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４波長ライダーとサンフォトメータによる大気エアロゾルの光学的厚さの研究

Study of Optical Thickness of Atmospheric Aerosol by means of a Four-wavelength Lidar and a Sun photometer

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ABSTRACT

Analysis of signals from a four-wavelength lidar is presented. Some *a priori* information and boundary conditions are estimated in solving the lidar equation by Fernald method. The retrieved results are compared with those from a sun photometer. It is shown that an approximation from a model atmosphere is basically suitable as *a priori* information for moderately turbid atmosphere. For relatively clean atmosphere, however, some modifications on the initial value at a reference point have to be incorporated..

1. Introduction

Lidar measurement provides superior resolution, both spatial and temporal, for atmospheric aerosol monitoring. For single wavelength lidar, return signals from atmosphere are governed by the well-known lidar equation.

A number of methods to solve the lidar equation have been proposed and investigated by many authors. Among them Klett's method[4], which is convenient for analysis of lidar data observed in very turbid atmosphere, and Fernald's approach[3], which is applicable to clear and moderately turbid atmosphere, are the most useful ones. However, a unique method that provides an absolutely reliable solution of the lidar equation does not exist. So it is necessary to estimate the boundary condition and confirm the results with certain additional experimental data.

For multi-wavelength lidar, the construction of the system is much more complex than a single-wavelength one, not only in optical source but also in receiving units. In order to make a physically consistent explanation for different wavelengths and examine the availability of the estimated boundary conditions and related assumptions, here, a well-calibrated multi-channel sun photometer is used.

2. Solution to the lidar equation

The Fernald's solution is discussed here, where both molecule and aerosol contributions are included. The basic equation is

$$P(r) = P_0 \frac{c\tau}{2} A \frac{\beta_m(r) + \beta_p(r)}{r^2} \exp\left[-2\int_0^r \alpha_m(r')dr'\right] \exp\left[-2\int_0^r \alpha_p(r')dr'\right] \quad (1)$$

where $P(r)$ is the instantaneous received power at time t, P_0 the transmitted power, c the velocity of light, τ the pulse duration, A the effective receiver area, r the range, $\beta_m(r)$, $\beta_p(r)$, respectively, the backscattering cross section of the molecule and aerosol, and $\alpha_m(r)$, $\alpha_p(r)$, the extinction cross sections of the molecule and aerosol at range r.

The molecular atmospheric profile of the US 1976 Standard Atmosphere is used in our calculation[6] with the molecular extinction-to-backscattering ratio of $S_2 = 8\pi/3$. For aerosol scattering properties, some assumptions have to be made. According to Takamura and

Sasano[5], the aerosol extinction-to-backscattering ratio S_1 value locates in the range of 30 ~83 with wavelength dependence. At present the value of $\alpha_p(r_c)$ at a reference range r_c is taken from the model atmosphere. In the next section, we discuss the effect of $\alpha_p(r_c)$ and S_1 value on the solution of lidar equation.

3. Data collection and analysis

Data were collected using the Four-wavelength lidar at CEReS, in Chiba University. Normally the operational wavelengths are 1064 nm, 532 nm, 355 nm and 756 nm. In one of the presented examples, however, only the first three wavelengths are available because of the recent malfunction of one of the Nd:YAG lasers. Data of April 11th, 1997 and December 3rd, 1996 are presented here. Fig.1 shows the logarithmic plot of the signals on May 7th. The sampling rate of receiver system is 20 MHz, which corresponds to the spatial resolution of 7.5 m.

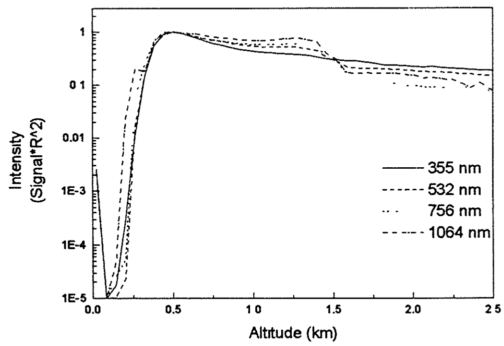

Fig.1 Lidar returns of four wavelengths at 14:05 Dec. 3rd, 1996. Signals shown are range corrected and normalized (maximum value is 1 and minimum value is 10^{-5}.

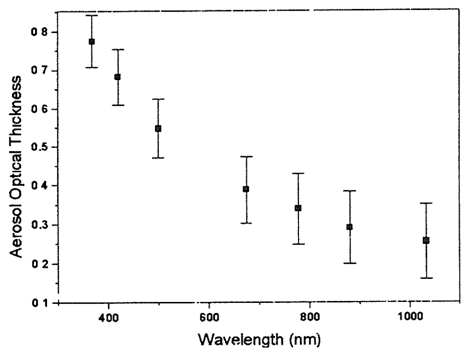

Fig.2 Total optical thickness of aerosol at 15:30, 11 Apr. 1997. The standard deviation of the data is marked on each data point.

At the same site a well-calibrated sun photometer with the channels of 368, 420, 500, 675, 778, 880 and 1033 nm, was used for the acquisition of corresponding data. The data were recorded around every 12 seconds and computed for the aerosol total optical thickness after removing the Rayleigh component, and averaged in accordance with the lidar measurement time duration (15 min). Using the Angstrom's relation

$$\tau(\lambda) = C_1 \lambda^{-C_2} \tag{2}$$

as well as the linear fitting for the original data, the aerosol optical thickness of 355, 532, 1064 nm can be obtained (Fig. 2). In eq.(2), $\tau(\lambda)$ is the total aerosol optical thickness, λ the wavelength in μ m, C_1, C_2 the coefficients determined from the fitting. For the data of Dec. 3rd, these two coefficients are $C_1 = 0.078$, $C_2 = 1.29$, and for the data of Apr. 11th, $C_1 = 0.26$, $C_2 = 1.11$, The detailed results of those two days are listed in Table 1 and 2.

For simplification only data in clear days (no clouds) are analyzed . In the present case, the relatively clear atmosphere with the surface visibility on the order of 20 to 50 km, and moderately turbid atmosphere are involved.

Figure 3 corresponds to a relatively clean atmosphere, showing the aerosol extinction coefficients for four wavelengths of the lidar, at about 14:05, December 3rd, 1996. From the figure, one can apparently see the wavelength dependence of aerosol extinction coefficient.

Figure 4. is a case of a slightly turbid atmosphere: the data were obtained at about 15:00, April 11^{th}, 1997. At that time only three wavelengths of our lidar system could be used. From these two figures one can find reasonable wavelength dependence in the analyzed range of 0.4 ~ 2.5 km. That means the alignments of all the wavelengths were consistent and the adjustment of the beam expander for each beam was appropriate.

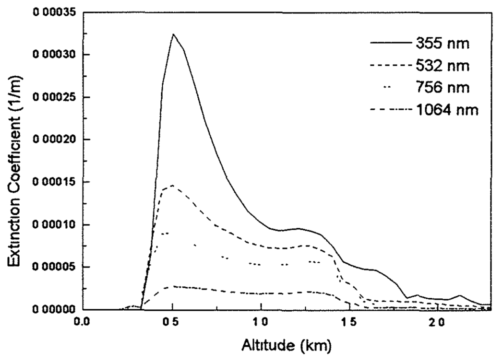

Fig.3 Aerosol extinction coefficients of four wavelengths (14:05 JST, 3 Dec. 1996), derived using Fernald method with reference point at 2.5 km (relatively clean atmosphere).

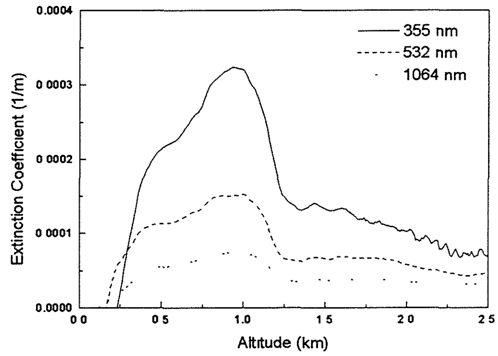

Fig.4 Aerosol extinction coefficients of three wavelengths (15:00 JST, 11 April 1997), derived using Fernald method with reference point at 2.5 km (relatively turbid atmosphere).

Table 1 and 2 list the results obtained from the lidar and sun photometer, i.e. the total aerosol optical thickness derived from the sun photometer data and the lidar data in addition to the value for S_1 parameters, the extinction to backscattering ratio, for each wavelength.

Table.1 Total optical thickness of aerosol by sun photometer and partial optical thickness by lidar with an appropriate S_1 value (14:05 JST, 3 December 1996)

	355 nm	532 nm	756 nm	1064 nm
Optical thickness(total)	0.29	0.18	0.11	0.07
Optical thickness(0~2.5km)	0.32	0.16	0.10	0.04
S_1	30	30	30	30

Table.2 Total optical thickness of aerosol by sun photometer and partial optical thickness by lidar with an appropriate S_1 value (15:00 JST, 11 April 1997)

	355 nm	532 nm	1064 nm
Optical thickness(total)	0.81	0.51	0.24
Optical thickness(0~3km)	0.52	0.25	0.13
S_1	50	45	40

In Fernald's method one has to assume the extinction coefficient $\alpha_p(r_c)$ and the S_1 parameter. From the detailed Mie calculation, S_1 can be assumed to be 30 sr as a first approximation. Then referring to sun photometer data, this value may be adjusted in the range of 30 ~83[5]. Concerning $\alpha_p(r_c)$, the extinction coefficient at the far-end, starting point, the way of determination is rather arbitrary. For example, a slope-type estimation from the signal itself[4] or a method using some additional experimental information can be applied. We use a method[6] based on the model atmospheric aerosol distributions and the extinction coefficients are adopted from LOWTRAN-7.

It is found that for a moderately turbid atmosphere (Fig.4, Table 2), this assumption is nearly suitable without any large modification on the $\alpha_p(r_c)$ values. The aerosol optical thickness at 2.5 km range derived from lidar data is smaller than the total one from the sun photometer data, which is easily explained by the difference in the range.

On the contrary, for relatively clear atmosphere with a small total optical thickness (Fig.3, Table 1), the initial assumption of $\alpha_p(r_c)$ needs some modifications. In the present case we fixed S_1 at value 30 and a correction factor was multiplied to make the $\alpha_p(r_c)$ approach a suitable value. Here this factor is 0.01, which means there is a large change for the initial assumption of $\alpha_p(r_c)$. Errors in $\alpha_p(r_c)$ will be the prime source of errors of $\alpha_p(r)$. Usually $\alpha_p(r)$ is in proportion to the $\alpha_p(r_c)$.

In summary, a fundamental criterion is that the aerosol optical thickness of each wavelength should locate in a proper region with respect to the value from the sun photometer. Other ways of validation includes the integrated nephelometer measurement and using of another smaller, additional lidar with a small inclination angle.

4. Conclusion

Lidar returns of four wavelengths from the relatively clear and turbid atmosphere are analyzed using Fernald method and the results are compared with sun photometer data. For the contribution of molecules, assuming a model atmosphere is acceptable. It is found that the value of $\alpha_p(r_c)$ from the model atmosphere is suitable for moderately turbid atmosphere. Especially for very clear atmosphere, the result of aerosol extinction coefficient becomes more sensitive to $\alpha_p(r_c)$. With appropriate supplement of additional data the multi-wavelength lidar system is useful to measure the profile of aerosol particles and obtain information about their micro-physical characteristics.

References:

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