A-1.1.1 Study on Accurate Measurement of Ozone in the Lower Stratosphere with Lidar

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Abstract

Lidar methods for accurate measurement of ozone in the lower stratosphere were studied. Correction methods for the effect of the wavelength dependence of aerosol scattering in the differential absorption lidar measurement are studied. The method was applied to the datas of the NIES ozone lidar system. High spectral resolution lidar method was studied to obtain vertical profiles of aerosol parameters in the stratospheric aerosol layer, which are useful for correction of ozone lidar measurement in high aerosol concentration cases. Experimental studies were carried out on a differential ansorption lidar with a small wavelength separation and a Raman differential absorption lidar. Study was also conducted on a new technique for measuring ozone and other atmospheric trace species using a baloon based on laser long-path absorption. An accurate baloon positioning technique using inverse differential GPS method was developed and demonstrated.

1. Introduction

Ozone depletion is observed most largely in the lower stratosphere. The change of ozone concentration in this altitude region affects the global warming, sensitively. Accurate ozone measurements in this altitude region, consequently, is indispensable for the study of mechanism of the destruction of ozone and the effect on climate change. Accurate observation of ozone in the lower stratosphere, however, is difficult because of the exstence of stratospheric aerosol layer. The datas measured with sondes somtimes largely differ from those measured with the SAGE/SAGEII satellites. Differential absorption lidars (DIAL) also suffer from interference due to the effect of wavelength dependence of aerosol scattering.

In this study, we studied advanced lidar methods for accurate ozone measurement in the lower stratosphere. We studied with the following three approaches; (1) correction of the aerosol effects in ozone DIAL measurements, (2) use of small separation wavelength pair in ozone DIAL measurements, (3) Raman DIAL technique. Also, we studied a new method for measuring ozone and atmospheric trace species using a baloon based on laser long-path absorption method. In this study, we developed accurate bolloon positioning techniques required for he measurement.

2. Study on advanced lidar techniques

(1) Correction of aerosol effects in DIAL measurement

The cause of the error in DIAL measurements of ozone in the lower stratosphere is the wavelength dependence of aerosols scattering. First, we studied a method to obtain aerosol profile, aerosol parameters, and ozone profile, simultaneously, from multi-wavelength ozone lidar data.1) An error analysis showed, however, it difficult to determine these unknown parameters accurately from the signals of the NIES ozone lidar2) at 308 nm, 339 nm, and 351 nm. Consequently, we studied a method, in which aerosol profile is obtained from the off-line signal with an assumption of the extinction-to-backscattering coefficient (S_1), and then the correction term in the DIAL equation is calculated with an assumption of the wavelength dependence.3)

Vertical profile of ozone concentration is calculated by the DIAL equation;

$$N(z) = 1/\{2(\sigma_{on}-\sigma_{off})\}\ [d/dz\{-\ln(n_{on}(z)/n_{off}(z))\}+B+E]\ , \qquad (1)$$

$$B = d/dz\ \ln\ (\beta_{on}(z)/\beta_{off}(z)),$$

$$E = -2\{\alpha_{on}(z) - \alpha_{off}(z)\}.$$

The terms B and E express the effect of aerosol scattering. The wavelength dependence of extinction and backscattering coefficients of aerosols are written as

$$\alpha_1(z, \lambda) = \alpha_1{}^0(z, \lambda^0)(\lambda/\lambda^0)^{-\gamma}, \qquad (2)$$

$$\beta_1(z, \lambda) = \beta_1{}^0(z, \lambda^0)(\lambda/\lambda^0)^{-\sigma}.$$

The sensitivity of ozone profile to the values of S_1, γ and σ were examined. Only slight change was found within the range of parameters, S_1=5-20, γ=-1-1 and σ=0.5-1.5. As the result, it was shown that sufficient accuracy of ozone profile is obtained with this method except for extremely high aerosol concentration cases. We applied this method to the datas of the NIES ozone lidar. Figure 1 shows the variation of ozone at altitudes of 20, 25, 30, 35, and 40 km.

In the method described above, it is assumed that the parameter S_1 is independent on altitude. Datas of multi-wavelength lidars using Nd:YAG laser fundamental, second harmonic, and third harmonic (1.06 μm, 532 nm and 355 nm) show, however, the S_1 depends on altitude in the stratospheric aerosol layer after volcanic erruptions. We studied the high spectral resolution lidar technique to improve the aerosol correction by measuring altitude dependence of S_1. We constructed an experimental system using an iodine molecular cell to separate the Mie and Rayleigh components in lidar backscattering signals.4)

Lidar signal is expressed by the lidar equation;

$$P(z) = (c/z^2)\beta(z)\ \exp[-2\int\alpha(z)\ dz], \qquad (3)$$

$$\beta(z) = \beta_1(z) + \beta_2(z), \qquad \alpha(z) = \alpha_1(z) + \alpha_2(z).$$

Subscripts 1 and 2 represents the contribution of Mie scattering and Rayleigh scattering, respectively. S parameters are defined separately as follows.

$$S_1(z)=\alpha_1(z)/\beta_1(z), \qquad S_2=\alpha_2(z)/\beta_2(z), \qquad (4)$$

where S_2 is known from the Rayleigh scattering theory. Equation (3) cannot be solved to obtain $\alpha_1(z)$ or $\beta_1(z)$ without assumption on $S_1(z)$.

In the high spectral resolution lidar using an iodine filter, a narrow band laser at 532 nm which is tuned to an absorption line of molecular iodine is used. Backscattering signal is detected with two optical channels. One of them receives the whole spectral range which contains both Rayleigh and Mie components. The other receives the return light through the iodine filter. The spectrum of the Mie scattering component is as narrow as the laser itself, but that of the Rayleigh component is broadened by Doppler effect due to the velocity distribution of scattering molecules. Consequently, Mie scattering component is blocked by the iodine filter, and only the Rayleigh component is received with the second channel.

The signal detected with the Rayleigh channel is written as

$$P_2(z)\ z^2 = c_2\ \beta_2(z)\ \exp[-2\int(\alpha_2(z)+\alpha_1(z))dz]. \qquad (5)$$

If we assume that the profile of molecules is known, i.e. $\beta_2(z)$ and $\alpha_2(z)$ are known, from an atmospheric model or from a sonde data, $\alpha_1(z)$ is obtained by

$$\alpha_1(z) = -(1/2)\, d/dz[\ln(P_2(z)z^2/\beta_2(z))] - \alpha_2(z). \qquad (6)$$

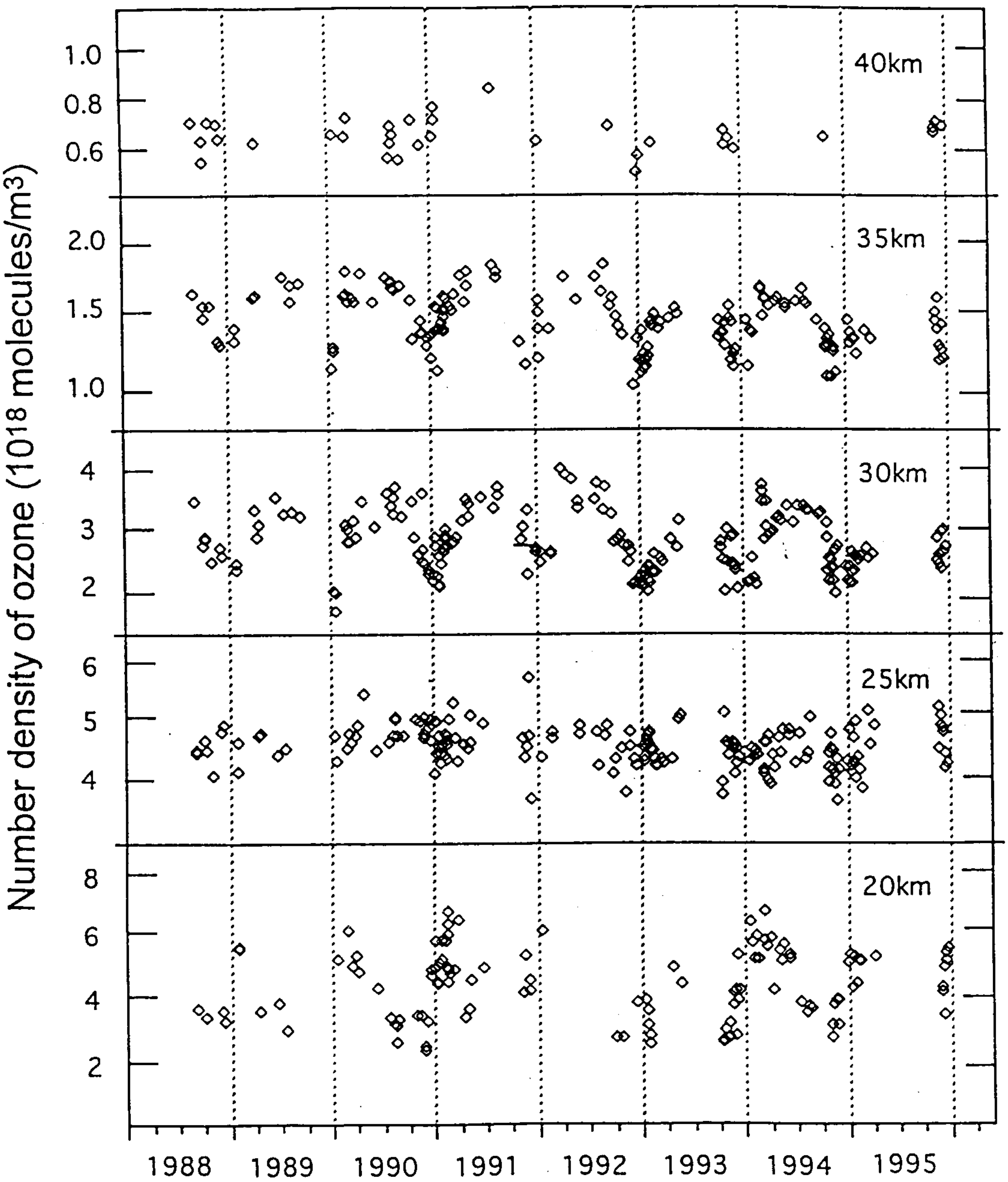

Figure 1 Variation of ozone at 20, 25, 30, 35, and 40 km measured with the NIES ozone lidar.

From the first receiver channnel we obtain

$$P_1(z)\, z^2 = c_1\, (\beta_2(z)+\beta_1(z))\exp[-2 \int (\alpha_2(z)+\alpha_1(z))dz]. \qquad (7)$$

from (5) and (7),

$$\beta_1(z)= (c_2/c_1)\beta_2(z)[\{P_1(z)/P_2(z)\} - 1]. \qquad (8)$$

Coefficient (c_2/c_1) can be determined from the $P_1(z)/P_2(z)$ where β_1 is zero. Consequently, we can obtain S_1 as a function of altitude z. Though we cannot obtain the wavelength dependence of aerosol scattering with this method, the correction to ozone profile will be improved because the accuracy of aerosol profile is improved. We have constructed an experimental high spectral resolution lidar system using a single-longitudinal-mode Nd:YAG laser and a telescope with 50 cm in diameter. The observation experiment has been continued.

(2) Differential absorption lidar with small wavelength separation

One of the methods to reduce the effect of aerosols in DIAL measurement is the use of wavelength pair with smaller separation. Because the difference of absorption coefficient also decreases when wavelength separation decreases, there is an optimum separation. In the low altitude system of the NIES ozone lidar, 277 nm, 292 nm, and 312 nm generated by KrF laser and H_2 and D_2 Raman shifters were originally used. The wavelength separations, however, were too large for accurate measurement when aerosol density is high. In this study, we added a fourth harmonic of Nd:YAG laser and H_2 and D_2 Raman shifters to the system (289 nm and 299 nm) and carried out differential absorption lidar experiments. Figure 2 shows a block diagram of the system.

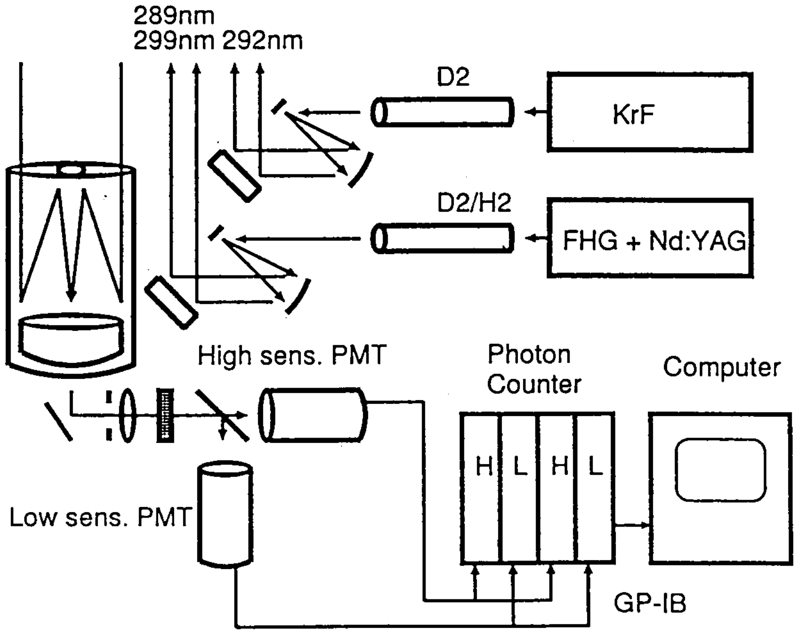

Fig.2 Block diagram of the DIAL for low altitude measurements.

We carried out the DIAL measurements with wavelength pairs of 289 nm - 292 nm, and 289 nm - 299 nm. Figure 3 shows an example of measured ozone profile. We obtained ozone profiles up to approximately 15 km with a high signal-to-noise ratio for both pairs.$^{5)}$

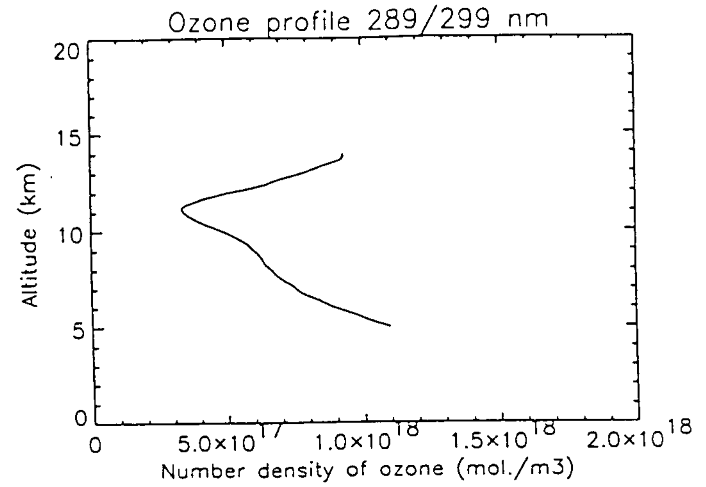

Fig.3 Ozone profile measured with 289 nm and 299 nm.

(3) Raman Differential absorption lidar

Another method to reduce the effect of aerosol scattering is the use of Raman scattering instead of Rayleigh/Mie scattering in DIAL measurement. We studied this method using a XeCl laser (308 nm) in the NIES ozone lidar to evaluate the signal-to-noise ratio (SNR) of the measurement. Because Raman scattering coefficient is much smaller than Rayleigh/Mie scattering coefficient, it is difficult to obtain high SNR at high altitude. We measured Raman signals at 332 nm and estimated measurement errors. The result shows that ozone profile up to approximately 25 km is obtained with one hour measurement.

3. Laser long-path absorption measurement using scientific balloon

Basic study was conductedon laser long-path absorption measurement between a ground-based station and a balloon. With the use of reflection of balloon body or a small retroreflector on the balloon, long-path differential absorption measurement can be performed in the infrared region to measure various atmospheric trace species. Vertical profiles is obtained from the change of the path length with the change of the altitude of balloon. In order to realize this method, a high accuracy balloon positioning technique using GPS was studied.

GPS, a high performance positioning system using satellites, is useful for detection of flight position of a balloon. However, the positioning accuracy is reduced intentionally by so called Selectable Availability (SA). The differential GPS method and the inverse differential GPS method are useful for removing the error with SA. Both methods are tested in this study using scientific baloons. It is concluded that the inverse differential GPS method is the most suitable for accurate positioning of a balloon because on-board system is simple.

An optical tracking method was also studied. It was shown that the reflection of laser from a 5 cm diameter retroreflector on a balloon at an altitude of 35 km can be easily detected with a CCD camera.

4. Conclusion

Lidar methods for accurate ozone measurement are studied. The result of experiments shows that a Raman DIAL and a DIAL with a small wavelength separation are useful for measureming ozone in the lower stratosphere and in the upper troposphere. However, correction to ozone profile will be still required when aerosol concentration is extremely high. In such cases, aerosol profiles measured with a high spectral resolution lidar is useful. These lidar techniques will be used in the observational studies and ozone monitoring at NIES.

High accuracy balloon positioning using the inverse differential GPS was demonstrated experimentally for laser long-path absorption measurements using balloons.

References

1) Y. Sasano, H. Nakane, S. Hayashida-Amano, N. Sugimoto and I. Matsui: Multiple-Wavelength DIAL and a New Analysis Technique to Deduce the Ozone Profile Without Systematic Errors Due to Aerosol Effects. Proc. Quedrennial Ozone Symp. and Tropospheric Ozone Workshop, 743-746 (1989).
2) N. Sugimoto, Y. Sasano, H. Nakane, S. Hayashida, I. Matsui, and A. Minato: Multiple wavelength Laser Radar for Measuring the Stratospheric and Tropospheric Ozone Profile, Oyo Buturi 58, 1385-1397 (1989).
3) H. Nakane, N.Sugimoto, Y. Sasano and I. Matsui: Ozone Lidar Monitoring, Monitoring Report on Global Environment -1994-, NIES, CGER-M004-'93.
4) P. Piironen and E.W. Eloranta, Demonstration of a High Spectral Resolution Lidar Based on an Iodine Absorption Filter, Opt. Lett. 19, 234-236 (1994).
5) I. Matsui, N. Sugimoto and H. Nakane: Observation of Tropospheric Ozone by DIAL, 17th Jpn Laser Sens. Symp. 83-84 (1995).