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Iteration method for the inversion of simulated multiwavelength lidar signals to determine aerosol size distribution

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A new method is proposed to derive the size distribution of aerosol from the simulated multiwavelength lidar extinction coefficients. The basis for this iteration is to consider the extinction efficiency factor of particles as a set of weighting function covering the entire radius region of a distribution. The weighting functions are calculated exactly from Mie theory. This method extends the inversion region by subtracting some extinction coefficient. The radius range of simulated size distribution is 0.1–10.0μm, the inversion radius range is 0.1–2.0μm, but the inverted size distributions are in good agreement with the simulated one.

Keywords: inversion, iteration, extinction coefficient, size distribution
PACC: 8270R, 7820D

1. Introduction

Atmospheric aerosols play an important role in the radiation effects of the Earth–atmosphere system through scattering and absorption of incoming Solar radiation, and aerosols in our planetary boundary layer have some relations with human health. Size distribution is a basic factor governing the physical, chemical, and optical properties of aerosols. Thus scientists have developed a number of methods to determine this characteristic. Some researchers have retrieved size distribution from spectral attenuation measurements.[1−3] Some have retrieved size distribution from scattering measurements.[4,5] Others have retrieved size distribution from multiwavelength lidar signals [6,7] and from a mixture [8,9] of lidar, sunphotometer and aureolemeter. As for inversion methods, an iteration, a matrix algorithm, a mixture of matrix with iteration, etc, are all used. Wolfson [10] has given a summary.

The extinction coefficient is not only used in the atmospheric field but also in other fields.[11] So the extinction coefficient is an important parameter, which can be calculated from the extinction efficiency factor. According to the properties of the extinction efficiency factor $Q(r,\lambda)$, if one wants to derive a broad radius region of size distribution, one must have a broad range of laser wavelengths. However, it is very difficult to acquire lasers having so wide a range of wavelengths.

In this paper, the iteration method devised by Grassl [2] is developed. In Section 2 the proposed method is presented; in Section 3 simulated multiwavelength lidar signals are used to test this method; and some discussions are given in Section 4.

2. Iteration method

Based on Mie theory, the extinction efficiency factor $Q(r,\lambda)$ depends on r (radius of a particle), λ (wavelength), m^* (refractive index of the particle). Figure 1 shows $Q(r,\lambda)$ as a function of r (where λ is a parameter that can take values of 355, 683, 1064, 1389, 1907nm, and m^* is assumed to be a constant). At the left of the curves, the value of $Q(r,\lambda)$ increases with increasing r. At the right of the curves, the value of $Q(r,\lambda)$ approximately equals 2. In the middle there are some interference structures and ripple structures.

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For a fixed wavelength, the first maximum value with increasing r is also the absolute maximum.

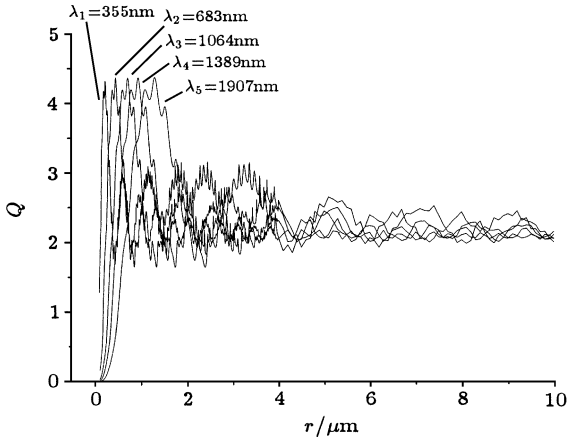


Fig.1. Extinction efficiency versus radius of the particle for different wavelengths.

The aerosol volume coefficient α_λ is defined by

$$\alpha_\lambda = \pi \int_0^\infty Q(r,\lambda) n(r) r^2 \mathrm{d}r, \qquad (1)$$

where $n(r)$ which is called the size distribution is the aerosol number density in the radius range between r and $r+\mathrm{d}r$. In the expression of α_λ, $Q(r,\lambda)$ curves can be called weighting functions for the function $n(r)r^2$. Although the limit of integration in Eq.(1) varies from 0 to ∞, the size distribution lies in fact within a limited radius range from r_a to r_b, while r_a and r_b are determined by the kind of the aerosol (for example, the typical range is from 0.1–10.0μm). So Eq.(1) becomes

$$\alpha_\lambda = \pi \int_{r_a}^{r_b} Q(r,\lambda) n(r) r^2 \mathrm{d}r. \qquad (2)$$

In the iteration inversion method, the range from r_a to r_b is divided into N (N equals the number of lidar wavelengths) intervals. Each interval corresponds to the first maximum of a $Q(r,\lambda_j)$ curve. In each radius interval, $n(r)$ is considered constant instead of variable, i.e. we use a histogram to replace the curve of $n(r)$. Then Eq.(1) further becomes

$$\alpha_{\lambda_j} = \pi \sum_{i=1}^{N} n_i \int_{r_i}^{r_{i+1}} Q(r,\lambda_j) r^2 \mathrm{d}r, \quad j = 1,\cdots,N. \qquad (3)$$

Based on Eq.(3), we invert the size distribution. The following iteration procedure makes use of the property of $Q(r,\lambda_j)$. Firstly, we assume that the extinction coefficient for a wavelength is only caused by particles from the radius interval corresponding to the maximum of the associated weighting function, and then according to Eq.(3) we calculate the zeroth-order size distribution n_{0i} ($i = 1,\cdots,N$). Secondly, using zeroth-order n_{0i}, the calculated extinction coefficient $\alpha'_{\lambda j}$ is obtained by use of Eq.(3) again. We then use the following iterative formula (Eq.(4)) to compute the first-order n_{1i}:

$$n_{1i} = (\alpha_{\lambda i}/\alpha'_{\lambda i}) n_{0i}, \quad i = 1,\cdots,N. \qquad (4)$$

The second procedure is to iterate M times until $|\alpha_{\lambda i} - \alpha'_{\lambda i}|$ is smaller than the expected error of the measured extinction coefficient. Finally, n_{Mi} is the size distribution we obtain.

Because the available lidar wavelengths are limited for measuring the aerosol extinction coefficient, especially in the infrared region, it is difficult for the radius range corresponding to the first maxima of $Q(r,\lambda)$ of the limited wavelengths to cover the radius range of $n(r)$. Thus the first step of the iteration method can be hardly carried out (for example, for wavelengths 355, 683, 1064, 1389 and 1907nm, the radius range corresponding to the first maxima of $Q(r,\lambda)$ is about 0.12–2.0μm which is regarded as the range $(r_a - r'_b)$; however, the range of $n(r)$ is usually from 0.1–10.0μm which is regarded as the range $(r_a - r_b)$). In order to overcome this difficulty, we invert the size distribution within the range $(r_a - r'_b)$ of the maxima of $Q(r,\lambda_)$, while we subtract some extinction coefficients that come from the contribution of the surplus range $(r'_b - r_b)$. The subtraction procedure is as follows:

(a) Within the range $(r_a - r'_b)$, for example 0.1–2.0μm, we gain the size distribution histogram.

(b) We extend the size distribution histogram to the range $(r'_b - r_b)$, for example 2.0–10.0μm, and calculate the extinction coefficient α''_λ within the range $(r'_b - r_b)$.

(c) Taking the value of $(\alpha_\lambda - \alpha''_\lambda)$ as the measured extinction coefficient, we invert the size distribution histogram again within the range $(r_a - r'_b)$.

(d) Steps (b) and (c) are repeated until the difference between the last two $(\alpha_\lambda - \alpha''_\lambda)$ is smaller than an assumed value. The last size distribution histogram is the one we want to obtain.

3. Simulation test

The simulated multiwavelength lidar signals are used to test the iteration method. We use the following model size distributions:

(1) $n_1(r) = 0.2r^{-3}$,

(2) $n_2(r) = 0.2r^{-4}$,

(3) $n_3(r) = 0.2r^{-5}$,
(4) $n_4(r) = 5.0 \times 10^4 \cdot r \cdot \exp(-9.0\sqrt{r})$,

within the radius region of 0.1–10.0μm. The simulated extinction coefficients are given in Table 1.

Table 1. Simulated extinction coefficients (in radius region 0.1—10.0μm).

Wavelength/μm	Extinct. coeff. distribution (1)/cm^{-1}	Extinct. coeff. distribution (2)/cm^{-1}	Extinct. coeff. distribution (3)/cm^{-1}	Extinct. coeff. distribution (4)/cm^{-1}
0.355	7.152669	17.310223	85.679858	90.677851
0.683	6.487308	10.256824	32.663535	98.392401
1.064	5.911199	6.672499	14.580431	97.736616
1.389	5.560696	5.100914	8.745341	91.751130
1.907	5.125566	3.684520	4.703685	78.035283

Within the region 0.1–2.0μm, using the above method we have inverted the size distribution. The inverted size distribution is shown in Fig.2, this distribution is in good agreement with the stimulated one.

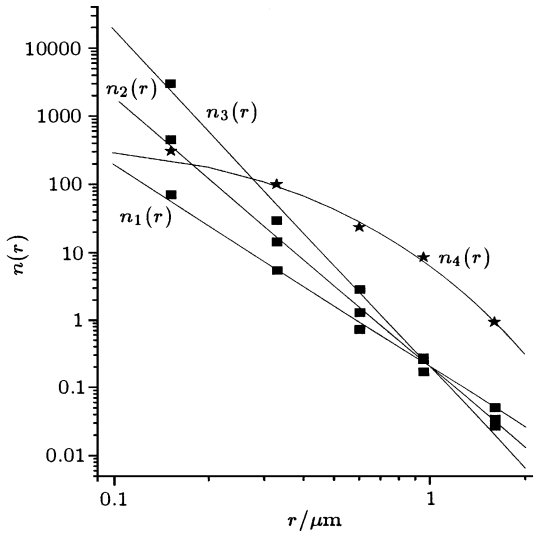


Fig.2. Comparison of iterated and simulated size distributions. The solid lines are model size distribution, and the squares and stars show the iterated values.

The stability of this method has been tested by addition of random errors to the extinction coefficients. These errors result in an increasing deviation from the distribution iterated with the exact value of the extinction coefficient, but they do not influence the convergence. Addition of great errors of 5% rms result in an increasing variation of size distribution, and the iteration converges to a size distribution in which the summed deviation is also increasing. This result is the same as that in Ref.[2].

4. Conclusion and discussion

We have developed an iteration method that can use limited lidar wavelengths to effectively invert the broad radius region size distribution. This technique consists of subtracting some extinction coefficients beyond the range that corresponds to the first maximum range of $Q(r, \lambda)$ of all the lidar wavelengths. The simulation test shows that this method is feasible.

In the inversion process, the retrieved size distribution depends on radius interval boundaries. If the radius interval boundaries are not suitable, they will cause greater deviation of the size distribution. The greater the number of multiwavelengths used, the more weakly the result of iteration depends on the radius interval boundaries. For example, when we used seven wavelengths, the sensitivity to the radius interval boundaries is decreased compared with that using five wavelengths. The wavelengths used should be selected in such a way that their first maxima of $Q(r, \lambda_j)$ would be lined up neither overlapped nor gapped. In fact, it is almost impossible to carry out this way exactly because of limited lidar wavelengths, but we could do this as exactly as possible. The wavelengths we used can be gained from the Nd:YAG laser, i.e. its third harmonic and the stimulated Raman scattering pumped by it.

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