Optik 160 (2018) 283–297

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Determination of the boundary value of the aerosol extinction coefficient and its effects on the extinction coefficient profile of aerosol in lower atmosphere

Yuzhao Ma[a,b,*], Jiaqi Liu[b], Nan Chen[b], Huiliang Gao[b], Xinglong Xiong[a,b]

[a] *Tianjin Key Laboratory for Advanced Signal Processing, Civil Aviation University of China, Tianjin 300300, China*
[b] *College of Electronic Information and Automation, Civil Aviation University of China, Tianjin 300300, China*

ARTICLE INFO

Article history:
Received 6 January 2018
Accepted 30 January 2018

Keywords:
Extinction coefficient
Lidar
Jarratt's iteration
Atmospheric aerosol
Boundary value

ABSTRACT

It is known that the boundary condition is important for deriving the aerosol extinction coefficient profiles from the lidar return signals using the popular Fernald's method. However, when the lidar return signals are available only for the lower atmosphere, the determination of the boundary condition is a hard task. In this paper we propose an approach for determining the boundary value of the aerosol extinction coefficient. Starting from the lidar equation we firstly derive a nonlinear equation in terms of the boundary value of the aerosol extinction coefficient, considering the extinction coefficient of the atmosphere molecules. The equation is numerically solved using the known Jarratt's iterative method. The boundary value of the aerosol extinction coefficient is hence obtained. As numerical examples, we obtain the boundary values of the aerosol extinction coefficient and their variations for two lidar signals, considering the effects of the boundary position, aerosol extinction-to-backscattering ratio, signal power, and the extinction coefficient of the atmosphere molecules. Further, the aerosol extinction coefficient profiles are derived using the Fernald's method. Our simulation results reveal that the derived aerosol extinction coefficient profiles have good consistencies. The proposed method is efficient for determining the boundary value of the aerosol extinction coefficient that is necessary for the derivation of the aerosol extinction coefficient profiles. Our method may find applications in investigating aerosol optical properties using lidar signals.

1. Introduction

Optical properties of aerosols in the atmosphere have attracted great interests in the fields of atmospheric science and environmental science since long time. Lidars have been exploited for quite a number of applications in various fields due to its high resolution in time and space as well as high sensitivity. In particular, a lidar can be used for the determination of aerosol optical properties [1–3]. Using the well-known Fernald's approach the aerosol extinction coefficient profiles, i.e., the aerosol extinction coefficients via height, can be derived from the lidar return signals [4–6]. Following the Fernald's approach, the boundary condition, namely the boundary position and the corresponding aerosol extinction coefficient, is necessary and important for deriving the aerosol extinction coefficient profiles with high accuracy. When the lidar return

* Corresponding author at: Tianjin Key Laboratory for Advanced Signal Processing, Civil Aviation University of China, Tianjin 300300, China.
E-mail address: yzma@cauc.edu.cn (Y. Ma).

https://doi.org/10.1016/j.ijleo.2018.01.116

signals are available for the whole troposphere, the boundary condition can be easily determined. A position at the upper troposphere is used as the boundary position. The corresponding aerosol extinction coefficient is determined by assuming a backscattering ratio of a specific value [7]. The backscattering ratio is defined as the ratio of total backscattering coefficient to the molecular backscattering coefficient. The aerosol extinction coefficient at the boundary position is hence obtained because the molecular backscattering coefficient and the aerosol extinction-backscattering ratio can be usually assumed to be known.

However, the assumption of the specific backscattering ratio cannot be done for lower atmosphere where the density of the atmosphere aerosols may be larger and various. For some applications, the detection range of the lidar is only 4–6 km. Several methods have been developed to derive the extinction coefficient profiles with high accuracy for lower atmosphere. Kunz and Leeuw have invented the slope method, i.e., from a linear least-squares fit to the logarithm on the range-compensated lidar return [8]. However, the slope method was efficient only for the homogeneous atmosphere which is often not the case. Kovalev has used the variable extinction-to-backscattering ratios for determining the aerosol extinction coefficient profiles [9]. However, the boundary value of the aerosol extinction coefficient was assumed to be constant within a specific region and its accuracy was not guaranteed. Recently, Chen has derived the nonlinear equation in terms of the boundary value of the aerosol extinction coefficient from the lidar equation [10]. The aerosol extinction coefficient was obtained by numerically solving the equation using the enumerative algorithm. However, in the derivation the scattering effect of the atmosphere molecules has not been considered. In fact although the aerosol often has a larger concentration in the lower altitude, the scattering effect of the atmosphere molecules cannot always be ignored.

In the present work an approach is proposed to determine the boundary value of the aerosol extinction coefficient with high accuracy. In Section 2 the well-known Fernald's method for deriving the aerosol extinction coefficient profiles is briefly introduced. In Section 3, starting from the lidar equation, we derive a nonlinear equation in terms of the boundary value of the aerosol extinction coefficient, considering the extinction coefficient of the atmosphere molecules. The Jarratt's iterative method used for numerically solving the equation is detailed. Hence, the boundary value of the aerosol extinction coefficient can be obtained as the solution of the equation. In the 4th section, following the proposed approach we obtain the boundary values of the aerosol extinction coefficient and their variations for two lidar signals, with full consideration of the effects of the boundary position, aerosol extinction-to-backscattering ratio, signal power, and the extinction coefficient of the atmosphere molecules. The obtained boundary values of the aerosol extinction coefficient are used to derive the aerosol extinction coefficient profiles. At the end of the paper we draw the conclusions.

2. Deriving the aerosol extinction coefficient profile using the Fernald's method

A monostatic lidar measures returned power that for a nonabsorbing, elasticscattering atmosphere is governed by the lidar equation

$$P(z) = P_0 C z^{-2} \beta(z) \exp[-2 \int_0^z \sigma(z') dz'], \tag{1}$$

where $P(z)$ is the return signal from the range z, P_0 is proportional to the energy of the transmitted light, C is the lidar system constant, $\beta(z)$ is the backscattering coefficient of the atmosphere at the range z, and $\sigma(z)$ is the extinction coefficient of the atmosphere. The backscattering and extinction coefficients of the atmosphere are induced by aerosols and molecules. Therefore, $\sigma(z) = \sigma_a(z) + \sigma_m(z)$ and $\beta(z) = \beta_a(z) + \beta_m(z)$, where $\sigma_a(z)$ and $\sigma_m(z)$ are the extinction coefficients of the aerosols and molecules, respectively, and $\beta_a(z)$ and $\beta_m(z)$ are the backscattering coefficients of the aerosols and molecules, respectively.

Using the known Fernald's method, the extinction coefficient profiles of the aerosols can be derived from the lidar return signals assuming the boundary condition and the extinction-to-backscattering ratio are known. Here the boundary condition is denoted by the boundary position z_c and the corresponding aerosol extinction coefficient, $\sigma_a(z_c)$. According to the Fernald's method, the extinction coefficients of the aerosols at the range z are given by equations

$$\begin{cases} \sigma_a(z) = -S_a \sigma_m(z)/S_m + \dfrac{c(z)}{a(z_c) + b(z)} \\ a(z_c) = X(z_c)/[\sigma_a(z_c) + S_a \sigma_m(z_c)/S_m] \\ b(z) = 2 \displaystyle\int_z^{z_c} X(z) \cdot \exp \left[2(S_a/S_m - 1) \cdot \int_z^{z_c} \sigma_m(z') dz' \right] dz. \\ c(z) = X(z) \cdot \exp \left[2(S_a/S_m - 1) \cdot \displaystyle\int_z^{z_c} \sigma_m(z') dz' \right] \end{cases} \tag{2}$$