# USING AIRBORNE HIGH SPECTRAL RESOLUTION LIDAR DATA TO EVALUATE COMBINED ACTIVE PLUS PASSIVE RETRIEVALS OF AEROSOL EXTINCTION PROFILES

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## ABSTRACT

Aerosol extinction profiles are derived from backscatter data by constraining the retrieval with column aerosol optical thickness (AOT), for example from coincident MODIS observations and without reliance on a priori assumptions about aerosol type or optical properties. The backscatter data were acquired with the NASA Langley High Spectral Resolution Lidar (HSRL). The HSRL also simultaneously measures extinction independently, thereby providing an ideal data set for evaluating the constrained retrieval of extinction from backscatter. We will show constrained extinction retrievals using various sources of column AOT, and examine comparisons with the HSRL extinction measurements and with a similar retrieval using data from the CALIOP lidar on the CALIPSO satellite.

## INTRODUCTION

Accurate aerosol measurements are required for understanding shortwave radiative transfer since aerosols affect climate by scattering and absorbing solar radiation and also by altering the lifetime and development of clouds. Aerosol radiative forcing depends strongly on the vertical distribution of aerosols [1]. Scattering particles exhibit a greater forcing when most of the aerosol mass is located in the lower troposphere because of the increase in aerosol size with relative humidity. In contrast, absorbing aerosols produce a greater radiative forcing when the aerosol mass is above cloudy layers or when the underlying surface albedo is high [1].

Lidar remote sensing is a valuable means of measuring the vertical distribution of aerosol properties. The lidar equation relates the total backscatter and extinction to the lidar signal as a function of range from the instrument.

$$P(r) = \frac{C}{r^2}[\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^r[\sigma_m(r') + \sigma_a(r')]dr'\right\}$$

where $r$ is the range, $P(r)$ is the measured signal, $C$ is a calibration constant, $\beta_m$ and $\beta_a$ are the molecular and aerosol backscatter coefficients, respectively, and $\sigma_m$ and $\sigma_a$ are the molecular and aerosol extinction coefficients, respectively. For a backscatter lidar such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor, both the aerosol backscatter and extinction at a given range are unknown variables to be retrieved, so the equation is underdetermined. The two unknowns can be related to each other by the aerosol extinction to backscatter ratio or "lidar ratio," $S_a$. The lidar ratio is frequently either assumed or inferred from additional measurements and used as a means of solving the lidar equation.

Recently, work has been done on retrieving both aerosol extinction and backscatter profiles from lidar data by constraining the solution with column aerosol information from coincident satellite measurements, thereby avoiding the need to assume a value for $S_a$ [2], [3]. A successful implementation of such a technique would potentially improve extinction retrievals from the CALIOP sensor on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. The CALIOP extinction retrievals rely on accurately specifying $S_a$, and uncertainties in the lidar ratio are a major source of uncertainty in the CALIOP extinction retrievals.

One active+passive method of retrieving extinction was performed by Ferrare et al. [4] from the NASA Langley UV-DIAL lidar using aerosol optical thickness (AOT) measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Model of Atmospheric Transport and Chemistry (MATCH). A time series of column AOT values along the airborne

lidar flight track is derived. For each point along the track, the retrieval of extinction from backscatter returns is constrained by requiring that the resulting AOT matches the measured AOT.

Here we discuss a similar calculation, using satellite aerosol optical thickness from MODIS and from PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar) to constrain the retrieval of extinction from total (i.e., aerosol plus molecular) attenuated backscatter profiles obtained by the NASA Langley High Spectral Resolution Lidar (HSRL) [5]. The HSRL provides a unique opportunity to validate and evaluate this technique, because it also provides a direct extinction measurement, which can be used as ground truth in determining the strengths and limitations of the method. Retrieving extinction from HSRL total attenuated backscatter measurements of course is not done for the sake of the derived extinction profiles themselves, but because it can provide valuable insight into the AOT-constraint technique, a technique that may help reduce uncertainties in aerosol extinction profiles derived from CALIOP measurements.

The HSRL instrument measures backscattering and depolarization at two wavelengths, 532 nm and 1064 nm. It also measures extinction at 532 nm, by using the Doppler broadening of the molecular backscattering signal to separate the molecular and aerosol components of backscattering [6]. Since the molecular backscattering is also known from the atmospheric density profile (as in standard lidar techniques) the attenuation of the molecular backscatter signal by atmospheric extinction can be obtained.

The HSRL instrument has flown aboard the NASA Langley King Air B200 on over 120 flights since March 2006 during a variety of missions including the Gulf of Mexico Atmospheric Composition and Climate Study (GOMACCS) and the Cumulus Humilis Aerosol Processing Study (CHAPS). Approximately 40 of these flights contain segments coordinated with CALIPSO overpasses, providing an opportunity to validate extinction retrievals from the CALIOP sensor.

### EXTINCTION RETRIEVAL

To retrieve aerosol extinction from HSRL attenuated backscatter signals, we implement a Fernald near-field solution [7] using a given $S_a$ value. Rather than assume a value for $S_a$, however, we search for the value of $S_a$ that satisfies the requirement that the column integral of the extinction values must correspond to a column AOT value provided by a coincident MODIS or PARASOL measurement or another source such as an aerosol transport model. The solution is obtained in a straightforward way by forming the Fernald equation and the numerical integration into root-finding form (i.e., an equation with one side equal to zero) and solving for $S_a$ with an off-the-shelf non-linear root finder. By these means, the ratio of aerosol extinction to backscattering is free to vary with time and location along the flight track, although the method still contains the underlying assumption that $S_a$ is constant with altitude.

There are several possible sources of AOT data to constrain the extinction retrieval. The simplest to start with is the AOT integrated from the extinction measured by the HSRL instrument itself. The spatial coincidence is of course perfect so we expect to get very good agreement. Figure 1 shows the results of the retrieval for a three hour HSRL flight over the Mid-Atlantic and off the coast of Virginia on August 4, 2007. Laser shots with cloud attenuation have been excluded from the retrieval. The agreement between the measured extinction and the retrieved extinction is very good. The percent difference is shown for each bin where the extinction is greater than 0.01, which is each bin below 4.5 km. For these altitudes, the percent difference is between -5% to 12%. These results indicate that, for this case, the assumption of a constant lidar ratio with altitude is valid.
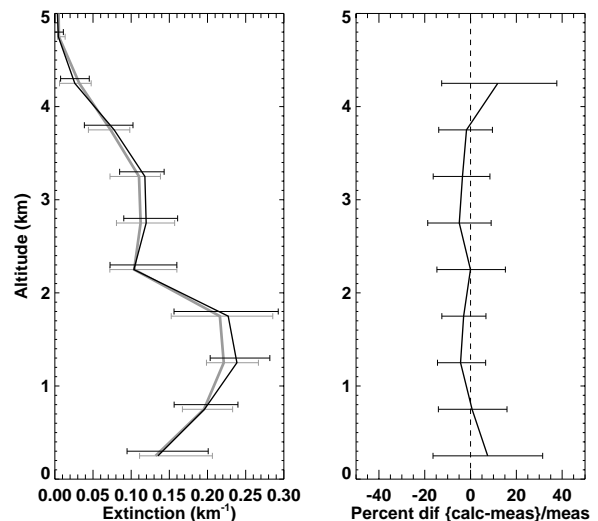


Figure 1. Median profiles [left] and percent difference profile [right] in ½ km bins of the extinction retrieved from HSRL attenuated backscatter data constrained using the HSRL AOT (gray), compared to the measured HSRL extinction (black). These data are from a flight on August 4, 2007 off the coast of Virginia. Cloudy shots have been excluded from the retrieval. The error bars show the 25th and 75th percentiles of the extinction values and of the difference.

It is desirable to obtain the aerosol optical thickness from a coincident passive sensor such as MODIS or PARASOL, to evaluate the active+passive extinction retrieval for use with lidar measurements that do not have associated AOT measurements. Figure 2 demonstrates the extinction retrieval using HSRL attenuated backscatter data with AOT from MODIS on Aqua. Only the shots over land are shown. The AOT that is used in the extinction retrieval is "Corrected_Optical_Depth_Land" at 550 nm from coincident MODIS Aqua measurements from an overpass at 18:25 UT (during the HSRL flight), from which all the pixels within 25 km of the HSRL track are averaged for each point on the track. The 550-nm AOT is also converted to the HSRL wavelength of 532 nm and a further adjustment is made to reduce the MODIS AOT for the fact that HSRL backscatter measurements, and thereby the resulting derived extinction, are available only in a partial column (i.e. only below the aircraft). The agreement between the retrieved extinction and the measured extinction in this case is about as good as before, with percent differences from -6% to 14%.
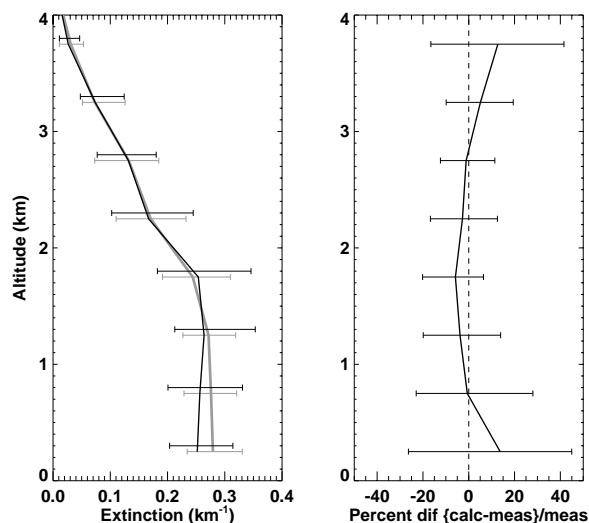


Figure 2. Like Figure 1, but the AOT constraint to the extinction retrieval was from MODIS Aqua, as described in the text. Only the data over land are included.

The results for the portion of the same flight over water are less successful, as shown in Figure 3. In this case, the retrieval underestimates the extinction at all altitudes, and the percent difference varies from -5% to -44%. Direct comparison of the MODIS Aqua AOT used in this experiment with the AOT derived from the HSRL extinction measurements reveals a large difference as well, in Figure 4. With such a difference in AOT between MODIS and HSRL over much of the flight track, it is no surprise that the extinction retrieval

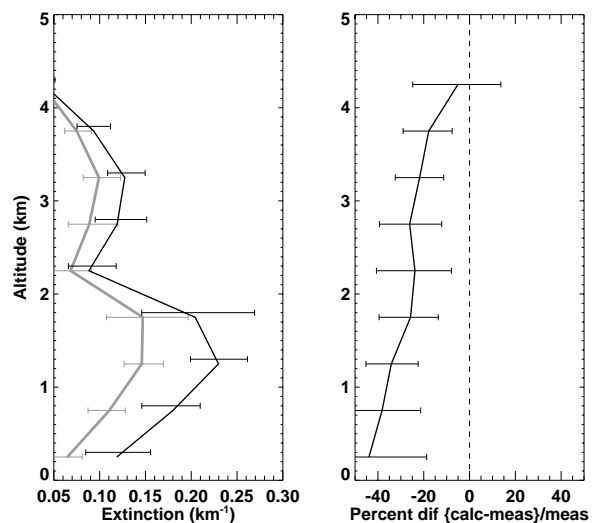produces much smaller extinctions than the HSRL measurements for this case.



Figure 3. Like Figure 2, but for the water portion of the August 4, 2007 flight.

The MODIS Terra swaths for two overpasses that occurred a few hours earlier, at 15:05 and 16:45 UT, also include the HSRL flight track. Using the same spatial coincidence criteria and applying the same adjustments for wavelength and for the partial column produces along-track AOT for MODIS Terra that is also shown in Figure 4. There is a large bias between the MODIS Aqua and MODIS Terra AOT. Even given the difference in time between the Aqua and Terra overpasses this large difference is surprising. The reason for the difference is currently under investigation, but we have seen similar bias in occasional other cases over water.

Because of the Terra vs. Aqua difference for the water portion of this flight, we examine another source of AOT measurements. PARASOL is a wide-field imaging radiometer and polarimeter and another member of the "A-train" satellite constellation, trailing Aqua by about 3 minutes. Since PARASOL measurements over water are made at 670 nm and 865 nm, extrapolation of aerosol optical thickness measurements to the HSRL wavelength of 550 nm is required. For this experiment, the Ångström coefficient is derived by a multiple linear regression on the 670 nm and 865 nm data within a rectangular box surrounding the entire flight track. The extrapolated AOT is then treated as before to combine with the HSRL measurements. The adjusted along-track AOT for PARASOL is also shown in Figure 4. While there are still significant differences with the measured HSRL AOT, there is better agreement than

with the MODIS Aqua AOT. These values have been used in the active+passive retrieval with HSRL back-scatter measurements to produce the results shown in Figure 5. Here the percent difference varies from -11% to 6%.
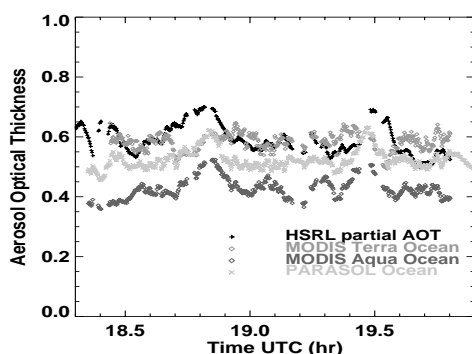


Figure 4. The partial AOT value from HSRL extinction measurements (black) and derived from MODIS Aqua (dark gray), MODIS Terra (medium gray) and PARASOL (light gray) along the Aug. 4, 2007 HSRL flight track over water. The MODIS and PARASOL AOT have been averaged and converted to partial column AOT at 532 nm as described in the text.

## SUMMARY

Aerosol HSRL measurements are used to evaluate aerosol extinction profiles derived by combining lidar backscatter profiles and satellite retrievals of aerosol optical thickness. The HSRL data indicate the vertical variability of the lidar ratio can be small enough in some cases to assume a single altitude-independent lidar ratio.

In these cases, using AOT derived from MODIS or PARASOL provides a useful constraint to derive aerosol extinction profiles that are in generally good agreement with extinction profiles derived from airborne measurements using the HSRL technique. For measurements over water, we have the option of using the AOT from the MODIS ocean algorithm, or, for some flights, aerosol data from the PARASOL sensor. We hope to be able to better characterize when the active plus passive technique described here works well, and also when and why it does not always work. We will also show comparisons with extinction from a similar retrieval using CALIOP backscatter returns.
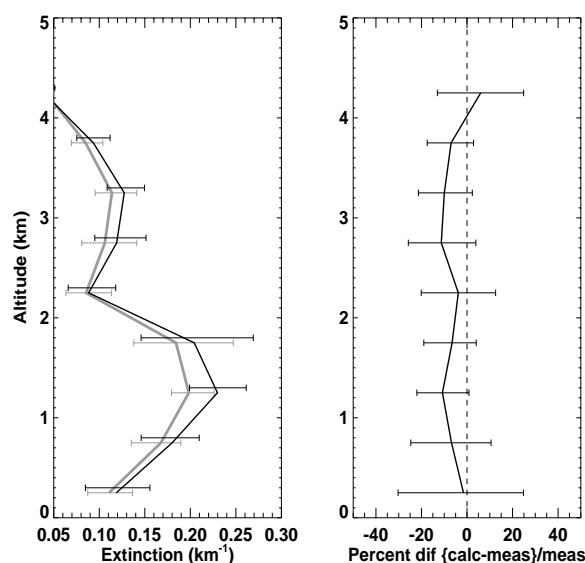


Figure 5. Like Figure 3, but the AOT constraint used in the retrieval was from PARASOL as described in the text. Once again, only shots over water are shown.

## REFERENCES

[1] Haywood, J. M., et al., A limited-area-model case study of the effects of sub-grid scale variations in relative humidity and cloud upon the direct radiative forcing of sulfate aerosol, *Geophys. Res. Letters,* **24**, 143-146, 1997.

[2] Kaufman, Y. J., J. M. Haywood, P. V. Hobbs, W. Hart, R. Kleidman, B. Schmid, Remote Sensing of vertical distributions of smoke aerosol off the coast of Africa during SAFARI 2000, *Geophys. Res. Lett.* **30**, 1831, 10.1029/2003GL017068, 2003.

[3] Léon, J.-F., et al., Profiling of a Saharan dust outbreak based on a synergy between active and passive remote sensing, *J. Geophys. Res.,* **108**, doi:10.1029/2002JD002774, 2003.

[4] Ferrare, R. A., et al., The Vertical Distribution of Aerosols: Lidar Measurements vs. Model Simulations, *23rd International Laser Radar Conference,* Nara, Japan, 2006.

[5] Hair, J. W., L. M. Caldwell, D. A. Krueger, and C.-Y. She, High-spectral-resolution lidar with iodine-vapor filters: measurements of atmospheric-state and aerosol profiles, *Applied Optics,* **40**, 5280-5294.

[6] Grund, C. J. and E. W. Eloranta, The University of Wisconsin High Spectral Resolution Lidar, *Optical Engineering,* **30**, 6-12, 1991.

[7] Fernald, F. G., Analysis of atmospheric lidar observations: some comments. *Applied Optics* **23**, 652-653, 1984.