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Effective lidar ratios of dense dust layers over North Africa derived from the CALIOP measurements

Zhaoyan Liu [a,b,*], David Winker [b], Ali Omar [b], Mark Vaughan [b], Charles Trepte [b], Yong Hu [b], Kathleen Powell [b], Wenbo Sun [b,c], Bing Lin [b]

[a] *National Institute of Aerospace, 100 Exploration Way, Hampton, VA 23693, USA*
[b] *NASA Langley Research Center, Hampton, VA 23681, USA*
[c] *Science Systems and Applications, Inc., Hampton, VA 23681, USA*

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ABSTRACT

Lidar ratio (i.e., extinction-to-backscatter ratio) is a key parameter required for retrieving extinction profiles and optical depths from elastic backscatter lidar measurements, and the quality of any extinction retrieval depends critically on the accuracy of the assumed or measured lidar ratio. In this study, we analyze the first two and a half years of the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) data acquired during nighttime. Distributions of the effective lidar ratio (ELR), which is the product of the lidar ratio and an instrument-dependent multiple scattering factor, are derived for opaque dust layers observed by CALIOP over the North Africa. The median and mean ELR values are, respectively, 36.4 and 38.5 sr at 532 nm and 47.7 and 50.3 sr at 1064 nm. For these opaque dust layers, the derived ELR decreases as the volume depolarization ratio (VDR) increases, reflecting the impact of multiple scattering within the dense layers. The particulate depolarization ratio is typically ~0.3 at 532 nm for African dust observed by CALIOP. This ratio can increase to ~0.4 in the presence of significant multiple scattering. Correspondingly, the calculated ELR will decrease to ~20 sr at 532 nm and to ~30 sr at 1064 nm. The median and mean effective lidar ratio values approach, respectively, to 38 and 40 sr at 532 nm and 52 and 55 sr at 1064 nm for smaller VDR values measured in less dense layers where the multiple scattering is relatively insignificant. These values are very close to those derived in previous case studies for moderately dense dust. Case studies are also performed to examine the impacts of multiple scattering. The results obtained are generally consistent with Monte-Carlo simulations.

1. Introduction

The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), on board the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, is a two-wavelength, polarization-sensitive lidar. Since the first scientific data was acquired in June 2006, CALIOP has been providing nearly continuous global observations of vertically resolved cloud and aerosol distributions [1]. Near real-time data processing by NASA's Atmospheric Science Data Center (ASDC) now generates a complete suite of data products that describe the physical and optical properties of clouds and aerosols. Meanwhile, the CALIOP data products are the subject of numerous on-going validation campaigns using ground-based and airborne lidar observations and other sensor measurements [e.g., 2–6].

To retrieve the cloud and aerosol optical properties, an extinction retrieval is performed [7]. The lidar ratio

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[*] Corresponding author. Tel.: +1 757 864 7192.
E-mail address: zhaoyan.liu@nasa.gov (Z. Liu).

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(i.e., extinction-to-backscatter ratio) is a key parameter required by the extinction retrieval, and its accuracy ultimately determines the quality of aerosol extinction profile obtained [8]. Both measurements (e.g., [9]) and model studies (e.g., [10]) show that the lidar ratio (LR) for any aerosol species can vary over a large range. In practice, however, this parameter cannot be retrieved from elastic backscatter lidar measurements, and thus has to be estimated for most cases based on the aerosol type determined by the CALIOP data processing [10]. Only for a few specific situations (e.g., lofted layers with clear air regions above and below) can the lidar ratio be derived directly from the CALIOP measurement [10]. Therefore, accurate modeling of the aerosol LR is critical for high quality aerosol extinction retrieval.

Because of the complicated chemical compositions of mineral dust aerosols [e.g., 11] and the irregularity of dust particles [e.g., 12], it is challenging to accurately model LR for dust aerosols. The measured LR values for dust aerosols can vary between 20 and 100 sr depending on the location where the measurement is made [12–21]. Dust aerosols originating from different sources may have different optical properties. During long range transport, dust may also be mixed with other types of aerosols and, depending on the transport pathways, the microphysical and optical properties of the aerosol mass may change substantially.

North Africa is home to the Sahara Desert, the world's largest nonpolar desert. Dust activities in this area occur constantly, all year round [22]. During much of the year, great quantities of African dust are advected across the Atlantic Ocean into and over North and South America [23]. As part of the CALIOP validation activities, we have previously analyzed the long-range transport of an African dust event, focusing on possible changes in dust intrinsic optical properties along the transport track as the dust crossed the Atlantic [24]. This case study revealed that the transported dust experiences only small changes in its intrinsic optical properties. Near the source, the retrieved dust LR was 41 ± 3 sr at 532 nm and 52 ± 5 sr at 1064 nm, and this value changed only slightly during the first half of the transport to the mid-Atlantic. The particulate depolarization ratio (PDR) of this dust layer remained almost unchanged (0.31 ± 0.015) in the free troposphere during the entire course of more than 10 days of transport to the Gulf of Mexico. The static nature of the Saharan dust intrinsic optical properties revealed in the previous case study may reflect the fact observed by in-situ measurements that the particle size distributions of the Saharan air layer generally remain invariant both vertically and horizontally along the dust transport track [25,26].

A more extensive validation study was performed recently based on the CALIOP observations and in-situ measurements made during the NAMMA campaign over the northwestern Africa and eastern Atlantic in summer 2006 [27]. The dust LR derived from the CALIOP measurements used in this study is 39.8 ± 1.4 sr at 532 nm and 51.8 ± 3.6 sr at 1064 nm. Calculations using a T-Matrix scheme based on the size distributions measured aboard the NASA DC-8 yielded a dust LR value of 39.1 ± 3.5 and 50.0 ± 4 sr, respectively, at 532 and 1064 nm. A sensitivity study was also performed using noisy size spectra and refractive indices, and this revealed LR values of 39.4 ± 5.9 and 56.5 ± 16.5 sr at 532 and 1064 nm, respectively, corresponding to relative uncertainties of 15% and 29%. Another recent study [28] that applied multiple approaches to a dataset of 17 CALIOP observations of lofted African dust layers suggested similar LR ranges of 45 ± 5 sr at 532 nm and 52 ± 7 sr at 1064 nm. These retrieved LR ranges were then used to revise the Enhanced-Constrained Ratio Aerosol Model-fit (E-CRAM). The revised E-CRAM analysis was further applied to additional 16 cases of African dust observed over Atlantic, revealing that the LR ranges only show a minor trend along the Atlantic transport pathway, consistent with the previous case study [24].

In this paper, we analyze an even larger set of CALIOP dust measurements. These data were acquired over North Africa (12–30°N; 30°W–35°E) during the first two and a half years of the CALIPSO mission (June 2006–December 2008). By focusing solely on opaque dust layers, we can employ a venerable and well-known technique to retrieve high-quality estimates of ELR directly from the CALIOP measurements. In the following sections, we describe the methods of analysis we use and the data set to which we apply these methods. In discussing the results obtained, we assess the role of multiple scattering in the CALIOP signals, and explore its relationship to the measured depolarization ratio.

2. Methodology and CALIOP data

If the molecular backscattering coefficient, $\beta_m(z)$, is negligibly small when compared to the particulate scattering, $\beta_p(z)$, within a cloud or aerosol layer; the layer effective lidar ratio (ELR), S^*, which is the product of the single-scattering lidar ratio, S, and the multiple scattering factor, $\overline{\eta}$, can be computed using [29] the following equation:

$$S^* = \overline{\eta} S \approx \frac{1-\exp(-2\overline{\eta}\tau_p)}{2\gamma'} = \frac{1-T_p^2}{2\gamma'} \tag{1}$$

Here τ_p is the optical depth (OD) of the particulate scattering between the layer's top and base, z_{top} and z_{base}, and T_p^2 is the corresponding two-way transmittance. $\gamma\prime = \int_{z_{top}}^{z_{base}} \beta'(z')\,dz'$ is the layer integrated attenuated backscatter, where $\beta'(z) = (\beta_m(z)+\beta_p(z))T_p^2(z)$ is the range-resolved attenuated backscatter coefficient. $\overline{\eta}$ is a multiple scattering factor introduced to account for the apparent decrease in layer optical depth due to the multiple scattering generated in dense layers. Values of $\overline{\eta}$ range from 0 to 1. $\overline{\eta} = 1$ when no multiple scattering is present, and decreases as the multiple scattering makes increasing contributions to the backscattered signal. When a layer is opaque at a given wavelength (i.e., $\overline{\eta}\tau > \sim 3$), the exponential term in Eq. (1) is very small (< 0.0025) and can be ignored; therefore, Eq. (1) becomes

$$S^* = \overline{\eta} S \approx \frac{1}{2\gamma'} \tag{2}$$