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Ultraviolet high-spectral resolution lidar with polarization detection for accurate measurement of optical properties of aerosol and clouds

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ABSTRACT

To investigate the correlation among the meteorological events relating with global warming issue, development of accurate atmospheric observation systems of the troposphere is required. An ultraviolet high-spectral-resolution (HSR) lidar with polarization detection has been developed using narrowband Fabry-Perot interference filters. Ultraviolet wavelength is used in the system for eye-safety characteristics and high accuracy measurements compared with visible lidar systems. Various meteorological phenomena have been observed by the HSR lidar system for 10 months. By simultaneous measurement of depolarization ratio with extinction coefficient and lidar ratio, the system could separated and classify spherical and non-spherical aerosol, water clouds and ice clouds. Probability distribution of lidar ratio of aerosol and clouds has also been measured. The UV-HSR lidar system in combination with depolarization ratio measurement has shown a potential for classifying qualitative and quantitative information of aerosol and clouds and useful for analyzing the influences on the heat balance of the earth.

Keywords: high spectral resolution lidar, ultraviolet wavelength, depolarization ratio, Fabry-Perot interference filter, aerosol and clouds

1. INTRODUCTION

The atmospheric optical properties such as extinction coefficient, lidar ratio and depolarization ratio of aerosol and clouds are useful for analyzing the influence on heat balance of the earth in relating with global warming issue.[(1)] To investigate the correlation among the meteorological events like warming and cooling effect of the troposphere, development of accurate atmospheric observation systems is required. For measuring the atmospheric optical properties of aerosol and clouds, the Mie scattering lidar, the Raman scattering lidar and the high-spectral-resolution (HSR) lidar have been developed. [(2-6)] The Mie scattering lidar is a useful tool for measuring the backscattering coefficient of aerosol and clouds because of low power requirement, simple construction and easy operation. However, accurate measurement of optical properties is limited by the requirement of assuming special aerosol models like Klett's inversion technique. [(7)] The Raman scattering lidar can measure extinction coefficient of aerosol and clouds by assuming height profiles of atmospheric density. However, high power laser is required for the accurate measurement of optical properties because of inefficient scattering cross-section of this scattering process.

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The HSR lidar system has been developed by using an iodine absorption filter or a Fabry-Perot filters. (4-6)
In this system, the Rayleigh backscatter power and Mie backscatter power is separated and the spatial profile is used for determining the backscattering and extinction coefficients. Accurate measurement of extinction coefficient and lidar ratio can be realized without assuming special aerosol models. Long range and high sensitive measurement can be realized by the HSR lidar system because of large cross-section of the Rayleigh backscattering more than two orders of magnitude compared with Raman backscattering cross-section. We have developed the UV-HSR lidar system using the Fabry-Perot interference filters for measuring wind velocity and optical properties of clouds. (8-9)

The polarization detection with Mie scattering lidar was developed and widely used for the research of clouds in the atmosphere. (10) Depolarization ratio measurement gives an ability to discriminate spherical and non-spherical particles and thermodynamic phase of clouds can be realized.

We have developed the UV-HSR lidar system with polarization detection of the Mie backscatter. By simultaneous measurement of depolarization ratio in the HSR lidar, a new possibility of qualitative analysis of aerosol and clouds has been studied.

2. ULTRAVIOLET HIGH-SPECTRAL RESOLUTION LIDAR WITH POLARIZATION DETECTION

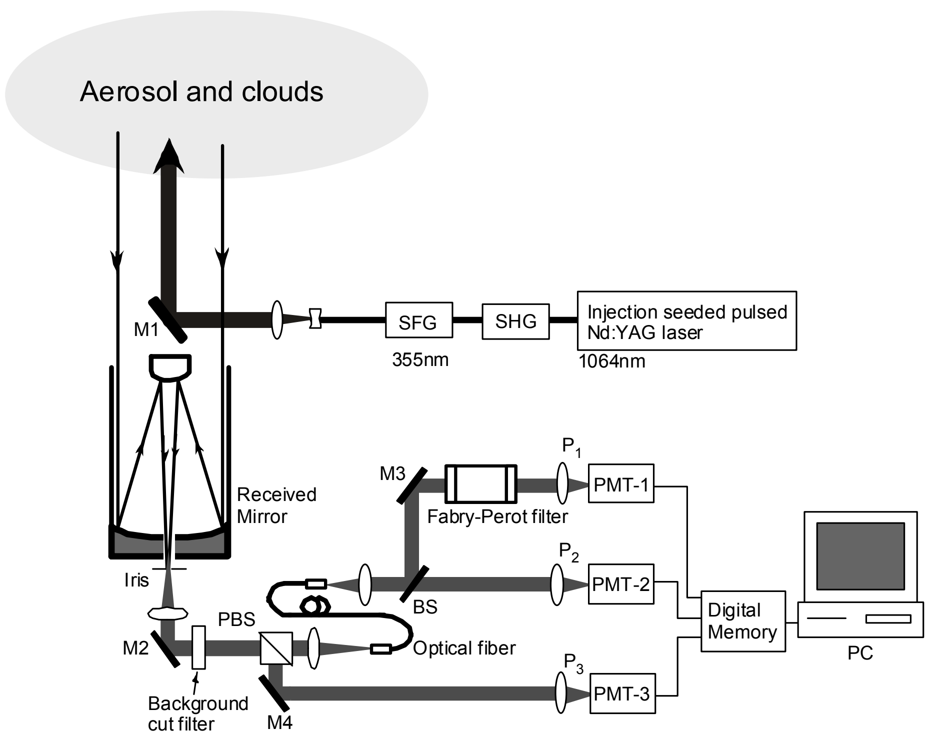


Fig. 1 Schematic of the ultraviolet high-spectral resolution lidar with depolarization measurement.
M-1 ~ M-4 are mirrors, BS beam splitter, PBS polarization beam splitter, PMT-1 ~ PMT-3 photo-multiplier detectors.

Schematic diagram of the Ultraviolet high-spectral resolution lidar system is shown in Fig.1. The single-frequency and linearly polarized third harmonic of ultraviolet wavelength at 355 nm of the injection seeded Nd:YAG laser is used as the transmitter beam. The ultraviolet wavelength exhibits eye-safety characteristics and large Rayleigh backscattering cross section compared with visible wavelength which is useful for realizing high accuracy measurements. Output energy of the laser pulse is 200 mJ with 10 ns pulse width and repetition frequency of 20 Hz and the laser beam diameter is enlarged to 60 mm by the beam expander. Backscattering light is collected by the 250 mm diameter receiving mirror with a 100-μm diameter iris. The received light is collimated and transmitted thought an background cut filter for reject the solar radiation and splitted into two beams by a polarization beam splitter PBS. The reflected depolarized light is detected by the photomultiplier (PMT-3) for measuring the depolarization ratio. The light polarized parallel to the laser beam polarization is focused into a multi-mode optical fiber for mode-scrambling for realizing stable transmittance of the Fabry-Perot filter. Output beam is collimated and transmitted thought the Fabry-Perot filter and Mie scattering power is detected by the PMT-1. The photomultiplier PMT-2 is used for detecting the total scattering light composed of Mie and Rayleigh scattering power.

Figure 2 shows the Mie and Rayleigh scattering spectrum and the Mie filter transmission function. The Fabry-Perot filter with spectral width of 300MHz at FWHM is used for transmitting the Mie scattering. Received signals are sampled with range intervals of 3.75 m (25 ns) and smoothed afterward with intervals with 200 m or 400 m.

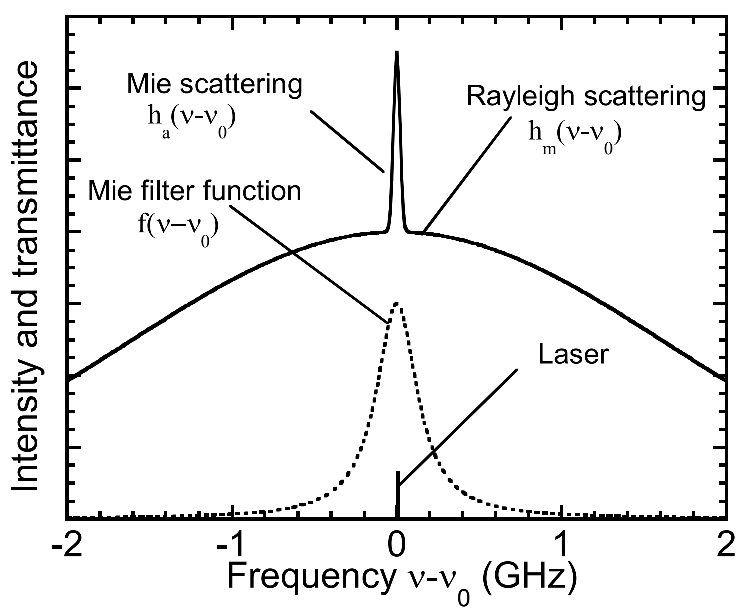


Fig. 2 Spectral profiles of the Mie and the Rayleigh backscatter and the filter transmission function.

3. DERIVATION OF ATMOSPHERIC BACKSCATTER POWER

The Mie and Rayleigh backscattering signals are derived by using the high-spectral resolution technique. The molecular Rayleigh power $P_m(z)$ is derived from the total scattering power $P_2(z)$ by subtracting the Mie detector power $P_1(z)$ and is given by

$$P_m(z) = \frac{P_2(z) f_a(\nu_0)/T - P_1(z)/R}{f_a(\nu_0) - f_m(\nu_0)}, \tag{1}$$

where $f_a(\nu_0)$ and $f_m(\nu_0)$ are effective Mie and the Rayleigh backscatter transmittances of the Mie filter, T and R are the transmittance and the reflectance of the beam splitter BS, respectively. The Mie backscattering power of aerosol and clouds $P_a(z)$ is obtained from the Mie filter power $P_1(z)$ by subtracting the Rayleigh scattering power as

$$P_a(z) = \frac{P_1(z)/R - P_2(z) f_m(\nu_0)/T}{f_a(\nu_0) - f_m(\nu_0)}. \tag{2}$$

The extinction coefficient of aerosol and clouds can be derived from a slope of the range profile of the molecular Rayleigh scattering power. Using the molecular Rayleigh scattering power $P_m(z)$, the aerosol and clouds Mie extinction coefficient $\alpha_a(z)$ is derived by

$$\alpha_a(z) = -\frac{1}{2}\frac{d \ln\{P_m(z) z^2\}}{dz} + \frac{1}{2\beta_m(z)}\frac{d\beta_m(z)}{dz} - \alpha_m(z), \tag{3}$$

where $\beta_m(z)$ is the Rayleigh volume-backscatter coefficient assuming a height profile of the standard atmospheric molecular density, and $\alpha_m(z)$ is the molecular extinction coefficient. The lidar ratio is given by compensating of the depolarized Mie backscatter power as

$$S_1(z) = \alpha_a(z) \frac{1 + \delta_m(z)}{R_s(z)\beta_m(z)\{1 + \delta_a(z)\}}. \tag{4}$$

From this method, the lidar ratio can be obtained without assuming special aerosol models.

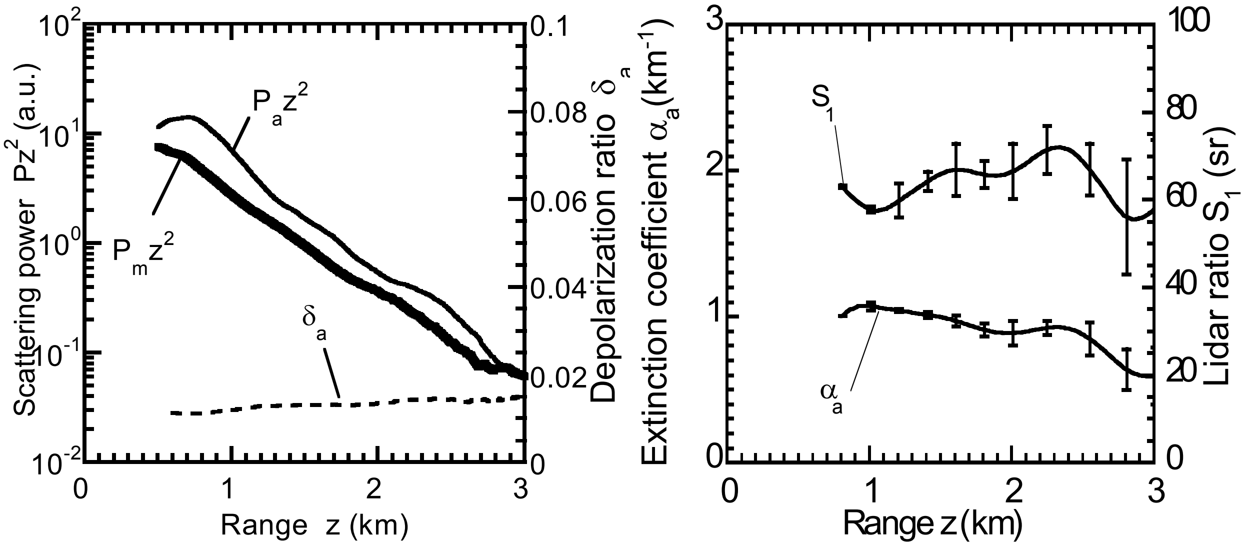
The depolarization ratio of the Mie scattering is given by

$$\delta_a(z) = \frac{\delta_t(z)\{R_s(z) + 1\} - \delta_m(z)}{R_s(z)}, \tag{5}$$

where $\delta_m(z)$ is the depolarization ratio of air molecule, $R_s(z)$ is the scattering ratio for parallel component to the laser beam given by $R_s(z)=P_a(z)/P_m(z)$, $\delta_t(z)$ is depolarization ratio of total backscattering defined by $\delta_t(z)=P_3(z)\eta_f T_2/P_2(z)$ for the depolarized power $P_3(z)$ and η_f is the transmission efficiency of the optical fiber.

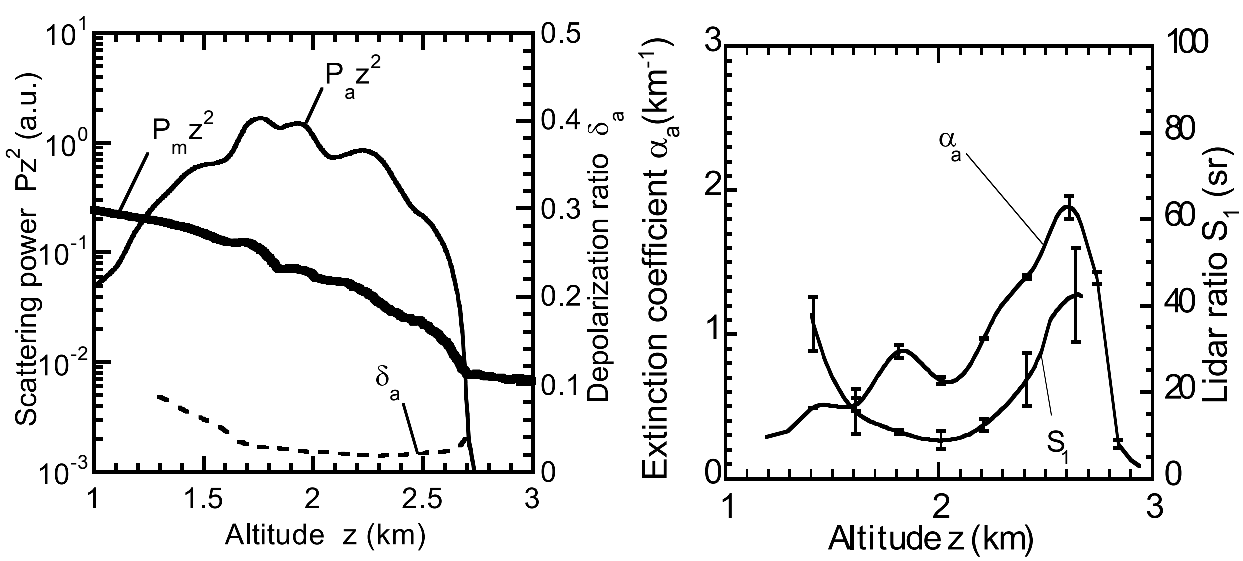
4. MEASUREMENT OF ATMOSPHERIC OPTICAL PHENOMENA

The ultraviolet HSR lidar system has been operated for measuring optical properties of aerosol and clouds at University of Fukui, Japan (36.04° N, 136.13° E). Figure 3 shows the result of measurement of light haze condition in horizontal direction averaged over 1.6×10^4 pulse shots. Backscatter ratio was all most 2 and the depolarization ratio was smaller than 0.05. From the value of depolarization ratio, the haze was identified to be spherical particle. The extinction coefficient was ~1 km^{-1} and the lidar ratio was ~60 sr. The error bars indicate the standard derivation of the mean values. The horizontal measurement can be used for calibration system sensitivity using uniform aerosol distribution.



(a) Mie and Rayleigh power and depolarization ratio, (b) Extinction coefficient and lidar ratio

Fig. 3 Horizontal distribution of the return signal and atmospheric optical properties. (a) is the range corrected Mie and Rayleigh backscatter power and the depolarization ratio, (b) is the extinction coefficient and lidar ratio. The measurement was made with 400 m averaging interval for 1.6×10^4 shot average from 4:36 JST of 26 December 2006.

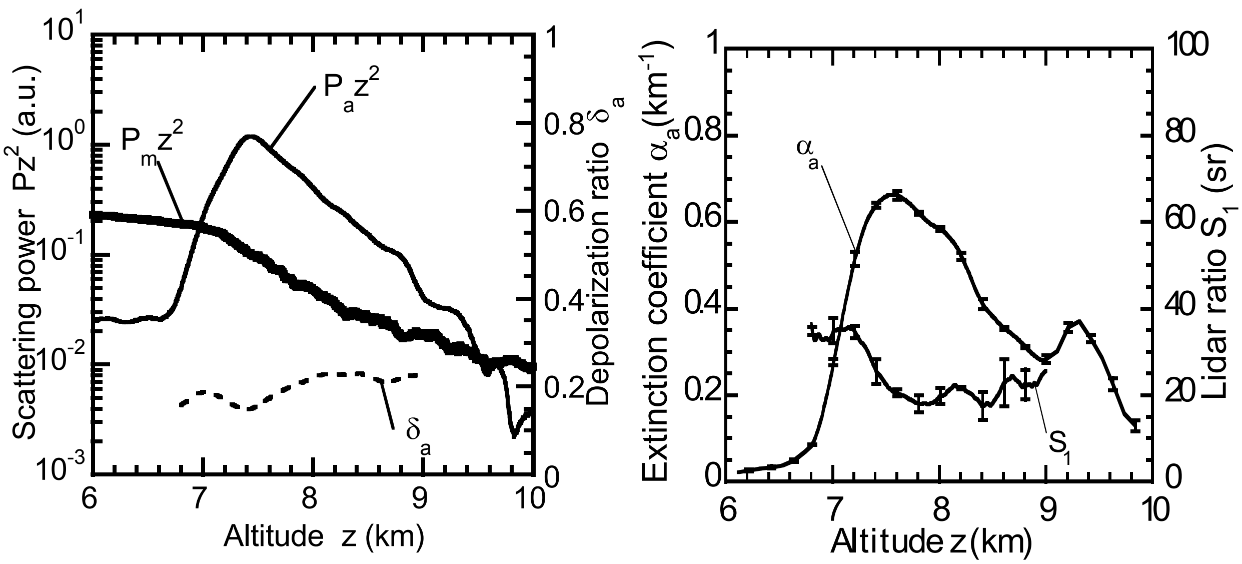


(a) Mie and Rayleigh power and depolarization ratio, (b) Extinction coefficient and lidar ratio

Fig. 4 Height distribution of the return signal and atmospheric optical properties of low altitude water clouds. (a) is the range corrected Mie and Rayleigh backscatter power and the depolarization ratio, (b) is the extinction coefficient and lidar ratio. The measurement was made with 200 m averaging interval for 4×10^3 shot average from 14:05 JST of 11 January 2007.

Figure 4 shows an example of height distribution of return signal from water cloud with top height of 2.7 km. The observed Mie backscatter was from the spherical droplets because of the depolarization ratio was measured to be near-zero and backscatter ratio ~10. The value of the lidar ratio is decreasing to 10 sr inside of the cloud and increasing to 40 sr.

Figure 5 shows a height distribution of the return signal from ice cloud at high altitude with $4x10^4$ shots average. The observed Mie target identified to be non-spherical particle because of high depolarization ratio to be ~0.2 and estimation of low clouds temperature in mid winter. The lidar ratio was measured to be 30 sr at the bottom and decrease inside the cloud.



(a) Mie and Rayleigh power and depolarization ratio, (b) Extinction coefficient and lidar ratio

Fig. 5 Return signal and atmospheric optical properties of high altitude ice clouds. (a) is the range corrected Mie and Rayleigh backscatter power and the depolarization ratio, (b) is the extinction coefficient and lidar ratio. The measurement was made for $4x10^4$ shot average and 200 m range interval from 15:45 JST of 5 January 2007.

Figure 6 shows the distribution of the depolarization ratio and extinction coefficient of aerosol and clouds data observed for 10 months from April 2006 to January 2007. These data are classified into spherical aerosol, non-spherical aerosol, water clouds and ice clouds. Spherical aerosol and clouds correspond the value of depolarization ratio δ_a<0.05 and non-spherical aerosol and clouds to δ_a>0.05. The aerosol is classified by small extinction coefficient to α_a<0.5 km^{-1} and clouds to α_a>0.5km^{-1}. The region of extinction coefficient of high density aerosol and thin clouds overlaps and can not separate clearly. For air molecule near ground level, we could observe depolarization ratio δ_m≈0.007 and extinction coefficient α_m≈0.06 km^{-1} at 355nm wavelength.

From the measurement of depolarization ratio and extinction coefficient, we could classify four cases of spherical and non-spherical aerosol, water clouds and ice clouds for particle cases.

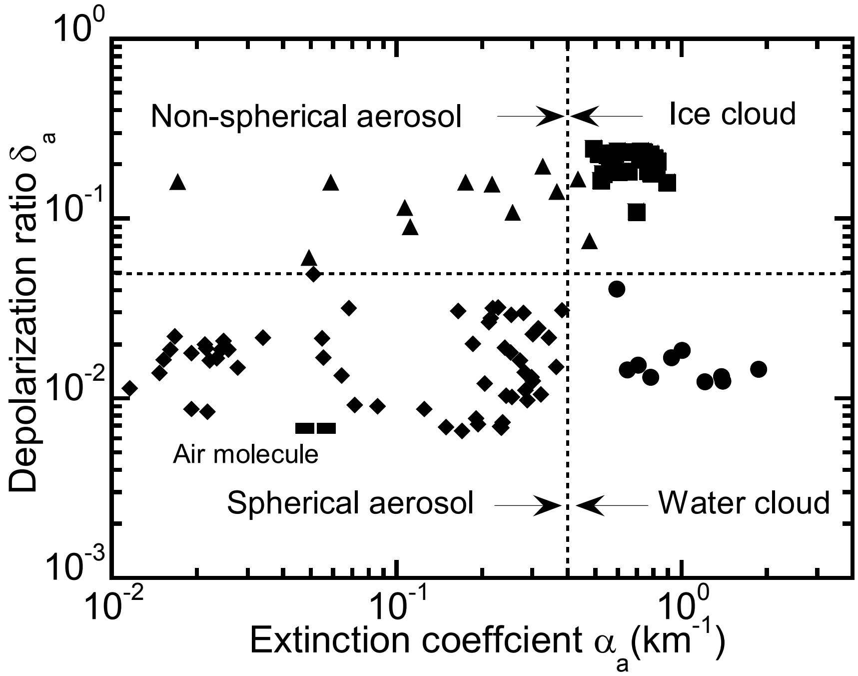


Fig. 6 Distribution of the depolarization ratio and extinction coefficient of aerosol and clouds data observed for April 2006 to January 2007.

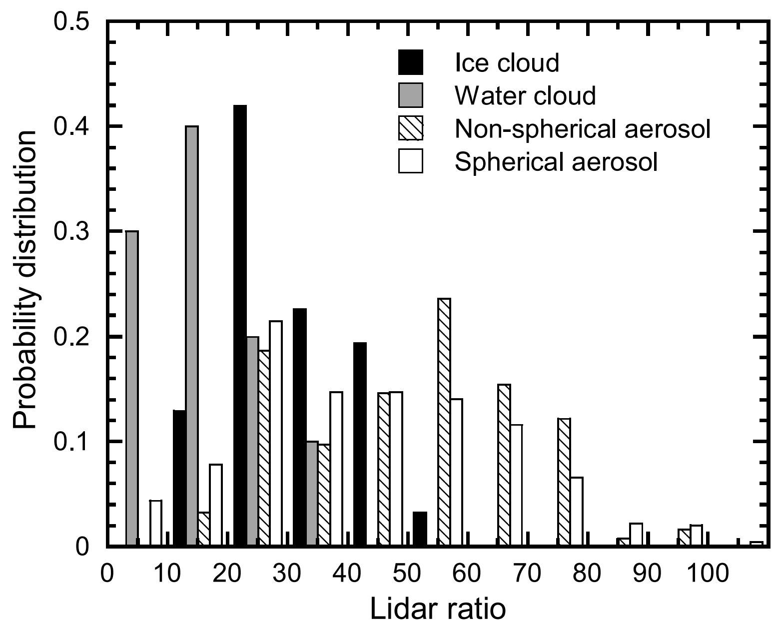


Fig. 7 Probability distribution of the lidar ratio of spherical and non-spherical aerosol, water clouds and ice clouds.

Probability distribution of the lidar ratio of spherical and non-spherical aerosol, water clouds and ice clouds are shown in Fig.7. Mean values of lidar ratio with standard deviation are 42 ± 21.5 sr for spherical aerosol, 51 ± 17.5 sr for non-spherical aerosol, 21 ± 14.2 sr for water clouds and 29 ± 11.3 sr for ice clouds. Mean value of the lidar ratio of aerosol is larger than clouds, which indicates higher absorption characteristics of aerosol.

This distribution profile of the lidar ratio is similar to the data obtained by the HSR lidar system with iodine absorption filter at visible wavelength. [11]

5. CONCLUSION

We have developed the UV-HSR lidar system with polarization measurement of the Mie backscattering of aerosol and clouds. The narrow-band Fabry-Perot interference filters have been used for detecting the Mie backscattering and the received power is separated into the Mie and the Rayleigh power using the total scattering power. Various meteorological phenomena have been observed by the HSR lidar system for 10 months. By simultaneous measurement of depolarization ratio with extinction coefficient and lidar ratio, the system could separated and classify spherical and non-spherical aerosol, water clouds and ice clouds. Probability distribution of lidar ratio of aerosol and clouds has also been measured.

Ultraviolet wavelength is used in the system for eye-safety characteristics and high accuracy measurement can be realized compared with visible HSR lidars and Raman lidars. The UV-HSR lidar system in combination with depolarization ratio measurement has shown a potential for measuring qualitative and quantitative information of aerosol and clouds and useful for analyzing the influence on the heat balance of the earth.

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