Measurements of cirrus clouds with a three-wavelength lidar

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Received October 12, 2011; accepted November 9, 2011; posted online January 17, 2012

A three-wavelength lidar system is set up. The backscatter signals of 355, 532, and 1 064 nm are measured simultaneously to derive the optical depth, lidar ratio, and backscatter color ratio of cirrus clouds, respectively. The lidar configuration and the data processing are described. The case study shows that the optical depths of cirrus clouds are not dependent on wavelength while the backscatter color ratios are.

OCIS codes: 010.1615, 280.3640, 290.5850.
doi: 10.3788/COL201210.050101.

Cirrus clouds have a large influence on weather and climate because they can absorb long-wavelength outgoing radiation from the Earth's surface while reflecting short-wavelength incoming solar radiation[1]; moreover, their occurrence probability over the Earth's surface can reach 30%[2,3]. The optical property of cirrus clouds is an important parameter, such as the scattering and absorption properties determined by the complex refractive index, shape, and size distribution of cirrus clouds[4]. Lidar is a powerful tool in deriving the range-resolved optical properties of clouds—a knowledge essential in understanding cloud-radiation effects.

Our lidar system consists of transmitter, receiver, and data acquisition subsystems. The light source deployed in the transmitter is a Nd:YAG laser (Quantel Brilliant b) with a repetition of 10 Hz at the fundamental wavelength of 1 064 nm, frequency doubled wavelength of 532 nm, and frequency tripled wavelength of 355 nm. The receiver is composed of a Cassegranian telescope whose primary mirror is 14 inches in diameter. Two photomultiplier tubes (PMT) and an avalanche photodiode (APD) detector are used to measure the return signal at 355-, 532-, and 1 064-nm wavelengths, respectively. Narrow band interference filters are used to suppress the sky background radiation in order to increase signal-to-noise ratio (SNR). This lidar is a bistatic system whose geometric overlap of the receiver and transmitter is adjustable from a few ten meters to a few hundred. The data acquisition system uses a lidar transient recorder (Licel TR-20-160), which can be set to operate in either analog or photon-counting modes. However, for the measurements reported herein, only the analog mode signal was used. For the analog detection, lidar signals were sampled using a 12-bit digitizer. The specifications of our lidar system are summarized in Table 1.

The range-corrected signals measured can be written as

$$X(z) = C[\beta_1(z) + \beta_2(z)] \times \exp\Big\{-2\int_0^z [\alpha_1(z') + \alpha_2(z')]\mathrm{d}z'\Big\}, \qquad (1)$$

where C is the lidar system constant, and subscripts "1" and "2" represent particulate and molecular scattering, respectively. $\beta_1(z)$ and $\beta_2(z)$ are the volume backscatter coefficients at altitude z for particles and molecules, and $\alpha_1(z)$ and $\alpha_2(z)$ are the volume extinction coefficients at the altitude z for particles and molecules, respectively. The particulate terms $\alpha_1(z)$ and $\beta_1(z)$ include aerosol and/or cloud: $\beta_1(z) = \beta_{\rm a}(z) + \beta_{\rm c}(z)$ and $a_1(z) = a_{\rm a}(z) + a_{\rm c}(z)$. The effective region of $\alpha_{\rm c}(z)$ and $\beta_{\rm c}(z)$ is from $z_{\rm b}$ (cloud base) to $z_{\rm t}$ (cloud top). In other altitude regions, their values are set to zero.

For the inversion of the optical depth of cirrus clouds, a referenced range corrected signal $X'(z)$ was constructed in advance as

Table 1. Specifications of the Bistatic 14-inch Lidar

Nd: YAG Laser (Quantel Brilliant b)	
Wavelength (nm)	1 064, 532, and 355
Pulse Energy (mJ)	280 at 1 064 nm, 260 at 532 nm, 165 at 355 nm
Repetition Rate (Hz)	10
Divergence (mrad)	0.5
Telescope (Meade Cassegrain LX400-ACF-14")	
Diameter (inch)	14
Focal Length (mm)	2 845
Interference Filters	
Bandwidth (nm)	1.0 at 355 nm, 532 nm, and 1 064 nm
Transient Recorder	(Licel TR-20-160)
Sampling Rate (MHz)	20
Photon Counting Rate (MHz)	250
Detectors	
PMT	R7400U-02 for 532 nm, R7400U-03 for 355 nm
APD	EG&G C309546

$$X'(z) = \beta_2(z)\exp\Big[-2\int_0^z \alpha_2(z')\mathrm{d}z'\Big]. \qquad (2)$$

The molecular backscatter and extinction coefficients at each wavelength are calculated from the US standard model. In this research, in the region above and below the cirrus layer, aerosols are assumed to be limited in number; therefore, we fit the measured range corrected signals $X(z)$ and $X'(z)$ in the proper region above and below cirrus cloud layer, resulting in the two parameters C_1 and C_2, shown as

$$C_1 = \frac{X(z)}{X'(z)} = C\exp\Big[-2\int_0^{z_\mathrm{b}} \alpha_\mathrm{a}(z)\mathrm{d}z\Big], \qquad (3)$$

$$\begin{aligned} C_2 &= \frac{X(z)}{X'(z)} \\ &= C\exp\Big[-2\int_0^{z_\mathrm{t}} \alpha_\mathrm{a}(z)\mathrm{d}z\Big]\cdot\exp\Big[-2\int_{z_\mathrm{b}}^{z_\mathrm{t}} \alpha_\mathrm{c}(z)\mathrm{d}z\Big]. \end{aligned} \qquad (4)$$

The transmission T_c of cirrus clouds was determined by

$$T_\mathrm{c} = (C_2/C_1)^{\frac{1}{2}}. \qquad (5)$$

The optical depth τ of cirrus clouds was defined by

$$\tau = -\ln T_\mathrm{c}. \qquad (6)$$

This method was described in detail by Young[5] and developed by Chen *et al.*[6].

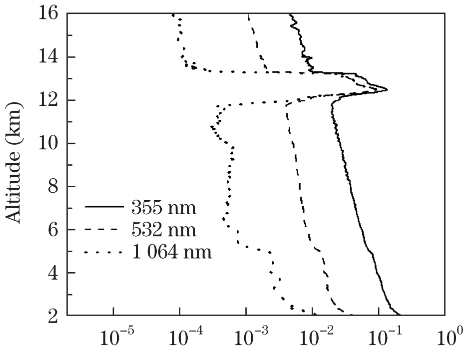

Fig. 1. Attenuated backscatter profiles.

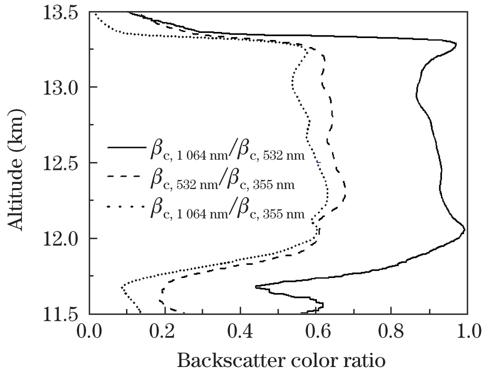

Fig. 2. Backscatter color ratio.

Table 2. Retrieved Parameters of the Measured Cirrus Cloud

	355 nm	532 nm	1 064 nm
Optical Depth	0.30±0.01	0.31±0.02	0.28±0.03
Lidar Ratio (Sr)	25±1	39±3	39±7

The retrieved optical depths can be used to constrain and retrieve the extinction coefficient of the cirrus cloud. By adjusting the trial value of the cirrus cloud lidar ratio S1 from 5 to 120 Sr at an increment of 1 Sr, three sets of extinction coefficient profiles using the Fernald method at three wavelengths can be computed[7]. Then three sets of cirrus clouds' optical depth can be calculated from the extinction coefficient profiles using

$$\tau_\mathrm{c} = \int_{z_\mathrm{b}}^{z_\mathrm{t}} \alpha_\mathrm{c}(z)\mathrm{d}z. \qquad (7)$$

When the optical depth from Eq. (7) is equal to the optical depth from Eq. (5), the corresponding S1, extinction, and backscatter profiles are the solution for cirrus clouds. Thus, the cirrus cloud backscatter color ratio χ between two wavelengths is computed as

$$\chi = \beta_{\mathrm{c},\lambda1}/\beta_{\mathrm{c},\lambda2}. \qquad (8)$$

We presented the case measured by our lidar system to retrieve the optical depth, lidar ratio, and backscatter color ratio of cirrus cloud. The experimental backscatter signal was the average of 1 000 shots at a 7.5-m altitude resolution. The measurement was carried out at 18:01 Beijing time on April 20, 2011. Figure 1 shows the attenuated backscatter of the measured cirrus cloud at three wavelengths, demonstrating that the cirrus cloud altitude is approximately 13 km with a physical depth of about 1.5 km. Using the previously introduced methods, three backscatter color ratios ($\beta_{\mathrm{c,1\,064\ nm}}/\beta_{\mathrm{c,532\ nm}}$, $\beta_{\mathrm{c,532\ nm}}/\beta_{\mathrm{c,355\ nm}}$, and $\beta_{\mathrm{c,1\,064\ nm}}/\beta_{\mathrm{c,355\ nm}}$) are given in Fig. 2, and some retrieved parameters of the measured cirrus cloud are summarized in Table 2.

So far, limited literature[8−12] has reported the measured backscatter color ratio of cirrus clouds with lidar, computing only two wavelengths of the backscatter color ratio of cirrus clouds. To the best of our knowledge, the current paper is the first time reporting measures of optical properties of cirrus clouds by lidar at 355-, 532-, and 1 064-nm wavelengths simultaneously. For cirrus clouds, the optical depth of 355, 532, and 1 064 nm are assumed to be the same because the extinction coefficient is wavelength independent for large particles. Our retrieved optical depths in Table 2 at three wavelengths are almost the same in the error range, and these experimental results coordinate with the scatter theory. As for the backscatter coefficient, it is still wavelength dependent for large particles, so the lidar ratio (extinction to the backscatter coefficient ratio) correlates to the cirrus cloud size distribution at different wavelengths. For 532 nm, the lidar ratio varies from 15 to 50 Sr[13]; our experimental results fall within this range.

The backscatter coefficient of cirrus clouds is determined by the shape and size distribution of cirrus clouds, the complex refractive index, and the incident wavelength. Cirrus clouds can have many different shapes[4]. Thus, the backscatter color ratio is an important parameter for cirrus clouds and reflects their shapes and size distribution information. Figure 2 indicates the backscatter color ratio profiles of cirrus clouds. $\beta_{\mathrm{c,1\,064\ nm}}/\beta_{\mathrm{c,532\ nm}}$ value is about 0.9; $\beta_{\mathrm{c,532\ nm}}/\beta_{\mathrm{c,355\ nm}}$ and $\beta_{\mathrm{c,1\,064\ nm}}/\beta_{\mathrm{c,355\ nm}}$ values are around 0.6. In other cases of our experiments (not presented in this paper), the values of backscatter color ratios differed from the presented values, suggesting that the measured cirrus clouds may have different shapes and size distributions. Still, the value 0.9 of $\beta_{\mathrm{c,1\,064\ nm}}/\beta_{\mathrm{c,532\ nm}}$ is similar to the statistical peak value 0.88 in Ref. [12]. The statistical relationship among lidar ratios, backscatter color ratios, and size distributions of cirrus cloud will be studied in detail in the future.

For very thick cirrus clouds, the laser beam cannot penetrate the entire cirrus cloud or the SNR is too small around the cloud top; thus, the retrieved method introduced in this letter is not effective. In this case, by calibrating the lidar signal, we use the attenuated backscatter color ratio to approximate the backscatter color ratio[12].

In conclusion, our lidar system can measure cirrus cloud backscatter signals at 355-, 532-, and 1 064-nm wavelengths simultaneously. Using suitable inversion methods, the optical depth, lidar ratio, and backscatter color ratio of cirrus clouds can be retrieved. The case study demonstrated that the optical depths of cirrus clouds are not dependent on wavelengths whereas the backscatter color ratios are.

This work was supported by the National Natural Science Foundation of China under Grant Nos. 40975010 and 41075016.

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