Progress on Approaches for Maximizing the Aerosol Information Retrievable from CALIPSO Observations

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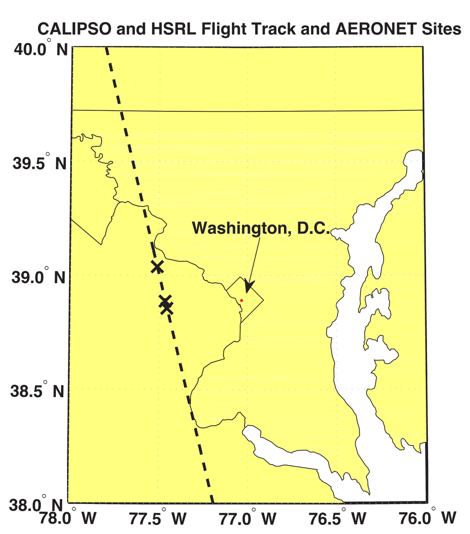
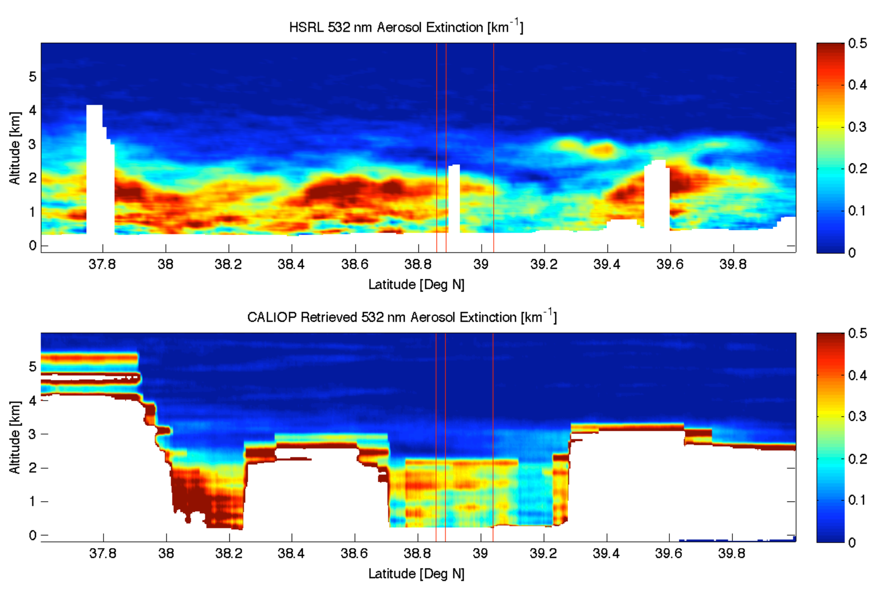
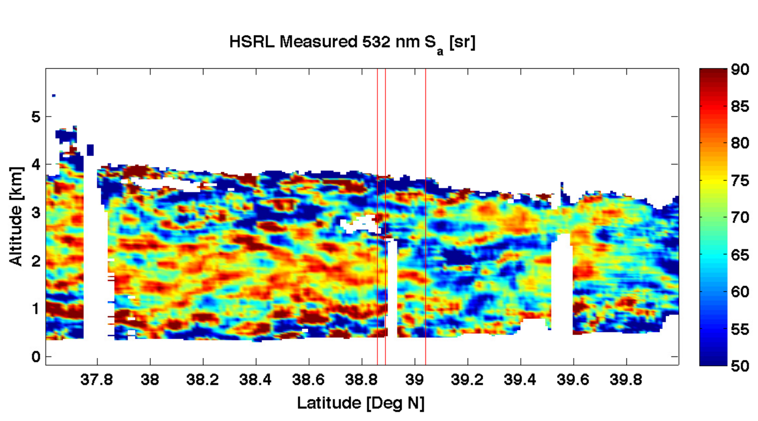
Abstract - The key to maximizing the aerosol information retrieved from CALIPSO lidar (CALIOP) observations is to make full use of the data from the two CALIOP lidar channels (532 and 1064 nm), including the depolarization measurement capability of the 532 nm channel which permits discrimination of dust aerosols. While lidar measurements at just two elastic scatter channels do not permit a practical inversion to retrieve aerosol backscatter and extinction, it is possible with the inclusion of meaningful constraints to achieve these retrievals. The Constrained Ratio Aerosol Model-fit (CRAM) technique is one such method by which aerosol optical properties may be retrieved from dual-wavelength elastic scatter data by applying constraints from aerosol models developed from the analysis of more extensive aerosol observations such as those acquired by the AERONET global network. In particular, CRAM employs aerosol models which associate spectral ratios (~532/1064 ratios) of aerosol extinction, backscatter and the extinction-to-backscatter ratio (lidar ratio) of various aerosol types with a window range of the 532 nm aerosol lidar ratio, Sa, for a given type. Dual-wavelength retrievals on lidar data made assuming the Sa values for a given model yield extinction and backscatter spectral ratios that can be compared to the model ratios to confirm goodness of fit to the assumed model. Success with the CRAM approach has been demonstrated with several satellite lidar data sets. Enhanced CRAM (E-CRAM) retrievals which make use of added information (e.g., Sa at 532 nm determined by say HSRL observations) can be employed to more independently determine the properties of aerosols for a given situation where the CRAM models do not give a good fit, including determining CRAM model mixtures that yield an improved fit. Also, as each CRAM model has an associated aerosol phase function, size distribution and single scatter albedo, achieving a CRAM fit provides significantly more useful information than just the retrieved aerosol backscatter and extinction profiles for assessing aerosol radiative effects.

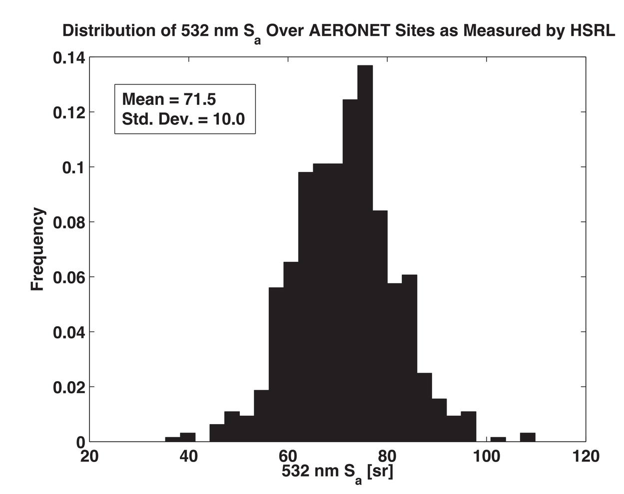
4 August, 2007 (CATZ) Campaign
CALIPSO, HSRL and AERONET Coincident Measurements



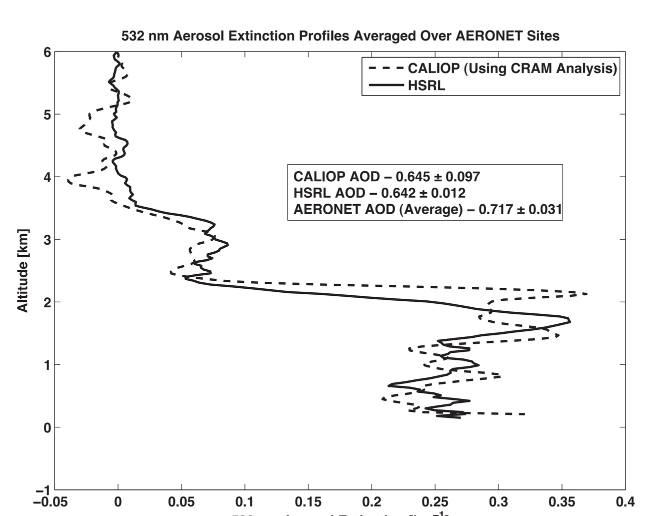


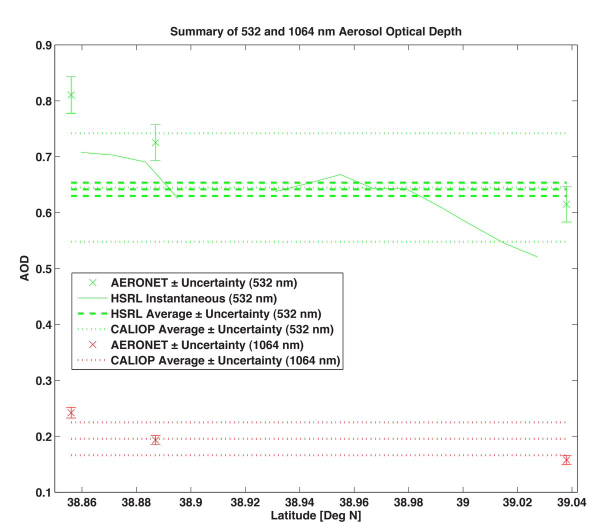
- Black 'x' marks on map above and vertical red lines on time series plot indicate locations of Cimel sunphotometers
- Extinction profile retrieved from CALIOP based on CRAM analysis of the region covered by the Cimels
- ~33 min. difference in time between HSRL and CALIOP overpasses of Cimels
- White areas of extinction retrieval indicate invalid solutions for areas in which CRAM was not applied



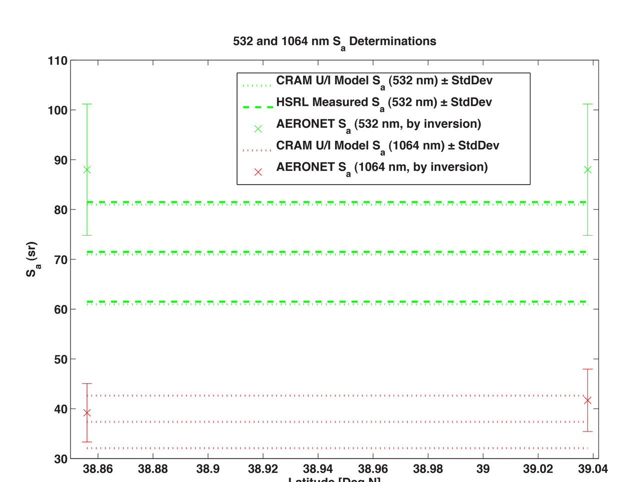


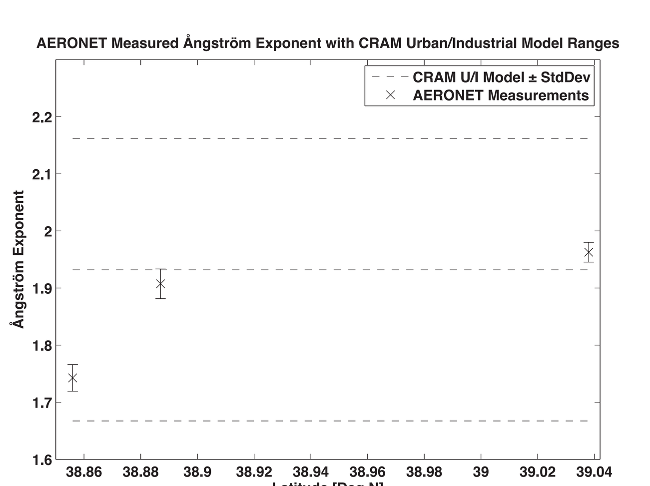
- HSRL measurement of S_a throughout the pass, together with its distribution over the ~20km area of Cimel sites





- At left, CALIOP aerosol extinction profile retrieved based on CRAM analysis, together with measured HSRL extinction profile at 532 nm.
- At right, a comparison of aerosol optical depth (AOD) through the Cimel neighborhood computed for the various instruments





- At left, a comparison of 532 and 1064 nm S_a as determined by HSRL, Cimel inversion and the CRAM best fit model (Urban/Industrial)
- At right, the range of Ångström exponent predicted by the CRAM Urban/Industrial model with accompanying Cimel measurements.

Enhanced CRAM (E-CRAM) Technique

A method described as the "enhanced," or E-CRAM method was developed to facilitate retrievals from the NASA Langley Research Center Airborne HSRL, given the full scattering solution from HSRL at 532 nm. The retrieval at 1064 nm is predicated upon the homogeneity assumption of the Fernald solution, namely the spatial invariability of S_a over the solution region. With HSRL at 532 nm, this assumption can be verified by the data so as to find regions of aerosol which satisfy this assumption. The E-CRAM method is then based on two key assumptions, which follow naturally from the assumption of spatial homogeneity of S_a. The first is that if the spatial homogeneity assumption is valid for S_a at 532 nm, it will also be valid for "homogeneous" aerosol at another wavelength, 1064 nm, and furthermore the S_a at 1064 nm will be related to the S_a at 532 nm by some constant, K_1.

$$S_{a,1064} = K_1 S_{a,532} \quad (1)$$

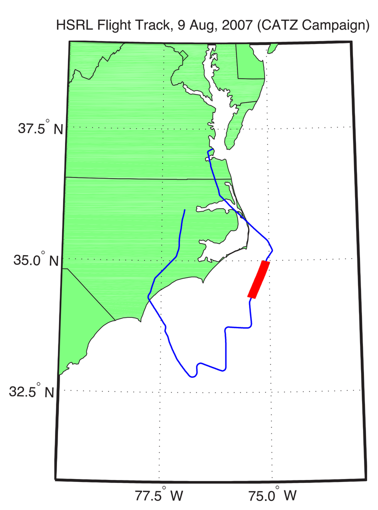
The same assumption is made about the aerosol backscatter.

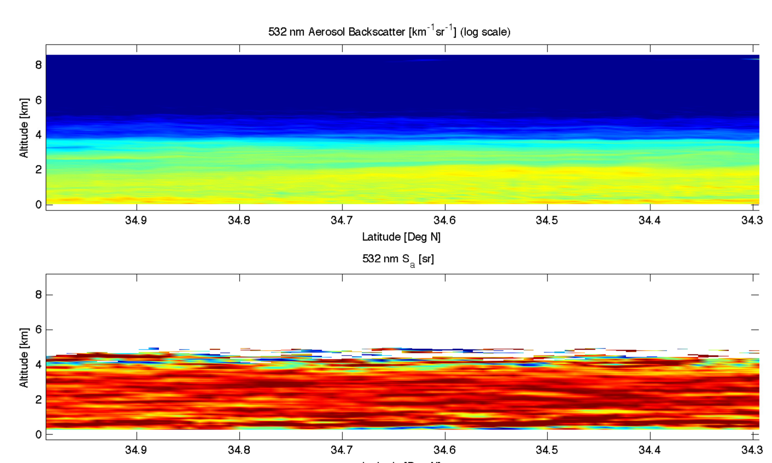
$$\beta_{a,1064} = K_2 \beta_{a,532} \quad (2)$$

By extending the homogeneity assumption, a solution for K_1 is found by repeatedly applying the Fernald retrieval equation at 1064 nm to find a value for K_1 (S_a at 1064 nm relative to 532 nm) which minimizes the spatial variability of K_2 (the 532 to 1064 nm ratio of aerosol backscatter). Simulations demonstrated exceptional tolerance of the technique to high levels of noise and spatial variability of S_a (at 532 nm relative to 1064 nm). Attenuated backscatter returns at 1064 nm were simulated with a signal-to-noise ratio of 50 and normally distributed spatial variability of S_a with a 15% standard deviation relative to the mean. Simulations from such returns demonstrated consistent retrieval of the K_1 and K_2 parameters with an uncertainty comparable to or less than that of current models. With full aerosol extinction and backscatter at 532 nm from HSRL, such a technique can be used to determine a similar solution at 1064 nm based upon the constraints of equations 1 and 2 without further assumption. Through application of this method to data from the NASA Langley Research Center Airborne HSRL, CRAM aerosol model parameters may be verified and updated based on HSRL observations of various aerosol classes.

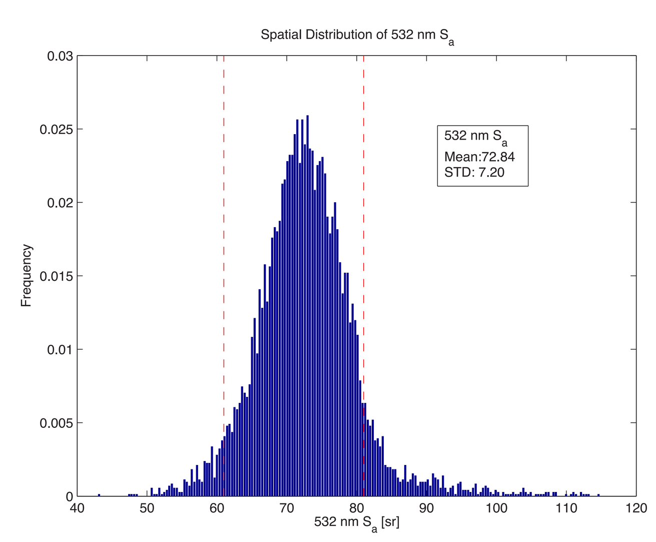
As an example of how such a technique may be used to update the CRAM models, a case study is presented using HSRL data from 9 August, 2007.

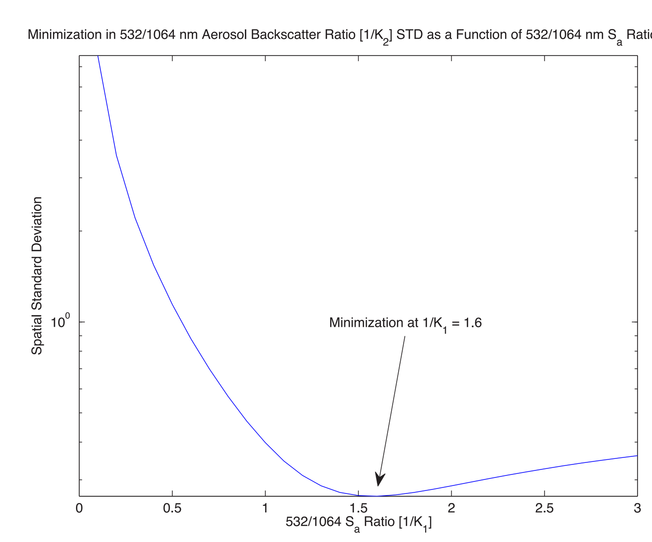
9 August, 2007 E-CRAM Case Study Using HSRL Data



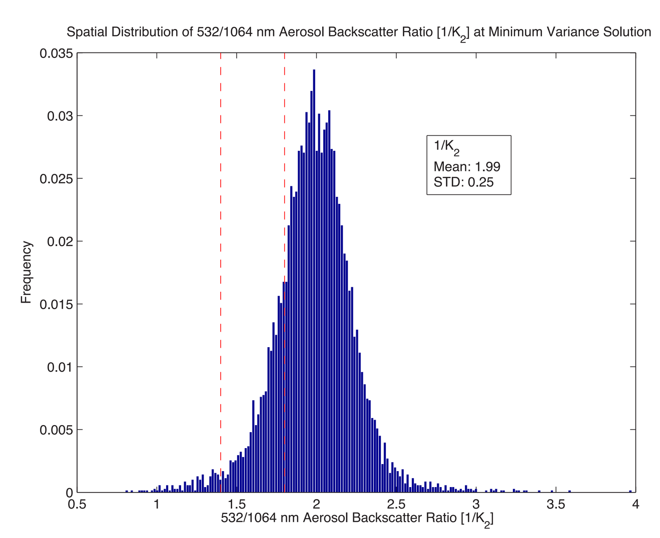


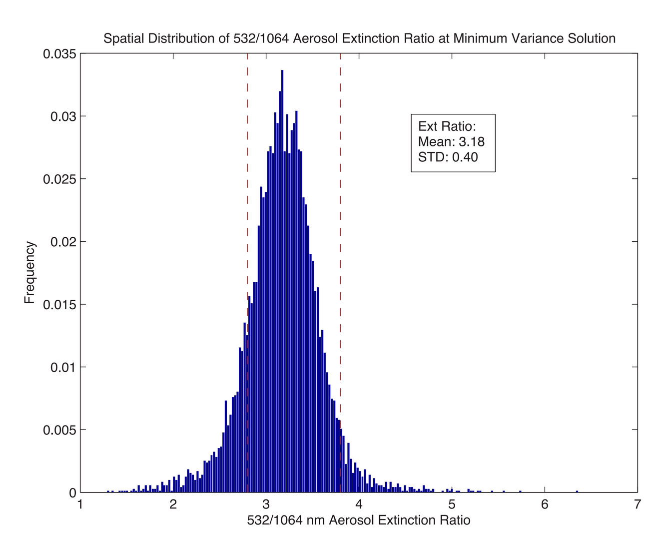
- At left, the HSRL flight track with the region of interest marked in red
- At right, the 532 nm aerosol backscatter and S_a measured by HSRL
- The spatial consistency of the S_a verifies the constraint necessary for E-CRAM (equation 1)





- In the distribution at left, the spatial homogeneity of S_a at 532 nm is confirmed. The range of values of 532 nm S_a associated with the corresponding model (Urban/Industrial) is bracketed in red.
- At right, the minimization of the spatial standard deviation of the K_2 parameter is shown as a function of K_1. Here we deal with $1/K_1$ and $1/K_2$ to be consistent with how the CRAM models have been defined, as ratios of 532 to 1064 nm rather than of 1064 to 532 nm, though the distinction obviously makes no difference in the application of the technique.





- At left is the spatial distribution of the aerosol backscatter spectral ratio (532 to 1064 nm). At right is the spatial distribution of the aerosol extinction spectral ratio.
- The backscatter spectral ratio distribution has been minimized over a range of 1064 nm S_a to give the K_1 and K_2 parameters consistent with the E-CRAM constraints.
- Good agreement with the present Urban/Industrial model is demonstrated in terms of the aerosol extinction spectral ratio as shown in the figure at right.
- The aerosol backscatter spectral ratio distribution (left) indicates some amount of deviation from the Urban/Industrial model parameters as they are currently formulated.
- Such data (over many independent observations by HSRL) might be used to motivate a revision of the Urban/Industrial aerosol model parameters.

Saharan Dust Observations

This study initially concentrated on 17 distinct observations of Saharan dust from May to July, 2007 located over continental West Africa and nearby over the Atlantic. As these cases were analyzed via CRAM retrievals, it became clear that the retrieved aerosol backscatter and extinction ratios (532 to 1064 nm) were largely inconsistent with the present model for dust aerosol, derived from the analysis of ensemble AERONET data by Cattrall, et al., suggesting that these models were not accurately descriptive of the dust observed in terms of spectral backscatter and extinction relationships as well as the extinction-to-backscatter ratio, S_a at 1064 nm. These inconsistencies led to a closer examination of the dual-wavelength information available from the CALIPSO observations in order to revise the dust model in such a way as to be not only consistent with observations, but statistically predictive of other observations so as to improve the accuracy of CRAM aerosol retrievals made on Saharan dust. After further analysis of these 17 cases to determine as well as possible the 532 and 1064 nm Sa as well as the spectral ratios of retrieved extinction and backscatter (forming the basis for a revised model), 16 additional cases were studied to shed light on the performance of the revised model on dust events observed (in general) at greater distances from the source regions in continental West Africa.

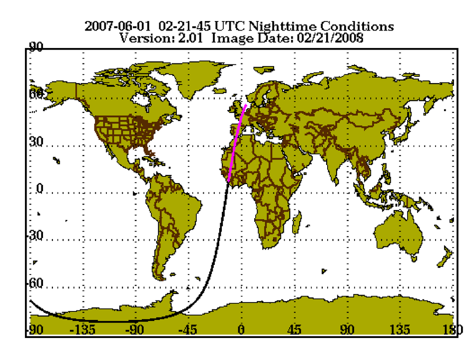
The study initially relied upon observations of lofted dust layers, as this was the only method of independently determining S_a in the absence of a satisfactory CRAM solution. So long as the scattering ratio

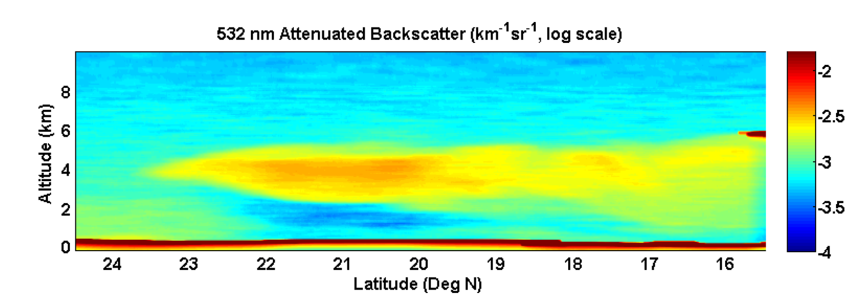
$$R = \frac{\beta_a + \beta_R}{\beta_R} \quad (3)$$

is known to be the same at points r_1 and r_2 above and below the layer, respectively, the AOD of the layer may be determined in the following manner:

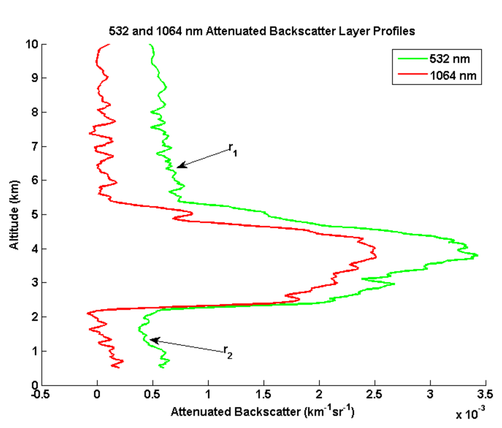
$$\delta = -\frac{1}{2}\left[\ln\left(\frac{X(r_2)}{X(r_1)}\right) + \ln\left(\frac{\beta_R(r_1)}{\beta_R(r_2)}\right) + \ln\left(\frac{T_R^2(r_1)}{T_R^2(r_2)}\right)\right] \quad (4)$$

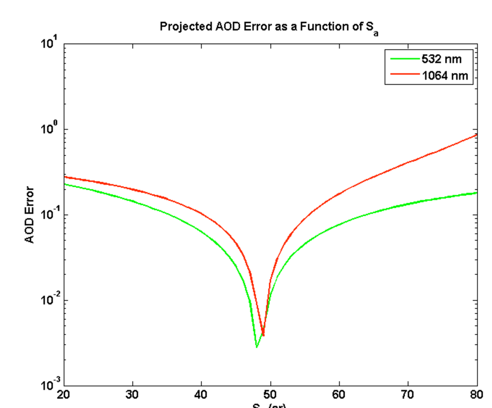
where X is the attenuated backscatter, β_R is the Rayleigh backscatter, and T^2_R is the Rayleigh transmittance. S_a is then determined by repeatedly applying the Fernald retrieval solution over a range of S_a until the retrieved AOD is consistent with that predicted by the layer transmittance analysis.





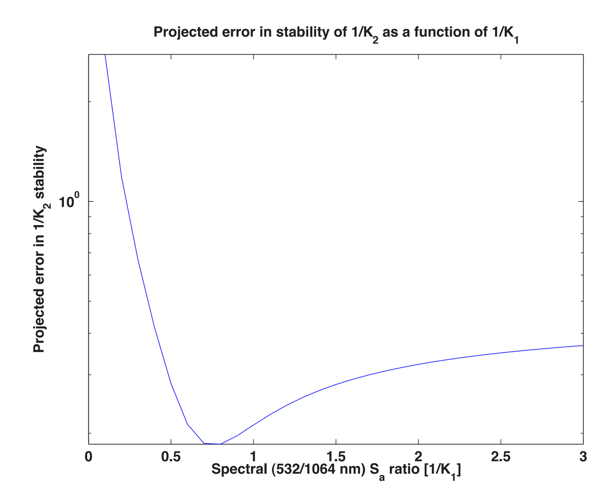
- An example of such a lofted dust layer, from a 1 June, 2007 CALIPSO orbit.

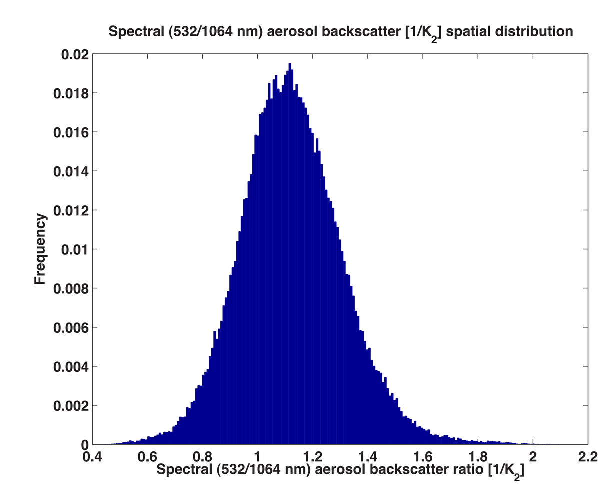




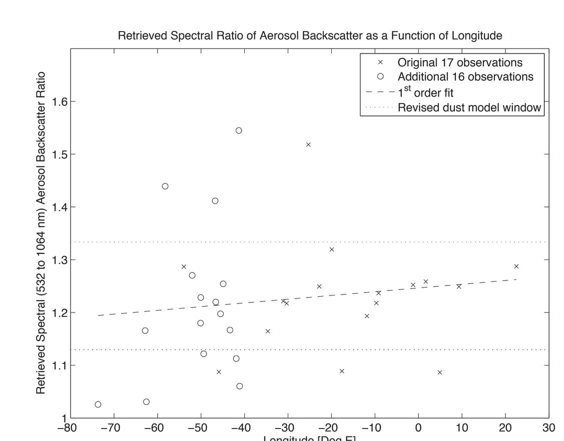
- Above, an illustration of the method of S_a determination from estimated layer transmittance.

With results of S_a from the transmittance analysis at 532 nm consistent with established observations and models for dust, solutions at 532 nm were assumed to be correct, with disagreement at 1064 nm giving rise to the poor CRAM fits. E-CRAM analysis was then performed on a number of lofted layers from which a reliable 532 nm solution was available.





- Example E-CRAM analysis for Saharan dust
- At left, a value of $1/K_1$ of ~0.8 minimizes $1/K_2$ spatial variability
- "Revised" model parameters formed with S_a at 1064 nm ~52±7 sr and S_a at 532 nm ~45.3±5 sr, and spectral ratios of backscatter and extinction of ~1.23±0.10 and ~1.29±0.11, respectively.



- Comparison of retrievals of the spectral ratio of aerosol backscatter from a number of independent dust observations, demonstrating the applicability of the "revised" model (created from a subset of the total number of observations, 17 of 33 total) to dust more generally.
- The trend shows little longitudinal variation based on the revised model parameters, suggesting little variation in aerosol parameterization close to dust source regions vs. at greater distances in the Atlantic.

Acknowledgment

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