ON THE RESTORATION OF PROFILES OF SOME OPTICAL PARAMETERS OF CIRRUS CLOUDS USING LIDAR TECHNIQUES

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A lidar technique for determining the backscattering and extinction coefficients of cirrus clouds is discussed. The technique requires lidar return and cloud transmission measurements. The cloud transmission is determined using Raman lidar returns from N_2 molecules from layers above and below the cloud.

Determination of the spatial distribution of optical characteristics of cirrus clouds from lidar data is of definite importance for studies of this type of cloud including their microstructure.

Typical values of the extinction coefficient β_t of cirrus clouds do not exceed $2.5.10^{-3}$ m^{-1} (Ref. 5). The values of the backscattering coefficient are normally between 10^{-5} and 10^{-4} $m^{-1}sr^{-1}$ at the same time that the backscattering coefficients for the atmosphere at heights of 6 to 12 km usually vary from 10^{-6} to 43.10^{-6} $m^{-1}sr^{-1}$. Cirrus clouds are usually regarded as semitransparent clouds, with a thickness of no more than 2 km and an optical depth of about 2 (Ref. 2). The analysis made using these values of the optical parameters shows that it is possible to record the lidar return through the entire cirrus cloud and obtain signals from clear atmosphere the cloud.

The technique proposed in this paper assumes that measurements of the extinction coefficient in cirrus clouds are made using lidar return profiles within clouds and that the total attenuation of radiation is assessed using Raman lidar signals from molecular nitrogen received from the layers just above and below the cloud.

The lidar return signal is described by the so-called lidar equation

$$S(z) = Az^{-2}\beta_\pi(z)\exp\left(-2\int_0^z \beta_t(z')dz'\right) \quad (1)$$

$S(z)$ is the optical energy received from an elementary volume at the distance z, A is the instrumental constant, $\beta_\pi = \beta_s$, γ_π is the volume backscattering coefficient, $\beta_s(z)$ and $\beta_t(z)$ are the volume scattering and extinction coefficients, respectively, and $\gamma_\pi(z)$ is the scattering phase function for backward direction (scattering angle π).

Normally it is assumed that in the visual range $\beta_s(z) = \beta_t(z)$. Then Eq. (1) takes the form

$$S(z) = A\, z^{-2}\gamma_\pi(z)\ \beta_s(z)\exp(-2k\int_0^z\beta_s(z')dz') \quad (2)$$

Since a direct solution of Eq. (2) with respect to $\beta_s(z)$ requires an absolute lidar calibration, in order to determine the constant A, we suggest the use of a modified technique of successive layers to solve it. This procedure only requires the knowledge of the signal ratios from two adjacent layers along the sounding path. It also assumes weak changes of the scattering phase function γ_π along the path, i.e.,

$$\gamma_\pi\ (\Delta z_i) \cong \gamma_\pi(\Delta z_{i+1}) \text{ and } \beta_s(\Delta z_i) = \beta_t(\Delta z_i), \quad (3)$$

where $i = 1, \ldots, N$ is the number of the range increments the path is divided into within the cloud. As a result one obtains the following recurrence formulas for the $\beta_s(\Delta z_i)$ values[4]

$$\beta\ (\Delta z_{i+1})\ T^2(\Delta z_i) \times \frac{S(\Delta z_{i+1})}{S(\Delta z_i)}, \quad (4)$$

where

$$T^2(\Delta z_i) = \exp(-2\beta_s(\Delta z_i)\times\Delta z_i)$$

However, additional information on $\beta_s(\Delta z_i)$ is required to solve Eq. (4) relative to $\beta_s(\Delta z_i)$. This information can be obtained, at least during nighttime, with a Raman lidar from the ratio of the Raman lidar returns received from below and above the cloud. In the case of nitrogen molecules excited by laser radiation at $\lambda = 532$ nm the vibrational Raman line is shifted to $\lambda_{HORam} = 605$ nm. Since the altitude distribution of N_2 molecules is a well-known function with no strong fluctuations, the ratio of two Raman lidar returns recorded in two spatial gates Δz at two heights z_1 and z_2 is also a known function, $F(\Delta z,\ z_1,\ z_2)$, under clear atmospheric conditions. The presence of a cloud layer between the altitudes z_1 and z_2 will change this relationship by a factor of T^2, where T is the cloud's transmission at the Raman wavelength, i.e.

$$F\ (\Delta z, z_1, z_2) = T^2F\ (\Delta z, z_1, z_2) \quad (5)$$

A somewhat more complicated relationship can be obtained for the cloud transmission T, when using the Raman lidar return profiles above and below the cloud.

Discussed below is an algorithm for restoring the profile of $\beta_s(z)$ from lidar data, provided the signal profile $S(z)$ and the cloud transmission T are determined using the above-discussed technique.

First, the value $\beta_s(\Delta z_k)$ is selected, where z_k is the altitude of the cloud layer near its top. The choice of the upper cloud layer provides better stability of the successive layers method according to Ref. 3.

Then, the profile $\beta_s(\Delta z_i)$, $i = 1, \ldots, N$, is calculated using iteration formulas (4).

The calculated optical depth of the cloud $\tau = \sum_i \beta_s(\Delta z_i)\Delta z_i$ is then compared with the logarithm of the measured value of T.

$$\tau = -\ln T \tag{6}$$

The aforesaid steps of the algorithm are reiterated until condition (6) is fulfilled within preset accuracy limits.

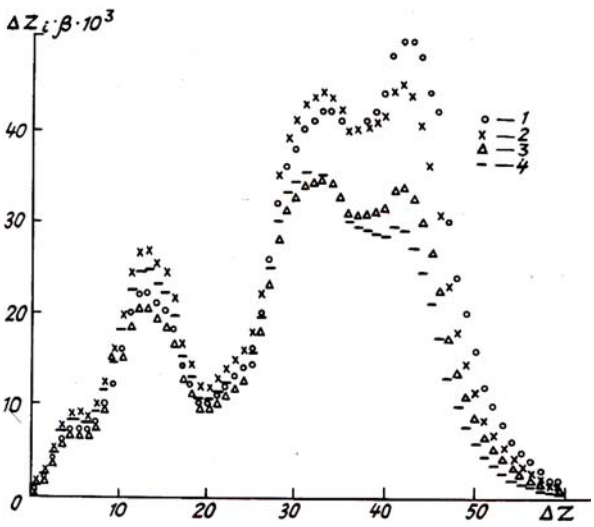

FIG. 1. Calculational results demonstrating the influence of variations of the backscattering phase function and uncertainties in the optical depth on the accuracy of restoration $\beta_s(z)\Delta z$ within a cirrus cloud. Curve 1 is a preset profile at $\tau = 1.3$. Curve 2 is the restored profile at $\tau = 1.3$ with γ varying linearly from 0.03 to 0.07. Curve 3 is the restored profile at $\tau = 1.0$ for γ = const, and curve 4 is the profile of $\beta_s(z)\Delta z$ calculated for $\tau = 1$ and γ from 0.03 to 0.07. The cloud was divided into 60 intervals (arbitrary length units).

Reconstructed profiles of β_s obtained by the above method are presented in Fig. 1. Curve 1 in this figure represents a preset profile of $\beta_s(z)$ within a cloud of an optical depth $\tau = 1.3$. The profile of $\beta_s(z)$ was chosen for these calculations in the form of a step function with 60 steps. The horizontal axis in the figure represents the range within the cloud in arbitrary units. The ordinate axis presents the values $\beta_s(\Delta z_i) \times 10^3$, where Δz_i is the range increment. Using this preset profile of β_s, we calculated the profiles of lidar return signals for the cases of constant backscattering phase function and for those in which it varied linearly from 0.07 to 0.03. The thusly calculated lidar return signals were then used for restore the profiles of $\beta_s(z)$ using the above-discussed technique. Curve 2 in Fig. 1 represents the $\beta_s(z)$ profile restored using a linearly varying backscattering phase function, and $\tau = 1.3$. Curves 3 and 4 represent the $\beta_s(z)$ profiles calculated at $\tau = 1$. In other words, it is assumed that the error in setting the value of τ is 30%.

Comparison of the calculated profiles $\beta_s(\Delta z_i)$ and the preset one showed that variations of the backscattering phase function only slightly affect the accuracy of restoration. Thus a more than doubling of the backscattering phase function in the linearly varying model produces only a 10% uncertainty in the restoration of β_s restoration at the upper boundary of the cloud. Uncertainties in the optical depth τ have a greater effect on the accuracy of restoration. But nevertheless even in the worst case, for a 30% error in τ and the varying backscattering phase function[6,7], allows it is possible to obtain more or less reasonable agreement between preset and restored profiles within the greater part of the cloud. It should be noted that the values of τ chosen for the above calculations are too large for cirrus clouds. At low values of τ the restoration uncertainties are decreased. Thus for $\tau = 0.13$ the calculations show that the discrepancy between the restored and preset $\beta_s(z)$ profiles does not exceed several per cent.

This technique has been used for processing the data from field lidar measurements. The lidar facility used in the experiments had the following parameters. The energy of the pulse emitted by a Nd-glass laser was about 1.5 J at the second harmonic. The beam divergence was 3 mrad. The 0.5-m diam telescope used as the receiver had a 3-mrad field of view. Figure 2 presents an example of a scattering coefficient profile restored from lidar data obtained during a complex experiment which studied cirrus clouds over Zvenigorod.

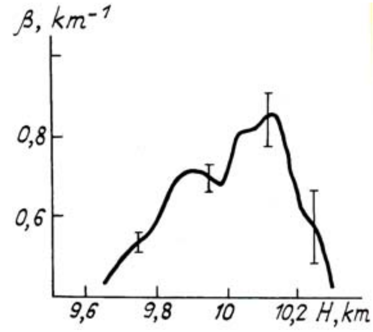

FIG. 2. Altitude behavior of $\beta_s(H)$ within a cirrus cloud, the cloud optical depth $\tau = 0.34 \pm 0.07$. The data were obtained on May 29, 1986 from 1.05 to 1.15 (local time).

Thus the proposed method of lidar sensing of cirrus clouds allows one to restore optical parameter profiles within cirrus clouds using a simple algorithm based on the use of experimental data only.

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