# CORRECTION OF THE FERNALD METHOD USING REAL-TIME AVERAGE LIDAR RATIOS WITH MIE-RAYLEIGH-RAMAN LIDAR**

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*A Mie-Rayleigh-Raman lidar system was used to invert the optical properties of aerosol and determine the lidar ratio. Subsequently, the real-time lidar ratio was used to modify the Fernald method; 1167 groups of data were used to invert the aerosol lidar ratios. We determined the average aerosol lidar ratio profile, which ranged from 30 to 45 in Nanjing, China. Because the Raman signal had a low SNR (Signal Noise Ratio) and the Raman channel was only available at night, it was not possible to make the correction using a real-time lidar ratio. Therefore, an average lidar ratio was used for the correction. The hypothetical value of the lidar ratio used in the Fernald method deviates from the actual value, which can result in errors. Furthermore, large errors can be produced when clouds are present on the lidar line. The accuracy of inversion of the aerosol optical characteristics can be significantly improved by correcting the Fernald method using the real-time lidar ratio or average lidar ratio.*

***Keywords:*** *aerosol, Mie-Rayleigh-Raman Lidar, lidar ratio, Fernald method, average lidar ratio.*

# КОРРЕКЦИЯ МЕТОДА ФЕРНАЛЬДА С ИСПОЛЬЗОВАНИЕМ ПОЛУЧЕННОГО В РЕЖИМЕ РЕАЛЬНОГО ВРЕМЕНИ СРЕДНЕГО ЛИДАРНОГО ОТНОШЕНИЯ ЛИДАРА МИ-РЭЛЕЙ-РАМАНА

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*Лидар Ми-Рэлей-Рамана использован для исследования оптических характеристик аэрозоля и определения лидарного отношения путем инвертирования данных лидарного зондирования. Лидарное отношение, полученное в режиме реального времени, использовано для модификации метода Фернальда. Для инвертирования аэрозольных лидарных отношений взяты 1167 групп данных. Определен профиль среднего аэрозольного лидарного отношения в Нанкине, который варьировался от 30 до 45. Поскольку КР-сигнал имеет низкое отношение сигнал/шум, а КР-канал доступен только ночью, невозможно выполнить коррекцию с использованием лидарного отношения в реальном времени. Поэтому для коррекции использовано среднее лидарное отношение. Гипотетическое значение лидарного отношения, которое обычно используется в методе Фернальда, отличается от фактического, что может привести к ошибкам. Большие ошибки могут быть вызваны наличием облаков на лидарной трассе. Точность инверсии оптических характеристик аэрозоля может быть значительно улучшена путем коррекции метода Фернальда с использованием лидарного отношения, полученного в режиме реального времени, или среднего лидарного отношения.*

***Ключевые слова:*** *аэрозоль, лидар Ми-Рэлея-Рамана, лидарное отношение, метод Фернальда, среднее лидарное отношение.*

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**Introduction.** Aerosol pollution is having an increasingly serious impact on the atmosphere. Therefore, research relating to aerosols has become important in the field of atmospheric science. High concentrations of aerosols pose a threat to human health. In addition, aerosols can affect the weather and climate system, thus effective observation of them is important. Lidar is widely used in the measurement of aerosols because of its high temporal and spatial resolution. The Fernald method is commonly used in inversion algorithms of atmospheric optical characteristics using the Mie signal detected by the lidar. However, in the Fernald method, the optical properties of aerosols need to be calculated by assuming the lidar ratio of aerosols. When the hypothetical lidar ratio does not match the actual lidar ratio, an error occurs. Moreover, when clouds exist in the sky, the lidar ratio of clouds is significantly different from that of atmospheric aerosols. Performing the same correction for both greatly impacts the calculation outcomes. The Raman signal can be used to calculate the backscattering and extinction coefficient of the atmospheric aerosols without making assumptions. Therefore, to improve the accuracy of the Fernald method, the lidar ratio used when calculating the Fernald method can be replaced by what was obtained from the inversion of the Raman signal. The Fernald method [1] is frequently used in the analysis of aerosol optical properties. To obtain aerosol optical properties through the Fernald method, the lidar ratio must be known, which is a hypothetical value. So, when the assumed lidar ratio deviates from the actual value, or when there are clouds on the line of lidar (the lidar ratio of cloud particles is vastly different from that of normal aerosols), it may cause considerable uncertainties [2]. The Raman backscattering signal can be used alone to invert aerosol extinction profiles [3]. Combining this with the Mie signal data, an aerosol backscattering profile can be obtained [4]. To obtain the lidar ratio used in the Fernald method, we can use the Raman-Mie lidar system to measure the extinction and backscattering coefficients [5]. Compared with the assumption of using the lidar ratio, the measurement accuracy is increased. Because the Raman echo signal is very weak, the requirements for signal denoising and environmental setting are stringent. The Raman lidar can only be used at night; hence, not all Mie echo signals have correspondingly available Raman signals. Nice Raman echo signal observations between 2009 and 2015 were selected and used to calculate the average lidar ratio of the Nanjing aerosols. The average lidar ratio can then be used in the Fernald method. We selected good Raman signal data between 2009 and 2015 to calculate the average lidar ratio in the northern suburbs of Nanjing; we used these results to correct the Fernald method.

**Mie-Fernald method.** The Fernald method is one of the most common methods for retrieving aerosol properties using Mie scattering echoes [1]. In the Fernald method, the molecular atmospheric scattering properties can be determined from the best available meteorological data or approximated from appropriate standard atmospheres. However, the lidar ratio of aerosols is always an assumed value. This means that the lidar ratio of aerosols on the lidar line is constant with the range; hence, the radius, shape, and chemical constituents of the particles are the same on the lidar line [2]. In this hypothesis, the type of aerosol was determined before retrieval, and only one type of aerosol exists on the lidar line. The constituent of aerosols in the real atmosphere is very complicated; aerosols are often mixed by particles of different properties and there are several types of aerosol present at different altitudes. Considerable uncertainties maybe introduced if an assumed constant is used as the lidar ratio for retrieval.

**Measurements with Raman-Mie lidar.** The properties of aerosols can also be retrieved by the Raman echo signal [3]. Aerosol extinction profiles can only be retrieved by Raman backscattering signals. The air density and Rayleigh scattering coefficients are determined from actual radiosonde data of temperature and pressure (if available), or from a standard atmosphere model that fits to the measured ground-level temperatures. The aerosol backscattering coefficient profile can be obtained by combining the Mie data and the aerosol extinction coefficient profile. Because of the fewer hypotheses, the precision of measurement can be improved compared with the Mie-Fernald method. The Raman scattering echo signal is greater by two orders of magnitude than that of the Rayleigh scattering echo. Furthermore, its signal-to-noise ratio (SNR) is sensitive to atmosphere background noise [6]. For this reason, the signals must be properly denoised or else significant statistical errors can occur. Without proper denoising, we cannot produce effective aerosol profiles.

Figure 1a shows the aerosol extinction coefficient profile determined from the original Raman echo signal (without denoising), observed at 20:02 local time on April 17, 2011. At lower altitudes, the signals are large enough and the profiles below 4 km are smooth. With the extinction of aerosols, signals detected above 4 km are few; the SNR is too low to retrieve the profile well. The Raman echo signal should have proper denoising performed to accurately invert the optical properties of aerosols. Three-point smoothing performs well in Mie signal denoising, but not for Raman signals. To improve the SNR, wavelet denoising is used to process the Raman signal. The curved graphs of the original and wavelet-denoising signals are shown in Fig. 1b.

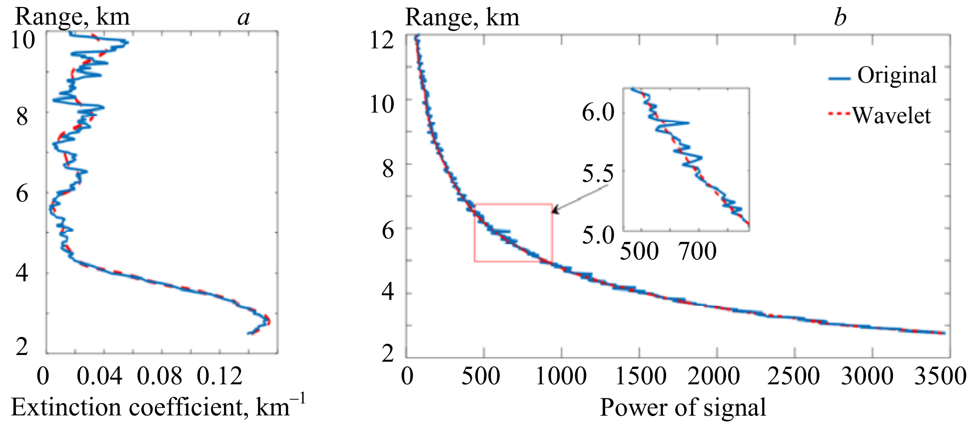


Fig. 1. (a) Extinction coefficient retrieved from the original signal and wavelet denoising signal; (b) original signal contrast with wavelet denoising signal.

Compared with the original signal, the wavelet-denoising signal is smoother. Regarding wavelet denoising, the aerosol information in the original signal is preserved, while noise filtering and the SNR increases significantly. Figure 1a shows the aerosol extinction coefficient profile retrieved from the original signal and the wavelet-denoising signal. Compared with the profile retrieved from the original signal, the extinction coefficient profile retrieved from the wavelet denoising is smoother and more accurate; aerosol optical properties were well presented.

**Lidar ratio.** By combining the wavelet-denoising Raman signal and Mie data, the aerosol extinction and backscattering coefficient profiles can be acquired accurately and independently, after which the lidar ratio can be obtained. The results of four measurements of lidar ratio profiles are shown in Fig. 2a. The date, time, and weather conditions of the measurements 1, 2, 3, and 4 are April 26, 2011, at 21:01 (cloudy); March 27, 2012, at 19:38 (fine); March 27, 2012, at 19:41 (fine), and March 28, 2012, at 20:37 (fine), respectively. The lidar ratio varies with height, with the values varying from 10 to 40. Because of the enormous difference in measurement time, there is a large discrepancy between profile 1 and profiles 2, 3, and 4. Although the trends pertaining to profiles 2, 3, and 4 are similar, the small deviations of the measurement times between them leads to some deviation between their profiles. Therefore, it is not reasonable to assume that the lidar ratio is a constant that can invert the aerosol optical properties. Figure 3 shows the aerosol extinction coefficient profiles of the four measurements; some clouds are present below 4.5 km in measurement 1, and the lidar ratio of the cloud particles is smaller than that of the aerosols [7]. For this reason, a lidar ratio below 4.5 km should be smaller than when above 4.5 km, which corresponds to the lidar ratio profile in Fig. 2a. As Fig. 3 shows, in measurements 2, 3, and 4, there are fewer clouds at 2.5-3.0 and 3.5-4.5 km compared with other regions. The lidar ratio profiles in Fig. 2a present two peak value areas at the corresponding region; it also corresponds to the aerosol distribution.

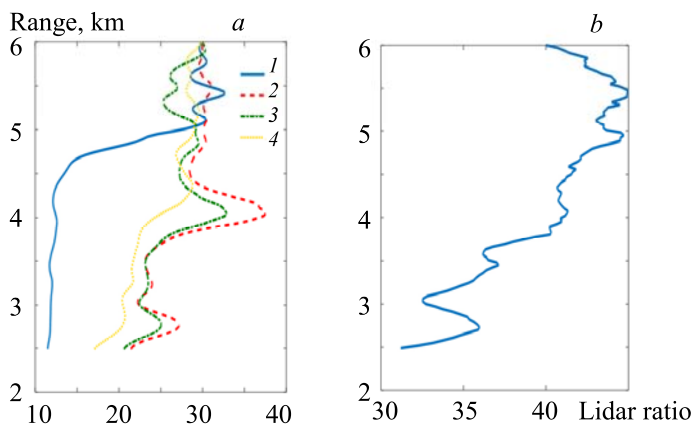


Fig. 2. The lidar ratio profiles of four measurements of lidar ratio (a) and the average lidar ratio profile of Nanjing (b).

**Result and discussion.** *Fernald method correction of the real-time lidar ratio.* The real-time lidar ratio profiles are determined from the real-time Raman echo signal and can be used to correct the Fernald method in order to improve measurement accuracy. Using the data from the four measurements (measurement 1 – March 31, 2011, at 19:38 (fine Weather), measurement 2 – April 17, 2011, at 19:54 (cloudy), measurement 3 – April 26, 2011, at 21:01 (cloudy), and measurement 4 – September 15,2011, at 20:29 (cloudy)), the extinction coefficient profiles were retrieved by the Mie Fernald method before correction. The Mie Fernald method obtained after the correction and Raman echo signal are shown in Fig. 3; the lidar ratio is assumed to have a constant value of 50 without correction. In Fig. 3, using the constant as the lidar ratio in the Fernald method resulted in an overestimation of extinction when clouds existed on the lidar line. Because the assumed lidar ratio is an estimate of the normal aerosol, the lidar ratio of cloud particles was smaller than this value [7]. When the estimated extinction coefficient of cloud particles is determined by a larger lidar ratio, the estimation results will be higher. After the correction of the real-time lidar ratio, the deviation caused by the assumed lidar ratio is corrected. Extinction coefficient profiles retrieved by the corrected Mie Fernald method are similar to the profiles retrieved by the Raman signal. Although the difference between the three profiles is small in the area without clouds, the profiles after correction are closer to the profiles retrieved by the Raman signal. After correction, the inversion accuracy of the aerosol optical properties by the Mie Fernald method was improved significantly.

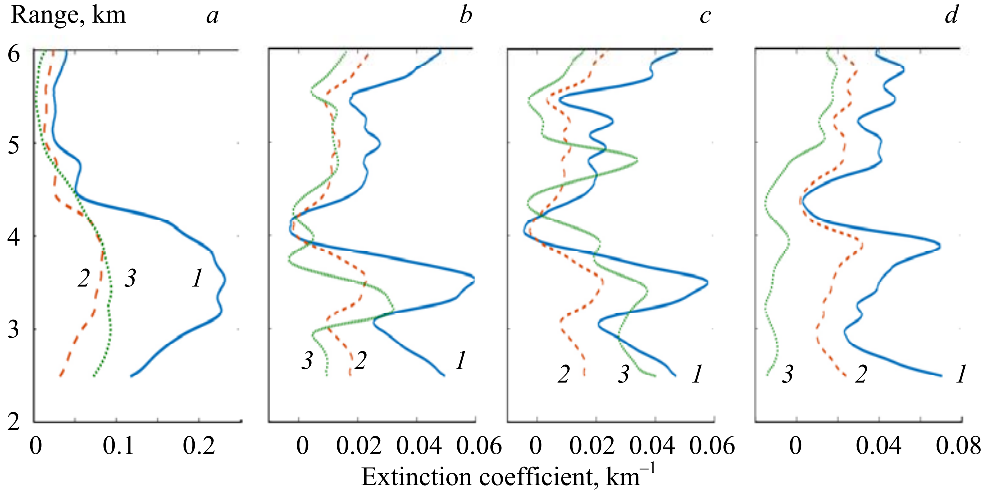


Fig. 3. Extinction coefficient profiles retrieved by the Mie Fernald method before and after correction contrasted with that retrieved by Raman echo signal for measurement 1 (a), 2 (b), 3 (c), and 4 (d). The lidar ratio before correction is assumed to be 50; *1* – lidar ratio = 50, *2* – real-time lidar ratio, *3* – Raman.

The real-time lidar ratio performs well in the Mie Fernald method correction. However, at times the SNR of the Raman signal is too small to produce satisfactory denoising; it cannot retrieve the aerosol optical properties well, even with the wavelet denoising. If the extinction coefficient profiles were determined from a bad signal, we cannot achieve the available extinction coefficient from the Raman signal. Because information relating to the aerosol is disturbed by noise, the available real-time lidar ratios could not be obtained. Furthermore, the Raman channel is only available at night, so the extinction coefficient determined from the daytime observational data cannot be corrected by the real-time lidar ratio.

To make the correction method universal, the average lidar ratio is used to correct the Mie Fernald method; 1167 groups of data were observed between 2009 and 2015 and chosen to determine the retrieval of the aerosol lidar ratio profiles. The average aerosol lidar ratio profile is shown in Fig. 2b, which shows that the lidar ratio of the Nanjing area varies from 30 to 45 and is not spatially distributed in a homogeneous manner.

The average lidar ratio is also used to make corrections to the Fernald method. With the data from the four measurements (measurement 1 – April 26, 2011, at 21:01 (cloudy weather), measurement 2 – March 27, 2012, at 19:38 (fine), measurement 3 – March 27, 2012, at 19:41 (fine), and measurement 4 – March 28, 2012, at 20:37 (fine)), the extinction coefficient profiles retrieved by the Mie Fernald method before correction, the Mie Fernald method after correction, and the Raman echo signal are all shown in Fig. 4. Furthermore, the lidar ratio is assumed to be a constant 50, without correction. After correction of the average lidar ratio, the deviation caused by the assumed lidar ratio was corrected and the extinction coefficient profiles retrieved by the corrected Mie Fernald method were close to the profiles retrieved by the Raman signal. With the correction made using the average lidar ratio, the accuracy of the retrieval of aerosol optical properties by the Mie Fernald method improved significantly.

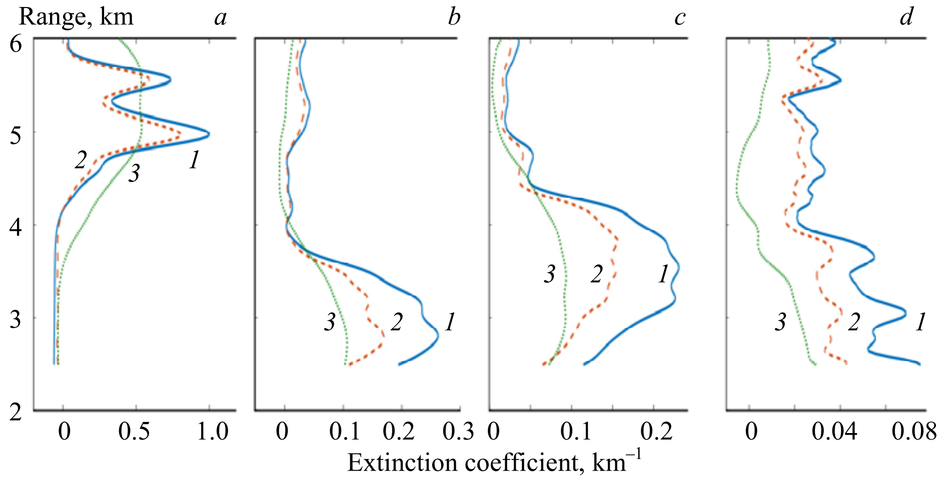


Fig. 4. Extinction coefficient profiles retrieved by the Mie Fernald method before and after correction contrasted with that retrieved by the Raman echo signal for measurement 1 (a), 2 (b), 3 (c), and 4 (d). The lidar ratio before correction was assumed to be 50; *1* – lidar ratio = 50, *2* – average lidar ratio, *3* – Raman.

**Conclusion.** Using the Mie-Rayleigh-Raman lidar method, we measured the lidar profile of the aerosol, and obtained the average lidar ratio profile. The average lidar ratio of the Nanjing area varied from 30 to 45 in height. The Fernald method can be corrected satisfactorily by the real-time lidar ratio. When there is no real-time lidar ratio available, the average lidar ratio can also be used for correction.

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