Estimation of the Error Caused by Smoothing on DIAL Measurements of Stratospheric Ozone

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Abstract

Several ozone retrievals from DIAL (Differential Absorption Lidar) measurements have been proposed. Each retrieval method has its own definition of the range resolutions and therefore one cannot easily compare the ozone concentration errors resulting from the use of these different methods. In this paper, assuming the atmospheric model quoted from the U.S. Standard Atmosphere 1976 and the system constants of our lidar system, we numerically compared the differences between some representative DIAL methods by means of estimating the error caused by smoothing. Initially we defined a common range resolution as a scale. Using the common scale, we focused on the distortions arising from smoothing and the uncertainty of statistical signal errors. These estimates revealed that some algorithms reduce statistical error but make substantial distortions at higher altitude. It was possible to distinguish for each algorithm both the statistical errors and the systematic errors.

1. Introduction

Since the discovery of the ozone hole in the Antarctic region, public awareness of the depletion of the stratospheric ozone layer has grown and more attention is being paid to this environment. Studies of the mechanism of ozone depletion and the establishment of a global ozone monitoring system have been encouraged to protect the ozone layer. The ozone monitoring must be done with both high resolution and high accuracy (WMO Ozone Trend Panels, 1988). There are several ozone observing instruments including ozone-sondes and satellite-borne passive sensors. Lidar (Laser Radar) systems are active remote sensors and relative newcomers for ozone measurements (Uchino *et al.*, 1978; Megie *et al.*, 1985). The advantages of this type of instrument are a higher sounding range compared with the ozone-sonde and better altitude resolution than passive instruments achieve. The lidar measurement range also covers the region where ozone reduction due to chlorofluorocarbon reactions are expected to occur.

Lidars utilizing developments in laser technology are now used to measure ozone, both improving accuracy and measurement range (McDermid *et al.*, 1990; Steinbrecht *et al.*, 1989; McGee *et al.*, 1991; Nakane *et al.*, 1993). Due to these advantages, lidar

systems were recommended as one of the primary instruments in the NDSC (Network for the Detection of Stratospheric Changes, 1990) project. Thus the number of lidar stations is increasing worldwide.

The MRI Mark II mobile lidar employs three wavelengths, 308 nm, 355 nm and 532 nm, and has been developed for simultaneous observations of stratospheric ozone, temperature and aerosols (Uchino and Tabata, 1991). This system has operated since 1988.

However, recently a problem has been encountered in comparing results from the MRI Mark II with other systems. A systematic error is caused by smoothing which depends on the retrieval algorithm applied. Focusing on the retrieval method, namely DIAL, we tried to estimate the errors included in its algorithms. To estimate the error, we defined a common range resolution because each algorithm has its own smoothing parameters and range resolution.

2. DIAL algorithms

The DIAL method is one procedure to calculate ozone concentration from lidar system data. The DIAL uses at least two different laser lines. For example, the MRI lidar system uses 308 nm and 355 nm wavelengths. The laser beams emitted from lidar are backscattered in the atmosphere and return to a receiving telescope. The received photons are translated into electric signals through

PMT(photomultiplier tube)s. Both the number and travel time of returning photons are counted. The photon travel time corresponds to the altitude where backscattering occurred. The photon number decreases in inverse proportion to the square of the altitude. Thus the signals from a higher altitude are weaker and their signal-to-noise ratio is smaller. Statistical errors arise mainly due to this lower signal. To increase the signal-to-noise ratio, we smooth the data. The smoothing procedures decrease the statistical error, but distort the results to some extent. This distortion is one of the systematic errors which is characteristic of the system. The measurement uncertainty consists of both the systematic and statistical errors. The aim of this paper is to estimate the above-mentioned systematic and statistical errors associated with various DIAL algorithms.

There are several ozone retrieval algorithms based on the DIAL method. Each method has its own smoothing. In this paper, the following types of representative algorithms are dealt with:

- A) difference method type (Uchino and Tabata, 1991)
- B) differential type (Pelon and Megie, 1982)
- C1) differential 2nd order polynomial fitting type (McDermid and Gordin, 1989)
- C2) differential 3rd order polynomial fitting type (Nakane *et al.*, 1993)

Each algorithm is deduced from the following lidar equation at a wavelength λ_i ,

$$n_i(z) = \frac{kn_0\beta_i(z)\delta z}{z^2} \exp \left[-2 \int_0^z \{ \alpha_i(r) + \sigma_i N(r) \} dr \right] \quad (1)$$

where the parameters in Eq. (1) are defined as,

- $n_i(z)$: number of backscattered photons from δz at the altitude z ,
- k : lidar system constant,
- n_0 : number of emitted photons in each laser pulse,
- δz : range cell width,
- $\beta_i(z)$: atmospheric backscatter coefficient,
- $\alpha_i(z)$: atmospheric extinction coefficient,
- σ_i : ozone absorption cross section,
- $N(r)$: ozone number density.

The suffix $i = 1$ indicates the on-line wavelength with strong ozone absorption and $i = 2$ indicates the off-line wavelength with weak ozone absorption.

The outlines of each algorithm are described as follows.

Fig. 1. The distributions of range resolutions for a Type A algorithm. The smoothing parameters are SM_a and Δz_a .

1) Type A

Using Eq. (1), the average ozone number density, N , between z and $z + \Delta z_a$ is obtained by:

$$N = \frac{1}{2(\sigma_1 - \sigma_2)\Delta z_a} \left\{ \log_e \left(\frac{n_1(z)n_2(z + \Delta z_a)}{n_1(z + \Delta z_a)n_2(z)} \right) \right\} + T, \quad (2)$$

where Δz_a is the height difference and T is the correction component of the extinction coefficient calculated as follows:

$$T = - \frac{\int_z^{z+\Delta z_a} \{ \alpha_1(r) - \alpha_2(r) \} dr}{(\sigma_1 - \sigma_2)\Delta z_a}. \quad (3)$$

In this algorithm, the photon numbers backscattered from δz of 100 m are averaged using a running mean. The smoothing of this algorithm is determined by two parameters, SM_a and Δz_a . SM_a is the range of the running mean.

2) Type B

The smoothing of the Type B algorithm is determined by two parameters, SM_b and Δz_b . The parameters and the algorithm are described as follows.

$D_i(z)$ is defined from Eq. (1) as:

$$D_i(z) = \frac{d}{dz} \left[-\log_e \{ z^2 n_i(z) \} \right] \quad (4)$$

The derivative (4) at z can be calculated by fitting the function $\log_e [z^2 n_i(z)]$ to a second-order polynomial function using a least-mean-square method

Fig. 2. The distributions of range resolutions for a Type B algorithm. The smoothing parameters are SM_b and Δz_b .

Fig. 3. The distributions of range resolutions for a Type C algorithm. The smoothing parameters are SM_c and Δz_c .

within the range of SM_b . SM_b is defined as $m \times \delta z$ where “ m ” is the number of continuous cells within the range of SM_b . The average of D_i between z and z' is:

$$\bar{D}_i = \frac{1}{\Delta z_b} \int_z^{z'} D_i(r) dr, \quad (5)$$

where $z' = z + \Delta z_b$. Then the average ozone number density, N , in the range between z and z' is obtained as:

$$N = \frac{\bar{D}_1 - \bar{D}_2}{2(\sigma_1 - \sigma_2)} + T, \quad (6)$$

where the correction component of the extinction coefficient T is written as:

$$T = - \frac{\int_z^{z'} \{\alpha_1(r) - \alpha_2(r)\} dr}{(\sigma_1 - \sigma_2) \Delta z_b}. \quad (7)$$

3) Type Cs

From Eq. (1):

$$N(z) = \frac{1}{2(\sigma_1 - \sigma_2)} \frac{d}{dz} [\log_e \{n_1(z)/n_2(z)\}] + T', \quad (8)$$

where $N(z)$ is the ozone number density at z , and T' is the correction component of the extinction coefficient:

$$T' = - \frac{\{\alpha_1(z) - \alpha_2(z)\}}{(\sigma_1 - \sigma_2)}. \quad (9)$$

To calculate the derivative in the right hand side of Eq. (8), the value of $\log_e [n_1(z)/n_2(z)]$ at range z is fitted to a second-order (Type C1) or third-order (Type C2) polynomial using a least-mean-square method. The smoothing of this algorithm is determined by a parameter, Δz_c . Δz_c is defined as $m' \times \delta z$, where m' is the number of range cells used for fitting.

3. Range resolution

The aim of this paper is to evaluate the algorithms as described above by comparing the errors caused by their smoothing procedures. However, the definitions of the smoothing parameters and the range resolution are different for each algorithm. Here, smoothing is considered to be a type of low-pass filter to eliminate noise and a common range resolution is defined as follows.

First, we made a profile of ozone concentration modulated by various wave number sine curves. Using this ozone concentration, the received signals can be calculated under the ideal conditions that the atmospheric density is constant and aerosols and other noise sources are excluded. The maximum intensity of the sine curve is set at one tenth of the ozone concentration. This intensity is reasonable for upper stratospheric ozone anomalies. Using these modulated signals, we can re-calculate ozone concentrations with each algorithm. After this procedure, the calculated noise can be analyzed spectroscopically with an FFT (Fast Fourier Transform) method and the range resolution can be defined as the wavelength which corresponds to 1/2 of the intensity of

Table. 1 Configuration of MRI Mark II lidar.

Laser	Nd:YAG		XeCl
Wavelength(nm)	355	532	308
Output energy(mJ)	130	100	110
Pulse repetition rate(Hz)	20	20	80
Telescope diameter(m)	.78		
Optical efficiency(%)	7.7	20	4.7
Quantum efficiency(%)	20	10	20

Fig. 4. The distortions caused by smoothing at the common range resolution = 3 km. The solid-thin line, solid-thick line, broken thin-line and broken-thick line show the deviation for Type A, Type B, Type C1 and Type C2 algorithms by percent, respectively.

the sine curves.

The original range resolutions are Δz_a , Δz_b and Δz_c in Type A, Type B and Type Cs, respectively in Figs. 1–3. However, the original resolutions are only the smoothing parameters in this paper. The original range resolutions differ from the calculated range resolutions and have their own shapes. The common range resolutions are higher than the originals in Types A, B and C1. The common range resolution in Type C2 is lower than that in the original.

4. Estimate algorithms

A common scale is needed to compare various algorithms. Adopting the common range resolution mentioned in Section 3 as a common scale, we compare DIAL algorithms with respect to both the systematic distortion which comes from smoothing and the statistical error which comes from signal weak-

Fig. 5. As in Fig. 4, except the common range resolution = 5 km.

Fig. 6. As in Fig. 4, except the common range resolution = 10 km.

ness.

The reference ozone concentration function $Q(z)$ was calculated by fitting each kilometer value quoted from the U.S. Standard Atmosphere 1976 to a third order polynomial function with a least-mean-square method. The photon number, n_i , corresponding to 1,200,000 shots of the on-line 308 nm ($i = 1$) and 300,000 shots of the off-line 355 nm ($i = 2$) wavelength pair is calculated by Eq. (1) using the values of $Q(z)$. The conditions for the calculation are that the atmospheric concentration refers to the U.S.

Fig. 7. Statistical error for Type A at the common range resolution = 10 km.

Fig. 9. Statistical error for Type C1 and Type C2 at the common range resolution = 10 km.

Fig. 8 As in Fig. 7, except for Type B.

Standard Atmosphere omitting aerosols and noises and that the system parameters are taken from MRI Mark II lidar, which configuration is described in Table 1.

4.1 Distortion (systematic error)

Using the signals calculated above, the ozone concentration can be retrieved with each algorithm. The results are shown in Figs. 4, 5 and 6 as percent differences between the calculated ozone concentration and the reference value for each algorithm, Type A, B, C1 and C2. Though there are

many combinations of $(SM_a, \Delta z_a)$ or $(SM_b, \Delta z_b)$ for Type A and Type B, the distributions are almost same as far as in a same range resolution for each type.

Each algorithm shows an error within 1 % at a range resolution of 3 km in Fig. 4. Using a 5 km range resolution, all errors but Type C2 show negative peaks at about 20 km (Fig. 5), which is the altitude of the maximum of the assumed ozone concentration. These errors become positive and increase with altitude, but remain less than 2 % below 50 km. The error for Type C2 is almost zero.

The error distributions of Type A, B and C1 are similar to each other at a range resolution of 10 km (Fig. 6). The values at 50 km are around 10 %. The distribution of errors for Type C2 is different and the remain less than 2 % for all altitudes 20–50 km.

4.2 Statistical error

Regarding statistical error, we applied the above-mentioned signals to the equation of error propagation (Russell *et al.*, 1979), assuming statistical error comes only from the signal (omitting back ground noise).

On the common range resolution of 10 km, the calculated statistical errors are shown in Figs. 7–9 for each algorithm. For Type A and Type B, various combinations of two smoothing parameters make various statistical errors (Figs. 7 and 8). For Type Cs, their statistical errors are almost same in comparison with Type C1 and Type C2 (Fig. 9).

5. Conclusions

Smoothing procedures are necessary with DIAL algorithms for ozone lidar both to remove high frequency noise and to increase the signal-to-noise ratio. However, smoothing causes systematic errors, *i.e.* distortions from the true values. This paper discusses these errors for representative DIAL algorithms. Although the distribution of errors is related to the distribution of ozone concentrations, the mid-latitude atmospheric models from the U.S. Standard Atmosphere are adopted in this case to generalize the conclusions.

The definition of a common range resolution is determined to estimate DIAL algorithms from the perspective of their errors. The common range resolutions are different from the original ones for all algorithms dealt with in this paper. Each algorithm has its own relation between the newly defined common range resolution and the original one.

For Type A and Type B algorithms, the errors are increasingly biased at altitudes above 30 km, and the errors are negatively biased around the maximum ozone concentration at 20–25 km. Although the negative errors are less than 1 % at a range resolution of 5 km, the errors at higher altitudes are 2 %. Comparing the systematic errors, we found that the Type C2 algorithm produces the smallest distortion among the representative algorithms considered. For Type Cs, the statistical errors are almost same. Thus the Type C2 algorithm is more effective for improving the errors. On the other hand, there are various combinations of smoothing parameters and various distributions of the statistical error for Type A and Type B algorithms. The character of objects, the objective height, lidar configuration and other factors must be considered before selecting a DIAL algorithm.

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DIAL法による成層圏オゾン測定における平滑化によって生じる誤差の評価

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本論文では、DIAL (差分吸収ライダー) 法の原理をもとに、ライダーの受信信号を使って成層圏オゾン密度を導出する過程で行われる信号の平滑化によって生じる系統誤差の評価を行った。このオゾン密度導出には何種類かのアルゴリズムが存在し、それぞれ独自に高度分解能の定義をしているため、異なるアルゴリズム間での誤差の評価の比較など困難である。ここでは、共通の高度分解能を定義し、それをもとにそれぞれのアルゴリズムで平滑化によって生じる誤差および平滑化によって改善されるランダム誤差の比較・評価を行い、その結果を示した。