METEOROLOGICAL VISIBILITY METER AS A PART OF LASER BEACON PART I. THEORETICAL RESULTS

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Computational results of magnitude and dynamic range of scattered light fluxes recorded within lidar angle are presented in the paper as a function of opto–geometric scheme of the visibility meter, which operates on recording the backscattered beacon laser radiation. A possibility for the lidar visibility meter to be realized as a part of one–positional laser beacon is also shown in the paper.

The use of lasers as sources of pencil light beams in beacons considerably advances the limiting detection range $L_{\rm lim}$ into the area of greater optical thicknesses in dense atmospheric hazes when traditional luminous navigation signs are not visible.[1] It is achieved due to high directivity of laser beams and their monochromatism, on the one hand, and high spectral brightness and relatively high output power of lasers, on the other hand.

Nevertheless, the achieved $L_{\rm lim}$ are not sufficient for many practical cases of navigation, particularly for the conditions of low atmospheric transmittance,[2] and problem of increasing $L_{\rm lim}$ will be urgent for a long time.

The further increasing $L_{\rm lim}$ of laser beacon is connected, first of all, with optimization of light conditions and increasing of beacon energy potential. However, direct increasing in laser output power is limited by reasons of safety characterized by maximum permissible energy level Q, which is a function of light signal parameter E and parameter $B_{\rm b}$ of brightness of background of vision adaptation.

The idea of laser beacon automatically changing energy of light signals in dependence on changing of meteorological visibility distance $S_{\rm m}$, $B_{\rm b}$, and distance L is quite natural.

Without considering questions concerning discussion of dependence $Q = f(B_{\rm b}, E)$, we examine feasibility of realization of lidar visibility meter built in laser beacon which operates on recording of backscattered beacon radiation. One–positional structure achieved in this version in contrast to basic method of measuring $S_{\rm m}$, i.e., combination of receiver and transmitter of light signals in one point, is considered to be absolute advantage in referring beacon to locality.

It is possible to use signal recording at any scattering angle within the framework of one–parameter model of optical haze characteristics[3] for estimation of the scattering coefficient (meteorological visibility distance).

Measuring at an angle of 45° by nephelometrical method gives the highest accuracy of volume scattering coefficient estimation.[3] But in this case in saving one–positional structure we have to work with small scattering volumes, moreover, placed in the region of beacon technical service where an extra aerosol load exists.

The measurements conducted near the angles close to 180° give lower accuracy of volume scattering coefficient estimation,[3] but allow us to move the scattering volume away the beacon technical zone for a larger distance (comparing with the case of 45°) in direction of navigation information transmission and integrate a signal over space much better.

Supplying meteorological visibility meter with sufficient energy potential under real conditions is connected with correct choice of opto–geometrical scheme of a meter. It is sensible for solution of this problem to study a dynamic range and peculiarities of changing of scattered light flux values recorded in the area of lidar angles in dependence on parameters of a meter, namely, source aperture and beam divergence, receiver aperture and its angle of vision, mutual arrangement of source and receiver (base) and angle of convergence of system optical axes detecting value and position of the scattering volume.

The computations were carried out for an opto–microphysical model of atmospheric haze of the shore region.[3] This haze is considered to be a characteristic type of opto–atmospheric turbidity. The following conditions were assumed: uniform turbidity along the path of laser beam that is adequately valid for shore hazes and horizontal paths which are characteristic for the majority geometries of beacon placement, absence of laser radiation absorption at the working wavelength of beacon $\lambda = 0.51$ μm, and small contribution from multiple scattering (single scattering approximation).

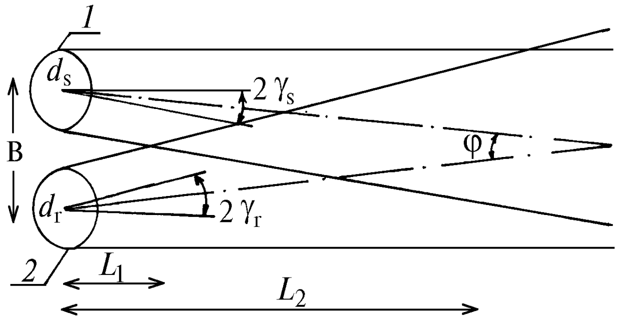

FIG. 1. Geometrical scheme of lidar visibility meter. Source aperture (1) and receiver aperture (2).

Monostatic scheme of backscattering lidar[4] taken as a basis for calculations is shown in Fig. 1, where $d_{\rm s}$ is source aperture, $2\gamma_{\rm s}$ is divergence of source laser beam; $d_{\rm r}$ is receiver aperture; $2\gamma_{\rm r}$ is receiver angle of vision. In this case d_s and $2\gamma_s$ are given by beacon construction, and d_r and $2\gamma_r$ are variable in computations. The mutual arrangement of transmitting and receiving optical systems is governed by the basis between axes of these systems B and convergence angle of optical axes of the systems φ.

As is shown in Ref. 5, light flux from elementary scattering volume $\mathrm{d}\,V_{sc}$ recorded by a receiver is defined as

$$\mathrm{d}\,\Phi_{sc}(\theta) = \mathrm{d}\,J_{sc}(\theta)\,\omega_r\,, \qquad (1)$$

where $\mathrm{d}\,J_{sc}(\theta)$ is luminous intensity of scattered radiation at an scattering angle θ; ω_r is a solid angle, in which scattered radiation is received. An expression $\omega_r = \pi \sin^2\gamma_r$ is valid for small receiver angles of vision $2\gamma_r \lesssim 1°$. In its turn, intensity of scattered radiation can be presented as follows:

$$\mathrm{d}\,J_{sc}(\theta) = \mu_h\,E\,\mathrm{d}\,V_{sc}(\theta)\,\mathrm{e}^{-2\tau}, \qquad (2)$$

where μ_θ is a coefficient of directed light scattering at an angle θ, in this case it is backscattering coefficient β_π; E is illuminance of elementary working scattering volume $\mathrm{d}\,V_{sc}$; τ is an optical thickness of scattering medium from transceiver to V_{sc}. The value of illuminance E is defined by the source output power P_0, distance to scattering volume L, and solid angle of divergence of source radiation ω_s:

$$E = \frac{P_0}{L^2\,w_s}\,. \qquad (3)$$

Taking into account that $\omega_s = \pi \sin^2\gamma_s$ and $\tau = \varepsilon\,L = 3.9\,L/S_m$, where ε is extinction coefficient of the atmosphere, equation (1) may be transformed into the following form:

$$\mathrm{d}\,\Phi_{sc}(\pi) = \frac{\beta_\pi}{L^2}\,P_0\,\frac{\sin^2\gamma_r}{\sin^2\gamma_s}\,\mathrm{e}^{-7.8/S_m}\,\mathrm{d}\,V_{sc}(\pi). \qquad (4)$$

The total light flux recorded by receiver is equal to a sum of flux differential components from all elementary scattering volumes $\mathrm{d}\,V_{sc}(\mathrm{L})$ included into the total scattering volume of aerosol V_{sc}:

$$\Phi_{sc}(\pi) = \int\limits_{V_{sc}} \mathrm{d}\,\Phi_{sc}(\pi) = \int\limits_{L} \mathrm{d}\,\Phi_{sc}(L,\,\pi). \qquad (5)$$

Equation (4) is a differential form of lidar equation, and it is used for numerical calculations of additive parts of light flux coming into receiver from separate sections of sounded path. Equation (5), in its turn, allows us to determine integral optical signal as a sum of separate signals.

Further calculation was performed in the following way:

1) opto–geometrical parameters of lidar scheme of transmittance meter were given and its geometrical function (space boundaries of scattering volume need for calculations by expressions (4) and (5)) was determined;

2) the procedure of correct calculation of elementary scattering volumes $\mathrm{d}V_{sc}(L)$ along the path of sounding was worked out;

3) the calculation with required space quantification over L of differential optical signals from path sections was performed;

4) estimation of calculated integral energy signal of transmittance meter was made, and possibility of its recording by a real photoreceiver was considered.

Further opto–geometrical parameters of transceiving system were given. Source parameters were as follows: radiation wavelength $\lambda = 0.51$ μm, output power $P_0 = 0.045$ W; $2\gamma_s = 5'$, and $d_s = 0.005$ m. Receiver parameters used in calculations are presented in Table I.

TABLE I. Parameters of receiver.

d_r	0.10 m	0.16 m
$2\gamma_r$	22′	1°
B	0.20 m	0.25 m
φ	0°	55′

It was also necessary to have extra input information about connection of backscattering coefficient β_π with extinction coefficient of atmosphere (meteorological visibility distance S_m) for making calculations by formula (4). The opto–microphysical model of atmospheric shore hazes suggested in Ref. 3 was used for this purpose. The model establishes in numerical form dependence of backscattering coefficient β_π on S_m for the given wavelength in the range from 5 to 50 km which is presented in Table II.

TABLE II. Values of backscattering coefficient β_p *for* $\lambda = 0.51$ μm *from the model of Ref. 3.*

S_m, km	5	10	20	30	50
ε, km^{-1}	$8.46\cdot10^{-1}$	$4.23\cdot10^{-1}$	$2.19\cdot10^{-1}$	$1.52\cdot10^{-1}$	$9.91\cdot10^{-1}$
β_π, km^{-1}·sr^{-1}	$1.41\cdot10^{-1}$	$8.54\cdot10^{-1}$	$5.79\cdot10^{-1}$	$4.57\cdot10^{-1}$	$3.62\cdot10^{-1}$

The most characteristic results of calculations of differential scattered light fluxes $\mathrm{d}\Phi_{sc}(L)/\mathrm{d}L$ are shown in Figs. 2, 3, and 4. Computations of integral light fluxes are presented in Table III.

TABLE III. Values of integral light fluxes (W) recorded by location transmittance meter when $P_0 = 0.045$ W, $2\gamma_s = 5'$, $\lambda = 0.51$ μm, *and* $d_s = 0.005$ m.

	Parameters		
S_m, km	$d_r = 0.1$ m; $B = 0.2$ m; $\varphi = 0°$		$d_r = 0.16$ m; $B = 0.25$ m; $\varphi = 55'$
	$2\gamma_r$		
	22′	1°	1°
	$L_1 = 10.2$ m; $L_2 = 37.6$ m	$L_1 = 15.6$ m; $L_2 = 31.5$ m	$L_1 = 6.6$ m; $L_2 = 50$ m
5	$8.8\cdot10^{-8}$	$8.7\cdot10^{-7}$	$6.4\cdot10^{-8}$
50	$2\cdot10^{-7}$	$1.4\cdot10^{-6}$	$1.7\cdot10^{-7}$

Discussion on the results of computations shows that changing of scattering volume V_{sc} and its place on the path of sounding is provided by changing of $2\gamma_r$ and φ. The change of $2\gamma_r$ from 1° to 22′ at $\varphi = 0°$ leads to increasing

V_{sc}, and boundary of zone L_2 shifts from 31.5 m to 102 m. The contribution of zone $L < L_2$ into a recorded signal increases here. So, if at $2\gamma_r = 1°$ contribution from $L < L_2$ is ~10% when $S_m = 5$ km and ~ 5% when $S_m = 50$ km, then at $2\gamma_r = 22'$ it is 25% and 15%, respectively. This dependence is more pronounced in changing φ from 0 to 55° (see Fig. 4).

Thus, variations of geometrical parameters for a given S_m having an influence on arrangement of the boundaries L_1 and L_2 do not change completely the shape of curves dΦ/dL (see Figs. 2–4).

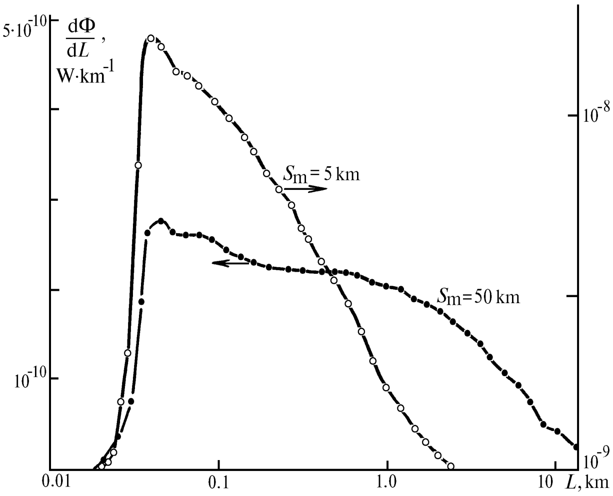

FIG. 2. Differential fluxes of backscattered radiation. Opto–geometrical parameters of lidar visibility meter: $P_0 = 4.5\cdot10^{-2}$ W, $2\gamma_s = 5'$, $d_s = 0.005$ m; $2\gamma_r = 1°$; $d_r = 0.1$ m, $B = 0.2$ m; φ = 0°.

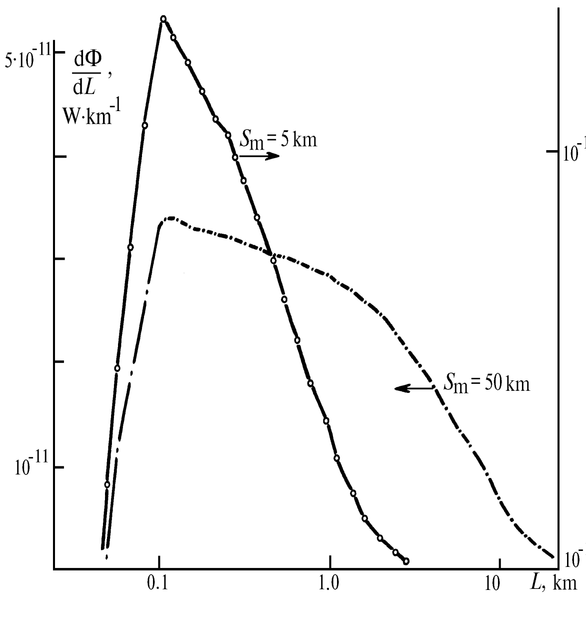

FIG. 3. Differential fluxes of backscattered radiation. Opto–geometrical parameters of lidar visibility meter: $P_0 = 4.5\cdot10^{-2}$ W, $2\gamma_s = 5'$, $d_s = 0.005$ m, $2\gamma_r = 22'$, $d_r = 0.1$ m, $B = 0.2$ m, φ = 0°.

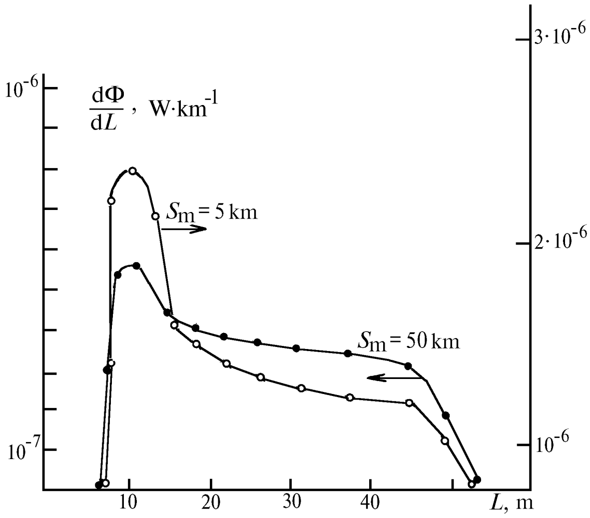

FIG. 4. Differential fluxes of backscattered radiation. Opto–geometrical parameters of lidar visibility meter: $P_0 = 4.5\cdot10^{-2}$ W, $2\gamma_s = 5'$, $d_s = 0.005$ m, $2\gamma_r = 1°$, $d_r = 0.16$ m, $B = 0.25$ m, φ = 55′.

Let us consider the influence of S_m variations on a total scattered signal. The visibility decreasing from 50 to 5 km results in sharp growth of level of differential signals coming from distances of $L \leq 0.9$ km. This fact is characteristic feature of curves in Figs. 2–4. Moreover, a working zone of scattering volume becomes considerably narrower. So, for $S_m = 50$ km signal dΦ/dL decreases down to 10% from maximum value at $L = 20$ km, whereas for $S_m = 5$ km such a signal decreasing is achieved even at $L \sim 3$ km. Hence, a lidar signal of transmittance meter is formed by scattering volumes more close to device when atmospheric visibility decreases ($S_m = 5$ km), and at $S_m = 50$ km the area of distances $L > L_2$ makes a main contribution into the total scattered signal. Hence, the error of S_m measurement by visibility meter will be large at good visibility when distance of detection of traditional luminous navigation signs is enough for requirements of navigation practice. That is why when creating such S_m meter it is sensible to deal with only measurement of such a range of S_m in which the use of laser beacons instead of traditional ones is most effective. Such a range of values S_m is equal to 2–10 km (see Ref. 2).

As is shown in Figs. 2–4, the changing of V_{sc} position and its value is achieved by means of variations of $2\gamma_r$. Technically it is simpler to do by means of choice of convergence angle of optical axes of source and receiver φ. Moreover, it is sensible to have φ being not equal to 0°. In this case V_{sc} will be placed rather close from receiver, and assumption about a small contribution from multiple scattering used in deduction of expression (2) will be justified, hence, systematic error of S_m estimation will be decreased. It should be noted that the errors arising in extension of S_m, having been measured in the place of beacon placement, along the whole distance L_{lim} are caused mainly by nonuniformity of shore haze, and for horizontal paths in our case they do not exceed 5–10% according to Ref. 3.

Thus, the results of lidar signals computation allowed us to optimize opto–geometrical parameters of S_m meter, estimate the order of magnitude and dynamic range of signal changing, and detect the sources of systematic errors of S_m measurement.

The recorded lidar signal can be surely received by silicon photodiodes[6] and equals 10^{-8}–10^{-6} W (see Table III) for the considered opto–geometrical parameters of receiver (B = 0.25 m; φ = 55′; γ_s = 22′ and 1°) which are provided rather easily by mass objectives of high quality.

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