FUNCTIONAL RELATIONS BETWEEN TOTAL SCATTERING AND BACKSCATTERING FOR RETRIEVING THE PROFILE OF THE ATTENUATION COEFFICIENT IN THE ATMOSPHERE FROM LIDAR–SENSING DATA

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The possibility of using a variable along a sensing path backscattering phase function in lidar data processing with the goal of increasing the accuracy of retrieving the profile of the attenuation coefficient in the inhomogeneous atmosphere is analyzed. Approximated dependences of the total aerosol scattering on aerosol backscattering are given based on the published experimental data. By way of example, the model profiles of the attenuation coefficient are given retrieved with the use of the scattering phase functions being constant and variable along the sensing path.

Practical use of the equation of laser sensing necessiates the employment of some assumptions about the relation between total scattering and backscattering of light. The simplest assumption about constancy of the aerosol scattering phase function at an angle of 180° ($x_{\pi,a}$) along the sensing path of the lidar is most often used in this case. With the segments of the path with large gradients of aerosol turbidity such an assumption leads to large errors in determining the optical characteristics of the atmosphere.[1–3] Moreover, in some cases such an assumption proves to be insufficient, since it involves the knowledge of the true numerical values of the parameter $x_{\pi,a}$ on the sensing path (for example, to find the corrections for the selectivity of aerosol scattering in differential lidar determination of gaseous components of the atmosphere). In fact, in these cases two assumptions about the relationship of aerosol total scattering and backscattering are employed: first, the assumption about the constancy of the parameter $x_{\pi,a}$ along the entire sensing path and, second, the assumption about its concrete numerical value under given conditions. So, for example, Browell et al.[1] consider that concrete values of $x_{\pi,a}$ should be chosen starting from the peculiarities of the position of measurement point, in particular, for a wavelength of 0.3 μm $x_{\pi,a}$ is equal to 0.01, 0.028, and 0.05sr^{-1} for urban, country, and sea and coastal regions, respectively.

In this paper I analyzed the possible ways for increasing the accuracy of lidar measurements of the attenuation coefficient under conditions of an inhomogeneous turbid atmosphere by means of using the functional relations between the total scattering and backscattering of aerosol. The concrete functional relations are given between these values which can be used in practice of lidar measurements of the optical parameters of the atmosphere.

At present most researchers consider that an assumption about linear relation between the logarithms of the total scattering and backscattering[2,4–8] is more adequate than the condition $x_{\pi,a}$ = const, which is valid only in some particular cases, i.e.,

$$\ln r_\pi = A + n \cdot \ln\mu \,, \tag{1}$$

where r_π is the absolute brightness phase function at an angle of 180°, μ is the attenuation coefficient, and A and n are the constants. An analysis of Ref. 9 has shown that this dependence is valid, at least, in the wavelength region 0.25–0.5 μm. However, Klett[10] concluded that it is more correct to assume the parameters r_π and μ be linearly dependent but in this case the proportionality factor by itself depends on μ. For measurements performed under conditions of fogs and low cloudiness he proposed the dependence of the following form:

$$r_{\pi,a} = 0.00174 + 0.055\exp\{-[(\ln\mu - 4)/3.1]^2\} \,. \tag{2}$$

My analysis has also shown that the relation between the logarithms of the total scattering and backscattering is nonlinear and cannot be approximated with satisfactory accuracy by the linear dependence in the form of Eq. (1) for the entire range of atmospheric turbidity varying from highly transparent to the dense fogs, since for the values of the scattering coefficients exceeding 2–3 km^{-1} backscattering sharply increases.[11] Therefore, in the case of measurents performed in a two–layer media the results are more acceptable when the dependence of r_π on the parameter μ is approximated on different segments of the path by two different linear dependences with different slopes.[3]

Experimental dependence of r_π on μ for a wavelength of 0.55 μm presented in Ref. 11, which was obtained on the basis of an analysis of published data (and, partially, on the basis of my experimental investigations) can be approximated by the relation

$$r_\pi = 0.02\mu^{0.6+0.1\sqrt{\mu}} \,, \tag{3}$$

where r_π and μ are expressed in km^{-1}. Figure 1 shows the dependence of r_π on μ obtained in Ref. 11 (curve *1*) and its approximation with the help of relation (3) (curve *2*). Corresponding dependences x_π on μ are shown in Fig. 2 (curves *1* and *2*, respectively). Curve *3* shows the dependence x_π on μ obtained on the basis of Klett's relation (2).

Dependences depicted by curves *1* and *2* on the above figures have been obtained based on the measurements carried out on the Earth's surface. In this case the atmosphere was assumed to be single–component, i.e., molecular and aerosol scattering were considered as a single whole. However, for the problems of tropospheric sensing in which aerosol and molecular scattering become commensurate, aerosol scattering must be separated from

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molecular scattering and, consequently, it is necessary to operate independently with aerosol and molecular scattering phase functions at an angle of 180° (see Ref. 1). In other words, the coefficients of total scaterring (r) and backscattering (r_π) should be considered in general as a sum of two components

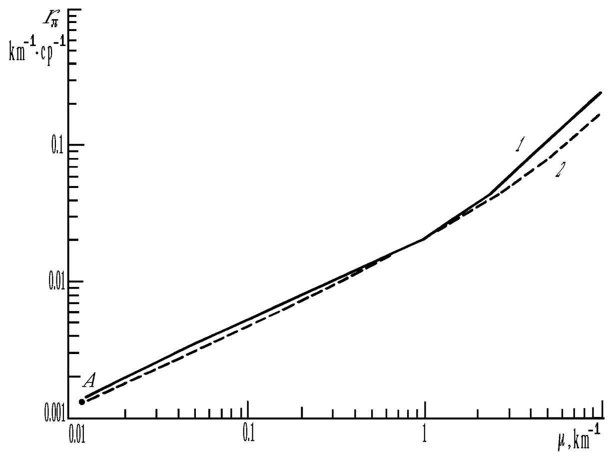

FIG. 1.

$$r = r_a + r_m\,; \tag{4}$$

$$r_\pi = r_{\pi,\,a} + r_{\pi,\,m}\,, \tag{5}$$

where the subscripts a and m stand for aerosol and molecular components.

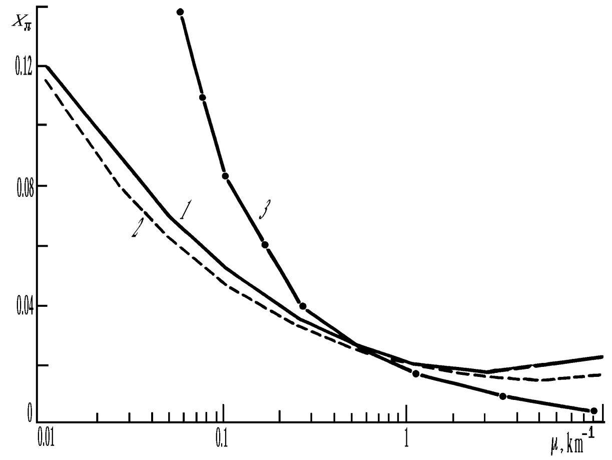

FIG. 2.

For a wavelength of 0.55 μm under standard atmospheric conditions (temperature is equal to 288.15 K and pressure is equal to 1013.25 mb) the parameters r_m and $r_{\pi,\,m}$ can be written as follows: $r_m = 0.0114$ km^{-1} and $r_{\pi,\,m} = 0.0136$ km^{-1} (the point A in Fig. 1). Then, in accordance with Eq. (3) the dependence of the aerosol component of the backscattering coefficient $r_{\pi,\,a}$ on the coefficient of total aerosol scattering r_a for a purely scattering atmosphere can be written down in the form

$$r_{\pi,\,a} = 0.02\,(r_a + 0.0114)^{0.6+0.1\sqrt{r_a+0.0114}} - 0.00136\,. \tag{6}$$

The dependence of the aerosol scattering phase function at an angle of 180° on the parameter r_a can be represented in the form

$$x_{\pi,\,a} = \frac{0.02}{r_a}\,(r_a + 0.0114)^{0.6+0.1\sqrt{r_a+0.0114}} - \frac{0.00136}{r_a}\,. \tag{7}$$

It is shown by curve *1* in Fig. 3 and can be approximated by the formula:

$$x_{\pi,\,a} = 0.02\,r_a^{-0.23+0.03\sqrt{r_a}}\,, \tag{8}$$

where r_a is expressed in km^{-1}. Curve *2* in Fig. 3 depicts dependence (8). In accordance with Eq. (8) the aerosol component of the backscattering coefficient can be written down in the form

$$r_{\pi,\,a} = 0.02\,r_a^{\,0.77+0.03\sqrt{r_a}}\,. \tag{9}$$

Range of application of Eqs. (8) and (9) was restricted by the range of variations of the scattering coefficients for which the relation between r_π and μ was obtained in Ref. 11. For lidar operation under conditions of an increased transmittance of air in the low troposphere, relations (8) and (9) must be determined more accurately (extrapolated toward the region of small values of the aerosol scattering coefficients for $r_a < 0.01$km^{-1}). Assuming that as $r_a \to 0$ the parameter $x_{\pi,\,a} \to x_{\pi,m}$, i.e., scattering becomes the pure Rayleigh one, relation (8) can be represented in the form

$$x_{\pi,\,a} = 0.02\,(r_a + 0.000415)^{-0.23+0.03\sqrt{r_a}}\,. \tag{10}$$

This relation can be used over a wide range of turbidity starting from the extremely transparent atmosphere and including the dense fogs ($r = 20$ km^{-1} and more). The dependence of $x_{\pi,\,a}$ on r_a is shown in Fig. 4 (curve *1*). Curve *2* shows the limiting value $x_{\pi,\,a} = x_{\pi,m}$ corresponding to the Rayleigh scattering, and curve *3* is analogous to curve *1* in Fig. 3.

Formulas (8) and (10) are obtained on the basis of experimental relations between the total scaterring and backscattering for a wavelength of 0.55 μm. However, from the available data we can conclude that the dependence of the parameter $x_{\pi,\,a}$ on the wavelength is quite weak.[1,9,11] Therefore, I consider that the above formulas can be used in practice, at least, in the wavelength region 0.3–0.7 μm.

The possibility of principle to use relation (10) in lidar measurements of the scattering coefficient in the atmosphere was tested in the model calculations. The essence of this approach is as follows. The profile of the attenuation coefficient obtained on the primary assumption that $x_{\pi,\,a}$ = const is considered to be the first approximation. The next stage provides for determination of this aerosol profile more accurately. Such an operation is performed using the standard iterative procedures.

The examples of retrieving the profiles of the attenuation coefficient in the atmosphere with sharply pronounced inhomogeneous layers along the sensing path with the use of the constant and variable functions $x_{\pi,\,a}$ are shown in Fig. 5. The preset model profile of the scattering coefficient as a function of the distance z is shown by curves *1*. Based on these profiles the profile of the backscattered signal at output the lidar receiver was calculated and then the profile of r was retrieved from this signal with the help of conventional relations (1)–(3) in the iterative calculations. Curves *2* represent the retrieved profile of the scattering coefficient for $x_{\pi,\,a}$ = const., curves *3* – for relation (10). The results obtained are assumed to be quite acceptable.

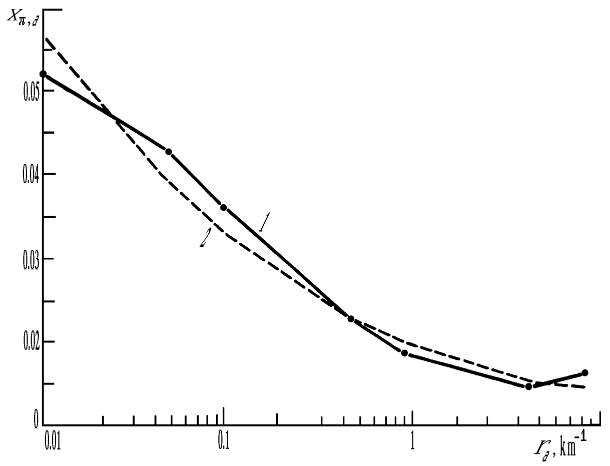

FIG. 3.

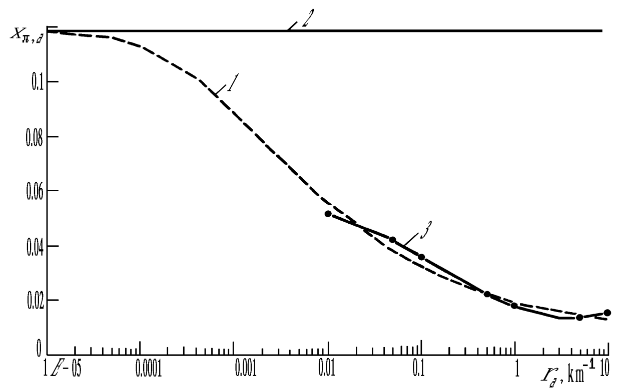

FIG. 4.

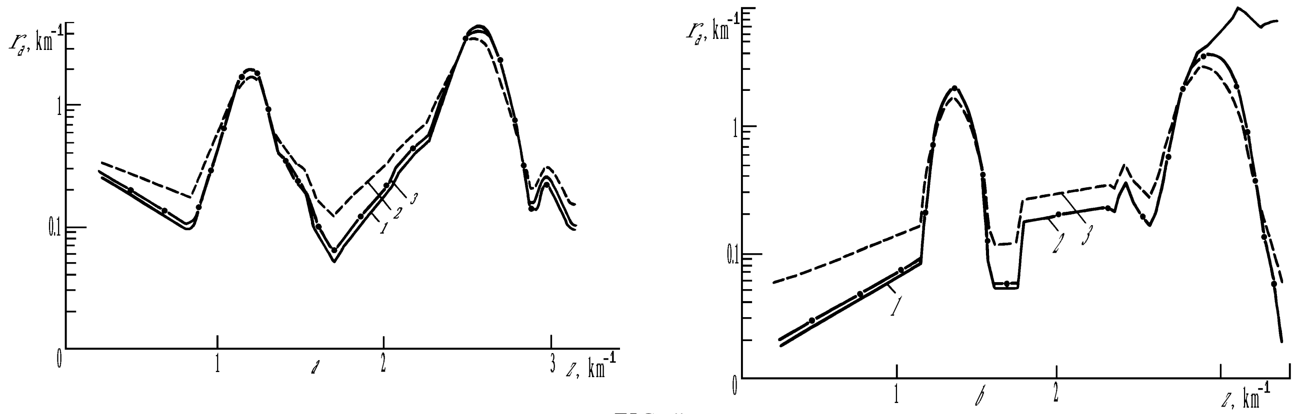

FIG. 5.

The above approach to the solution of this problem is applicable for measurements of the transmittance and visibility range in the atmosphere, for monitoring of aerosol pollutants of air, for determination of the corrections for the selectivity of aerosol and molecular scattering (in lidar determination of the profile of the concentration of ozone or other gaseous components in the troposphere), etc.

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