

# EXTINCTION-TO-BACKSCATTER RATIOS OF SAHARAN DUST LAYERS DERIVED FROM IN-SITU MEASUREMENTS AND CALIPSO OVERFLIGHTS DURING NAMMA

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## ABSTRACT

We determine the aerosol extinction-to-backscatter ( $S_a$ ) ratios of dust using airborne in-situ measurements of microphysical properties, and CALIPSO observations during the NASA African Monsoon Multidisciplinary Analyses (NAMMA). The NAMMA field experiment was conducted from Sal, Cape Verde during Aug-Sept 2006. Using CALIPSO measurements of the attenuated backscatter of lofted Saharan dust layers, we apply the transmittance technique to estimate dust  $S_a$  ratios at 532 nm and a 2-color method to determine the corresponding 1064 nm  $S_a$ . Using this method, we found dust  $S_a$  ratios of  $39.8 \pm 1.4$  sr and  $51.8 \pm 3.6$  sr at 532 nm and 1064 nm, respectively. Secondly,  $S_a$  ratios at both wavelengths is independently calculated using size distributions measured aboard the NASA DC-8 and estimates of Saharan dust complex refractive indices applied in a T-Matrix scheme. We found  $S_a$  ratios of  $39.1 \pm 3.5$  sr and  $50.0 \pm 4$  sr at 532 nm and 1064 nm, respectively, using the T-Matrix calculations applied to measured size spectra. Finally, in situ measurements of the total scattering (550 nm) and absorption coefficients (532 nm) are used to generate an extinction profile that is used to constrain the CALIPSO 532 nm extinction profile.

## 1. INTRODUCTION

In order to estimate the optical depth of the Sahara dust layers from elastic backscatter lidar measurements, the  $S_a$  ratio must be known or prescribed. Given aerosol free regions above and below a lofted dust layer,  $S_a$  can be calculated from the attenuated backscatter profile of a space-based lidar return [1].  $S_a$  for dust aerosols is dependent on the mineral composition, size distribution, and shape parameters (e.g., aspect ratio, and complexity factor). All of these are highly variable and for the most part not well known. For these reasons, lidar ratios obtained from scattering models have larger uncertainties than models of the nearly spherical urban pollution or marine aerosols.

There have been several studies and measurements of dust  $S_a$  at 532 nm and relatively few such measurements or studies of dust  $S_a$  at 1064 nm [2-4]. NAMMA studies along with CALIPSO measurements provide a unique opportunity to compare extinction measurements derived from in situ profile measurements of total scattering and absorption aboard the NASA DC-8 and CALIPSO extinction profiles estimated from two wavelength retrieval methods. These profiles by extension provide the constraints from which the

lidar ratios can be determined, as explained in the following sections.

## 2. CALIPSO LIDAR DATA AND $S_a$ RATIO RETRIEVAL METHODS

The CALIPSO lidar data used for these studies are the version 2.01 lidar level 1 attenuated backscatter returns at the 532 nm perpendicular and parallel channels, and 1064 nm total attenuated backscatter. The volume depolarization ratio is determined from the perpendicular and parallel channels and used to identify dust aerosols [cf. 5, 6]. For NAMMA underflights of CALIPSO and near spatial coincidences where both missions observed dust layers of optical depths greater than about 0.3, we compare the extinction profiles from in situ measurements to CALIPSO profiles. In such cases, we calculate the extinction using  $S_a$  that was determined using the transmittance method or an  $S_a$  ratio constrained by the in-situ extinction profiles. In both cases, we use 2-color methods to retrieve the 1064-nm  $S_a$ , after determining the 532-nm  $S_a$ .

The transmittance method is discussed in [1]. The 2-color or two-wavelength method was first proposed by Sasano and Browell [7] and adapted to spaceborne lidar measurements using an optimization technique by Vaughan et al. [8]. The method requires *a priori* knowledge of  $S_a$  at 532 nm and a suitable profile of 532-nm attenuated backscatter amenable to the calculation of 532-nm aerosol backscatter coefficient profiles. In cases where coincident NAMMA measurements are available, the  $S_a$  ratio at 532 nm is the value that provides the best fit between the retrieved CALIPSO extinction profiles and the NAMMA in situ extinction profiles, which are obtained by summing the total scattering and absorption measured by a nephelometer and a Particle Soot/Absorption Photometer (PSAP), respectively, aboard the DC-8.

## 3. NAMMA IN SITU and CALIPSO LIDAR MEASUREMENTS August 19, 2006

August 19 was one of the days the DC-8 performed an under flight of CALIPSO. Figure 1 shows the 532-nm attenuated backscatter image of the CALIPSO measurements and flight track on August 19, 2006. This is a southeast-to-northwest daytime orbit. The profiles of interest are bounded by the white lines.

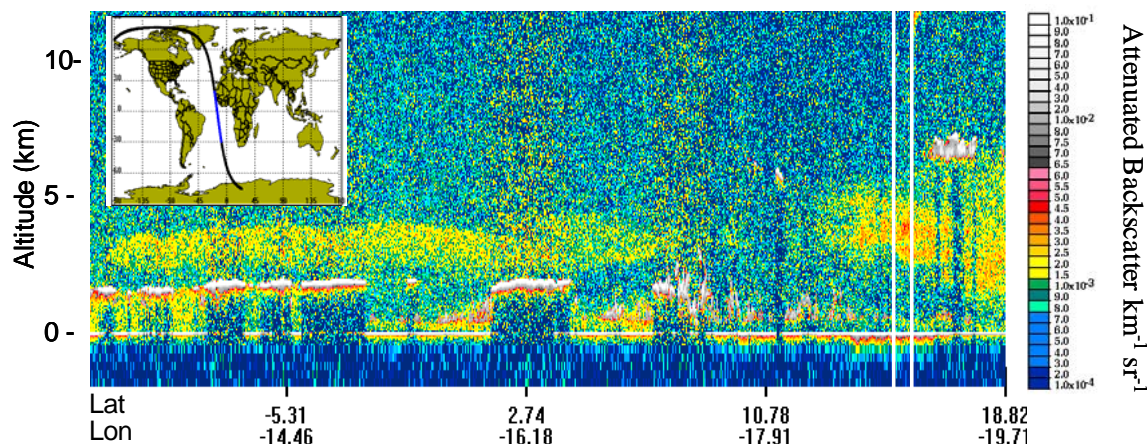


Figure 1. 532 nm Attenuated Backscatter image of the CALIPSO flight track on August 19, 2006 shown in blue in the inset map and the location of the near coincidence of the CALIPSO flight track and the DC-8 flight 4 during NAMMA

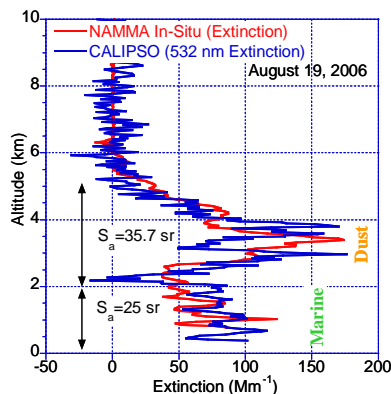


Figure 2. A comparison of the profiles of the in situ extinction coefficient derived during the DC-8 ascending segment as shown in Figure 4 and the extinction coefficient retrieved from the CALIPSO measurement

Figure 2 is a plot of the extinction profiles retrieved from CALIPSO's 532-nm backscatter profiles and the in-situ extinction profiles obtained by summing the scattering (550 nm) and absorption (532 nm) determined by the nephelometer and the PSAP aboard the NASA DC-8, respectively. The boundary between the two layers is determined by the demarcation in the extinction profile. The two  $S_a$  ratios are values that provide the best fit in a least squares sense of the CALIPSO data to the NAMMA in-situ measurements. The 532-nm  $S_a$  ratios are consistent with a dust plume ( $S_a$  ratio = 35.7 sr) above seasalt in the marine boundary layer ( $S_a$  ratio = 25 sr). The root mean square (rms) of the differences between the CALIPSO and the NAMMA in-situ extinction coefficient profiles are 20.2  $Mm^{-1}$ , and 47.4  $Mm^{-1}$ , for the marine and dust layers, respectively. Atmospheric context for this flight is given by Figure 3(a) and (b), in which both the DC-8 and CALIPSO flight tracks are superimposed on

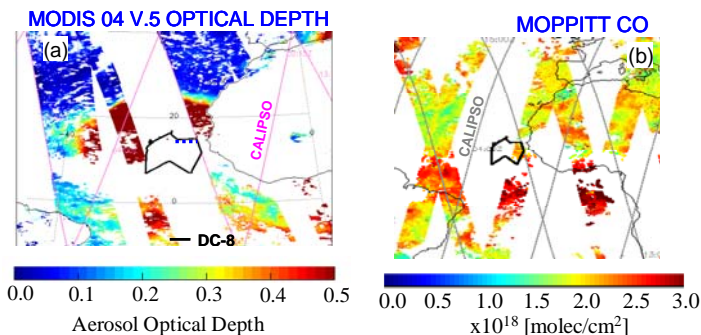


Figure 3. CALIPSO flight tracks superimposed on (a) the MODIS optical depth and (b) the MOPITT CO concentrations. The DC-8 flight track for August 19, 2006 is shown by the black lines in the middle of both figures. The blue dots in (a) denote the portion of the DC-8 flight segment during which the in-situ measurements were taken. Daytime CALIPSO tracks run from the southeast to the northwest while the nighttime tracks run from northeast to the southwest

images of measurements made by the Moderate Resolution Imaging Spectroradiometer (MODIS) and Measurements of Pollution in the Troposphere (MOPITT), respectively.

Figure 4 is a plot of the results of (a) the cloud-aerosol discrimination and (b) aerosol classification algorithms applied to the data shown in Figure 1 including the NAMMA underflight (Flight 4 of August 19, 2006). The CALIPSO level 2 algorithms first discriminate between aerosol and clouds [6] and then classify the aerosol layers into aerosol subtypes [5]. Figure 4(a) shows that some of the optically thick aerosol near 15° N was misclassified as clouds, and thus was not examined by the aerosol subtyping algorithm. There is biomass burning smoke and polluted dust (mixture of dust and smoke) during the first part of the flight.

CALIPSO also measured a dense Saharan dust layer to the southwest of the coincident measurements during a

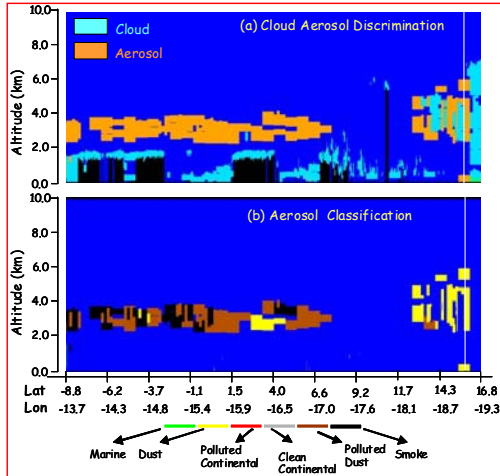


Figure 4. CALIPSO (a) cloud-aerosol discrimination and (b) aerosol subtype classification schemes for the data in the browse image shown in Figure 1.

nighttime orbit on the same day (August 19, 2006). The browse images of attenuated backscatter at 532 nm for this orbit are shown in Figure 5. The inset map in Figure 5 shows the CALIPSO track in blue. This dust layer appears to be a part of the same dust plume observed during the coincident measurement.

As shown (by the red dotted oval) in Figure 5(a), the layer exceeds 1000 km in horizontal extent (from 18.3N to 10.3N). The 532-nm aerosol optical depth

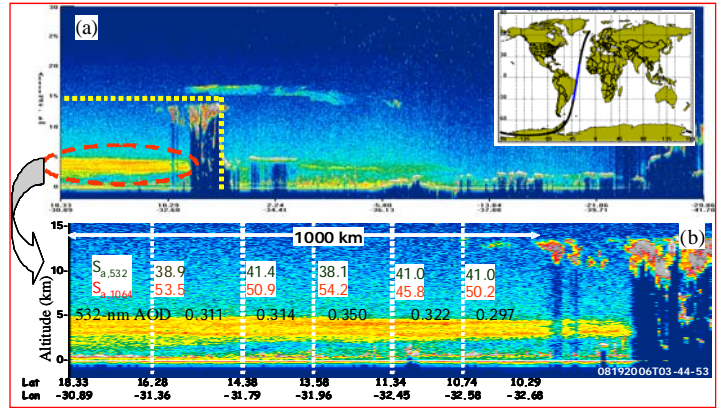


Figure 5(a) Browse image of the orbit segment denoted by the blue track in the inset map and (b) an expansion of the dust layer region of the plot marked by yellow dots in (a).

(AOD) is greater than about 0.3 across most of the 1000-km orbital segment shown in Figure 5(a). Figure 5(b) is a magnified illustration of the region in 5(a) subtended by the yellow dotted line. We divided the layer into five segments and applied the transmittance method to calculate a 532-nm  $S_a$  and the 2-color method to calculate a 1064-nm  $S_a$  ratio.

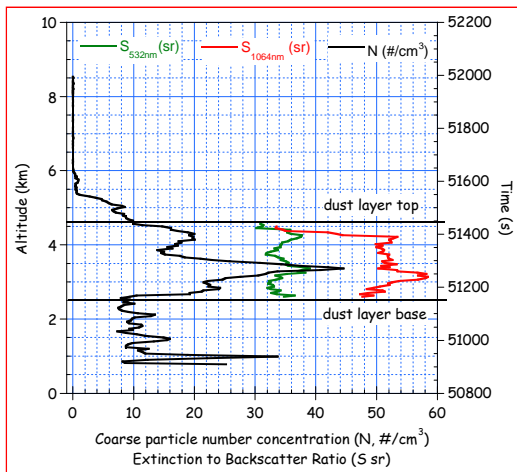


Figure 6. A profile of the 1064 and 532-nm  $S_a$  ratios and measurements of the integrated number distribution of coarse particles (0.583  $\mu\text{m}$  – 6.264  $\mu\text{m}$ ) taken during Flight 4 on August 19, 2006. The dust base and top are shown by the lines at altitudes of 2.5 km and 4.6 km, respectively. The mean 532-nm and 1064-nm  $S_a$  ratios for the layer is 34.3 $\pm$ 2.0 sr and 50.2 $\pm$ 5.7 sr, respectively.

These values are shown in green (532 nm) and red (1064 nm) in Figure 5(b). Clear air regions above and below each dust layer were identified manually, by inspection of the profiles. Note that for this mesoscale layer the 532-nm  $S_a$  ratios range from 38 to 41 sr with

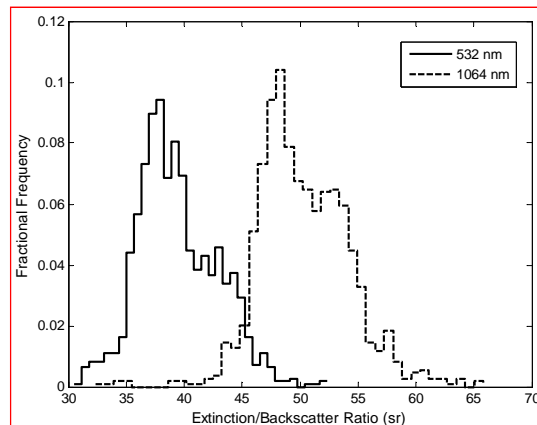


Figure 7. An ensemble of all the  $S_a$  ratio estimates (~1100 records) based on the NAMMA in-situ size distributions of dust layers and T-Matrix calculations. The average  $S_a$  ratios are 39.1  $\pm$ 3.5 sr and 50.0  $\pm$  4 sr at 532 nm and 1064 nm, respectively

an average of 40.1 sr and the 1064-nm  $S_a$  ratios range from 45.8 to 54.2 with an average of 50.9 sr.

To determine profiles of  $S_a$  ratios and validate the retrieved values, we performed numerical calculations for Saharan dust based on NAMMA in-situ size

distribution measurements. We use the DC-8 size distribution measurements [9] to determine coarse and fine size distributions, and then calculate coarse and fine mode phase functions, using a T-Matrix scheme.

The  $S_a$  ratio of the aerosol is derived from an area-weighted integral of the two modes. Figure 6 is a plot of the profile of  $S_a$  ratios of the 2-km dust layer encountered by NAMMA Flight 4 on August 19, 2006. The figure shows a profile of the coarse number concentration which marks the bottom and top of the layer at 2.5 and 4.6 km, respectively. The mean  $S_a$  ratios are very similar to the values shown in Figure 2 for dust. Moreover, the 532-nm and 1064-nm  $S_a$  ratios calculated here of  $34.3 \pm 2.0$  sr and  $50.2 \pm 5.7$  sr, respectively, are in agreement with  $S_a$  ratios of 38 to 41 sr at 532 nm and 45.8 to 54.2 sr at 1064 nm determined from CALIPSO measurements (Figure 5b) on the same day, albeit further downfield. Figure 7 is a histogram of all the 532-nm and 1064-nm  $S_a$  ratios (~1100 points) determined using the size distributions measured during NAMMA for this study. There is very little overlap of the two nearly normally distributed  $S_a$  ratios. The 532- and 1064 nm mean  $S_a$  ratios ( $\pm$  one standard deviation) are  $39.1 \pm 3.5$  sr and  $50.0 \pm 4.0$  sr, respectively. The 532-nm values ranged from 30 to 53 sr and the 1064-nm values ranged from 32 to 66 sr.

#### 4. Conclusion

We have determined the  $S_a$  ratios of Saharan dust layers using three methods: transmittance constraint technique for lofted layers, in-situ extinction profile constraint method, and T-Matrix calculations. We found nearly constant values of  $S_a$  at 532 nm and a slightly wider spread at 1064 nm. The three methods yielded 532 nm and 1064 nm  $S_a$  ratios that are quite close.  $S_a$  ratios of  $39.8 \pm 1.4$  sr and  $51.8 \pm 3.6$  sr at 532 nm and 1064 nm, respectively, were derived using the transmittance and 2-color methods applied to CALIPSO measurements of Saharan dust lofted layers. T-Matrix calculations applied to size distributions measured aboard the NASA DC-8 during NAMMA yielded  $S_a$  ratios of  $39.1 \pm 3.5$  sr and  $50.0 \pm 4$  sr at 532 nm and 1064 nm, respectively. The measured extinction profile obtained by the aggregate of nephelometer measurements of total scattering coefficient and the PSAP measurements of the absorption coefficient was used to constrain the inversion of the CALIPSO measurements. This technique yielded a 532-nm  $S_a$  ratio of 35.7 sr for a dust layer and 25 sr for the aerosol in the marine boundary layer.

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