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Experimental Estimation of the Error Due to the Fluctuation of Aerosol Backscattering in DIAL Measurements

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1. Introduction

A differential absorption lidar system for the measurement of the vertical distribution of ambient NO_2 has been developed at NIES. Before construction, we experimentally estimated errors in the DIAL measurement, especially, in the transmission of the two wavelengths, i.e., simultaneous or alternate. In a system using the alternate transmitting method, the error due to the fluctuation of the aerosol backscattering coefficient within the time interval of the wavelength switching may be very important. This paper reports the experimental estimation of the error as a function of the time interval of the wavelength switching. Also, the effect of the data accumulation on the error is investigated.

2. Error Due to the Aerosol Fluctuation

The error due to the fluctuation of the aerosol backscattering coefficient was estimated using data measured by the NIES large-scale lidar(1,2). The lidar signals at 532 nm were recorded every 0.08 sec with a range resolution of 7.5 m. The data were processed in the same way as in the DIAL measurements regarding each shot as the signal of the wavelength on resonance or off resonance.

The concentration is obtained by the following equation(3)

$$N(R)=(1/2\sigma_d L)\ln[F(R)] \tag{1}$$

where σ_d is the differential absorption coefficient, and L is the range resolution of the DIAL measurement. F(R) is defined as

$$F(R)=f_{off}(R)/f_{on}(R) \tag{2}$$

$$f_i(R)=P_i(R+L)/P_i(R) \tag{3}$$

where $P_i(R)$ is the received signal. The error in N(R) is written as follows

$$\begin{aligned}(\Delta N(R)/N(R))^2 &= [1/(2\sigma_d LN(R))]^2(\Delta F(R)/F(R))^2 \\ &= \mathrm{const}[(\Delta f_{on}/f_{on})^2+(\Delta f_{off}/f_{off})^2 -2(\Delta f_{on}/f_{on})(\Delta f_{off}/f_{off})] \\ &= \mathrm{const}\Big(\sum_i[(\Delta P_i(R+L)/P_i(R+L))^2+(\Delta P_i(R)/P_i(R))^2 -2(\Delta P_i(R+L)/P_i(R+L))(\Delta P_i(R)/P_i(R))] \\ &\quad -2(\Delta P_{on}(R+L)/P_{on}(R+L)-\Delta P_{on}(R)/P_{on}(R)) \\ &\quad \times(\Delta P_{off}(R+L)/P_{off}(R+L)-\Delta P_{off}(R)/P_{off}(R))\Big).\end{aligned} \tag{4}$$

The last three terms are correlation terms, and if there are correlations between $\Delta P_{on}(R)$, $\Delta P_{off}(R)$, $\Delta P_{on}(R+L)$ and $\Delta P_{off}(R+L)$, the error in N(R) is cancelled. The error in P_i includes shot noise, the fluctuation of the laser output, the fluctuation of the aerosol backscattering, and so on. Among these errors, the shot noise is independent of the four measured quantities, but as for the fluctuation of the aerosol backscattering there is a correlation between P_{on} and P_{off}.

Figure 1 shows the error $\overline{(\Delta F/\overline{F})^2}$ as a function of the time interval of the two wavelength switching. When the time interval lengthens, the error increases as seen in the figure. In the long interval limit, there is no correlation between ΔP_{on} and ΔP_{off}, and $\overline{(\Delta F/\bar{F})^2}$ would be equal to 2 x $(\Delta f/\bar{f})^2$. On the other hand, when the time interval becomes shorter, the error decreases. In our experiment, the minimum time interval was 0.08 sec. It is known that there is atmospheric turbulence with a time scale of the order of 1 msec(3,4). Therefore, the error may be further improved by shortening the time interval, but the improvement would not be large. It seems that the error becomes almost constant at the interval of about 0.1 sec. The errors remaining in the short time interval limit is random noise, such as the shot noise. A shot noise of 10^{-3} in $(\Delta F/F)^2$ corresponds to a received power of 3 x 10^{-7} W, and this is reasonable at R=1.5-2 km.

It can be seen from Fig.1 that the dominant time scale of the aerosol fluctuation is 1 - 10 sec. The same thing can be seen in Fig.2, which shows the self-correlation coefficient of foff(R). The self-correlation coefficient was calculated by the following equation

$$S(j)=(1/(N-j))\sum_{i=j+1}^{N}(f_i(R)-\overline{f(R)})(f_{i-j}(R)-\overline{f(R)}). \qquad (5)$$

where

$$\overline{f(R)}=(1/N)\sum_{i=1}^{N}f_i(R), \qquad (6)$$

i represents data number, and j corresponds to the time lag. The temporal fluctuation of the aerosol backscattering is related to the spatial distribution of aerosols and the wind velocity. Figure 3 shows the temporal behavior of a line-of-sight aerosol concentration profile. It can be seen from Fig.3 that the dominant spatial scale of aerosol distribution is about 100 m.

3. Dependence of Error on Data Accumulation Method

Here, three methods are investigated.

(I) The signals of the two wavelengths are measured alternately, and the concentration is calculated for each pair, and data for M pairs are averaged.

(II) The signals of the two wavelengths are measured alternately, and the signals of each wavelength are averaged for M pairs, and then the concentration is calculated.

(III) First, the signals of the one wavelength are measured and averaged for M shots, next, the other wavelength is measured and averaged for M shots, then the concentration is calculated.

Figure 4 shows the dependence of the error $\overline{(\Delta F/\bar{F})^2}$ on the averaging time. The three methods for data averaging are shown with circles, triangles and diamonds (I,II,III, respectively). In all cases the repetition rate of the laser was 12.5 pps. Method (I) is ideal for the cancellation of the change in the aerosol backscattering. However, when $\Delta P(R)$ is large compared to P(R), very large error may be caused in the calculation of N(R). Method (II) may be the best way to accumlate the data, if power normalization is ideal. Also, this method is technically easy.

For Methods (I) and (II), the error decreases exactly according to 1/M. On the other hand, for Method (III), large error is caused due to the decrease of the correlation.

Conclusion

The effective time scale of the fluctuation of the aerosol backscattering is 1 - 10 sec. Therefore, the alternate, two wavelength method with a 10 pps laser is sufficient for ground-based DIAL in the visible region, if there is no strong scattering, such as from clouds and heavy stack plumes.

References
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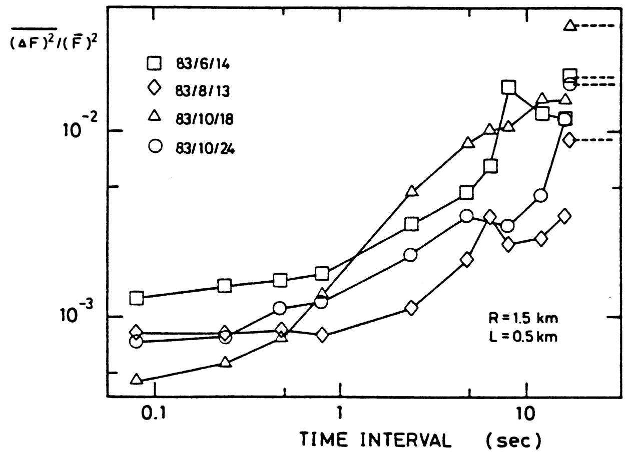

Fig.1 Dependence of the error $\overline{(\Delta F/\bar{F})^2}$ on the time interval of the wavelength switching.

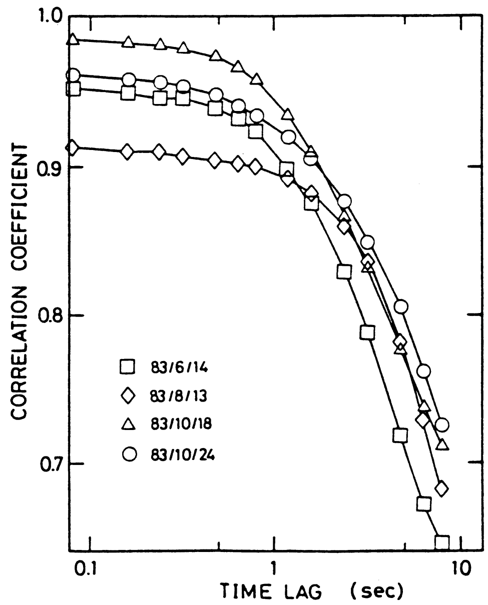

Fig.2 Self-correlation coefficient of the ratio of the received signals, f=P(R+L)/P(R). R=1.5 km, L=0.5 km.

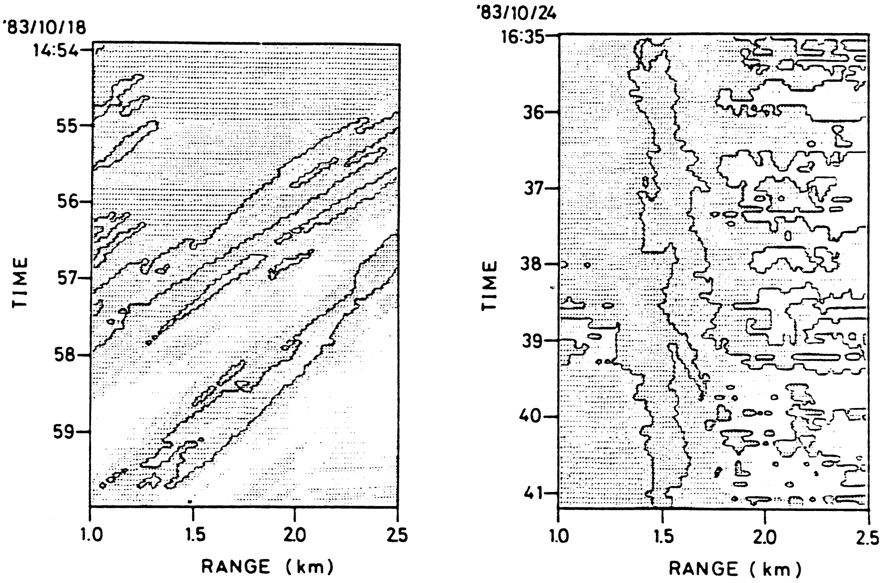

Fig.3 Temporal profiles of a line-of-sight aerosol concentration. Deviation from the mean value at each distance is shown.

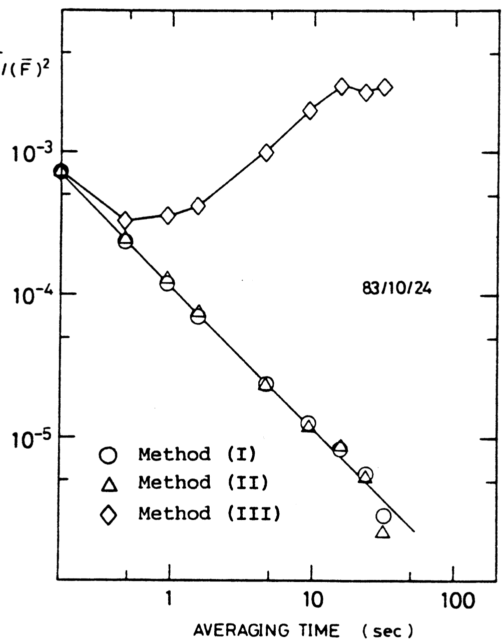

Fig.4 Dependence of the error $\overline{(\Delta F/\bar{F})^2}$ on the averaging time.