DETERMINATION OF EXTINCTION COEFFICIENT PROFILES FROM MULTIANGLE LIDAR DATA USING A "CLONE" OF THE OPTICAL DEPTH

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ABSTRACT

An iterative "clone" method for extracting the extinction-coefficient profile from the optical depth is discussed. The method was used to retrieve vertical extinction-coefficient profiles from signals of a scanning elastic lidar. The initial profile of the optical depth was obtained with a Kano-Hamilton multiangle solution. Examples of simulated data and experimental data, obtained in the vicinity of large-scale wildfires near Missoula (Montana, USA) are presented.
The clone principle may be applicable when processing signals measured in the one-directional mode with a combined Raman elastic-backscatter or a high spectral resolution lidar.

1. INTRODUCTION

The Kano-Hamilton multiangle method [1, 2] is the only method in which the particulate extinction coefficient can be determined from elastically scattered signals without an a priori selection of the particulate extinction-to-backscatter ratio. However, this method has two basic drawbacks. First, it works only under the condition of a horizontally stratified atmosphere, which may not be valid in real conditions. Second, to obtain the vertical profile of the particulate extinction coefficient, two consecutive slope-determination procedures need to be fulfilled. In the first, the vertical optical depths from the ground level to the stepped heights are found by determining the slopes of the range-corrected signal logarithms at these heights. In the second procedure, the extinction coefficient profile is found by determining local increments of the particulate optical depth over selected height intervals.
An improved measurement methodology was recently proposed for processing data obtained with an elastic scanning lidar in clear atmospheres [3]. In this study, a combined azimuthal-slope scanning method was tested. The areas of strong horizontal heterogeneity were established by an analysis of the signals measured over a wide azimuthal sector under fixed elevation angles. After excluding signals that do not meet established criteria of homogeneity, the remaining signals were averaged, and this average was used for the inversion.
In August 2005, such a methodology was utilized for processing elastic lidar data obtained in vicinities of large-scale wildfires near Missoula (Montana, USA). The primary goal of these measurements was to test the applicability of the modified Kano-Hamilton method for investigations of the optical properties of smoke particulates. The analysis of the experimental data revealed that horizontally structured multilayered atmosphere was a typical situation in vicinities of these wildfires (Fig. 1). The use of the method [1, 2] allowed us to obtain the profiles of the vertical optical depth and then extract the corresponding profiles of the extinction coefficient. Initially we used the conventional numerical differentiation technique for determining the latter. However, due to relatively strong random noise in the extracted optical depth profiles, this technique did not allow us to discriminate and properly separate thin horizontal layering and thus determine a fine vertical structure of the layers. To obtain more accurate information about the vertical structure we developed a special "clone" method of which the essence and some results of its application are considered.

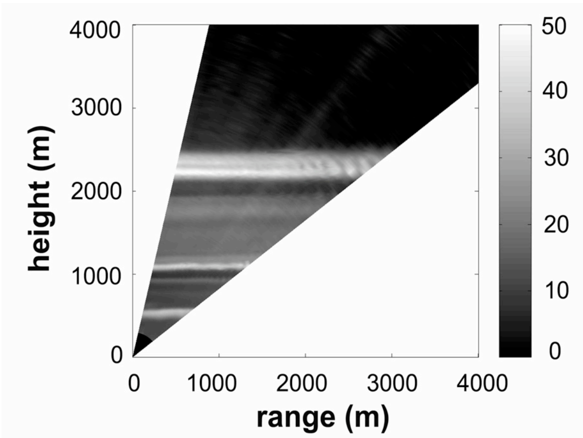

Fig. 1. Vertical lidar scan at 1064 nm showing multilayer structure of the atmosphere in the vicinity of large wildfires in Montana on August 15, 2005. The light-colored horizontal structures show areas of increased backscattering.

2. DATA-PROCESSING TECHNIQUE

The basic equation of the multiangle Kano-Hamilton method for areas of the lidar complete overlap can be written as:

$$\ln\left[P_i(h)(h/\sin\varphi_i)^2\right] = \ln[C\beta(h)] - 2\,\tau(0,h)/\sin\varphi_i \qquad (1)$$

where $P_i(h)$ is the lidar backscatter signal measured at the height h under elevation angle φ_i ($i = 1\ldots m$), C is a lidar system constant, $\beta(h) = \beta_m(h) + \beta_p(h)$ is the total (molecular and particulate) backscatter coefficient, and $\tau(0, h) = \tau_m(0, h) + \tau_p(0, h)$ is the total optical depth from the ground level to the height h. Using a linear least square fit for the dependence $\ln[P_i(h)(h/\sin\ \varphi_i)^2] = f(1/\sin\ \varphi_i)$ for stepped heights, the intercept and the slope of that linear fit are determined, from which the profiles of the relative backscatter, $C\beta(h)$ and the optical depth, $\tau(0, h)$ are obtained. The particulate optical depth, $\tau_p(0, h)$, found as the difference of $\tau(0, h)$ and the known molecular profile, $\tau_m(0, h)$, is used to compute the extinction coefficient profile of interest, $\kappa_p(h)$. The conventional procedure of determining $\kappa_p(h)$ applies numerical differentiation to the function $\tau(0, h)$ or $\tau_p(0, h)$; this operation is the most critical point in the inversion procedure because of strong random noise in the inverted functions, especially over high altitude ranges.

In our method of determining the profile of $\kappa_p(h)$, we start with an analysis of the initial function, $\tau_p(0, h)$. Using all available data points of this function over the total measurement range, we perform a special smoothing of the function to determine an initial smoothed duplicate, or a "zero clone", $\tau_p(0,h)^{(0)}$ for this function. This clone and the profile of the relative backscatter, $C\beta(h)$, are then used to obtain the extinction coefficient profile, $\kappa_p(h)$. The solution for $\kappa_p(h)$ is found through an iteration procedure that minimizes the function

$$\xi^{(i)} = \frac{1}{\Delta\tau}\sqrt{\frac{\sum_N \left[\tau_p(0,h)^{(i)} - \tau_p(0,h)^{(0)}\right]^2}{N}} \qquad (2)$$

where $\Delta\tau$ is the vertical optical depth of the atmosphere from h_{min} to h_{max}, N is the number of the data points over that range, and

$$\tau_p(0,h)^{(i)} = \tau_p(0,h_{\min}) + \int_{h_{\min}}^{h} \kappa_p(h)^{(i)}\,dh \qquad (3)$$

where $\tau_p(0, h_{min})$ is the optical depth over the height range $(0, h_{min})$, which can be determined, for example, from the initial profile of $\tau_p(0, h)$; $\kappa_p(h)^{(i)}$ is the extinction coefficient, obtained after the i-th iteration.

A simplified iterative scheme for the retrieval of $\kappa_p(h)$ is shown in Fig. 2. For the inversion, the following input quantities and functions are used: (a) the relative backscattering $C\beta(h)$ and the optical depth $\tau_p(0, h)$, derived from the linear fits of Eq. (1) for the stepped heights h; (b) the known molecular profiles, $\kappa_m(h)$ and $\beta_m(h)$; (c) an arbitrarily selected constant $\langle C\rangle$ and an initial "effective" backscatter-to-extinction ratio $\Pi_{p,eff(0)}$ = const. In general cases, these two arbitrarily selected constants will differ from the actual constant C and the real profile of $\Pi_p(h)$.

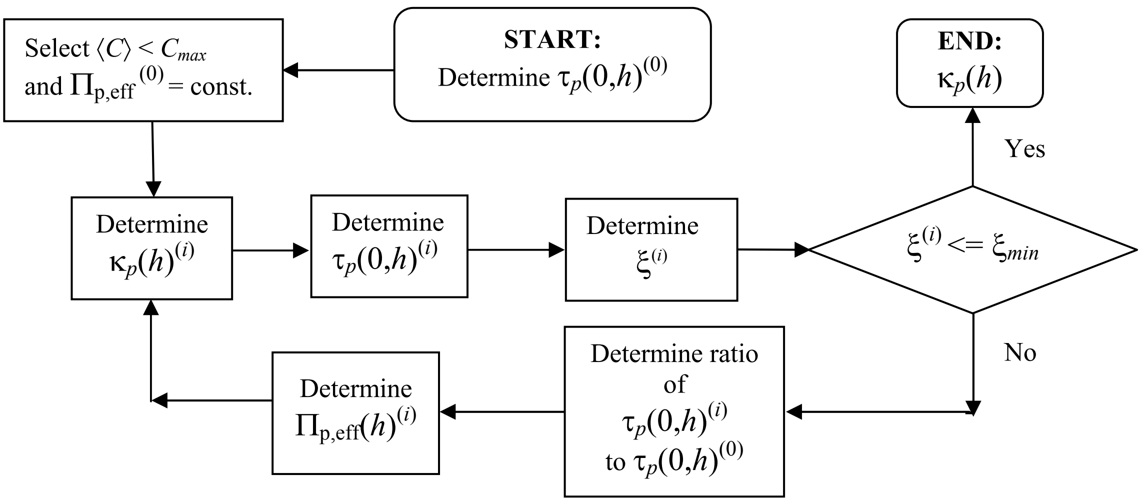

Fig. 2. Simplified flow chart of the retrieval of $\kappa_p(h)$ with the iterative clone method.

To prevent erroneous negative values in the retrieved $\kappa_p(h)$, the constant $\langle C \rangle$ should meet the condition $\langle C \rangle < C_{max}$; the value C_{max} depends on the selected $\Pi_{p,eff}^{(0)}$. To start the iteration the clone function $\tau_p(0, h)^{(0)}$ for the optical depth $\tau_p(0, h)$ should first be determined. To obtain a good quality function $\tau_p(0, h)^{(0)}$, $\tau_p(0, h)$ should be smoothed. The initial profile of the extinction coefficient, $\kappa_p(h)^{(1)}$ is obtained as

$$\kappa_p(h)^{(1)} = \frac{1}{\Pi_{\text{p,eff}}^{(0)}} \left[\frac{C\beta(h)}{\langle C \rangle} - \beta_m(h) \right] \tag{4}$$

The function $\kappa_p(h)^{(1)}$ is then used to calculate the next clone of the optical depth, $\tau_p(0, h)^{(1)}$. To estimate how close the retrieved function $\tau_p(0, h)^{(1)}$ is to the function $\tau_p(0, h)^{(0)}$, the quantity $\xi^{(1)}$ [Eq. (2)] is calculated. The ratio of these two functions, $R^{(1)}(h)$, is then used to determine a new profile of the "effective" backscatter-to-extinction ratio,

$$\Pi_{\text{p,eff}}(h)^{(i)} = R^{(i)}(h)\Pi_{\text{p,eff}}(h)^{(i-1)} \tag{5}$$

and then to find a new profile of $\kappa_p(h)^{(2)}$, which is used for the next cycle of the iteration. The best $\kappa_p(h)$ is obtained by the minimizing the function $\xi^{(i)}$ with an iteration procedure until a minimum value is obtained. After the last n-iteration, the final profile of $\kappa_p(h)$ is found by conventional numerical differentiation of the clone profile $\tau_p(0, h)^{(n)}$.

3. SIMULATED AND EXPERIMENTAL DATA

An example of simulated data obtained from a lidar operating in the multiangle mode at 532 nm in a multilayer atmosphere is shown in Figs. 3 and 4. The synthetic profile of the particulate optical depth, obtained with the Kano-Hamilton solution from artificially noise-corrupted signals, is shown in Fig. 3 as a thin curve; the bold curve shows the final clone profile, retrieved after completing the iterations. In Fig. 4, the thin solid curve shows the model multilayer profile of the vertical extinction used for these simulations. The bold curve shows the profile retrieved with numerical differentiation of the clone profile $\tau_p(0, h)^{(n)}$ with a range resolution of Δh = 150 m; the dashed line is the profile of $\kappa_p(h)$ retrieved with the conventional numerical differentiation of the original profile $\tau_p(0, h)$ with Δh = 450 m. Note that to suppress the random noise, the range resolution for the conventional method is chosen as much as three times more than in the clone method.

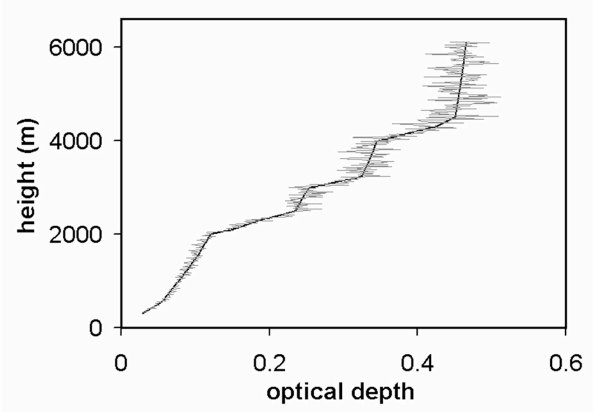

Fig. 3. Simulated particulate optical depth profile $\tau_p(0, h)$, extracted with the Kano-Hamilton solution (thin curve) and its clone $\tau_p(0, h)^{(n)}$ (bold curve).

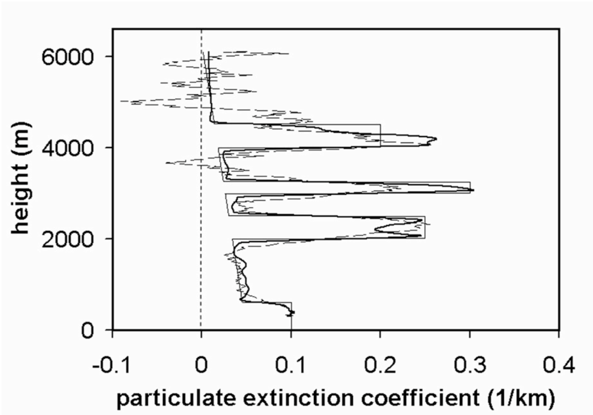

Fig. 4. Model profile of the particulate extinction coefficient used for the simulation (thin curve), the profile obtained with the clone method (thick curve), and that from conventional numerical differentiation (dashed curve).

The data obtained with the conventional method, especially at the far end of the measurement range, are significantly noisier than the data obtained with the clone method. Figs. 5 and 6 show an example of a real inversion result obtained from the lidar experimental data, measured at 355 nm near wildfires in Montana. The height resolution for determining $\kappa_p(h)$ is selected as 100 m for the clone method, and 300 m for the conventional method. As one can see in Fig. 6, the extinction coefficient profile extracted with the clone method is significantly less noisy than that obtained with the conventional differentiation.

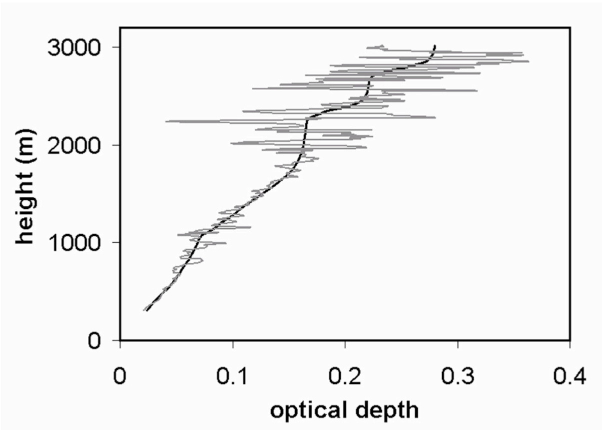

Fig. 5. Profiles of Kano-Hamilton $\tau_p(0,\ h)$ (thin curve) and clone $\tau_p(0,\ h)^{(n)}$ (bold curve) obtained from real signals of a scanning lidar at 355 nm, measured in the vicinity of wildfires in Montana on August 9, 2005, from 10:39 AM to 11:00 AM.

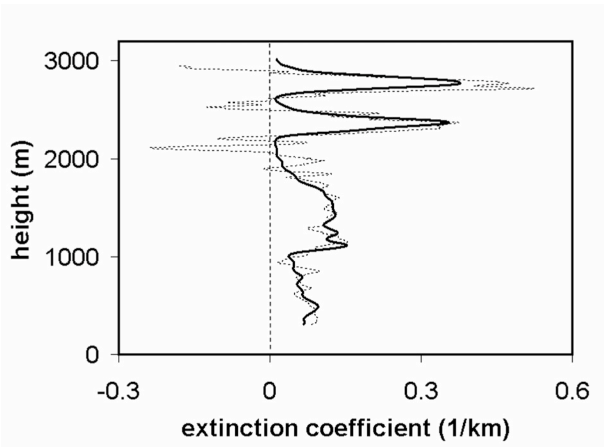

Fig. 6. Vertical extinction coefficient profiles obtained from the particulate optical depths in Fig. 5 with the clone method (thick curve) and with the conventional numerical differentiation (dotted curve).

4. SUMMARY

A clone method for processing data from elastic-lidar multiangle measurements is presented that determines a duplicate (clone), $\tau_p(0,\ h)^{(n)}$ for the initial optical depth, $\tau_p(0,\ h)$. When determining the extinction coefficient $\kappa_p(h)$, the numerical differentiation is applied to this function, rather than to the initial noisy function $\tau_p(0,\ h)$. The clone function is obtained through an iteration procedure, where both functions obtained with the Kano-Hamilton solution (the optical depth $\tau_p(0,\ h)$ and the relative backscatter $C\beta(h)$) are utilized. The use of the two functions allows one to obtain a significantly less noisy vertical profile of interest, $\kappa_p(h)$.

As compared to the conventional method of deriving $\kappa_p(h)$ with the numerical differentiation of the initial noisy function, $\tau_p(0,\ h)$, the clone method has the following advantages:

- The method makes it possible to obtain more accurate profiles of $\kappa_p(h)$ from corrupt profiles of $\tau_p(0,\ h)$, which may have intense noisy jumps of the data points, zones with an erroneous decrease of $\tau_p(0,\ h)$, or short gaps with no data points;
- The method does not yield erroneous negative values in the retrieved $\kappa_p(h)$;
- The data obtained with the clone method at the far end of the measurement range are generally much less noisy than the data obtained with the conventional numerical differentiation of the original function $\tau_p(0,\ h)$.
- The clone method of the retrieval of the extinction coefficient profile allows better discrimination of thin layering, especially over distant ranges.

The clone technique may also be applicable when processing data of a combined Raman elastic-backscatter lidar or high spectral resolution lidar, which operate in a one-directional mode.

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