O-6-03

ミー散乱ライダー信号における多重散乱効果の反復修正法

Iterative correction of multiple scattering effects in Mie-scattering lidar signals

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Abstract. Backscattered signal received by lidar systems contains both single and multiple scattering components. In ordinary lidar inversion techniques that employ Klett or Fernald method, only the single scattering effect is considered. This paper presents an iteration procedure for obtaining the extinction coefficient from lidar signal. This method, which is based on the single-scattering solution of the lidar equation, describes the multiple-scattering effect by introducing a multiple-scattering factor. The iteration is applied to examine the multiple-scattering effects of lidar signals from aerosols and clouds.

Introduction

When laser light encounters particulates in its path both single and multiple scattering occur. The backscattered signals received from a lidar system depend mostly on the optical properties of the scatterers. Lidar signals can be resolved into two components namely, the single-scattered $P_S(R)$ and the multiple-scattered signals $P_M(R)$. Thus, the total lidar signal can be written as $P_T(R) = P_S(R) + P_M(R)$ assuming pulse stretching due to multiple scattering is negligible.

The single-scattered signal $P_S(R)$ can be written as $P_S(R) = K\beta(R)T_S^2(R)/R^2$, where K is the system constant; $\beta(R)$ is the backscattering coefficient; $T_S(R) = \int_0^R a(R')dR'$ is the transmittance; and $a(R)$ is the extinction coefficient. Since both $a(R)$ and $\beta(R)$ are unknown, the ratio $S_1 = a(R)/\beta(R)$ is conventionally assumed and treated as constant. The multiple scattering effects are considered by introducing the ratio MSS(R) to the single scattering equation. Thus, the multiple-scattering equation becomes $P_M(R) = P_S(R)*MSS(R)$. Substituting this to the total scattering equation and using the single scattering equation, the total scattering equation will have the form $P_T(R) = K\beta(R)M(R)T_S^2(R)/R^2$ where $M(R) = 1 + MSS(R) \geq 1$. In this simulation, it is assumed that the contribution due to noise is insignificant.

The iteration procedure

I. One-component Atmosphere

Table 1 below shows the parameters used in the numerical simulation. Initially, the extinction coefficient is derived using Klett's inversion procedure. The total extinction coefficient has the form $a_T(R) = \dfrac{\exp[X_T(R) - X_T(R_c)]}{a(R_c)^{-1} + 2\int_R^{R_c} \exp[X_T(R') - X_T(R_c')]dR'}$ where $X_T(R) = \ln[P_T(R)R^2]$.

The boundary value is taken from U.S. Standard Atmosphere. The total extinction coefficient, $a_T(R)$, correspond to the extinction coefficient profiles acquired without multiple scattering consideration. The extinction coefficient profile for the single scattering case has the form

$$a_S(R) = \frac{\frac{M(R_c)}{M(R)}\exp\left[X_T(R) - X_T(R_c)\right]}{a(R_c)^{-1} + 2\int_R^{R_c} \frac{M(R_c)}{M(R)}\exp\left[X_T(R') - X_T(R_c')\right]dR'}$$

. The difference between the two solutions is used to assess the convergence of the iteration, i.e., $e_t = \frac{|t_S - t_T|}{t_S}$, where $t_S = \int_{R_1}^{R_2} a_S(R')dR'$ and $t_T = \int_{R_1}^{R_2} a_T(R')dR'$ are the optical thickness for both single and total scattering. R_1 and R_2 are the minimum and maximum lidar observed ranges.

Table 1. Parameters used in the numerical simulation

Wavelength	532nm
FOV	3 and 6 mrad
Type of lidar configuration	Coaxial
Elevation Angle	90°
Aerosol model:	Urban Aerosol
S1	30
N_1, N_2	0.999875, 0.000125 cm^{-3}
r_1, r_2	0.03, 0.50 μm
$\log\rho_1$, $\log\rho_2$	0.35, 0.4
m	1.53-0.006i
Cloud Model:	C1 cloud model
γ, ζ, a, b	1, 3.0, 2.604, 0.4
m	1.33-0.0i
S1	18
Visibility	20 – 50 km

A lookup table is constructed to describe the variation of M(R), t_T and e_t on the extinction coefficients.

The first step of the iteration procedure is to calculate the extinction coefficient, $a_S^{(0)}(R)$, from the observed signal, $P_T(R)$. The optical depth $t_S^{(0)}$ is then obtained as a first guess. Since no multiple scattering effects are considered yet, $t_S^{(0)}$ is considered as $t_T^{(0)}$. The extinction coefficient profile $a_S^{(0)}(R)$ is divided into several regions, each of which is characterized by a relatively homogenous value of $a_S^{(0)}(R)$. Then, the multiple-scattering ratio $M^{(0)}(R)$ of each region is calculated by means for Monte Carlo Method. After this step, $a_S^{(1)}(R)$ is calculated using the equation

$$a_S^{(1)}(R) = \frac{\frac{M^{(0)}(R_c)}{M^{(0)}(R)}\exp\left[X_S^{(0)}(R) - X_S^{(0)}(R_c)\right]}{a(R_c)^{-1} + 2\int_R^{R_c} \frac{M^{(0)}(R_c)}{M^{(0)}(R)}\exp\left[X_S^{(0)}(R') - X_S^{(0)}(R_c')\right]dR'}$$

. The purpose of this step is to correct $a_S^{(0)}(R)$ by means of $M^{(0)}(R)$. Mathematically, the procedure can be summarized as $a_S^{(0)}(R) = I^{(i-1)}[P_T(R)]$, where I denotes an inversion procedure with a multiple-scattering ratio $M^{(i-1)}(R)$ as a correction factor. The iteration is terminated until $e_t^{(i)} \le 0.001$, $(i = 1,2,3,...)$ is fulfilled. The interpolated MSS values are divided by a number D (10-100) to prevent computational instabilities.

II. Two-component Atmosphere

For a two-component atmosphere, the single scattering lidar equation has the form $P_S(R) = K\left[\beta_S^a(R) + \beta_S^m(R)\right]T_S^{a^2}(R)T_S^{m^2}(R)/R^2$, where a, m and s refer to Mie, molecular and single scattering, respectively. The multiple scattering signals can be expressed as $P_M(R) = K\left[\beta_S^a(R)MSS^a(R) + \beta_S^m(R)MSS^m(R)\right]T_S^{a^2}(R)T_S^{m^2}(R)/R^2$.

From the two equations, the total scattering signal $P_T(R) = P_S(R) + P_M(R)$ is written as $P_T(R) = K\left[\beta_S^a(R)M^a(R) + \beta_S^m(R)M^m(R)\right]\exp\left(-2\int_0^R\left[\alpha_S^a(R') + \alpha_S^m(R')\right]dR'\right)/R^2$. Thus, the total extinction coefficient has the expression

$$\alpha_T^a(R) = -\frac{S_1(R)\alpha^m(R)}{S_2(R)} + \frac{S_1(R)X_T(R)\exp[I(R)]}{\dfrac{X_T(R_c)}{\dfrac{\alpha^a(R_c)}{S_1(R_c)} + \dfrac{\alpha^m(R_c)}{S_2(R)}} + J(R)},$$

where $X_T(R) = \ln\left[P_T(R)R^2\right]$, $I(R) = 2\int_R^{R_c}\left[\frac{S_1(R')}{S_2(R')} - 1\right]\alpha^m(R')dR'$ and $J(R) = 2\int_R^{R_c} S_1(R')X_T(R')\exp\left[I(R')\right]dR'$. Here, S_1=8.52sr.

In the iteration that follows, the method of obtaining the single-scattering extinction coefficient is

$$\alpha_S^a(R) = -\frac{S_1(R)\alpha^m(R)M^m(R)}{S_2(R)M^a(R)} + \frac{S_1(R)X_T(R)\exp\left[K'(R)\right]/M^a(R)}{\dfrac{X_T(R_c)}{\dfrac{\alpha^a(R_c)M^a(R_c)}{S_1(R_c)} + \dfrac{\alpha^m(R_c)M^m(R_c)}{S_2(R)}} + L(R)},$$

where the variables $K'(R)$ and $L(R)$ have the forms $K'(R) = 2\int_R^{R_c}\left[\frac{S_1(R')M^m(R')}{S_2(R')M^a(R')} - 1\right]\alpha^m(R')dR'$ and $L(R) = 2\int_R^{R_c}\frac{S_1(R')}{M^a(R')}X_T(R')\exp\left[K'(R')\right]dR'$. The iteration procedure mentioned in the previous section can then be utilized using the equation for $\alpha_S^a(R)$.

Results and Discussion

Figure 1 shows a 532 nm signal taken from a multi-wavelength lidar system at Chiba University on April 3, 1998. Low cloud appears at around 1.35-1.55 km with a geometrical thickness of about 0.2 km. The complete overlap between the laser beam and the telescope FOV is at 450 m for a FOV of 3 mrad. Below this altitude, the extinction coefficient is assumed to be equal to the value at the overlap region. Below and above the cloud, we assume S_1=30 sr and within the cloud, S_1=18 sr. Figure 2 shows the differences between retrieved extinction coefficient profiles when the iteration was applied to both Klett and Fernald methods. From both graphs, the iterative method gives a higher extinction coefficient values below the cloud and lower values inside the cloud.

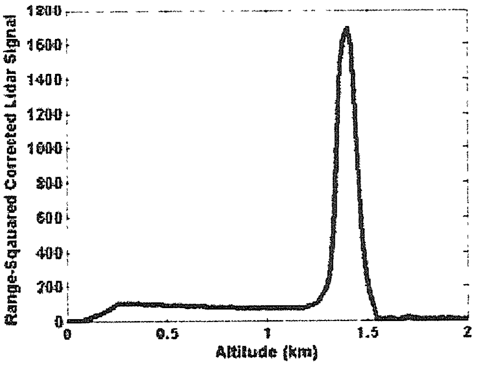

Figure 1. Lidar Signal

The estimated value of the optical thickness due to the single component atmosphere τ_S is about 0.95 (ε_τ=6.3%) and 1.4 (ε_τ=10.4%) for two-component atmosphere. Above the cloud, no significant differences between Klett or Fernald method and the final profile exist. Below the cloud, the error increases as the distance increases downward from the cloud. Inside the cloud, the error is found to increase with the penetration depth of the laser beam. This is due to the increase in the multiple-scattering ratio, leading to the decrease of the extinction coefficient.

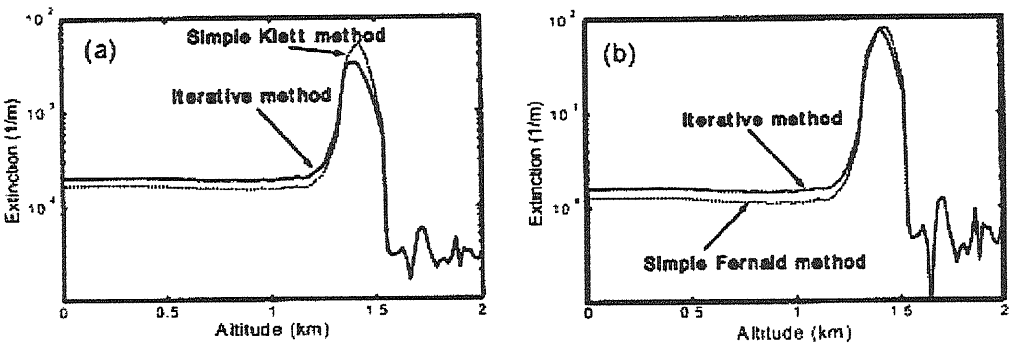

Figure 2. The extinction coefficient profiles derived from a.) Klett and b.) Fernald methods using the iteration procedure.

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