ITERATIVE DETERMINATION OF THE AEROSOL EXTINCTION COEFFICIENT PROFILE AND THE MEAN EXTINCTION-TO-BACKSCATTER RATIO FROM MULTIANGLE LIDAR DATA

Markus Pahlow[1], Vladimir A. Kovalev[2], Albert Ansmann[3] and Kathleen Helmert[4]

[1]NOAA, Environmental Technology Laboratory, Boulder, CO, USA; e-mail: markus.pahlow@noaa.gov

[2]USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT, USA

[3]Institute for Tropospheric Research, Leipzig, Germany

[4]German Weather Service, Offenbach, Germany

Introduction

Due to the indeterminacy of the lidar equation inversion algorithms have to resort to certain assumptions in order to determine atmospheric backscatter and extinction. One approach to the inversion problem involves two- or multiangle methods. Most of these methods either assume a unique relationship between optical depth and elevation angle and/or are based on the assumption that scattering within horizontal layers is homogeneous [1-5]. Reference or *a priori* data may also be included as a constraint [6]. In order to reduce the uncertainty introduced by these assumptions, we investigate the possibility of combining (a) Hamilton's [4] method with the two-angle minimization approach (TAMI) [5,7], and (b) Hamilton's [4] method with the optical depth solution with the local path transmittance as boundary value [7]. The key point is that these methods, when applied to the same scanning lidar data, are complementary. Using Hamilton's method, the mean particulate extinction coefficient can be determined without an *a priori* selected value of the particulate extinction-to-backscatter ratio (lidar ratio), whereas in TAMI and the optical depth solution, the lidar ratio is a prerequisite. However, unlike TAMI and the optical depth solution, Hamilton's method does not allow one to directly retrieve accurate local extinction coefficient profiles. We will show that combining those methods provides a means to simultaneously determine a more accurate vertical profile of the particulate extinction coefficient, and potentially, a stepped lidar ratio through an iterative procedure. The only *a priori* information required is the molecular extinction coefficient profile. In this initial study we consider the simplest case where the lidar ratio is constant with height.

Combination of Hamilton with TAMI

The method combines Hamilton's method [4] with TAMI in an iterative manner:

(i) The total optical depth $\tau(0,h)$ to height h is determined by linear regression from lidar measurements $P_i(h)$ at different elevation angles φ_i (i=1…N) using Hamilton's method

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

$\beta(h)$: total (molecular and particulate) backscatter coefficient

K: lidar system constant

Mean particulate extinction coefficient profile for height above zone of incomplete overlap h_1

$$\overline{\alpha_p(h_1,h)} = \left[\tau_p(0,h) - \tau_p(0,h_1)\right]/(h-h_1)$$

$\tau_p(0,h)$: particulate optical depth

(ii) Local particulate extinction coefficient profile along elevation angles φ_j (j=1,2) using TAMI

$$\alpha_{p,j}(h) = \frac{Z_j(h)}{C_j - 2\int_{h/\sin\varphi_j}^{h/\sin\varphi_j} Z_j(x)dx} - S\frac{3}{8\pi}\alpha_m(h)$$

$Z_j(h)=P_j(h)^2 Y_j(h)$ and $Y_j(h)$ is a transformation function [7]

$$Yj(h) = S\exp\left[-2\int_{h/\sin\varphi_j}^{h/\sin\varphi_j}\left(S\frac{3}{8\pi}-1\right)\alpha_m(x)dx\right]$$

S: lidar ratio

$\alpha_m(h)$: molecular extinction coefficient profile

The calibration constants C_j are determined by minimizing the function

$$\eta(h) = \ln\left[\frac{Z_1(h)}{Z_2(h)}\right] - \ln\left(\frac{C_1}{C_2}\right) - \ln\left[1 - \frac{2\int_{h/\sin\varphi_1}^{h/\sin\varphi_1} Z_1(x)dx}{C_1}\right] + \left[\frac{2\int_{h/\sin\varphi_2}^{h/\sin\varphi_2} Z_2(x)dx}{C_2}\right]$$

(iii) Mean particulate extinction coefficient profile from TAMI local $\alpha_p(h)$ profile

$$\overline{\alpha_p(h_1,h)} = \left[\int_{h_1}^{h}\alpha_p(h)dh\right]/(h-h_1)$$

(iv) Compare solutions for $\overline{\alpha_p(h_1,h)}$ obtained using Hamilton and TAMI

Vary lidar ratio S in TAMI solution until best agreement is reached

→ Simultaneous determination of mean S and local particulate extinction coefficient profile

Evaluation of the method

The combination of Hamilton and TAMI allows one to retrieve the local extinction coefficient profile and the mean lidar ratio with acceptable accuracy for the following conditions:

– Moderately turbid atmosphere
– Particulate and molecular constituents are comparable in value
– Atmosphere is homogeneous in the horizontal and strongly inhomogeneous in the vertical
– Requires high quality lidar data, especially when measuring in mildly turbid atmospheres

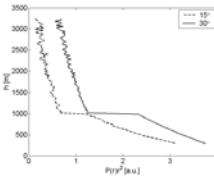
Test with synthetic data

- A model atmosphere representing a mildly turbid and distinct atmospheric boundary layer (ABL) up to 1000 m and clear troposphere from 1000 m to 3200 m has been chosen as test case
- Lidar ratio S = 50 sr has been used to compute synthetic lidar data at 532 nm
- Elevation angles: 15º and 30º

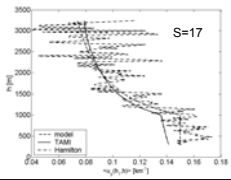
Relative error ε between model aerosol extinction coefficient profile and retrieved TAMI aerosol extinction coefficient profile for different values of the lidar ratio:

	Iteration 1 (S = 17 sr)	Iteration 2 (S = 90 sr)	Iteration 3 (S = 50 sr)
ε overall	4.7 %	8.1 %	2.9 %
ε within ABL	7.7 %	10.3 %	1.7 %
ε in free troposphere	3.7 %	7.3 %	3.3 %

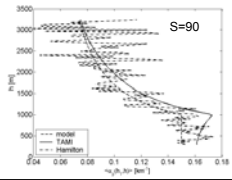
synthetic data



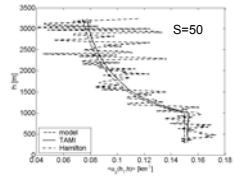
iteration 1



iteration 2



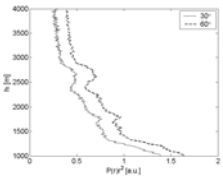
iteration 3



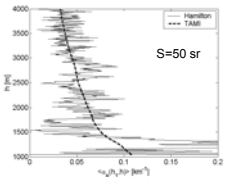
Application to experimental data

Data obtained with the Institute for Tropospheric Research (IfT Leipzig, Germany) lidar system [8] during the Indian Ocean Experiment (INDOEX) [9] are analyzed with the iterative method. The lidar system was set up to take data for five-minute periods at 30º and 60º elevation angles. A time segment of one hour was chosen for analysis, showing elevated aerosol concentration up to ~1300 m and two distinct layers at ~1700-1900 m and ~2400-2900 m in the free troposphere.

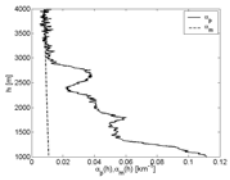
lidar data (532 nm channel)



mean aerosol extinction coefficient profiles



TAMI local aerosol extinction coefficient profile and molecular extinction coefficient profile



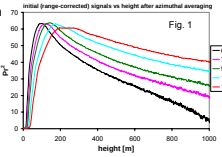
The best agreement between the mean aerosol extinction coefficient profiles obtained with Hamilton and TAMI was found for S = 50 sr. However, it becomes clear that the assumption of a height independent lidar ratio might lead to inaccurate results for parts of the profile as the Hamilton and TAMI profile deviate from each other from ~1000 m to 1500 m. Yet with TAMI it is possible to determine a local extinction coefficient profile with high vertical resolution, resolving structures in the atmosphere such as the two layers at altitude.

Combination of Hamilton and optical depth solution: Systematic distortions detection, correction and data inversion

Systematic distortions in the lidar data can lead to large errors in the retrieved extinction coefficient profile, particularly in clear atmospheres. In general there are two types of systematic distortions:

– near-range distortions caused by e.g. low-frequency noise generated after emitting the laser pulse [10]
– far-range distortions, e.g. due to signal induced noise [11]

As an example of the combination of the Hamilton-optical depth solution with systematic distortion corrections we show data obtained with the Missoula Fire Sciences Laboratory lidar system. The scanning data (elevation angles 6º, 7.5º, 9º, 12º and 15º) were taken in Missoula, MT in clear atmospheric conditions at a lidar wavelength of 355 nm (Fig 1).

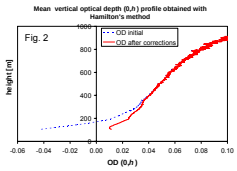


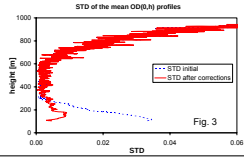
Data processing

Step 1.

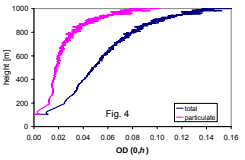
Total optical depth (OD) profiles versus height, $\tau(0,h)$, have been computed from the multiangle data using Hamilton's method, and then a mean $\tau(0,h)$ and its standard deviation (STD) were determined. Due to near-end systematic distortions, negative values of the optical depth and increased STD in the near field were obtained (blue curves in Figs. 2 and 3). [Similarly, increased STD were obtained at the far end, but these are not corrected here].

An analytic correction procedure was applied to the lidar data in Fig.1 to correct these for the systematic distortions in the near range. After data correction, new $\tau(0,h)$ profiles, their mean value, and STD have been computed again using Hamilton's method for different angle pairs. The revised data are shown as red curves in Figs. 2 and 3.





The corresponding mean $\tau(0,h)$ and the mean $\tau_p(0,h)$ profiles, obtained with Hamilton's method from the corrected data at a laser wavelength of 355 nm, are shown in Fig. 4. The profile of the mean $\tau_p(0,h)$ (magenta curve in Fig. 4) was used to determine the boundary value for the optical depth solution.

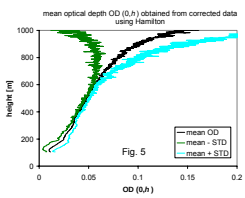


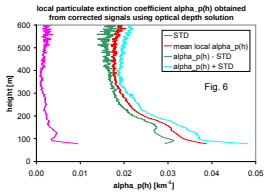
Step 2.

The boundary value of the local path transmittance for the optical depth solution [7], modified for two-component atmospheres, was determined from the $\tau_p(0,h)$ computed in step 1. Two constraints were determined: (1) the altitude range 300 – 600 m, over which standard deviation is minimal [see Fig. 3], and (2) the particulate path transmission over this range 300 – 600 m calculated from the mean profile of $\tau_p(0,h)$. Then an additional analysis was made, after which the final altitude range for determining the boundary value for the optical depth solution was reduced to the altitude range from 400 to 600 m, and the boundary value of the particulate path transmission over this altitude range was found.

Step 3.

Five local particulate extinction coefficient profiles have been calculated from the signals shown in Fig. 1 with the optical depth solution, using the boundary value found in step 2. Then a mean profile of the local $\alpha_p(0,h)$ together with its STD were calculated. These results are shown in Figs. 5 (mean optical depth) and 6 (mean local particulate extinction coefficient).





Because of large uncertainty in the retrieved profiles for heights >600 m (Fig. 5), the maximal measurement height for the local $\alpha_p(0,h)$ was confined to h=600 m (Fig. 6).

Summary

- Combining Hamilton's method with TAMI allows one to determine the local particulate extinction coefficient profile and the mean lidar ratio from scanning lidar data in an iterative manner.

- The *a priori* information needed is the molecular extinction coefficient profile (can be obtained either from standard atmosphere or from measurements).

- The test of the method with synthetic data exhibiting two strongly different atmospheric regimes showed that the $\alpha_p(h_1,h)$ profile can be retrieved with acceptable accuracy.

- The method also proved to be stable when applied to experimental data.

- For Hamilton-TAMI the assumption is used that the lidar ratio is constant with height, so that the practical application of the iterative method is limited. Future work will address this issue.

- Multiangle methods can aid in detecting systematic distortions in the lidar signal that must be removed or corrected before inverting the lidar data.

- A combined Hamilton – optical depth solution approach has been applied to experimental lidar data to extract the local extinction coefficient profiles.

References

1. Spinhirne, J. D., Reagan, J. A. and Herman, B. M., Vertical distribution of aerosol extinction cross section and inference of aerosol imaginary index in the troposphere by lidar technique, *J. Appl. Meteorol.*, 19, 426-438, 1980.
2. Sicard, M., Chazette, P., Pelon, J, Won, J. G. and Yoon, S. C., Variational method for the retrieval of the optical thickness and the backscatter coefficient from multiangle lidar profiles, *Appl. Opt.*, 41, 493-502, 2002.
3.Kano, M., On the determination of backscattered and extinction coefficient of the atmosphere by using laser radar, *Papers Meteorol. and Geophys.*, 19, 121-129, 1968.
4. Hamilton, P. M., Lidar measurement of backscatter and attenuation of atmospheric aerosol, *Atmos. Environ.*, 3, 221-223, 1969.
5. Pahlow, M., Kovalev, V. A. and Parlange, M. B., Calibration method for multiangle lidar measurements, *Appl. Opt.*, 48, 2948-2956, 2004.
6. Sasano, Y. and Nakane, H., Quantitative analysis of RHI lidar data by an iterative adjustment of the boundary condition term in the lidar solution, *Appl. Opt.*, 26, 615-616, 1987.
7. Kovalev, V. A. and Eichinger, W. E. *Elastic lidar. Theory, practice, and analysis methods.* J. Wiley & Sons Inc., 2004.
8. Althausen, D., Müller, D., Ansmann, A., Wandinger, U., Hube, H., Clauder, E. and Zoerner, S., Scanning 6-wavelength 11-channel aerosol lidar, *J. Atmos. Oceanic Technol.*, 17, 1469-1482, 2000.
9. Franke, K., Ansmann, A., Müller, D., Althausen, D., Venkataraman, C., Reddy, M. S., Wagner, F. and Scheele, R., Optical properties of the Indo-Asian haze layer over the tropical Indian Ocean, *J. Geophys. Res.*, 108, doi:10.109/2002JD002473, 2003.
10. Kovalev, V. A., Distortions of the extinction coefficient profile caused by systematic errors in lidar data, Appl. Opt., 43, 3191-3198, 2004.
11. Sunesson, J. A., Apituley, A., and Swart, D. P. J. Differential absorption lidar system for routine monitoring of tropospheric ozone, Appl. Opt. **33**, 7045-7058 (1994).

Acknowledgements

This research was supported by the NOAA Postdoctoral Program in Climate and Global Change, administered by the University Corporation for Atmospheric Research.