ON CORRECTING LIDAR RETURNS INVERTED INTO OPTICAL CHARACTERISTICS OF SCATTERING MEDIA

M.M. Kugeiko, I.A. Malevich, and D.E. Shiperko

V.I. Lenin Byelorussian State University, Minsk
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A method is proposed to improve the accuracy of lidar–retrieved attenuation coefficients of stratified inhomogeneous media by correcting backscattered signals for variation of the lidar ratio. An algorithm for determining the correction coefficients is described. It is shown that the absolute value of the correction coefficient characterizes qualitative variability of the composition of such media. The efficiency of the method is estimated, and the results of numerical simulation are presented.

At present numerous techniques of interpretation of lidar returns are available and researchers are looking for new algorithms which would solve this problem. All the known techniques start with the solution of the lidar equation:

$$P(z) = Az^{-2}T^2(0, z_0)\, \beta_\pi(z) T^2(z, z_0), \qquad (1)$$

where $P(z)$ is the recorded signal of the atmospheric backscatter at a point z, A is the instrumental constant of the lidar, $\beta_\pi(z) = \beta(z)g(z)$ is the backscattering coefficient; $g(z)$ and $\beta(z)$ are the lidar ratio and the extinction coefficient at the point z, respectively; $T(0, z_0)$ and $T(z_0, z)$ are the atmospheric transmission along the corresponding sections of the sounding path. The solution of Eq. (1) for $T(z_0, z)$ and $\beta(z)$, using experimentally determined function $\psi(z) = P(z)z^2A^{-1}\, g^{-1}(z)\, T^{-2}(0, z_0)$ (see Ref. 1) has the form:

$$\beta(z) = \psi(z) \left[\frac{\psi(z_k)}{\beta(z_k)} - 2\int_{z_k}^{z} \psi(z')\mathrm{d}z' \right]^{-1}, \qquad (2)$$

$$T^2(z_0, z) = \frac{\psi(z_k)}{\beta(z_k)} - 2\int_{z_k}^{z} \psi(z')\mathrm{d}z' . \qquad (3)$$

In what follows, we demonstrate that using solutions (2) (with a local calibration) and (3) (with an integral calibration) as well as their combinations it is possible to realize any of the schemes currently employed for processing lidar signals (including the asymptotic signal technique,[2,9] the Klett technique,[4] etc.). It should be noted that practically all known techniques based on Eqs. (2) and (3) necessarily use certain assumptions, since it appears to be impossible to set $g(z)$ *a priori* along the whole path. Most often it is assumed that $g(z)$ is constant along the path or that it changes rather slowly. Meanwhile the well–known linearly stochastic relation between $\ln\beta_p$ and $\ln\beta$ used to solve the lidar equation, well satisfies only the case of constant microstructure of aerosol.

It follows from the above said that in the case of a stratified inhomogeneous media, in which the scattering particles change both in their concentration and microphysical properties (their microstructure) along the path, and as a result in $g(z)$, the use of algorithms assuming that $g(z)$ remains constant along the path is too problematic. The consequence is quite obvious: the error in $\beta(z)$ then quickly grows. Below we show the possibility of increasing the retrieval accuracy for $\beta(z)$ in such media everywhere along the sounding path. Our technique is based on correcting the function $\psi(z)$ for a change in the lidar ratio. Algorithms are proposed for determining the respective correction coefficient. It is demonstrated that the absolute value of this coefficient characterizes the variation of the backscattered signal, due to qualitative changes in composition of the medium. We estimate the efficiency of the technique and demonstrate some results of numerical simulation.

Consider the case of sensing an n–layer medium. Relative change of the lidar ratio from the i–layer to k–layer may be described by the parameter $q_{ik} = \bar{g}_k / \bar{g}_i$, where $\bar{g}_k$ and $\bar{g}_i$ are, the average lidar ratios for the ith and kth layers, respectively. Let us compare the experimentally measurable functions $\psi(z)$ from Eq. (1) taken

$$\psi_i(z) = S(z)\, C_i, \qquad (4)$$

$$\psi_k(z) = S(z)\, C_k, \qquad (5)$$

at arbitrary points z in these two layers i and k. Here $S(z) = P(z)z^2$,

$C_i = A^{-1}T^{-2}(0, z_0)\bar{g}_i^{-1}$, and $C_k = A^{-1}T^{-2}(0, z_0)\bar{g}_k^{-1}$.

As can be seen from Eqs. (4) and (5) when proceeding from the i–layer to the k–layer the function $\psi(z)$ suffers certain change because of the change in the lidar ratio. The value of this change is q_{ik}, because $C_i = C_k q_{ik}$. The latter means, in its turn, that the constant C_k should be corrected for the value q_{ik} in the k–layer when calculating $\beta(z)$. The physical meaning of such a correction consists in using of one and the same constant throughout the multilayer path being sensed, i.e., in reducing our algorithm to a model with a constant lidar ratio along the whole path. In other words, in order to use those techniques which demand that $g(z)$ = const properly and apply them to stratified media, the backscattered signal should be tuned (corrected) to fit the used assumptions. Therefore, to retrieve accurately the extinction coefficient from the data of single–frequency sensing of stratified media one should know the relative change of the lidar ratio from layer to layer, i.e., the correction coefficient q_{ik}. Since, below we propose some techniques for determining q_{ik} from measured signals, the condition that q_{ik} is known does not complicate the technique. Moreover, it is also shown below that the

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correction for q_{ik} makes it possible to significantly improve the retrieval accuracy for the $\beta(z)$ profiles, even beyond the medium interfaces.

To validate the above statements consider the functionals $I(z) = \int_z^{z+\Delta z} S(z)\mathrm{d}z$, which have the form[2]

$$I(z, z + \Delta z) = \frac{1}{2} A \overline{g(z, z + \Delta z)}\, T^2(0, z) \times$$

$$\times \left[1 - \exp\left\{ - 2 \int_z^{z+\Delta z} \beta(z')\mathrm{d}z' \right\} \right]. \quad (6)$$

If conditions

$$\overline{g(z_i, z_i + \Delta z_i)} = \overline{g(z_i + \Delta z_i, z_i + 2\Delta z_i)} = \overline{g}_i ,$$

$$\overline{g(z_k, z_k + \Delta z_k)} = \overline{g(z_k + \Delta z_k, z_k + 2\Delta z_k)} = \overline{g}_k \text{ and}$$

$$T(z_i, z_i + \Delta z_i) = T(z_i + \Delta z_i, z_i + 2\Delta z_i) = T(\Delta z_i) ,$$

$$T(z_k, z_k + \Delta z_k) = T(z_k + \Delta z_k, z_k + 2\Delta z_k) = T(\Delta z_k)$$

are satisfied within the ith and kth layers, the following system of equations may be written for the functionals

$I_1 = I(z_i, z_i + \Delta z_i)$, $I_2 = I(z_i + \Delta z_i , z_i + 2\Delta z_i)$,

$I_3 = I(z_k, z_k + \Delta z_k)$, and $I_4 = I(z_k + \Delta z_k, z_k + 2\Delta z_k)$.

Here z_i and z_k are arbitrary points in the corresponding ith and kth layers; Δz_i Δz_k are arbitrary and not necessarily equal intervals. The solution of the system

$$I_1 = A\overline{g}_i T^2(0, z_i)[1 - T^2(\Delta z_i)] ,$$

$$I_2 = A\overline{g}_i T^2(0, z_i)T^2(\Delta z_i)[1 - T^2(\Delta z_i)] ,$$

$$I_3 = A\overline{g}_k T^2(0, z_i)T^4(\Delta z_i)T^2(z_i + 2\Delta z_i, z_k)[1 - T^2(\Delta z_k)] ,$$

$$I_4 = A\overline{g}_k T^2(0, z_i)T^4(\Delta z_i)T^2(z_i + 2\Delta z_i, z_k)T^2(\Delta z_k)[1 - T^2(\Delta z_k)] \quad (7)$$

for $\overline{g}_k/\overline{g}_i$ has the form

$$q_{ik} = \frac{\overline{g}_k}{\overline{g}_i} = \left(\frac{I_3}{I_2}\right)^2 \frac{(I_1 - I_2)}{(I_3 - I_4)} T^{-2}(z_i + 2\Delta z_i, z_k) . \quad (8)$$

The condition of equality of the average values of lidar ratios and of the extinction coefficients for arbitrary intervals of the path (both long and short) is less strict than the condition of constancy for $g(z)$ along the entire path, and for both g and β within the intervals (as in the technique of logarithmic derivative). This condition to an accuracy sufficient for practical applications is satisfied in the most actual situations (i.e., for extended intervals of the path even when the characteristics fluctuate quite strongly). For algorithm (8) to be operative it is sufficient that the difference between returns from two adjacent sections the absolute measurement error. Moreover, oxceeds when the value q_{ik} is estimated only approximately (because of strong variations in g and β) such a correction of the lidar signal to the above assumption improves the retrieved profile $\beta(z)$.

It follows from Eq. (8) that to determine q_{ik} one needs to know the transmission of relevant path intervals, including the interface between the layers. As demonstrated in Ref. 5, the following algorithm works well in such situations:

$$T^2(z_i + 2\Delta z_i, z_k) = \frac{I_6 - I_5}{I_6 - \frac{I_4}{I_8} I_5} , \quad (9)$$

where

$$I_5 = I(z_i + 2\Delta z_i, z_k) = \int_{z_i+2\Delta z_i}^{z_k} S(z)\mathrm{d}z ,$$

$$I_6 = I(z_i + 2\Delta z_i, z_k + 2\Delta z_k) = \int_{z_i+2\Delta z_i}^{z_k+\Delta z_k} S(z)\mathrm{d}z_j .$$

Conditions of Eq. (9) applicability are considered in detail in Ref. 5. In particular, an expression is given there for the spatially inhomogeneous media with noncorrelated fluctuations of their optical parameters that allows one to select proper path intervals dependending on the degree of the medium inhomogeneity.

Thus, the correction coefficient for tuning backscattered signals may be easily found from Eqs. (8) and (9) for any given layer of an n–layer scattering medium. As to the adjacent layers, i.e., for a double–layer scattering medium, such as sea – air, atmosphere – cloud, etc., the algorithm of retrieval for $q_{i,\, i+1}$ is simplified. In this case $T^2(z_i + 2\Delta z_i, z_k) \to 1$ and Eq. (8) takes the form

$$q_{i,i+1} = \frac{\overline{g}_{i+1}}{\overline{g}_i}\left(\frac{I_3}{I_2}\right)^2 \frac{I_1 - I_2}{I_3 - I_4} . \quad (10)$$

The parameter $q_{i,\, i+1}$ depends on the microphysical properties of the scattering medium alone, and is ondependent of on either the concentration of scatterers or the instrumental constants of the lidar itself. If the microphysics does not change at all, $q_{ik} = 1$, and this condition may be used to identify interfaces at which the scatterers suffer some qualitative change. The absolute value of q_{ik} shows how the backscattered signal changes due to a change in the qualitative composition of the medium. Even if the extinction coefficient (concentration) changes stepwise simultaneously with such a change in the lidar ratio, the value q_{ik} would still show what fraction of the lidar–return change is caused by the change in $g(z)$; i.e., by change in the qualitative composition of the medium. The latter statement follows from Eq. (10) since the expression for q_{ik} contains neither $T^2(\Delta z_i)$ nor $T^2(\Delta z_k)$ and no assumptions on the possible drops in $T^2(\Delta z_i)$ or $T^2(\Delta z_k)$ are made when deriving Eq. (10).

Let us now show that the use of the correcting function q_{ik} makes it possible to significantly improve the profile of $\beta(z)$ retrieved by any known technique based on the assumption of constancy of the lidar ratio along the path. To verify the efficiency of the technique a mathematical simulation was performed. Backscattered signals were computed in a single scattering aproximation using preset profiles $\beta(z)$ and $g(z)$. Then, according to Eqs. (8), (9), and (10) the values of the function q_{ik} were calculated for each layer, and using them the lidar signal was then corrected. The results of such a correction for a three–layer medium with an *a priori* set profiles of the lidar ratio (curve *1*) and the extinction coefficient are shown in Fig. 1. Curve *3* in this figure shows the backscattered signal computed without any correction for $g(z)$ and curve *2* gives the backscattered signal corrected for the function q_{ik} (as given by curve *1*) and obtained using Eqs. (8), (9), and (10).

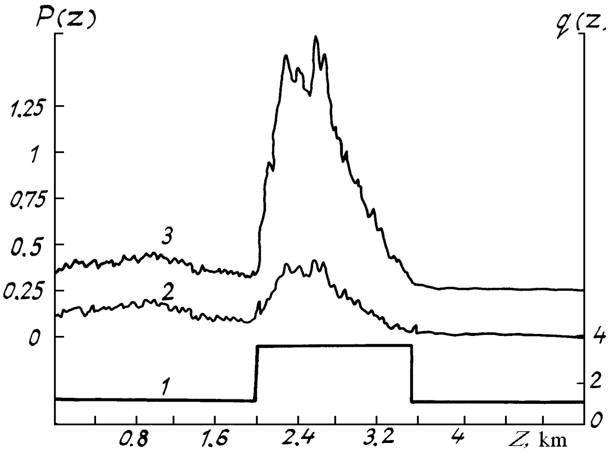

FIG. 1. Correction of the lidar signal with an account of the function q_{ik}: 1) correcting function $g(z)$ retrieved from the lidar return by Eqs. (8)–(10), 2) corrected lidar return, and 3) initial lidar return signal; curves 2 and 3 are shifted one and two scale divisions upward, respectively.

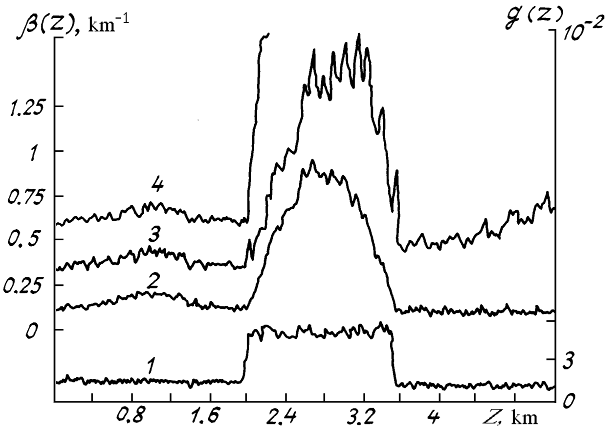

FIG. 2. Results of β(*z*) *reconstruction for a model atmosphere: 1)* a priori *profile of the lidar ratio g*(*z*); 2) a priori *profile of the extinction coefficient* β(*z*); 3) *profile* β(*z*) *reconstructed with an account of the correcting function q*(*z*) *obtained from Eqs. (8)–(10); and, 4) the profile of* β(*z*) *reconstructed without correction. The value* β = 0.2 km^{-1} (*z* = 1.0 km) *was used as a reference value in both cases and curves 3 and 4 are shifted* 1 *and* 2 *scale divisions upward, respectively.*

The efficiency of reconstructing the profile β(*z*) from actual backscattered signals is illustrated by curves *3* (for corrected signals) and curves *4* (for noncorrected signals) in Figs. 2 and 3. In both these figures curves *2* show the *a priori* profile β(*z*). The point to point scatter of *g* and β in the layers amounts to about 20%. This corresponds to the actual level of inhomogeneity encountered in such natural media as air, water, and the like. This circumstance opens the way for demonstrating the efficiency of the algorithm in processing of experimental data. Curves *3* and *4* are shifted one and two scale divisions upward, respectively, to prevent their overlapping.

The value (β = 0.2 km^{-1}) at the point *z* = 1 km was chosen in Fig. 2 as a reference value. This differed from the *a priori* value by 10%. The profile β(*z*) shown in Fig. 3 was reconstructed starting with the reference point at *z* = 5 km, where β = 0.18 km^{-1} was set, i.e., deffered by 20% from the *a priori* value. The reconstruction has been done using the Klett technique (Eq. (2) yields the algorithm proposed by Klett in Ref. 4, when the reference point is taken at the end of the path).

It can be seen from both figures that the correction made using the to function q_{ik} (curve *3*) results in a much better agreement between the reconstructed and *a priori* profiles β(*z*) as compared to reconstruction with no correction (curves *4*). It should be noted that higher accuracy of reconstruction is reached when the reference point is selected at the end of the path (Fig. 3). When that point is selected at the beginning of the sounding path, the reconstruction without correction becomes impossible at all (see curve *4* in Fig. 2). The proposed signal correction removes this drawback, and reconstruction of the profiles β(*z*) becomes feasible even for reference points at the beginning of the path (curve *3* in Fig. 2).

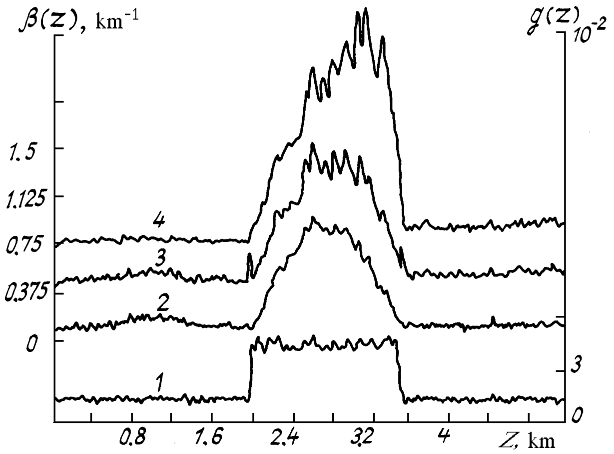

FIG. 3. Results of reconstruction of the profile β(*z*) *for a model atmosphere; 1) a priori profile of the lidar ratio g*(*z*); *2) a priori profile of the extinction coefficient* β(*z*); *3) profile* β(*z*) *reconstructed an account of the correcting function g*(*z*) *obtained from Eqs. (8)–(10); and 4) profile* β(*z*) *reconstructed without any correcting function. The value* β = 0.18 km^{-1} (*z* = 5.0 km) *was used as a reference value in both cases and curves 3 and 4 are shifted* 1 *and* 2 *scale divisions upward, respectively.*

Figure 4 shows the results of a mathematical modeling of reconstruction of the profile β(*z*) using the modified technique of asymptotic signal. Curves *1* and *2* show the initial profiles *g*(*z*) and β(*z*), respectively, which are inhomogeneous within 10% in all layers. The asymptotic signal was computed from the signal bacscattered from the interval [$z_i = 4.4$, $z_{i+1} = 5.4$]. Using the value of asymptotic signal obtained by the algorithm described in Ref. 3, the profile β(*z*) was found for both the corrected (curve *3*) and uncorrected signals (curve *4*). The accuracy of reconstruction can significantly be improved if the correction is used.

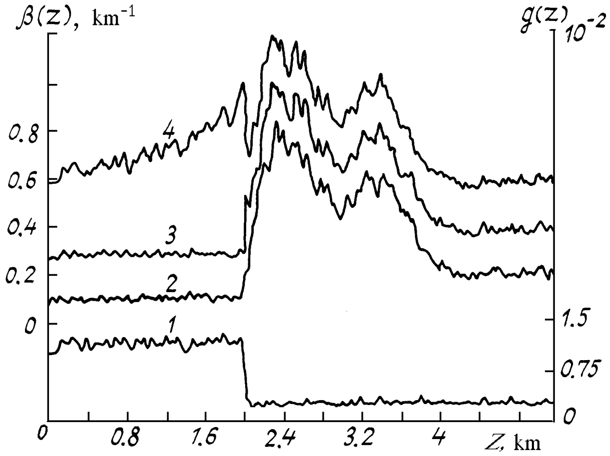

FIG. 4. Results of reconstruction of the profile β(*z*) *for a model atmosphere: 1) a priori profile of lidar ratio g*(*z*); *2) prescribed profile of the extinction coefficient* β(*z*); *3) profile of* β(z) *reconstructed with an account of the correcting function g*(*z*) *obtained from Eqs. (8)–(10); and 4) profile* β(*z*) *reconstructed without any correction. In both cases the reference values were chosen for the interval section* [z = 4.4, z = 5.4] *and curves 3 and 4 are shifted* 1 *and* 2 *scale divisions upward, respectively.*

Its use enables one to determine with rather high accuracy the profiles β(*z*) along the entire sounding path in multilayer media including interfaces (even for atmospheric and underwater sections of a sounding path at sounding from flying platforms). It is also valid for the case of a multilayer cloudiness, etc. It is important that the reference values of β(*z*) may be selected at the beginning of a sounding path. Moreover if one uses the technique[5] of the calibration values from the lidar returns themselves, with no additional (reference) measurements that would allow complete automation of the experiment to be performed providing a possibility of conducting measurements in real time. It is also quite important that information about the qualitative change in composition of the medium can be simultaneously extracted.

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