natural logarithm of the ratio of the signals in the reference and working channels.

In order to monitor on-line the transfer factor of the converter an electronic calibrator, which forms a signal whose form is identical to that of the signal from the pyroelectric bolometer with a regulatable differential of the levels in the reference and working channels, is built into the meter. The transfer ' factor is monitored and regulated when the output of the calibrator is switched to the input of the converter.

The output signal is recorded with a digital dc voltmeter or a microcomputer with an ADC and the values of the attenuation coefficients obtained in accordance with the formula (5) are printed out.

Technical characteristics of the meter

Working wavelength	10.6 μm
Alignment wavelength	0.63 μm
Range of measurement of the attenuation coefficients on a 0.5 km path	0.06–4.00 km^{-1}
rms error in the determination of the attenuation coefficients on a 0.5 km path	6%
Range of compensation of regular refraction	1′
Dimensions of the receiving-transmitting unit	770×570×1040 mm.

The main source of error in the measurements is the nonlinearity of the conversion process. Monitoring of the conversion of the optical-electronic channel by placing calibrated CaF_2 attenuating filters of different thickness in the working channel in front of the pyroelectric bolometer did not make it possible to determine the nonlinearity of conversion because the nominal error in the transmission coefficients of the filters was large (±1 %). The nonlinearity of the converter unit was determined separately by feeding into the input of the block with the calibrator the regulated level of the difference of the signals in the reference and measuring channels. The signal difference was measured with high accuracy (0.06 %). The output signal was then compared with the value computed in accordance with the formula (4). The relative systematic error of conversion varies from -3.5% to +1.3% over the measurement range.

The chosen frequencies of modulation and switching of the reference and working channels to the pyroelectric bolometer eliminate any effect due to the low-frequency power instability of the radiation source.

The instrument was checked during the summer and fall of 1988 near the shore of Lake Balkhash on a path of 179.4 m up to the reflector. The temperature, the relative humidity, and the air pressure at the start of the path as well as the structure constant of the refractive index of air C_n^2 were measured at the same time.[7]

The interception of the beam by the receiving mirror was monitored in the presence of developed turbulence ($C_n^2 \approx 10^{-15}$ cm$^{-2/3}$) by placing on the aperture of the receiving mirror ring-shaped diaphragms with different diameters in order of increasing size, and recording the output signal at the meter for each diaphragm installed. It was assumed that the diameter of the beam arriving from the path is equal to the diameter of the diaphragm for which the output signal did not change when the size of the diaphragm was increased. The beam diameter determined by this method, with the indicated value of C_n^2 on the path to the reflector L = 179.4 m, was equal to 210 mm. The obtained absolute rms error Дa in the measurements of the attenuation coefficients was equal to 0.006 km^{-1} with a confidence probability P = 95% for n = 10 observations.

The value a_e = 5.15 cm computed using the formula (2) with a_0 = 5 cm shows that in our case the diameter $D_{C.S.}$ and therefore the length of the path are determined by the gain and the quality of the transmitter optics.

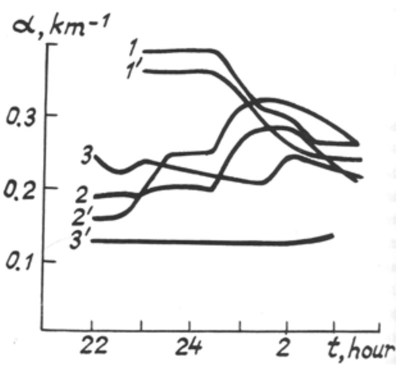

FIG. 2. The measurements and calculations of the attenuation coefficients at λ = 10.6 μm in the coastal zone of Lake Balkhash: 1, 2, 3 — the values measured on July 2, 1988; June 28, 1988, and October 25, 1988, respectively; 1′, 2′, and 3′ — computed values.

The performance of the system compensating regular atmospheric refraction was checked on a path L = 200 m based on the output signal of the meter with the laser beam deflected by discrete angles with a certified pair of BaF_2 optical wedges placed at the output of the transmitter. The angular step was equal to 2.4 angular seconds. The angle of deflection was regarded as compensated if the output signal of the meter after compensation does not change. The range of compensation was equal to 1 angular minute. The slope of the rangefinding characteristic along the X and Y axes was equal to 0.9 mV per angular second. The continuous absorption by water vapor and absorption on the $P(20)$ transition line of carbon dioxide gas were calculated from the measured values of the meteorological parameters in accordance with Refs. 8 and 9.

Figure 2 (curves 1, 1′, 2, 2′) shows examples of the measurements and calculations performed for June 28, 1988 and July 2, 1988 on days when with small fluctuations of the air temperature the relative humidity varied over wide ranges. The results presented show clearly that the measured and computed values of the attenuation coefficients are in good agreement. The systematic excess, reaching 0.04 km^{-1}, of the measured attenuation coefficient over the computed value can apparently be explained by attenuation by "gigantic" particles which characteristically form in the coastal zone.[10] The measurements performed during the fall (October 25, 1988) under different atmospheric conditions did not exhibit such a correlation (curves 3, 3′); this can obviously be explained by the effect of aerosol attenuation, which was neglected in the calculation of the curve 3′.

The obtained results allow us to conclude that the laser meter developed permits measuring on a path with a length of about 500 m, with calibration performed on-line, the values of the attenuation coefficients at λ = 10.6 μm in the range 0.06–4.00 km^{-1} with a relative error of not worse than 6 %. The unit can be employed for complex investigation of the parameters of the atmosphere.

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