Atmospheric Environment 177 (2018) 18–27

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

On-site ocean horizontal aerosol extinction coefficient inversion under different weather conditions on the Bo-hai and Huang-hai Seas

Xianjiang Zeng, Min Xia*, Yinghui Ge, Wenping Guo, Kecheng Yang

School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China

ARTICLE INFO

Keywords:
Aerosol extinction coefficient
Lidar
Ocean-atmosphere
Remote sensing
Retrieval

In this paper, we explore the horizontal extinction characteristics under different weather conditions on the ocean surface with on-site experiments on the Bo-hai and Huang-hai Seas in the summer of 2016. An experimental lidar system is designed to collect the on-site experimental data. By aiming at the inhomogeneity and uncertainty of the horizontal aerosol in practice, a joint retrieval method is proposed to retrieve the aerosol extinction coefficients (AEC) from the raw data along the optical path. The retrieval results of both the simulated and the real signals demonstrate that the joint retrieval method is practical. Finally, the sequence observation results of the on-site experiments under different weather conditions are reported and analyzed. These results can provide the attenuation information to analyze the atmospheric aerosol characteristics on the ocean surface.

1. Introduction

Atmospheric aerosols play an important role in humans' daily life because the substances that are carried by particles pass through air, land and water; these substances can cause many effects, including changes in climate and weather, the fertilization of oceans and land, the acidification of lakes and health effects to humans (Husar et al., 2000). Horizontal atmospheric aerosol characteristics provide a direct indication of aerosol loading, which is also important for activities on the ocean surface. For example, atmospheric visibility, which is defined as the maximum distance of a clear object that can be recognized on the horizon, is an important parameter for aviation and road safety and an indicator of air quality (Lee et al., 2014). Scientifically, visibility is determined by the light extinction from aerosols and molecules in the atmosphere. Light extinction is caused by many phenomena in the atmosphere, such as scattering, absorption and turbulence. In particular, scattering, which is the product of fog, haze and low clouds, causes considerable variation in atmospheric visibility (Prokes, 2009). Providing the attenuation information along the optical path on the spot is helpful in analyzing the atmospheric aerosol characteristics.

Mie-scattering lidar is widely used to detect the aerosol extinction characteristics by improving the observation range, the spatial resolution, and measurement accuracy, and lidar can provide atmospheric profiles (Mao et al., 2015a; Wu et al., 2015; Gao et al., 2013). For example, lidar measurements were used to determine the extinction profile in the Black Sea coastal zone by Kolve et al. (Kolev et al., 2000). The statistics of the aerosol extinction coefficient profiles were obtained by lidar measurements in Lanzhou, China in X. Cao's study (Cao et al., 2013). Markowicz et al. measured the optical properties of volcanic ash using remote techniques at 4 lidar stations in Poland (Markowicz et al., 2012). In Zhao's study, vertical aerosol profile products from the *Lidar climatology of Vertical Aerosol Structure (LIVAS)* for space-based lidar simulation studies were acquired (Zhang et al., 2016). Optical properties, such as the lidar ratio, particle depolarization ratio, and Ångström exponent at 355 and 532 nm were derived from lidar measurements and were investigated by Yukari Hara in Fukuoka, Japan from January to April 2015 (Hara et al., 2017).

Retrieving the aerosol extinction coefficients from a raw lidar signal is the key problem in analyzing aerosol extinction characteristics. Horizontally, the slope method is the most commonly used method to retrieve aerosol extinction characteristics. In the 1960s, Collis proposed this method to obtain the backscatter and extinction coefficients of a homogeneous atmosphere by the intercept and the slope that are inverted from the logarithm of the range-corrected lidar signal (Collis, 1967). Gerard et al. (Kunz and De Leeuw, 1993) investigated the accuracy of the slope method. Francesc et al. achieved the inversion of the backscatter profile and the extinction-to-backscatter ratio from the pulsed elastic-backscatter lidar returns through an extended Kalman filter to overcome the intrinsic limitations of the standard straightforward non-memory procedures of the slope method (Rocadenbosch et al., 1999). However, the use of the slope method to retrieve horizontal aerosol extinction characteristics is based on two assumptions: one assumption is that the aerosol in the horizontal direction is absolutely homogeneous, and the other assumption is that either aerosol or

* Corresponding author.
E-mail address: xiamin@hust.edu.cn (M. Xia).

https://doi.org/10.1016/j.atmosenv.2018.01.006
Received 29 September 2017; Received in revised form 22 December 2017; Accepted 3 January 2018
Available online 06 January 2018

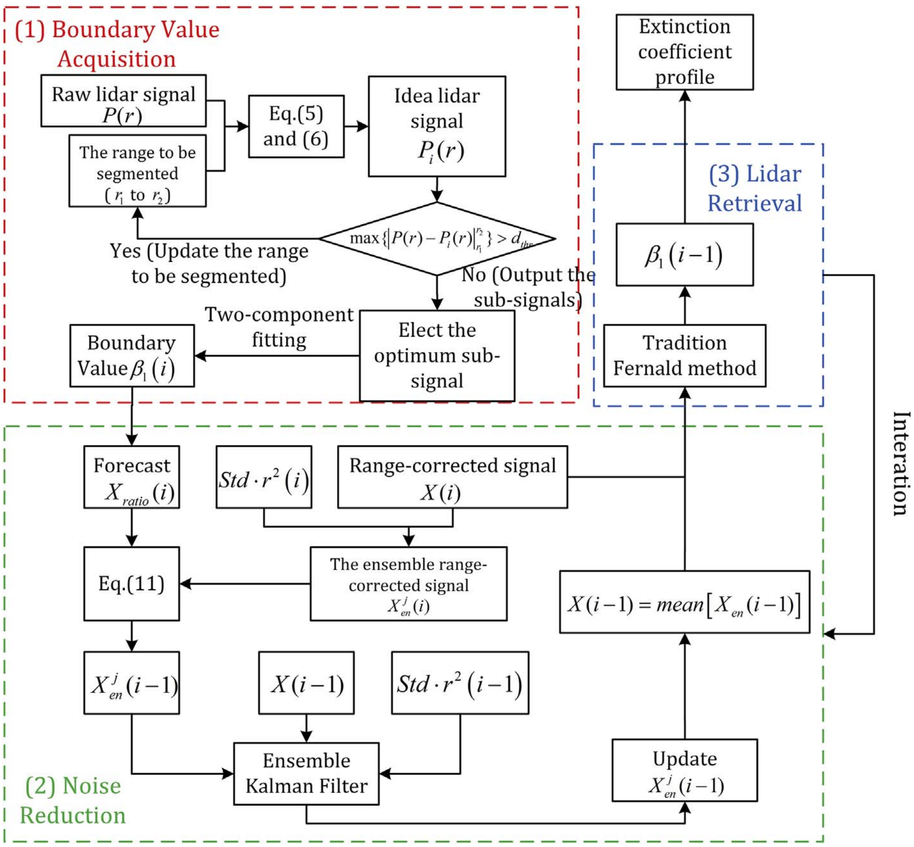

Fig. 1. The schematic of the joint retrieval method.

molecules exist in the atmosphere (Rocadenbosch et al., 2000).

In practical applications, great uncertainty may be caused by these two assumptions (Mao et al., 2015a). First, the horizontal aerosol cannot be fully homogeneous all the time (Qiu, 1988), especially under an ocean-atmosphere environment. Second, both aerosols and molecules exist in the atmosphere. To solve this problem, the method that is used in vertical aerosol retrieval can be introduced in this application because vertical aerosol is always considered to be stratified (Feiyue et al., 2012; Mao et al., 2015b). In 1981, a stable method was proposed by Klett (1981) to retrieve the extinction and backscatter coefficients in an inhomogeneous atmosphere; this method is based on the one composition model of the atmosphere. In 1984, a similar method that is based on the two-component atmosphere model was presented by Fernald (1984). The distinction between these two methods is that the Fernald method separately considers the aerosol and the molecular components, while the Klett method does not consider these components. These two methods are collectively regarded as the standard method for lidar retrieval. For a more accurate retrieval, the Fernald method is introduced to analyze the horizontal aerosol extinction characteristics because of the universality of this method. In practical applications, two issues should be considered. One issue is how to select an appropriate boundary value for the Fernald method, and the other issue is how to reduce the noise.

In this study, we explore the horizontal extinction characteristics on the ocean surface through on-site experiments on the Bo-hai and Huang-hai Seas in the summer of 2016. A self-designed Mie-scattering lidar is used to collect the field data. Next, we use a joint retrieval method that combines the original Fernald method with boundary value acquisition and noise reduction together to retrieve the aerosol extinction coefficient profiles. In Section 2, we introduce the lidar equation and the joint retrieval method. In Section 3, the on-site experimental setup is presented. In Section 4, the processes of the simulated signals and the single field data that address the joint retrieval method are reported. The on-site experimental results under different weather conditions are also presented and analyzed. The conclusion in Section 5 provides the attenuation information to analyze the atmospheric aerosol characteristics on the ocean surface.

2. Theory and processing method

2.1. Lidar equation

Mie lidar is commonly used in aerosol detection because of its relatively simple operational design. The general single-scattering Mie lidar equation (Kovalev and Eichinger, 2005) is written as

$$P(r) = \frac{C}{r^2}\cdot G(r)\cdot[\beta_1(r) + \beta_2(r)] \cdot \exp\{-2\int_0^r [\alpha_1(r) + \alpha_2(r)]dr\} + e(r) \tag{1}$$

where $P(r)$ represents the lidar signal, and r is the range. C is the lidar constant. $G(r)$ is the overlap factor, because the misalignment of the laser beam and the telescope is caused by the off-axis setting. $\beta_1(r)$ and $\beta_2(r)$ are the aerosol and molecular backscattering coefficients, respectively. $\alpha_1(r)$ is the molecular extinction coefficient, and $\alpha_2(r)$ is the aerosol extinction coefficient. $e(r)$ is the noise, which can be considered to follow a Gaussian distribution.

2.2. The joint retrieval method

To reduce the uncertainty that is caused by the inhomogeneous atmosphere in practice, the Fernald method, which is commonly used to retrieve the vertical aerosol extinction coefficients, can be applied in this study because it is appropriate for analyzing inhomogeneous aerosol. As we know, aerosol optical properties can be retrieved by the Fernald method when a boundary value is given. In vertical sounding, a reference height is usually selected to determine the boundary value by assuming that few aerosols exist. This reference height is always set above the tropopause, where the molecular backscattering coefficient is