

Data Processing Technique for Multiangle Lidar Sounding of Poorly Stratified Polluted Atmospheres. Theory and Experiment

Extended Abstract #12

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INTRODUCTION

Scanning elastic lidar, which can operate in different slant directions, is the most appropriate remote sensing tool for investigating the optical properties of smoke-polluted atmospheres. However, the commonly used methodologies of multiangle measurements are based on the assumption of horizontal stratification of the searched atmosphere^{1,2}. When working in real atmospheres, even a slight deviation from the required atmospheric stratification may result in an unacceptable measurement error, especially, in clear atmospheres which contain local layering with increased backscattering.

There have been attempts to overcome this impediment and find simple and practical lidar-data retrieval methods for the real atmospheres³⁻⁶. However, these case studies include the same retrieval principles as in the pioneer studies^{1,2}. Unlike these studies, the data processing method developed at the Missoula Fire Sciences Laboratory was based on using both parameters in the Kano-Hamilton solution^{7,8}. Such an approach minimizes the influence of the atmospheric horizontal inhomogeneity and systematic distortions in the inverted lidar signal. The variant of this solution, defined as the direct multiangle solution¹⁰, in which the two-way transmission and the corresponding extinction coefficient are retrieved directly from the zenith signal, may be considered as the optimal variant of multiangle searching in poorly stratified atmospheres. However, at the altitudes where horizontal heterogeneity of the atmosphere exceeds some critical level, no reliable information about the optical properties can be retrieved. This critical level depends on many factors, such as the gradient of the aerosol loading, the presence of local layering within the searched zone, parameters of the lidar instrumentation, etc.

In this paper we consider the essentials and restrictions of the direct solution technique in conditions of increased atmospheric heterogeneity, and some simple criteria for determining the maximum operative heights of the lidar instrumentation in such atmospheres, based on the analysis of the retrieved lidar data.

ESSENTIALS AND ISSUES OF THE DIRECT MULTIANGLE SOLUTION: SIMULATED AND EXPERIMENTAL DATA

The direct multiangle solution is based on the combination of the one-directional and multiangle retrieval principles. The usual scanning procedure is performed, but now the backscatter signal measured in zenith (or close to the zenith direction) is a basic function for determining the vertical transmittance and the corresponding extinction-coefficient profile. Unlike the conventional one-directional method, the direct multiangle solution uses the multiangle signals as the source of the auxiliary information for inverting the zenith signal.

The square-range-corrected backscatter signal, $P_{90}(h)h^2$, at the height, h , measured in zenith is the product of the lidar solution constant, C , the total (molecular and particulate) vertical backscatter coefficient, $\beta_{\pi,90}(h)$, and the total two-way vertical transmittance, $T_{90}^2(0, h)$, from ground level to the height h , that is,

$$P_{90}(h)h^2 = C\beta_{\pi,90}(h)T_{90}^2(0, h) \quad (1)$$

The two-way vertical transmittance,

$$T_{90}^2(0, h) = \exp[-2\tau_{90}(0, h)], \quad (2)$$

and the corresponding total vertical optical depth, $\tau_{90}(0, h)$, are the basic functions of interest to be determined. The estimate of the two-way vertical transmittance, $\langle T_{90}^2(0, h) \rangle$, is determined from Eq. (1) as

$$\langle T_{90}^2(0, h) \rangle = P_{90}(h)h^2 / \langle C\beta_{\pi,90}(h) \rangle, \quad (3)$$

using an estimate of the actual profile, $C\beta_{\pi,90}(h)$, symbolized here as $\langle C\beta_{\pi,90}(h) \rangle$; this function is found from the set of the multiangle signals, $P_i(h)$, measured by the same lidar under different elevation angles φ_i . As with the Kano-Hamilton solution, the data points, $y_i(h)$, are calculated in the form,

$$y_i(h) = \ln\left[P_i(h)(h/\sin \varphi_i)^2\right] \quad (4)$$

The linear fit, $\langle y(h) \rangle$, for the available set of the data points $y_i(h)$ has the general form,

$$\langle y(h) \rangle = \langle A(h) \rangle + b(h)x, \quad (5)$$

where $x = 1/\sin \varphi_i$ is the discrete variable, $b(h)$ is the slope of the linear fit, and the intercept, $\langle A(h) \rangle$, is found by the extrapolation of the linear fit $\langle y(h) \rangle$ to $x = 0$. The linear fit, $\langle y(h) \rangle$, and accordingly, the intercept, $\langle A(h) \rangle$, is shifted into the point $A'(h)$, which can be determined as,¹⁰

$$A'(h) = \ln\left[P_{90}(h)h^2\right] - b(h) \quad (6)$$

The parameter of interest, $\langle C\beta_{\pi,90}(h) \rangle$, is determined as the exponent of the shifted intercept, that is,

$$\langle C\beta_{\pi,90}(h) \rangle = \exp[A'(h)] \quad (7)$$

A simple formula that allows comparing the actual vertical profile of $P_{90}(h)h^2$ with the profile of a synthetic vertical signal, determined from the multiangle scanning, can be written as,

$$\Delta y_{90}(h) = \Delta A(h) - 2\Delta\tau(0, h) = [A_{90}(h) - A'(h)] - [2\tau_{90}(0, h) + b(h)] \quad (8)$$

where $A_{90}(h) = \ln [C\beta_{\pi,90}(h)]$ and the slope of the linear fit, $b(h)$, is negative. In an ideal case, $\Delta y_{90}(h) = 0$ within the total height interval from h_{min} to h_{max} . In practice, however, such an equality never takes place. However, when the condition $\Delta y_{90}(h) \ll y_{90}(h)$ over the total height interval is met, acceptable measurement accuracy of the signal inversion can be achieved. Conversely, if the condition is not met, the horizontal heterogeneity of the searched atmosphere at the heights of interest exceeds the required critical level and either no information or only some restricted information about the optical properties of such an atmosphere can be retrieved.

To clarify the technique, let us consider initially an artificial scanning lidar which scans a poorly stratified synthetic atmosphere under nine elevation angles, 12° , 15° , 18° , 24° , 30° , 40° , 55° , 70° , and 90° . The arbitrarily selected model data points of $C\beta_{\pi,\varphi}(h)$ and $\tau_{\varphi}(0, h)$ for the above nine angles, φ_i , at a height of interest, h , are shown in Fig. 1 as the filled squares and filled triangles, respectively. The empty triangles are the values of the vertical optical depths determined as the product of the corresponding slope optical depths, $\tau_{\varphi}(0, h)$, by $\sin \varphi_i$. One can see that this synthetic atmosphere is not stratified horizontally. The corresponding data points, $y_i(h) = \ln [P(h)h^2/\sin^2 \varphi_i]$ (the filled circles), and the linear fit, $\langle y(h) \rangle$, (the dashed line) versus the independent $x = [\sin \varphi_i]^{-1}$ obtained with Eq. (5) are shown in Fig. 2. The initial intercept point of the linear fit, obtained by the extrapolation of the linear fit into $x = 0$, is $\langle A(h) \rangle = 4.66$; it is shown on the vertical axis as the filled triangle. Meanwhile, the actual, that is, model values used for the simulations are $A_{90}(h) = 5.30$ (the empty circle).

Fig. 1. The data points, $C\beta_{\pi,\varphi}(h)$ (the filled squares), $\tau_{\varphi}(0, h)$ (the filled triangles), and $\tau_{\varphi}(0, h)\sin \varphi_i$ (the empty triangles) versus the elevation angle φ_i for the angles selected for the numerical experiment.

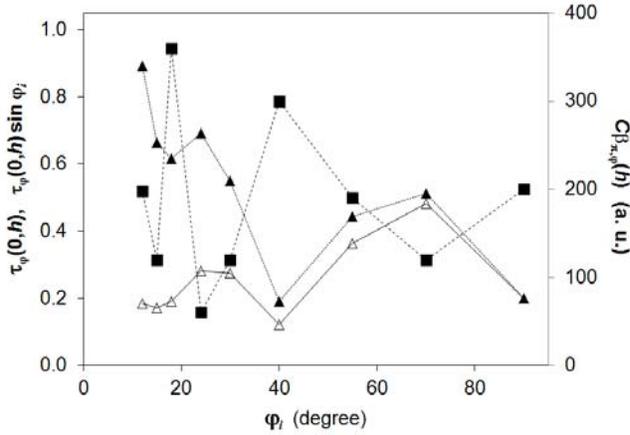
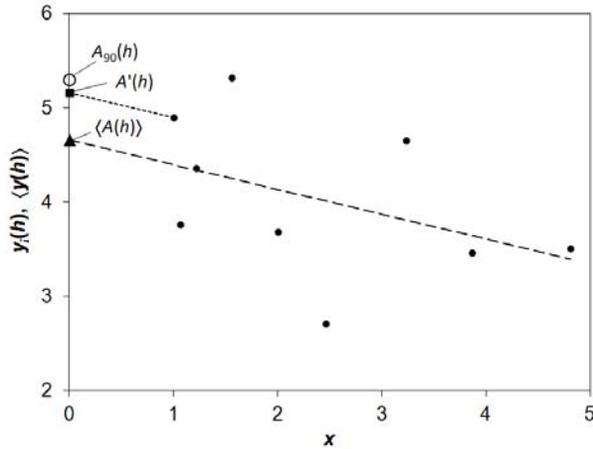


Fig. 2. Dependence of the data points, $y_i(h)$ (the filled circles) and the linear fit, $\langle y(h) \rangle$, (the dashed line) on $x = 1/\sin \varphi_i$. The actual intercept $A_{90}(h)$ for the zenith direction is shown on the Y-axes as the empty circle. The intercept points of the linear fit, $\langle A(h) \rangle$ and $A'(h)$ are shown as the filled triangle and the filled square, respectively.

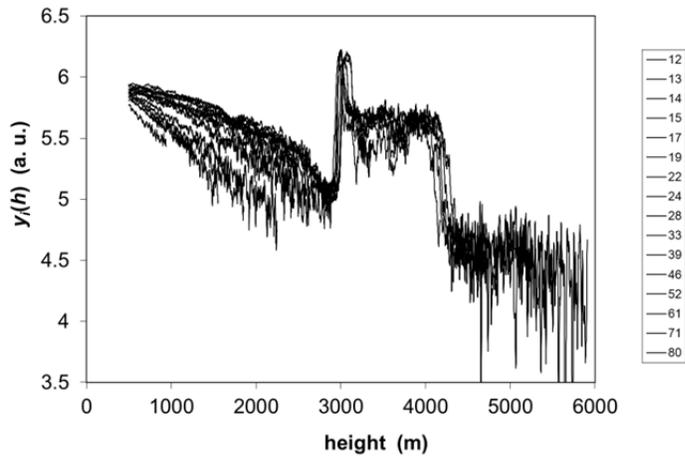


The use of Eq. (6) significantly decreases this error, putting the shifted data point $A'(h)$ (the filled square) closer to the actual point, $A_{90}(h)$, reducing the corresponding error in the estimate, $\langle C\beta_{\pi,90}(h) \rangle$, from 47% to ~13 %.

In practical multiangle measurements, the basic issue is determining the optical parameters of the searched atmosphere at increased altitudes. Here the available range of x for which data points $y_i(h)$ are available is significantly reduced. This, in turn, results in the higher sensitivity of the solution accuracy to the atmospheric heterogeneity.

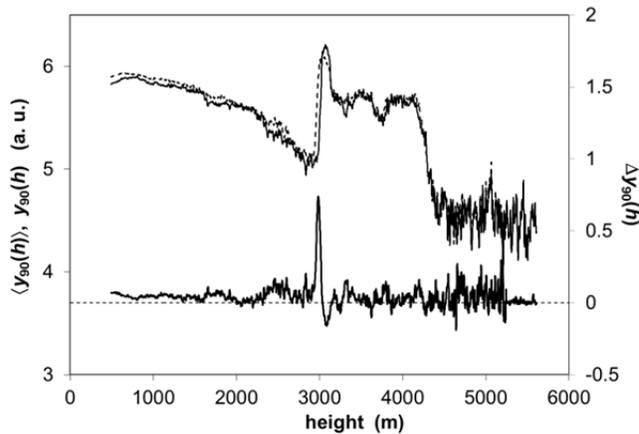
To clarify this issue we present experimental results with the Missoula Fire Sciences Laboratory (FSL) lidar searching a relatively clear atmosphere. The profiles, $y_i(h)$, determined at the wavelength 532 nm for sixteen elevation angles are shown in Fig. 3. One can see the strong layering located within the height interval from, approximately 2900 m to 4300 m.

Fig. 3. The profiles, $y_i(h)$, for sixteen elevation angles measured by the FSL scanning lidar on August 10, 2012. The selected $h_{min} = 500$ m.



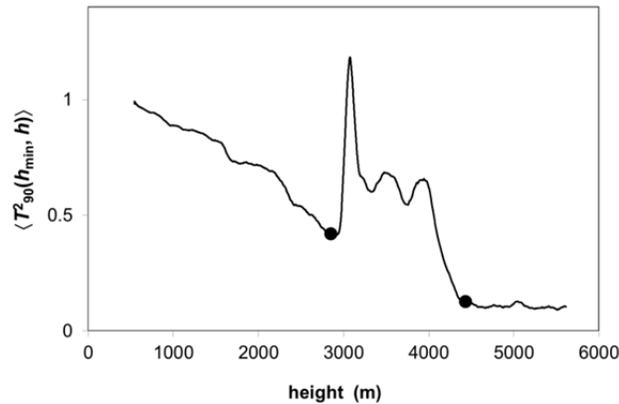
The question arises whether the atmosphere within this polluted layer is horizontally stratified enough that the range-resolved optical characteristics within the layer can be determined; or this operation is restricted to the lower heights up to ~ 3000 m. The corresponding functions $y_{90}(h)$, $\Delta y_{90}(h)$, and $\langle y_{90}(h) \rangle = A(h) + b(h)$ retrieved from the functions $y_i(h)$ in Fig. 3 are shown in Fig. 4.

Fig. 4. Functions $y_{90}(h)$ (thin solid curve), $\langle y_{90}(h) \rangle$ (the dotted curve), and their difference, $\Delta y_{90}(h)$ (the thick solid curve) for the same $y_i(h)$ profiles presented in Fig. 3.



One can see significantly increased values of the function $\Delta y_{90}(h)$ close to the height $h \approx 3000$ m. Such an increase means that the heterogeneity level within the layer 2900 m – 4300 m may be too high for the multiangle solution to yield accurate range resolved profiles of the optical characteristics within it.

Fig. 5. The estimate of the two-way transmission function, $\langle T_{90}^2(h_{min}, h) \rangle$.



The corresponding estimate of the transmission function, $\langle T_{90}^2(h_{min}, h) \rangle$, smoothed over the intervals, $\Delta h = 100$ m, is shown in Fig. 5. The erroneous increase of this function within this interval most likely occurs due to increased heterogeneity within the layer. The estimated optical depth of this layer marked in the figure by two filled circles is, approximately, 0.6; however, no detailed profile within the interval 2900 m – 4300 m can be determined without additional analysis. Principles for the retrieval of optical properties in such heterogeneous areas investigated and will be discussed in future publications.

SUMMARY

The goal of this study was to discuss some specifics and restrictions of the direct multiangle solution, a variant of the multiangle inversion methodology, which is less sensitive than conventional methods to both poor stratification of the atmosphere and to lidar signal distortions. However, as shown in this study, there may be a critical level of the horizontal heterogeneity in the lidar operative zone where the multiangle method can currently provide, at best, only restricted information. Some simple principles for the analysis of such an atmospheric situation are considered.

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