LIDAR AEROSOL RETRIEVALS FROM ICESAT USING A MODEL-BASED CONSTRAINED RATIO APPROACH

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1. INTRODUCTION

Global measurements of aerosol by satellite lidar are now a reality. There has long been a concern that quantitative interpretation of such data for extinction and optical depth would not be reliable due to the known high sensitivity of the lidar signal to multiple parameters (i.e., relation between the lidar observed backscatter cross section and extinction cross section for aerosol). Basic processing algorithms initially in use rely on location based look-up tables. In this paper we test an alternative procedure that would instead rely on the information content of the ratio of cross sections at two lidar wavelengths.

It is well known that aerosol backscatter and extinction profiles cannot be retrieved unambiguously from lidar observations without an assumption linking aerosol extinction and backscatter (e.g., that the extinction-to-backscatter ratio S_a is reasonably spatially constant through a solution layer) as well as also requiring additional boundary value or parameter specification information (e.g., a layer optical depth or specified value of S_a). For the mid-visible region (~550 nm), S_a typically ranges between ~20 to 80 depending on aerosol type. But simply selecting the mean of S_a values cited in the literature is subject to too much uncertainty (S_a standard deviation ~ 30%) to yield retrievals that are as useful as one would like for accurately quantifying aerosol radiative effects.

A recent in-depth analysis of the global aerosol solar radiometer network, AERONET, database has defined a relatively few, well defined aerosol types/models that predominately characterize aerosols observed around the world (Cattrall et al., 2005). These model aerosols have well bounded S_a standard deviations of ~ 15% or less. However, assuming a specific model/S_a value for a given retrieval, even using climatological/geographic considerations in the model selection, does not assure that the model really applies/that the retrieval is really correct. A Constrained Ratio Aerosol Model-fit (CRAM) approach (Reagan et al., 2004) can be applied to further bound/reduce uncertainty in the retrievals. Specifically, the aerosol models are characterized by spectral ratios (i.e., dual-wavelength, 532 to 1064 nm, ratios of backscatter, extinction and S_a), with uncertainty windows, that permit aerosol retrievals to be obtained subject to the constraint that the lidar data yield retrievals with spectral ratio parameters consistent with a given assumed model (or models).

From selected dual-wavelength lidar measurements made with the Geoscience Laser Altimeter System (GLAS) on the ICESat mission, profiles of aerosol backscatter and extinction and layer averaged S_a values have been retrieved by successfully applying CRAM to both smoke and dust layers. As these layers were elevated with clean regions below them, this permitted an independent determination of S_a via the direct-transmittance retrieval approach, which further substantiated that the layers were well characterized by the assumed dust and smoke models. Other cases, such as Urban/Industrial aerosol types, have also been investigated with the available GLAS data. The paper and presentation will include an overview of the CRAM approach and discussion of the results obtained from these CRAM based retrievals for a number of interesting aerosol cases.

2. LIDAR RELATIONS AND RETRIEVAL APPROACHES

The normalized lidar signal (range-squared and pulse energy normalized) or what is often referred to as the attenuated backscatter signal X(r), versus range r depends directly upon the atmospheric backscatter and extinction coefficients, β(r) and σ(r), respectively,

$$X(r) = C\beta(r)\exp\left[-2\int_0^r \sigma(r')dr'\right] \qquad (1)$$

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where C is the lidar calibration constant. This equation assumes that only single scattering is important and applies for a given lidar operating wavelength, λ. For λ selected to avoid molecular absorption regions, $\beta(r)$ and $\sigma(r)$ are due to the combined effects of air molecules (Rayleigh scattering) and atmospheric aerosols; $\beta(r)$ and $\sigma(r)$ may be expressed as

$$\beta(r) = \beta_a(r) + \beta_R(r) \tag{2}$$

and

$$\sigma(r) = \sigma_a(r) + \sigma_R(r) \tag{3}$$

where the subscripts a and R stand for aerosol and molecular (Rayleigh) components, respectively.

The Rayleigh factors $\beta_R(r)$ and $\sigma_R(r)$ may be theoretically determined from the Rayleigh scattering law and knowledge of the atmospheric temperature and pressure structure. However, an assumption linking aerosol extinction and backscatter(e.g., that S_a is spatially constant through a solution layer) must still be assumed for solving the lidar equation, which has two unknowns but only one measurement. Following the approach of Fernald et al. (1972), an analytic solution for $\beta_a(r)$ may be obtained for the general two types of scatterers case (when both molecular and aerosol scattering are important):

$$\beta_a(r) = \frac{X(r)\exp\left[-2(S_a - S_R)\int_{r_c}^{r}\beta_R(r')dr'\right]}{CT^2(r_c) - 2S_a\int_{r_c}^{r}X(r')\exp\left[-2(S_a - S_R)\int_{r_c}^{r'}\beta_R(r'')dr''\right]dr'} - \beta_R(r) \tag{4}$$

where $S_a = \dfrac{\sigma_a(r)}{\beta_a(r)}$, $S_R = \dfrac{8\pi}{3}$, and the two-way transmittance to a down-looking reference range r_c is $T^2(r_c) = \exp\left[-2\int_0^{r_c}\sigma_a(r)dr\right]$. The retrieval relation for $\beta_a(r)$ at near IR (~1064 nm) can be simplified to a one type of scatterer case, analogous to (4), given by

$$\beta_a(r) = \frac{X(r)}{CT_a^2(r_1) - 2S_a\int_{r_1}^{r}X(r)dr} \tag{5}$$

Using equation (4) or (5), aerosol backscatter/extinction retrievals typically employ one of three constraints: (1) Auxiliary-Transmittance, where the boundary value transmittance can be obtained from auxiliary measurements; (2) Self- or Direct-Transmittance, where the boundary value transmittance can be obtained by observing the lidar signal decrease through an isolated aerosol layer; (3) Modeled Lidar Ratio, where the aerosol extinction-to-backscatter ratio is assumed to be known.

3. AERONET BASED AEROSOL MODEL PARAMETERIZATION AND ICESAT/GLAS SCIENCE MEASUREMENTS

AERONET is a globally distributed network of sun/sky radiometers, in operation over a decade, for improving knowledge of global aerosol properties. AERONET observations allow retrieval of aerosol size/refractive index information, which was reported by Dubovik et al. (2000). Cattrall et al. (2005) have analyzed AERONET data from numerous sites to determine optical parameters (e.g., S_a) for the relatively few aerosol models/types that predominantly characterize aerosols observed around the world: (1) Biomass Burning; (2) SE Asia; (3) Urban/Industrial; (4) Oceanic; (5) Dust (spheres); and (6) Dust (spheroids) by T-matrix modeling. Table 1 from Cattrall et al. (2005) gives the modeling results for S_a (lidar ratio) at ~532 nm and ~532/1064 spectral ratios of S_a, σ_a and β_a based on retrievals from data collected at selected AERONET sites (See Fig. 1 of Cattrall et al.,2005).

The Dust(spheres) case is not considered viable, as dust particles are known to be non-spherical, but it is included to show how significantly S_a is altered by particle non-sphericity. As can be seen from Table 1, the spectral ratios of β_a and σ_a are sufficiently different, including their $\pm$ standard deviation spreads, to permit some aerosol models/types to be clearly discriminated (e.g., dust from smoke (Biomass burning) or Urban/Industrial from Oceanic). On the other hand, there is considerable overlap between the various "polluted"/high S_a models (Biomass burning, Urban/Industrial and SE Asia), but as their 532 nm S_a values are fairly close, they will all yield about the same extinction profiles. If additional auxiliary information were available (e.g., Angstrom exponent, depolarization, S_a, etc.), it would be possible to more finely discriminate between the aerosol types using the various table parameters and the auxiliary information.

Aerosol type	Lidar ratio (SD)[a]	S_a ratio	β_a ratio	σ_a ratio
Biomass burning	60 (8)	2.1± 0.3	1.8 ± 0.3	3.8 ± 0.4
SE Asia	58 (10)	1.5 ± 0.3	1.6 ± 0.2	2.4 ± 0.3
Urban /Industrial	71 (10)	1.9 ± 0.3	1.6 ± 0.2	3.3 ± 0.5
Oceanic	28 (5)	1.0 ± 0.2	1.4 ± 0.1	1.5 ± 0.4
Dust (spheres)	15 (2)	1.6 ± 0.2	0.7 ± 0.1	1.2 ± 0.1
Dust (spheroids)	42 (4)	1.2 ± 0.1	0.9 ± 0.1	1.2 ± 0.1

Table 1. Summary of Lidar Parameters Retrieved from Selected AERONET Sites ([a]SD = Standard deviatioin of Gaussian fit), Cattrall et al. (2005).

ICESat was launched on January 12, 2003. The ICESat Geoscience Laser Altimeter System (GLAS) provides two types of observations: 1) surface altimetry for ice sheet, sea ice and land topography studies and 2) atmospheric lidar soundings for cloud and aerosol studies. The atmospheric lidar provides 532 and 1064 nm laser backscatter profiles from clouds and aerosols with 75 m vertical resolution. The diameter of the laser footprint on the ground is ~70 m and the distance between the centers of two adjacent laser footprints is ~170 m. Samples of data collected by GLAS off the coast of West Africa, thought to be dust, and along the Southeast African coast, thought to be smoke, have provided a test bed for the CRAM approach. Additionally, what are likely Urban/Industrial aerosol types have also been investigated using some of the available GLAS observations of the continental mixed boundary layer over India. GLAS attenuated backscatter height-position images of these sample data sets are shown in Figs. 1, 2 and 3.

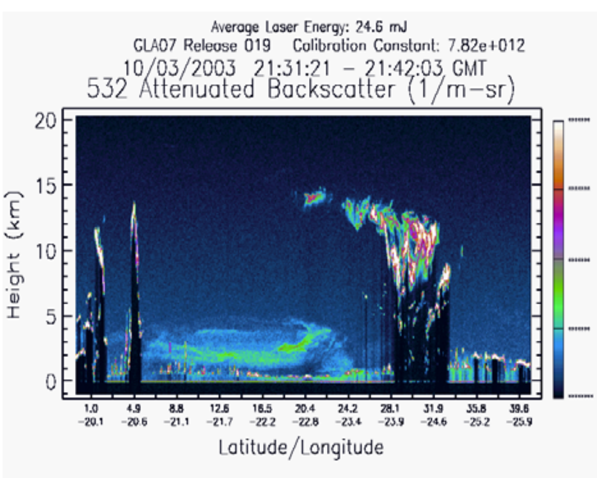

Figure 1. GLAS image of assumed elevated dust layer off West African coast.

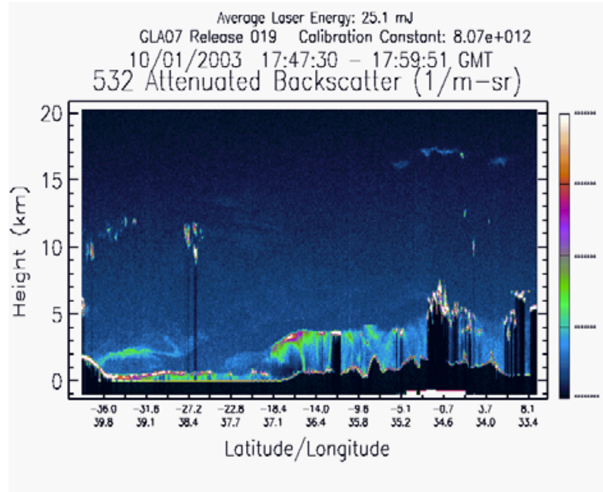

Figure 2. GLAS image of assumed elevated smoke layer along Southeast African coast.

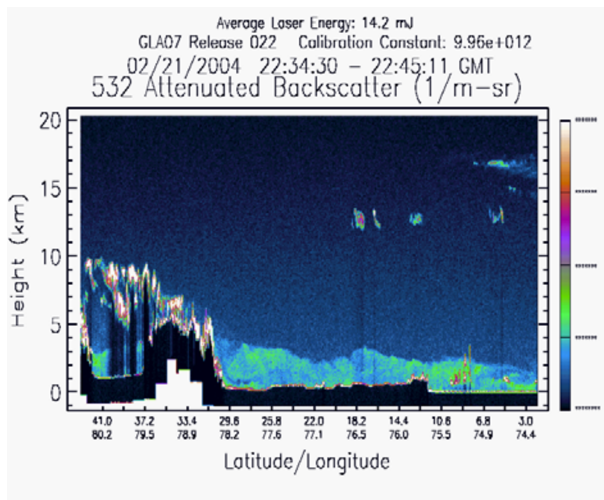

Figure 3. GLAS image of assumed Urban/Industrial mixed boundary layer aerosol over India.

4. CRAM ASSISTED LIDAR RETRIEVAL APPROACH

To implement the CRAM approach, lidar signals, X(r), are used in the lidar retrieval relations, (4) or (5), to retrieve $\beta_a(r)$ and $\sigma_a(r)$ at 532 and 1064 nm for a model set of assumed S_a values ($S_{a,\mathrm{mean}}$ and $S_{a,\mathrm{mean}}$ ± SD for given model). With the available GLAS data (Figs. 1-3), the CRAM approach was applied to three cases: elevated dust layer (Dust spheroids), elevated smoke layer (Biomass burning) and continental mixed boundary layer (Urban/Industrial). The resulting ratios of $\sigma_{a,532}/\sigma_{a,1064}$ and $\beta_{a,532}/\beta_{a,1064}$, retrieved from the GLAS lidar signals, are compared to the expected ratios for the assumed aerosol model type to verify if the retrievals are in agreement/consistent with the model assumption (i.e., retrieved spectral ratios, if correct, should fall within model spectral ratio windows due to model spread in S_a*).*

5. RESULTS AND DISCUSSION

The aerosol backscatter and extinction spectral ratios retrieved from the GLAS data for the three assumed aerosol model cases (Dust (spheroids), Biomass burning and Urban/industrial), obtained by averaging the retrieved profiles over the whole aerosol layer, are shown in Figs.4-5, respectively. As can be seen from the figures, the retrieval results obtained by assuming the aerosol model S_a and S_a ratio for the elevated dust layer (Dust spheroids) off the Western African coast, elevated smoke layer

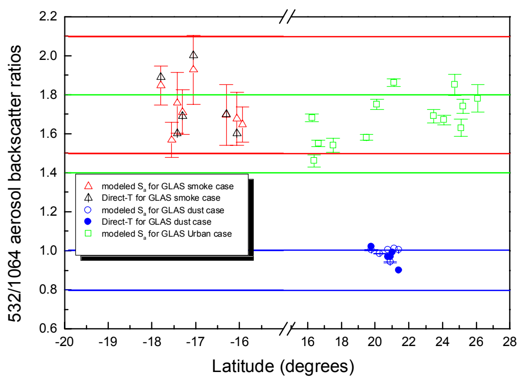

Figure 4. The retrieved 532/1064 aerosol backscatter ratios for GLAS Biomass burning, Dust(spheroids) and Urban/Industrial cases with Modeled-S_a approach and Direct-Transmittance approach, respectively.

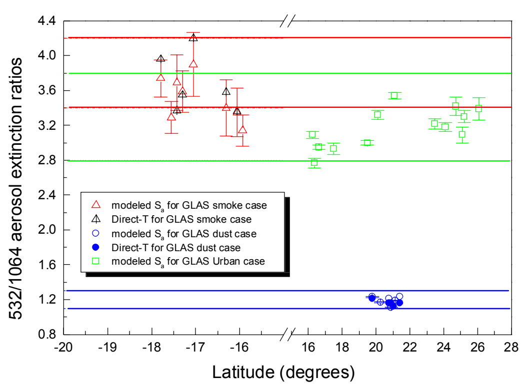

Figure 5. The retrieved 532/1064 aerosol extinction ratios for GLAS Biomass burning, Dust(spheroids) and Urban/Industrial cases with Modeled-S_a approach and Direct-Transmittance approach, respectively.

(Biomass burning) off the Southeastern African coast and the mixed boundary aerosol layer (Urban/Industrial) over India are in excellent agreement with the corresponding ratios in Table 1. In these two figures, the pair of horizontal red lines delineate the lower and upper limits of the backscatter (Fig. 4) and extinction (Fig. 5) spectral ratios for the Biomass burning model, while the green lines and blue lines represent the lower and upper limits of these ratios for the Urban/Industrial and Dust(spheroids) models, respectively.

The independent Direct-Transmittance results obtained for the elevated smoke and dust cases provide further validation of the assumed model results. As noted earlier regarding the retrieval relations (4) and (5), knowing the transmittance of a layer permits retrieval of the layer aerosol backscatter profile, S_a of the layer and, hence, the aerosol layer extinction profile ($\sigma_a = S_a\beta_a$). The Direct-Transmittance approach estimates the layer round-trip transmittance from the lidar signal decrease between the top and the bottom of the layer (for a down-looking lidar). To obtain an accurate transmittance estimate, the clean region aerosol backscatter must be nearly the same above and below the layer. As β_a is typically well less than β_R in clean regions for 532 nm, some variability in the background aerosol backscatter can be tolerated and still yield reasonable estimates of round-trip layer transmittance (i.e., with uncertainties in the 10% to 20% range).

Figure 6 shows the backscatter spectral ratio windows for the various aerosol types from Table 1 (excluding Dust (spheres) case) plotted versus the 532 nm S_a. Included in the plot (the "x" points) are the Direct-Transmittance determined results for S_a (abscissa value) and the resulting backscatter spectral ratio (ordinate value) for the several lat/long positions where Direct-Transmittance estimates were obtained in either the smoke or dust layer. As can be seen, the smoke layer S_a values (red "x" points) fall almost totally in the Biomass burning model window, while the dust layer S_a values (blue "x" points) fall in or quite close to the Dust model window. The scatter in each set of points (smoke or dust sets) is attributed to uncertainties in the estimated direct-transmittances and/or variability in aerosol physical properties. It is clear that the mean of each set of points would fall within the respective model window.

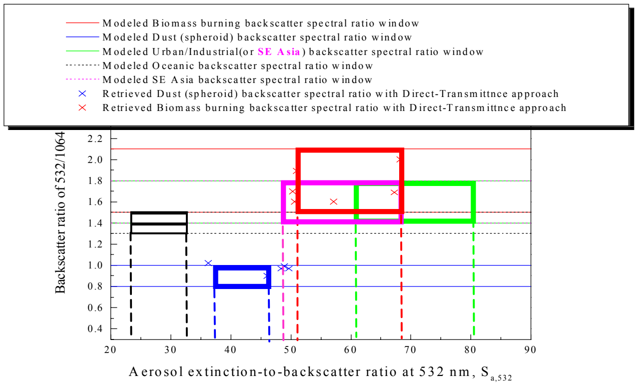

Figure 6. The model spectral backscatter ratio windows for Dust (spheroids), Biomass burning, Urban/Industrial, Oceanic and SEA cases. Also included are the corresponding results from Direct-Transmittance retrievals for Dust (spheroids) and Biomass burning cases.

As a final result, Fig. 7 shows the 532 nm layer aerosol optical depths obtained from the layer aerosol extinction profile retrievals at several positions for the three cases discussed here (i.e., from GLAS data shown in Figs. 1-3). Layer optical depths are shown as obtained by the Direct-Transmittance approach, when available, and for the various assumed model aerosol types, as already discussed in connection with Figs. 4-6. The uncertainty bars on the Modeled-S_a results are due to the standard deviation spread in S_a associated with each aerosol model (i.e., shown in Table 1). The Direct-Transmittance determined results obviously also have some uncertainties (as discussed relative to the scatter in S_a points in Fig. 6), likely about same as that due to the spread in S_a associated with the modeled-S_a approach, but such uncertainty estimates have not been added to the Direct-Transmittance determined layer optical depths. The most important point is that the modeled-S_a and Direct-Transmittance results are in quite good agreement.

6. CONCLUSIONS

Employing CRAM on dual-wavelength spaceborne lidar data in conjunction with improved aerosol models/parameterizations provides the means for obtaining more accurate/bounded profile retrievals of aerosol backscatter and extinction and layer optical depths. The CRAM approach has been successfully employed on three different GLAS data sets to confirm/discriminate dust, smoke and urban/industrial aerosol cases. Assumed aerosol model parameters for the dust and smoke cases were independently verified by Direct-Transmittance approach lidar retrievals. For the GLAS data cases presented here, the CRAM-based retrieval approach yielded 532 nm aerosol layer optical depths ranging from ~0.1 to ~0.5, with model based uncertainty estimates typically less than ~25%. Thus, it is anticipated that applying CRAM to the CALIPSO mission lidar data (that should soon be available) will enable global aerosol optical depth (AOD) retrievals with lower errors than passive satellite retrievals, such as those from MODIS, for aerosol optical depths with values up to at least about 0.2 at ~550 nm (which is about the global mean AOD). Extensions and enhancements to CRAM incorporating additional constraints provided by combining lidar and passive satellite observations offer the promise for obtaining even more accurate space-based aerosol retrievals.

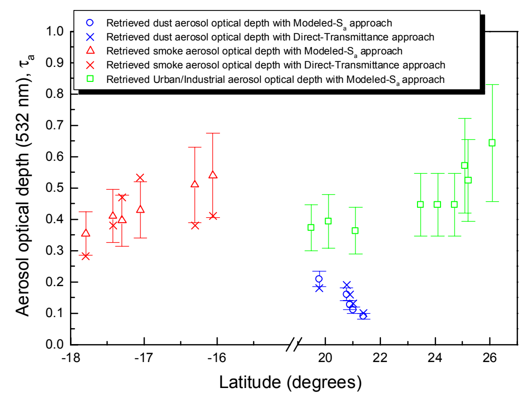

Figure 7. Aerosol layer optical depths at sample positions along GLAS tracks for three cases: dust, smoke and urban/industrial.

7. ACKNOWLEDGEMENTS

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