

PROFILING OF POORLY STRATIFIED SMOKY ATMOSPHERES WITH SCANNING LIDAR

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ABSTRACT

The multiangle data processing technique is considered based on using the signal measured in zenith (or close to zenith) as a core source for extracting the information about the vertical atmospheric aerosol loading. The multiangle signals are used as the auxiliary data to extract the vertical transmittance profile from the zenith signal. Simulated and experimental data are presented that illustrate the advantages of this data processing technique.

1. INTRODUCTION

The classical Kano-Hamilton multiangle method allows extracting the particulate extinction-coefficient profile from elastic lidar data without an a priori assumption on the vertical profile of the lidar ratio [1, 2]. However, the method only works properly in atmospheres that are well horizontally stratified.

Recently a number of the studies were published in which the authors analyzed methods of extracting the extinction coefficient using the estimate of the backscatter term in the lidar equation [3-5]. These inversion principles significantly reduce errors inherent to the conventional Kano-Hamilton solution. The data processing technique allows obtaining acceptable measurement accuracy even in the poorly stratified atmospheres, particularly in the vicinity of wildfires. In this paper, some variants of extracting the information of interest from the zenith signal using the backscatter term estimate are discussed and compared.

2. METHOD

The below data processing technique is based on a combination of the one-directional and multiangle retrieval principles considered in [5]. Here the backscatter signal measured in the zenith (or close to the zenith) direction is a basic function for the determination of the vertical profile of the extinction-coefficient. Unlike the conventional one-directional method, the data-processing technique uses a set of multiangle signals as the source of auxiliary information. It allows eliminating the

measurement uncertainty due the unknown lidar ratio and the lidar constant inherent to the vertically pointed elastic lidar.

The square-range-corrected backscatter signal, $P_{90}(h)h^2$, 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, $T_{90}^2(0, h)$ is determined using an estimate of the profile of the product, $C\beta_{\pi,90}(h)$,

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

The particulate transmission profile, $T_{p,90}^2(0, h)$ is extracted from the total transmittance by removing the molecular component, $T_{m,90}^2(0, h)$, that is, by determining the ratio,

$$T_{p,90}^2(0, h) = T_{90}^2(0, h) / T_{m,90}^2(0, h). \quad (3)$$

The particulate extinction coefficient profile, $\kappa_p(h)$, can be extracted from the transmission profile, $T_{p,90}^2(0, h)$, using different methods. First, $\kappa_p(h)$ can be determined from the logarithm of this function, using conventional numerical differentiation. To avoid this procedure, which often yields extremely noisy and corrupted results, in this study, we focused on an alternative method. Here a simplified solution is applied, which basically uses the same principle of determining piecewise profiles as in [5]. The profile of $T_{p,90}^2(0, h)$ in Eq. (3) is used as a basic function, but the below inversion variant does not require the numerical differentiation or the knowledge of the solution constant C for determining the vertical profile of the particulate extinction coefficient.

For extracting the piecewise profile of the particulate extinction coefficient, the total altitude range, $(h_{\min}, h_{\max})$, is divided by a number of the piecewise intervals, $h_{\min} - h_1, h_1 - h_2, \dots, h_j - h_{j+1}, \dots, h_n - h_{\max}$. The length of these intervals can be either equal, or can increase with height in order to reduce the influence of the increased noise at the higher altitudes.

The procedure of determining the mean extinction coefficient within each interval, $\Delta h_j = h_{j+1} - h_j$, is based on the inversion technique similar to that in [5]. However, unlike that study, no assumption on the behavior of the lidar ratio within each of these intervals is assumed. The auxiliary profile of the two-way transmittance within each piecewise interval, Δh_j , is calculated as,

$$\langle T_p^2(h_j, h) \rangle = \exp[-2\kappa_p(\Delta h_j)(h_j - h)], \quad (4)$$

assuming that the particulate extinction coefficient, $\kappa_p(\Delta h_j) = \text{const.}$ within this interval. The key procedure is the determination of such an extinction coefficient, $\kappa_p(\Delta h_j)$, that minimizes the difference between the piecewise profile, $T_{p,90}^2(h_j, h)$, retrieved from $T_{p,90}^2(0, h)$, and that in Eq. (4). As the initial extinction coefficient, $\kappa_p(\Delta h_j)$, in Eq. (4) is selected arbitrarily, the profiles $T_{p,90}^2(h_j, h)$ and $\langle T_p^2(h_j, h) \rangle$ generally diverge. They should be equalized by determining the appropriate $\kappa_p(\Delta h_j)$. To establish how close the profiles $T_{p,90}^2(h_j, h)$ and $\langle T_p^2(h_j, h) \rangle$ are, a simple criterion is implemented which compares the slopes of the linear fits of these piecewise profiles over the selected altitude range, Δh_j . As both profiles decrease with range, the linear fits of these for the selected altitude range can be written in the standard form,

$$T_{p,90}^2(h_j, h) = A_1 - B_1(h - h_j), \quad (5)$$

and

$$\langle T_p^2(h_j, h) \rangle = A_2 - B_2(h - h_j), \quad (6)$$

where A and B are constants. The only task is to find such an extinction coefficient, $\kappa_p(\Delta h_j)$ within the height interval Δh_j that minimizes the criterion,

$$\Lambda = (B_1 - B_2)^2. \quad (7)$$

After the criterion is minimized, the value of $\kappa_p(\Delta h_j)$ in Eq. (4) is taken as the mean extinction-coefficient profile of interest over the corresponding altitude interval, Δh_j . The operations are repeated for each piecewise interval, (h_j, h_{j+1}) , within the total altitude

range $(h_{\min}, h_{\max})$. For each such a piecewise interval, the extinction coefficient, $\kappa_p(\Delta h_j)$, is found that minimizes the criterion Λ in Eq. (7).

The use of the linear fit for the transmission profile, $\langle T_p^2(h_j, h) \rangle$, makes it also possible to elaborate on the maximal height, $h_{\max}$. A simple requirement, $B_2 \geq 0$, should be satisfied when selecting the maximal height of the last interval. If this inequality is not satisfied, the two-way transmission in this interval will have an unphysical increase within this range. The only way to avoid this effect is to reduce the maximal height as much as necessary. Note also that the physical minimum, $B_2 = 0$, means that there is no particulate component in this range interval or it is too small to be determined from the recorded data.

3. SIMULATED AND EXPERIMENTAL RESULTS

Let us consider an artificial lidar that scans a synthetic atmosphere at the wavelength 355 nm within the slope angular sector from some minimal vertical angle to zenith. The particulate extinction coefficient in this synthetic atmosphere, used as a model profile, decreases from $\kappa_p(h) = 0.4 \text{ km}^{-1}$ at ground level down to $\kappa_p(h) = 0.006 \text{ km}^{-1}$ at $h = 7000 \text{ m}$. In addition, a horizontally stratified turbid layer, presumably created by the atmospheric inversion in the vicinity of a wildfire, exists at the altitudes from 3000 m to 4000 m; the particulate extinction coefficient in this layer is $\kappa_p(h) = 0.2 \text{ km}^{-1}$. The lidar ratio is 20 sr in the clear air and 60 sr within the smoky layer. The vertical profile, $T_{p,90}^2(0, h)$, determined with Eq. (3) within the altitude range from $h_{\min} = 500 \text{ m}$ to $h_{\max} = 6000 \text{ m}$ is shown in Fig. 1. This simulated profile is very noisy, as

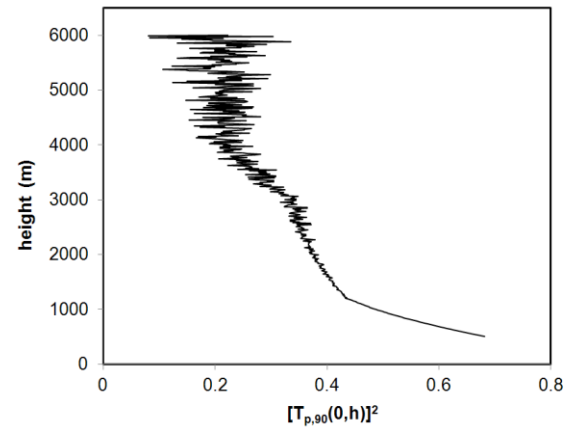


Fig. 1. Vertical transmission profile, $T_{p,90}^2(0, h)$, determined by an artificial lidar at the wavelength 355 nm in a simulated smoky atmosphere.

is generally typical in smoke polluted atmospheres. Note that this profile was retrieved without using the lidar solution constant C or making assumptions about the behavior of the vertical lidar ratio.

For the determination of the set of the local piecewise coefficients, $\kappa_p(\Delta h_j)$, within the altitude range from 500 m to 5700 m, ten overlapping piecewise intervals were used. In Fig. 2, the extracted piecewise values of $\kappa_p(\Delta h_j)$ versus height are shown as the separate vertical lines, whereas the model profile of the particulate extinction coefficient used for the simulation is shown as the dashed curve. The thin solid curve represents the extinction coefficient derived with the numerical differentiation of the profile, $T_{p,90}^2(0, h)$, using the sliding range resolution, $s \approx 750$ m. Note that even such a large range resolution does not allow estimating the extinction-coefficient behavior at the heights up to 4000 m. Meanwhile, the use of the piecewise profiles over overlapping height intervals allows the discrimination of the relatively slow changes in the extinction coefficient profile [the values of $\kappa_p(\Delta h_j)$ in the overlapping areas are close to each other] from sharp changes of $\kappa_p(h)$ [the values of $\kappa_p(\Delta h_j)$ in such areas are significantly different].

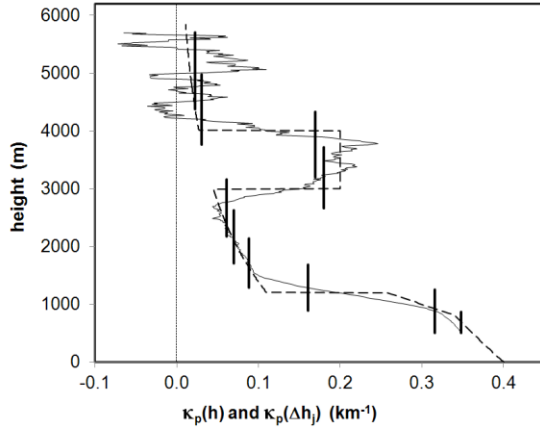


Fig. 2. Piecewise values of $\kappa_p(\Delta h_j)$ versus height (vertical lines) and the extinction coefficient derived with the numerical differentiation with $s \approx 750$ m (thin solid curve). The model profile of the particular extinction coefficient, $\kappa_p(h)$, used for the simulation is shown as the dashed curve.

An example of the experimental data obtained with the FSL lidar on 28 August 2009 and inverted with the above method is shown in Figs. 3 and 4. The lidar measurements were performed in the vicinity of wildfires where the atmospheric inversion created multiple smoke layers at different heights. To reduce the influence of local atmospheric horizontal heterogeneity, combined azimuthal-vertical searching was made [6]. The azimuthal scanning was made along twelve elevation angles, 9° , 12° , 15° , 18° , 22° , 26° , 32° ,

40° , 49° , 58° , 68° , and 80° . On the left panel of Fig. 3, the vertical profile of $T_{p,90}^2(0, h)$ calculated with Eqs. (2) and (3) using the profile of $C\beta_{\pi,90}(h)$ extracted from

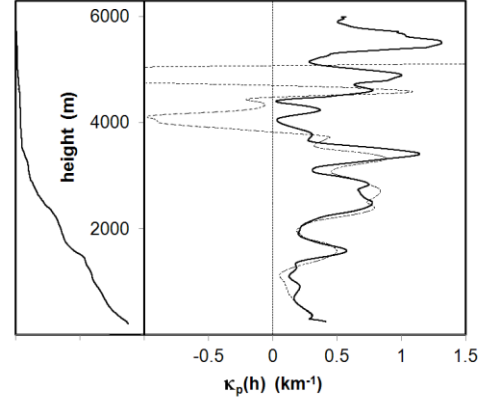


Fig. 3. Profile of the vertical transmittance measured on August 28, 2009 (the left panel) and the corresponding profiles of $\kappa_p(h)$, extracted with the numerical differentiation but using alternative variants of the inversion technique (the right panel).

the multiangle data is shown. On the right panel of the figure, the corresponding profiles of the extinction coefficient, extracted with the numerical differentiation using different inversion technique are shown. The bold curve is the particulate extinction coefficient, extracted from the logarithm of $T_{p,90}^2(0, h)$ using the sliding numerical derivative with the range resolution 300 m. The profile of the extinction coefficient, extracted by using the conventional Kano-Hamilton inversion method is shown as the dotted curve.

Comparing these two profiles, one can see that they agree relatively closely to each other only in the near zone, up to the height ~ 3500 m, but significantly diverge at higher altitudes. The strong fluctuations in the extinction coefficient profile, derived with the Kano-Hamilton method do not allow any estimation of the aerosol loading at the heights higher than 3500 m, whereas the extinction coefficient obtained from the logarithm of $T_{p,90}^2(0, h)$ yields sensible inversion results up to height, ~ 5000 m. This improvement is achieved because the inversion technique that uses the vertical signal as a basic retrieval profile yields more accurate information than that obtained from the linear fit slope in the Kano-Hamilton solution.

Nevertheless, the use of numerical differentiation, even with a relatively extended range resolution, in the smoky atmospheres generally yields wavelike profiles of $\kappa_p(h)$, which impede the discrimination of actual heights and dynamics of smoke layering. The use of

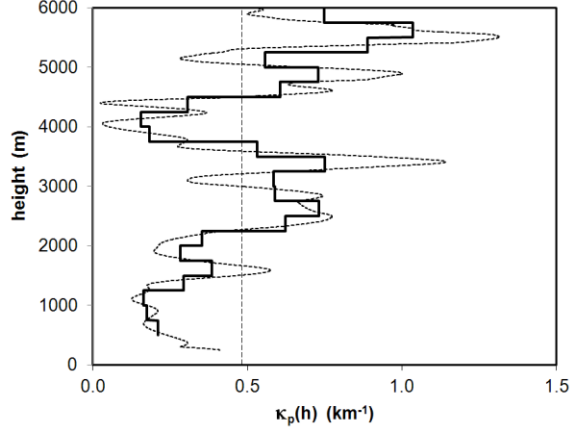


Fig. 4. Average particulate extinction coefficient profiles derived from the vertical transmittance shown on the left panel of Fig. 3 by minimizing the slopes of the linear fits in Eqs. (5) and (6) (the bold piecewise curve). The dashed curve shows the profile of the extinction coefficient, extracted with the numerical differentiation.

the inversion variant that equalizes the slopes of the linear fits of $T_{p,90}^2(h_j, h)$ and $\langle T_p^2(h_j, h) \rangle$ [Eqs. (5) - (7)] within the intervals Δh_j allows discriminating the smoke layering more easily [Fig. 4]. One can calculate also an average vertical extinction coefficient over the lidar measurement heights and determine the heights, in which $\kappa_p(\Delta h_j)$ exceeds this average; in our example such an average, equal to 0.48 km^{-1} , is shown in the figure as the dashed vertical line. Analyzing the piecewise profile of the extinction coefficient and comparing it with the average, one can discriminate the polluted layering within the heights from 2250 m to 3750 m and that over 4500 m. A detailed analysis allows also discriminating the weak layering between the heights 1500 m - 1700 m.

4. SUMMARY

The main issue in the practical use of the one-directional single-wavelength elastic lidar is the necessity to use some a priori assumption about the profile of the lidar ratio and determine somehow the lidar solution constant. The latter requirement can be satisfied in clear atmospheres by using the assumption of the aerosol-free atmosphere at high altitudes. However, in the multilayered atmosphere, the use of

this assumption is risky. On the other hand, the Kano-Hamilton method, which is free of such requirements, is extremely sensitive to the violation of the requirement of the horizontally stratified atmosphere and the lidar signal distortions, especially at the distant ranges. These factors result in significantly distorted profiles of the retrieved extinction coefficient of interest.

In this study, a variant of the inversion technique is given which to the greatest extent possible is less sensitive both to poor stratification of the atmosphere and the lidar signal distortions. To achieve this goal, the improved retrieval technique was developed in which the signal measured by the scanning lidar in zenith (or close to zenith) is used as a core source of information about the aerosol vertical profile. The set of multiangle signals is used as the source of auxiliary information to extract the profile of the vertical transmittance from the zenith signal.

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