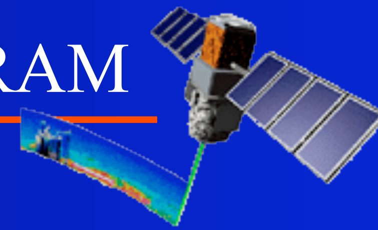
Dual-wavelength lidar aerosol retrievals via CRAM



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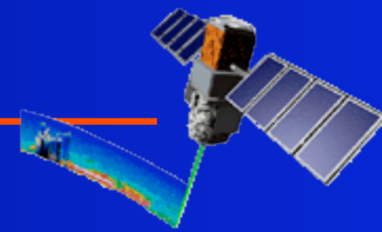
Summary – The Constrained Ratio Aerosol Model-fit (CRAM) aerosol retrieval approach is applied to dual-wavelength CALIPSO lidar (CALIOP) data, and nearly temporally/spatially coincident High Spectral Resolution Lidar (HSRL) observations collected by the NASA LaRC airborne HSRL are used to assess/validate CRAM retrievals and test extensions of CRAM.

CRAM Goal – To obtain from CALIPSO Lidar Observations better bounded, more accurate retrievals of aerosol extinction and backscatter than can be obtained with single-wavelength elastic scatter lidar retrievals.

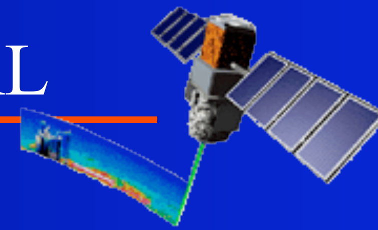
Support – This work supported by CALIPSO mission funding.

Outline



1. Introduction.
2. CALIPSO and Airborne HSRL Summary.
3. Lidar and lidar retrieval relations.
4. Retrieval uncertainty effects and HSRL observed S_a variability.
8. CRAM concept, models and retrieval approach.
9. CRAM retrieval examples/validations.
7. CRAM Saharan dust investigations/model modifications.
8. Enhanced CRAM (E-CRAM) retrieval approach and example result.
9. Conclusions.

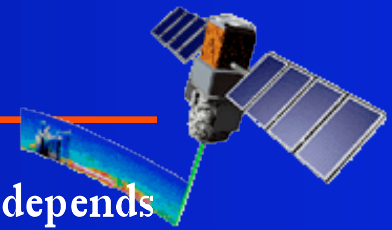
CALIPSO and Airborne LaRC-HSRL



- CALIPSO satellite with lidar CALIOP launched in April, 2006.
  - CALIOP has 532 and 1064 nm elastic scatter channels, including depolarization measurement capability at 532 nm for non-spherical scatterer (e.g., cirrus and dust) discrimination.

- NASA LaRC Airborne High Spectral Resolution Lidar (HSRL) operational since 2006, over 500 hours of measurements to date on various campaigns, including many CALIPSO validation flights
  - 532 nm HSRL channel and 1064 nm elastic scatter channel
  - Depolarization measurement capability at 532 and 1064 nm
  - By HSRL technique can unambiguously measure aerosol extinction and backscatter profiles at 532 nm, and, thus, the spatial profile of the aerosol extinction-to-backscatter ratio, S_a.

Lidar Relations and Retrieval Approaches



The normalized attenuated backscatter lidar signal, *X(r)*, versus range *r* depends directly upon the atmospheric backscatter, *β(r)*, and extinction, *σ(r)*, coefficients:

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

$$\beta(r) = \beta_a(r) + \beta_R(r)$$

$$\sigma(r) = \sigma_a(r) + \sigma_R(r)$$

a for aerosol and R for molecular (Rayleigh) components

lidar ratio $S_a = \dfrac{\sigma_a}{\beta_a}$ assumed constant with range for most lidar retrievals

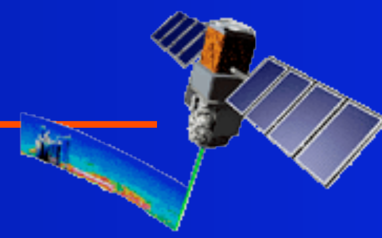
Aerosol backscatter/extinction retrievals typically employ one of three constraints:

Auxiliary-Transmittance — **boundary value transmittance from auxiliary measurements.**

Self-Transmittance — **boundary value transmittance from lidar signal decrease through an isolated layer.**

Modeled Lidar Ratio — **aerosol extinction-to-backscatter ratio, S_a, assumed known.**

Lidar Aerosol Retrieval Relations



β_a(r) retrieval relation at mid-visible (~532 nm) - Two types of scatterers approach (Fernald et al., 1972; Fernald 1984):

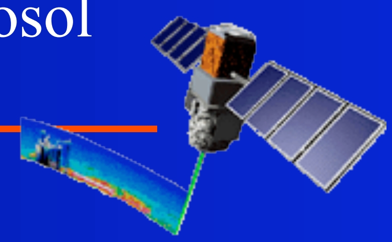
$$\beta_a(r) = \frac{X(r)\exp\left[-2\left(S_a - S_R\right)\int_{r_c}^{r}\beta_R(r')dr'\right]}{CT^2(r_c) - 2S_a\int_{r_c}^{r}X(r')\exp\left[-2\left(S_a - S_R\right)\int_{r_c}^{r'}\beta_R(r'')dr''\right]dr'} - \beta_R(r)$$

β_a(r) retrieval relation at near IR (~1064 nm, aerosol only) – Simplification to one type of scatterer case:

$$\beta_a(r) = \frac{X(r)}{CT_a^2(r_c) - 2S_a\int_{r_c}^{r}X(r')dr'}$$

$$\sigma_a(r) = S_a\beta_a(r) \quad \& \quad S_R = \frac{8\pi}{3}$$

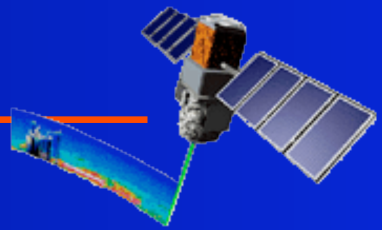
Effects of Uncertainties/Spatial Variability on Aerosol Extinction Retrievals



- Uncertainties in C, S_a and T_a^2
  - C bias error of 5% causes <~8% error in aerosol extinction retrievals.
  - S_a bias error of 15% causes <~20% error in aerosol extinction retrievals.
  - T_a^2 bias error of 15% causes <~20% error in extinction retrievals.

- HSRL measurements show S_a variability not too great
  - S_a is relatively constant about 60% of the time over 0-6 km region, S_a variations fairly random with standard deviations typically <~15%
  - Aerosol extinction retrieved using HSRL backscatter and the layer AOT (i.e., T_a^2) is within ± 15% of the aerosol extinction derived directly using HSRL technique about 60% of the time.

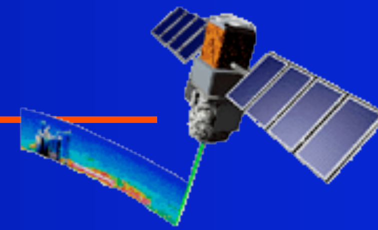
Background/CRAM Concept



- Elastic scatter lidar (e.g. CALIOP) single-wavelength retrievals of aerosol extinction, σ_a, and backscatter, β_a, profiles require the assumption that the aerosol extinction-to-backscatter ratio, S_a, is spatially constant over a solution layer, and either S_a is assumed known or a boundary condition, such as the layer transmittance, is also required to invert the lidar equation. This can be repeated for a second wavelength, which leads to the reasonable conclusion that the spectral 532/1064 ratios of S_a, σ_a and β_a are spatially constant over the solution layer. This is the basis for most dual-wavelength retrieval approaches, but sensitivities to noise and minor spatial variations require additional constraints to achieve practical retrievals.

- CRAM is an approach for achieving practical dual-wavelength lidar aerosol retrievals. It is not an inversion, but is a way of maximizing the aerosol information that can be extracted from dual-wavelength lidar data via modeling constraints. CRAM works on the most basic aerosol information available in the lidar signal, namely, the aerosol backscatter and extinction coefficients and spectral ratios thereof.

AERONET Modeling Results

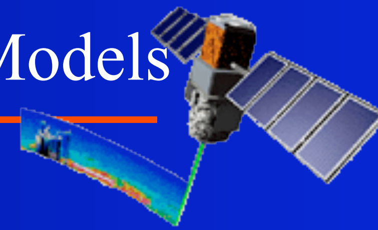


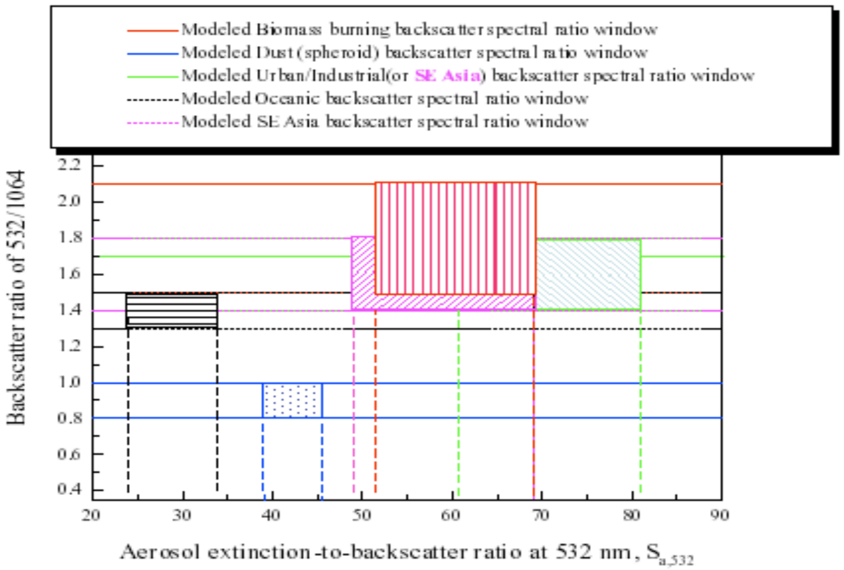
- Using AERONET database/retrievals, it was possible to obtain well defined sets of ~532 nm S_a values and spectral (550 nm to 1020 nm) ratios of S_a, β_a and σ_a for a few aerosol models/types that predominantly characterize aerosols observed around the world (Cattrall et al.; JGR 2005).

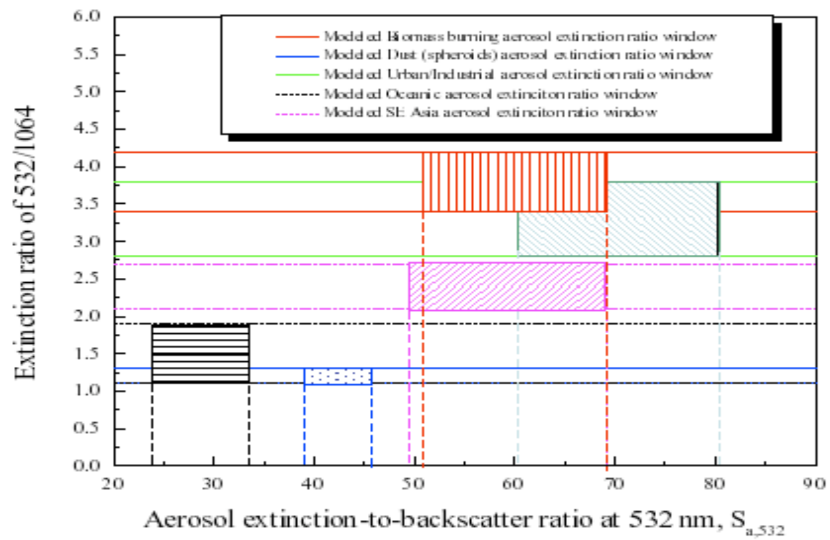
	Lidar Ratios @ 550 nm		550 to 1020 nm Ratios		
Aerosol Type	Reported in Literature	AERONET Modeled $S_a \pm$ SD	S_a ratio	β ratio	σ ratio
Biomass (Smoke)	62 ± 7	60 ± 8	2.1 ± 0.3	1.8 ± 0.3	3.8 ± 0.4
SE Asia	51 ± 5	58 ± 10	1.5 ± 0.3	1.6 ± 0.2	2.4 ± 0.3
Urban/Industrial	65 ± 4	71 ± 10	1.9 ± 0.3	1.6 ± 0.2	3.3 ± 0.5
Oceanic	29 ± 5	28 ± 5	1.0 ± 0.2	1.4 ± 0.1	1.5 ± 0.4
Dust (spheres)	n/a	15 ± 2	1.6 ± 0.2	0.7 ± 0.1	1.2 ± 0.1
Dust (spheroids)	46 ± 6	42 ± 4	1.2 ± 0.1	0.9 ± 0.1	1.2 ± 0.1

SD = Standard Deviation of Gaussian fit

Spectral Ratio Windows for AERONET Based Models



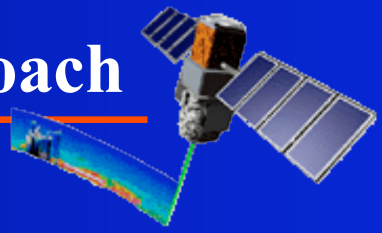




The agreement between the retrieved ratios and those predicted by the models can be evaluated quantitatively in terms of a performance function, Q

$$Q = \left(\frac{R_\beta^r - R_\beta^m}{R_\beta^m} \right)^2 + \left(\frac{R_\sigma^r - R_\sigma^m}{R_\sigma^m} \right)^2$$

CRAM Assisted Lidar Retrieval Approach



- Lidar signals, *X(r)*, are used in lidar retrieval relations to retrieve $\beta_a(r)$ and $\sigma_a(r)$ at 532 and 1064 nm for each model set of assumed S_a values (i.e., for $S_{a,\text{ mean}}$ and $S_{a,\text{ mean}} \pm$ SD for given model).
- Resulting ratios of $\frac{\beta_{a,532}}{\beta_{a,1064}}$ and $\frac{\sigma_{a,532}}{\sigma_{a,1064}}$ from retrievals are compared to expected ratios for assumed aerosol model type to verify if retrievals are in agreement/consistent with model assumption (i.e., retrieved spectral ratios, if correct, should fall within model spectral ratio windows due to model spread in S_a), thereby yielding an acceptable solution.
- A performance function, *Q*, can be used to quantitatively assess agreement in a least squares sense between the spectral $\beta_a(r)$ and $\sigma_a(r)$ ratios for a given model and those retrieved from the *X(r)* signals for different assumed model S_a values.
- Model assumption yielding minimum *Q* taken as best solution. But ratios that clearly fall outside model windows are obviously not acceptable fits, without need of Q assessment.

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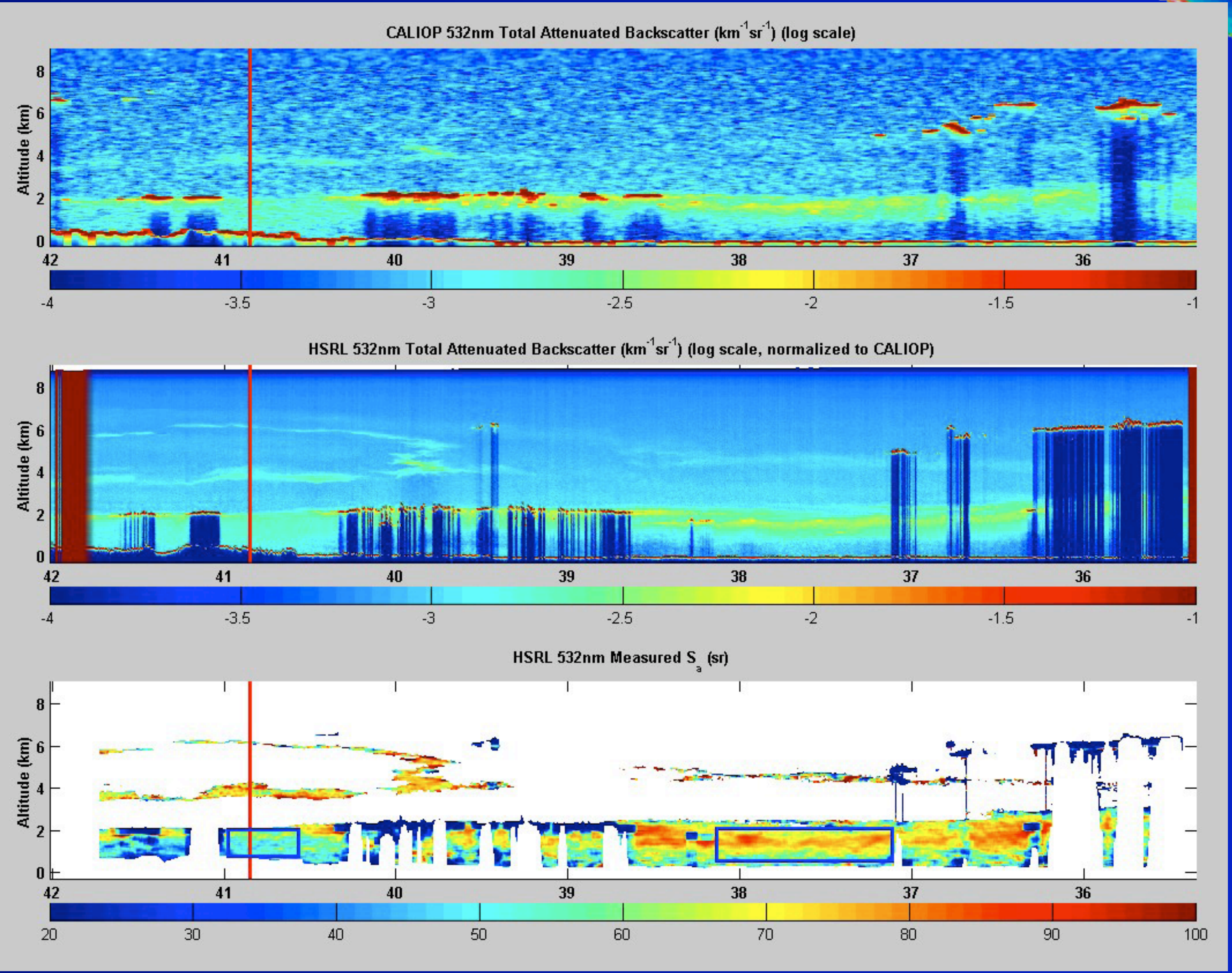
10 August, 2006 CALIPSO/HSRL Coincidence



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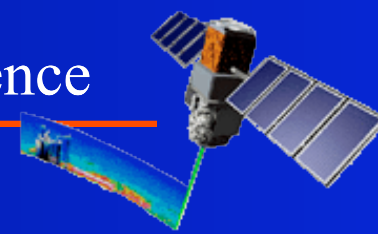
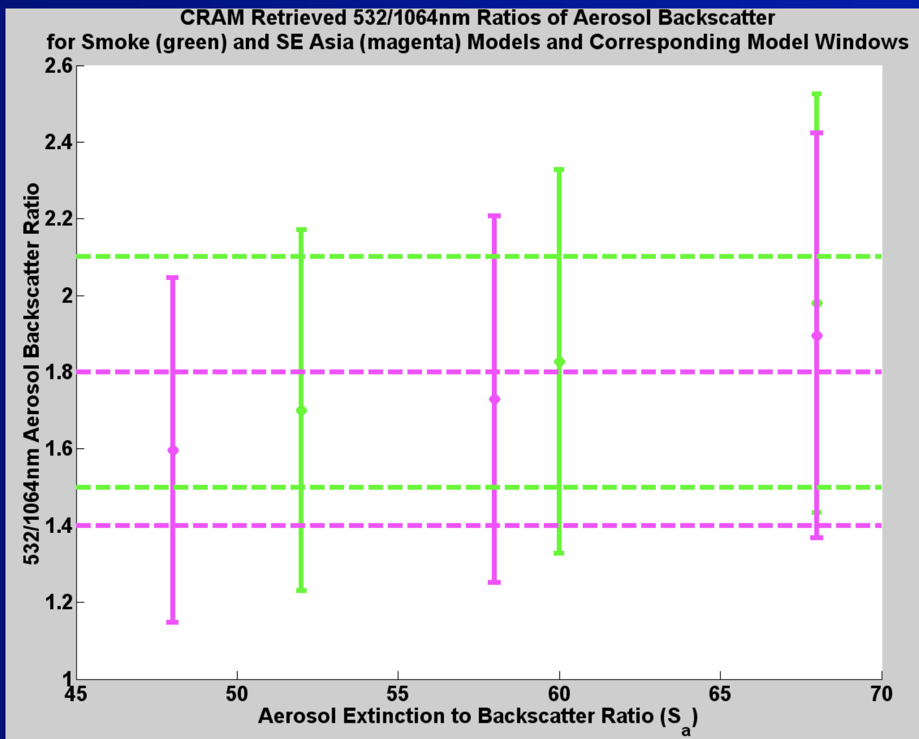
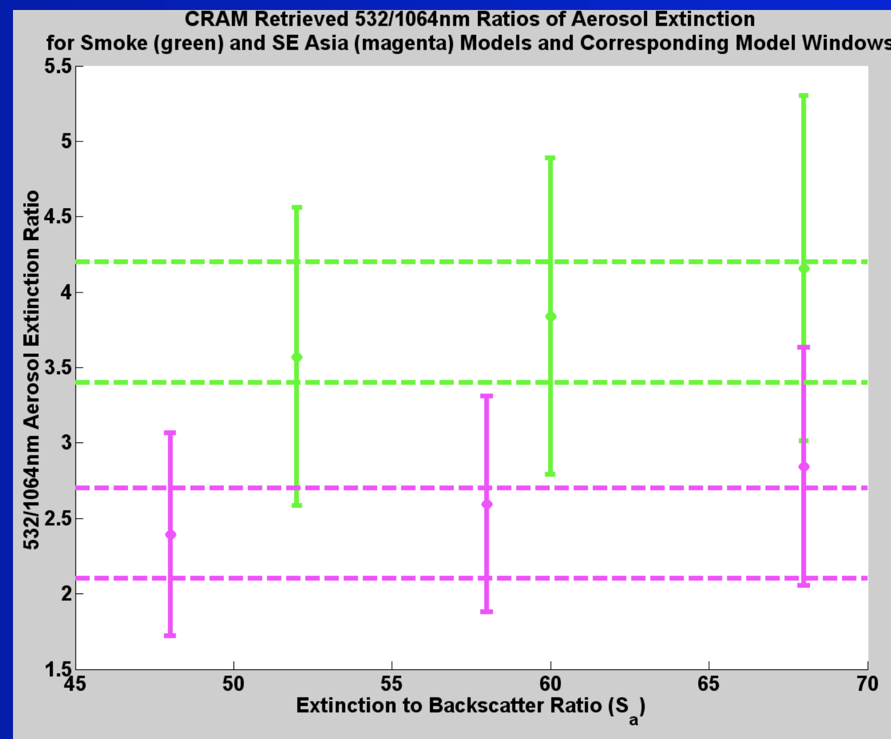
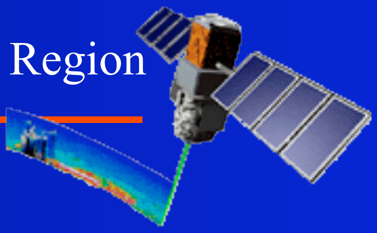


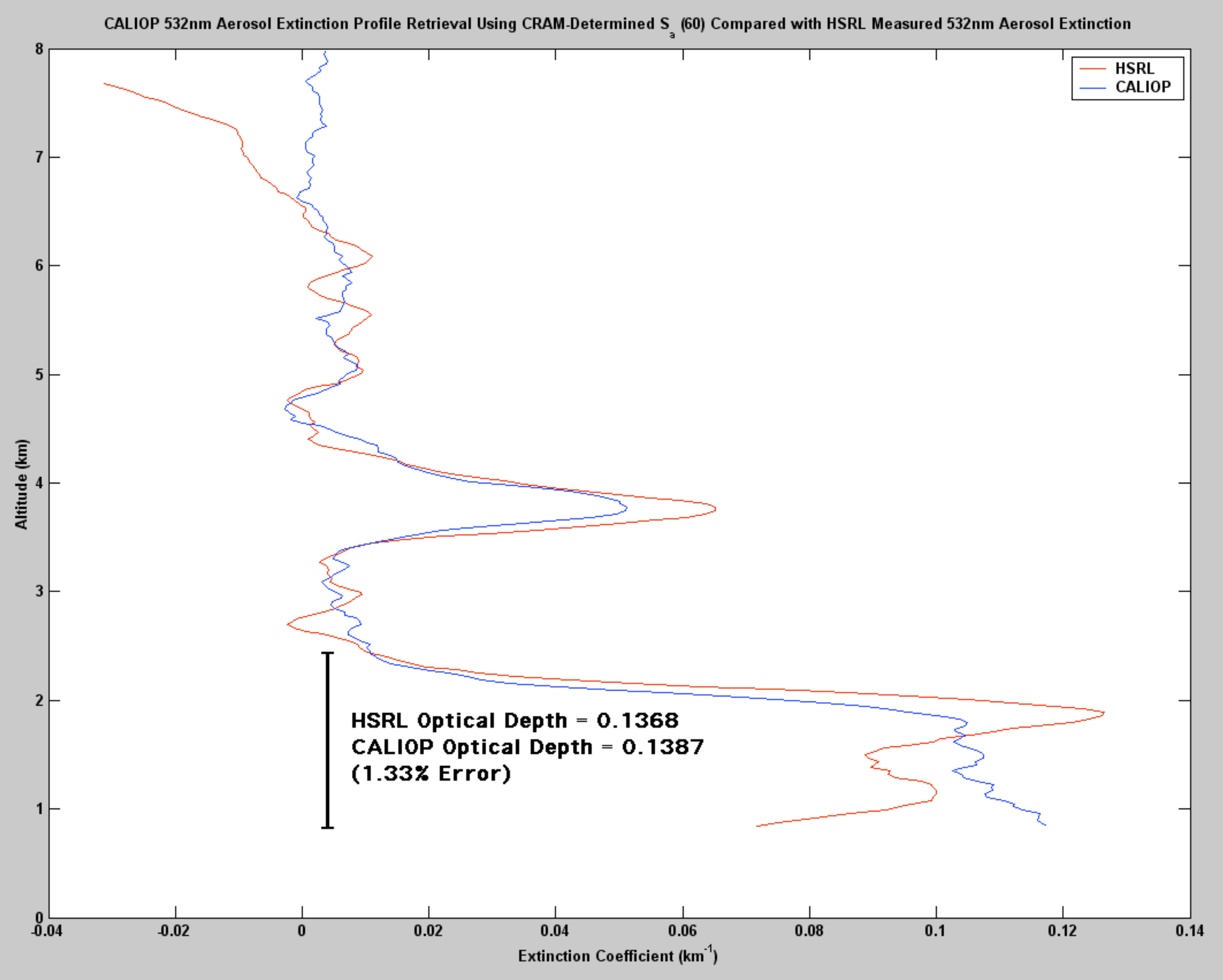




Ranges of retrieved ratios for northern region, together with corresponding CRAM model windows for Biomass and SE Asia models

10 August, 2006 CRAM Extinction Profile Retrieval, Northern Region





CALIOP/CRAM
Extinction Profile Retrievals
for Northern region

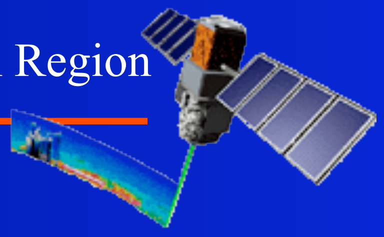
~20 km spatial averaging

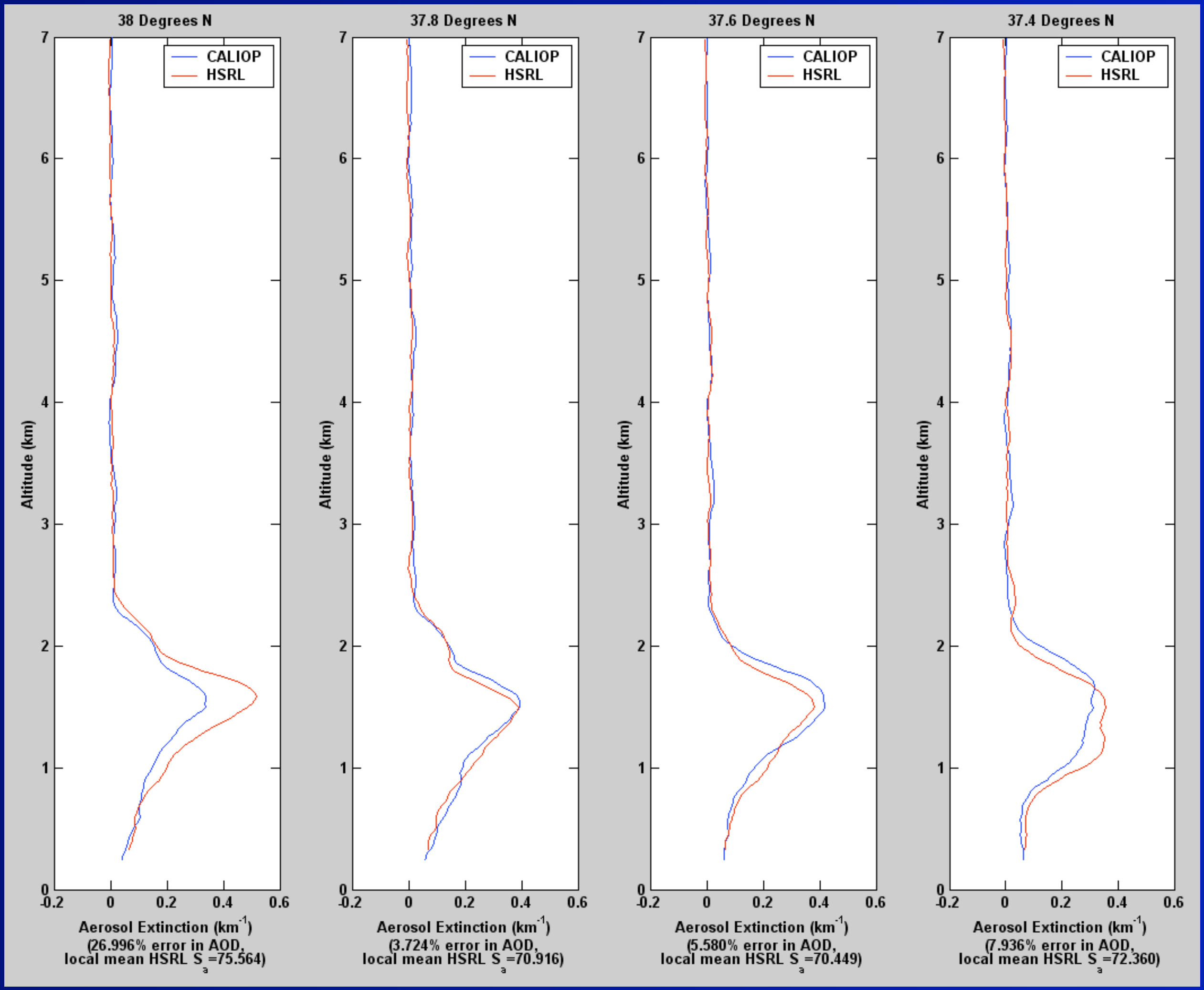
2006/08/10
40.5 N LAT
-76.0 E LON

CRAM determined S_a
(Biomass) = 60 sr

Mean HSRL S_a = 54.84 sr
STD HSRL S_a = 5.62 sr

10 August, 2006 CRAM Extinction Profile Retrieval, Southern Region





CALIOP/CRAM Extinction Profile Retrievals for Southern region

~20 km spatial averaging, 20 km separation

CRAM determined S_a (Biomass) = 60 sr

Mean HSRL S_a = 72.60 sr, for overall 80 km swath (local means on individual figures)

STD HSRL S_a = 5.373 sr

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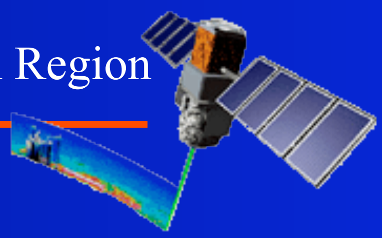
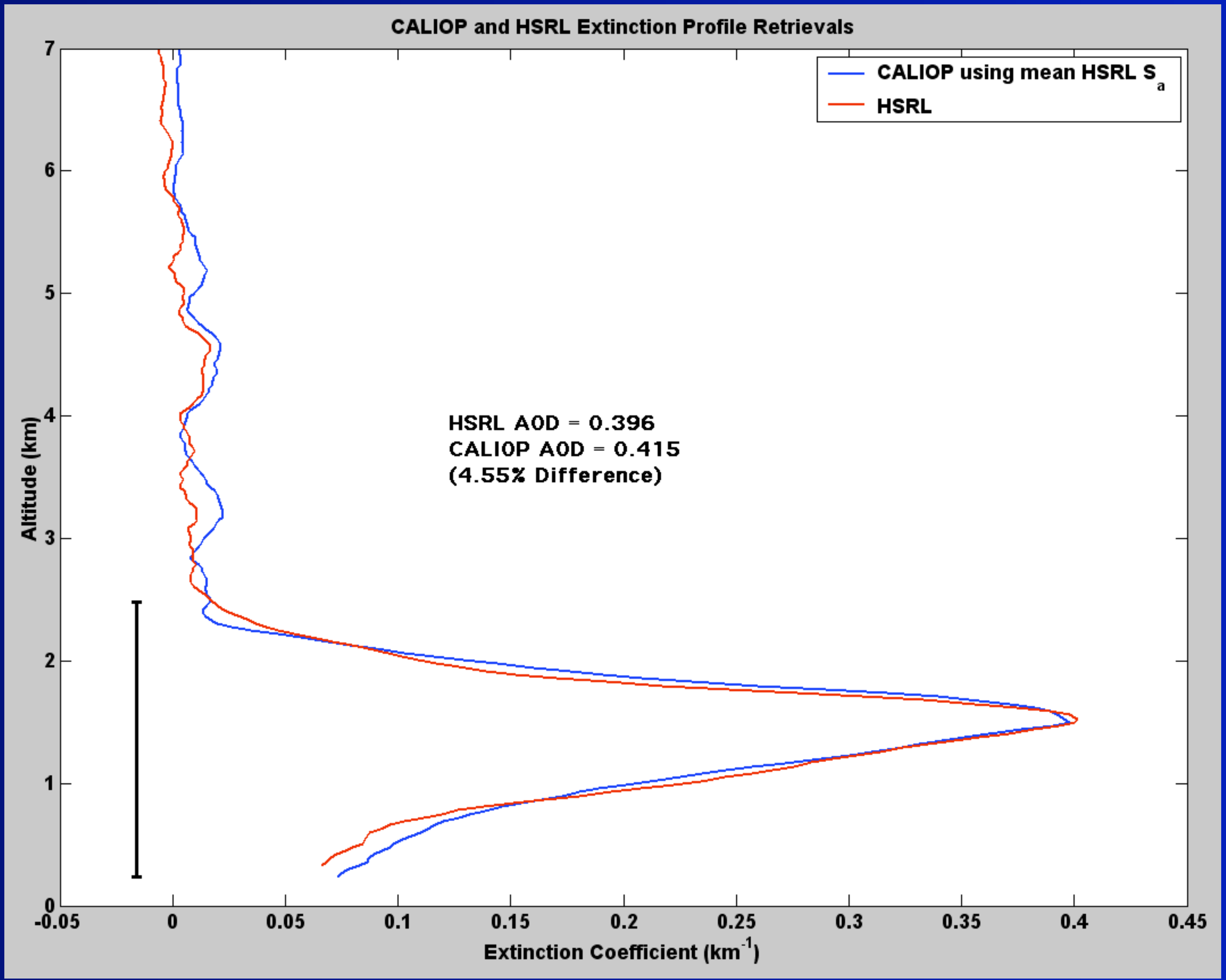
10 August, 2006 CRAM Extinction Profile Retrieval, Southern Region





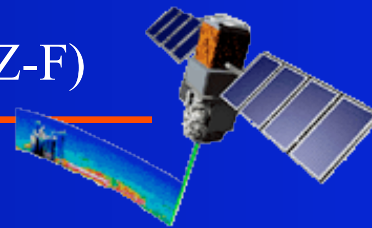
CALIOP
Extinction Profile Retrievals for Southern region, using mean HSRL S_a

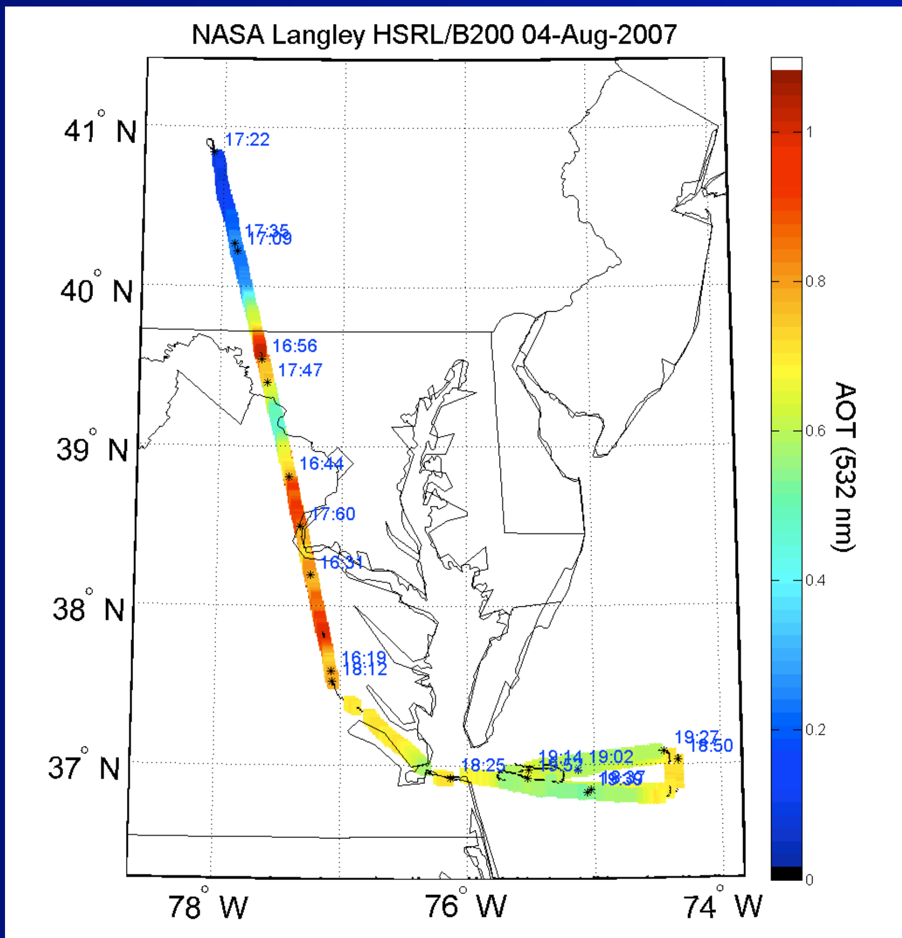
~80 km averaged swath

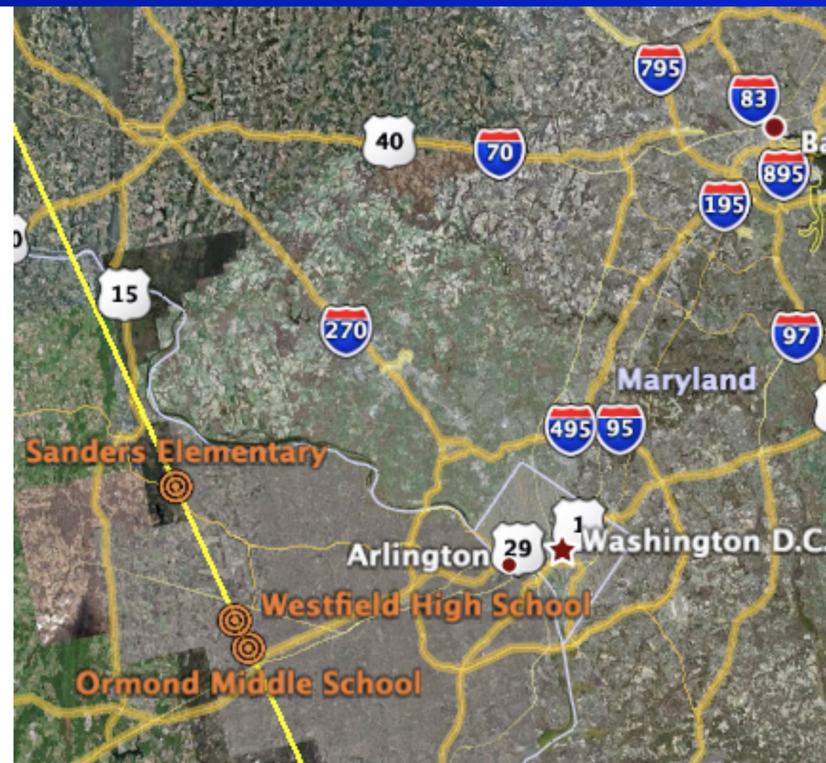
Mean HSRL S_a = 72.60 sr,

STD HSRL S_a = 5.373 sr

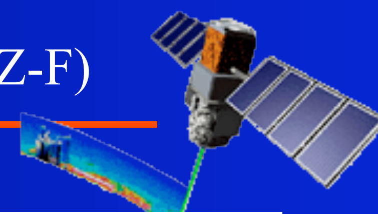
4 August, 2007 CALIPSO/HSRL Coincidence (CATZ-F)

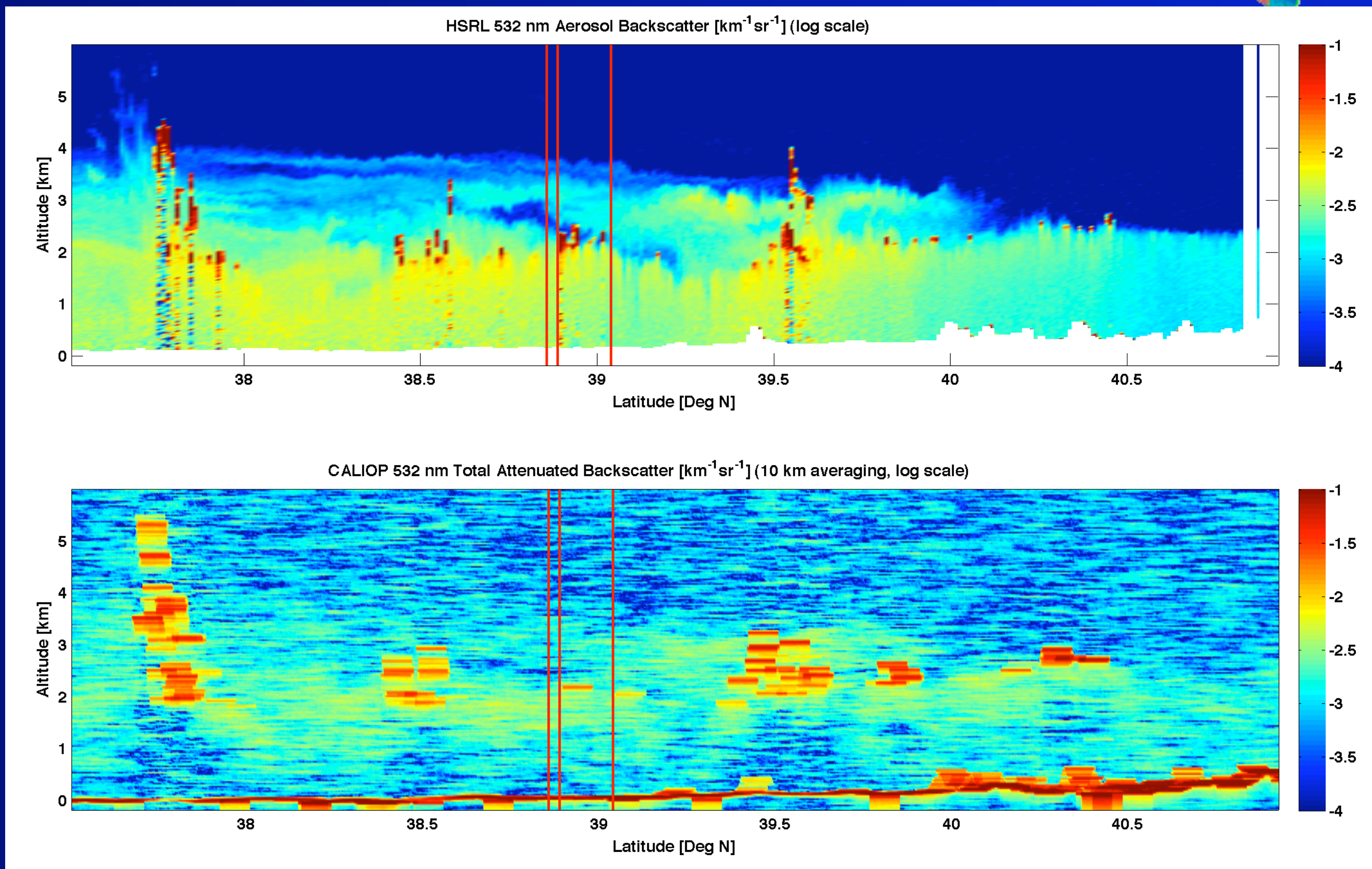




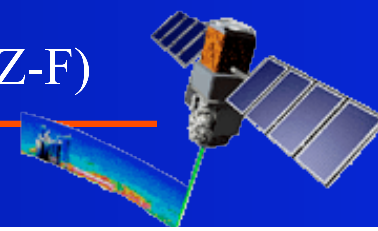


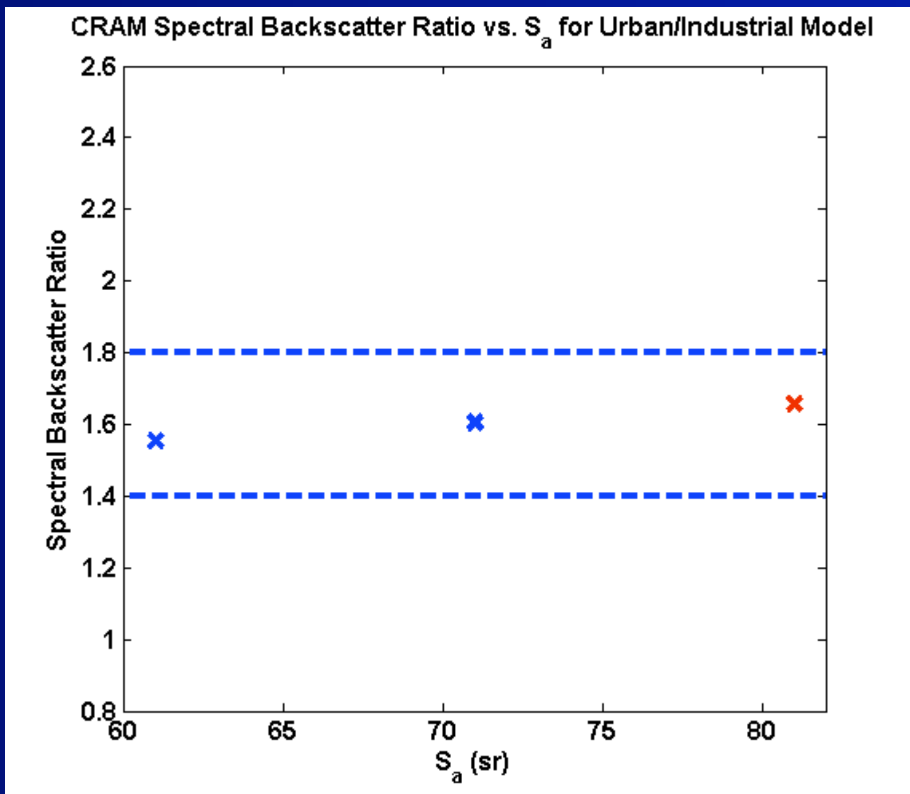
4 August, 2007 CALIPSO/HSRL Coincidence (CATZ-F)

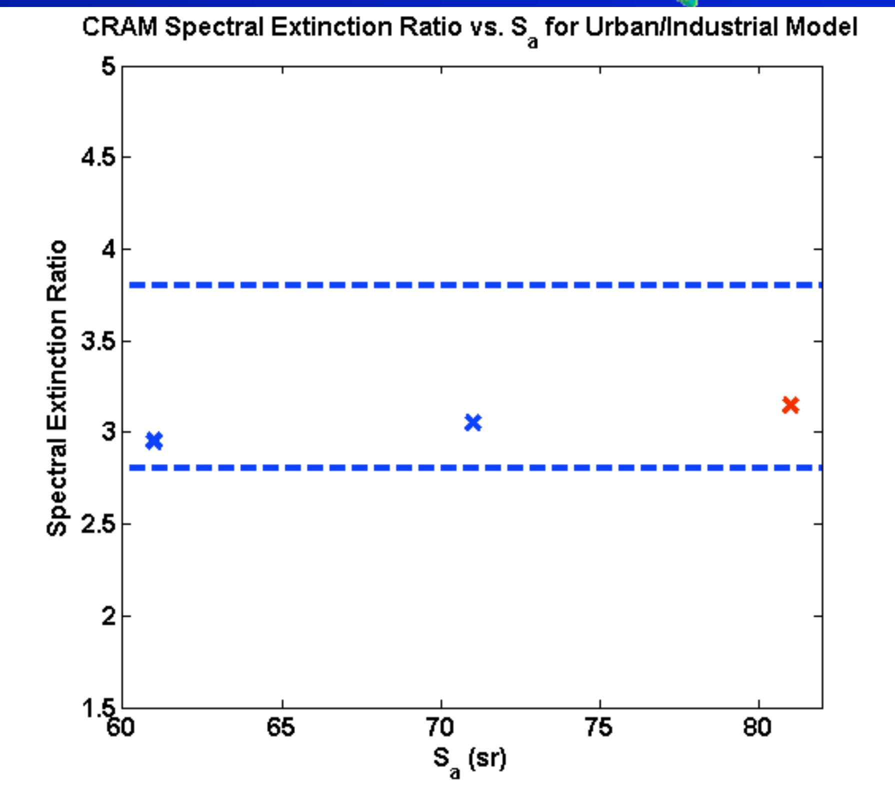




4 August, 2007 CALIPSO/HSRL Coincidence (CATZ-F)

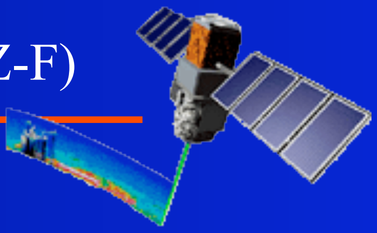




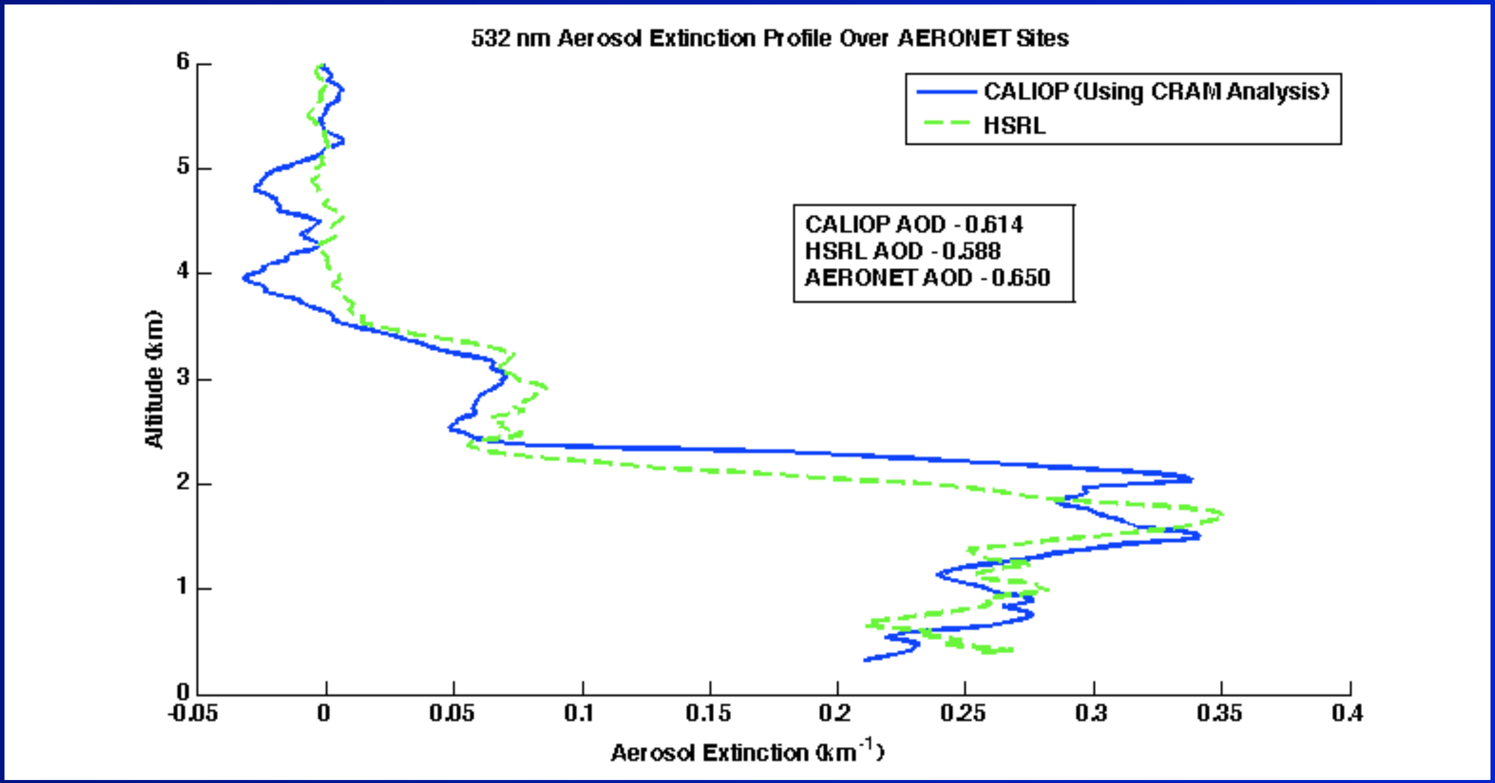


Solutions based on 40 km running average of attenuated backscatter, with CRAM solution evaluated over the neighborhood of AERONET sites (~21 km)

4 August, 2007 CALIPSO/HSRL Coincidence (CATZ-F)



HSRL/CALIOP Extinction Profile (38.85N – 39.04N)



Both CALIPSO and HSRL profiles averaged over AERONET sites (~21 km)

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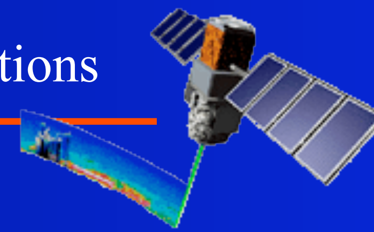
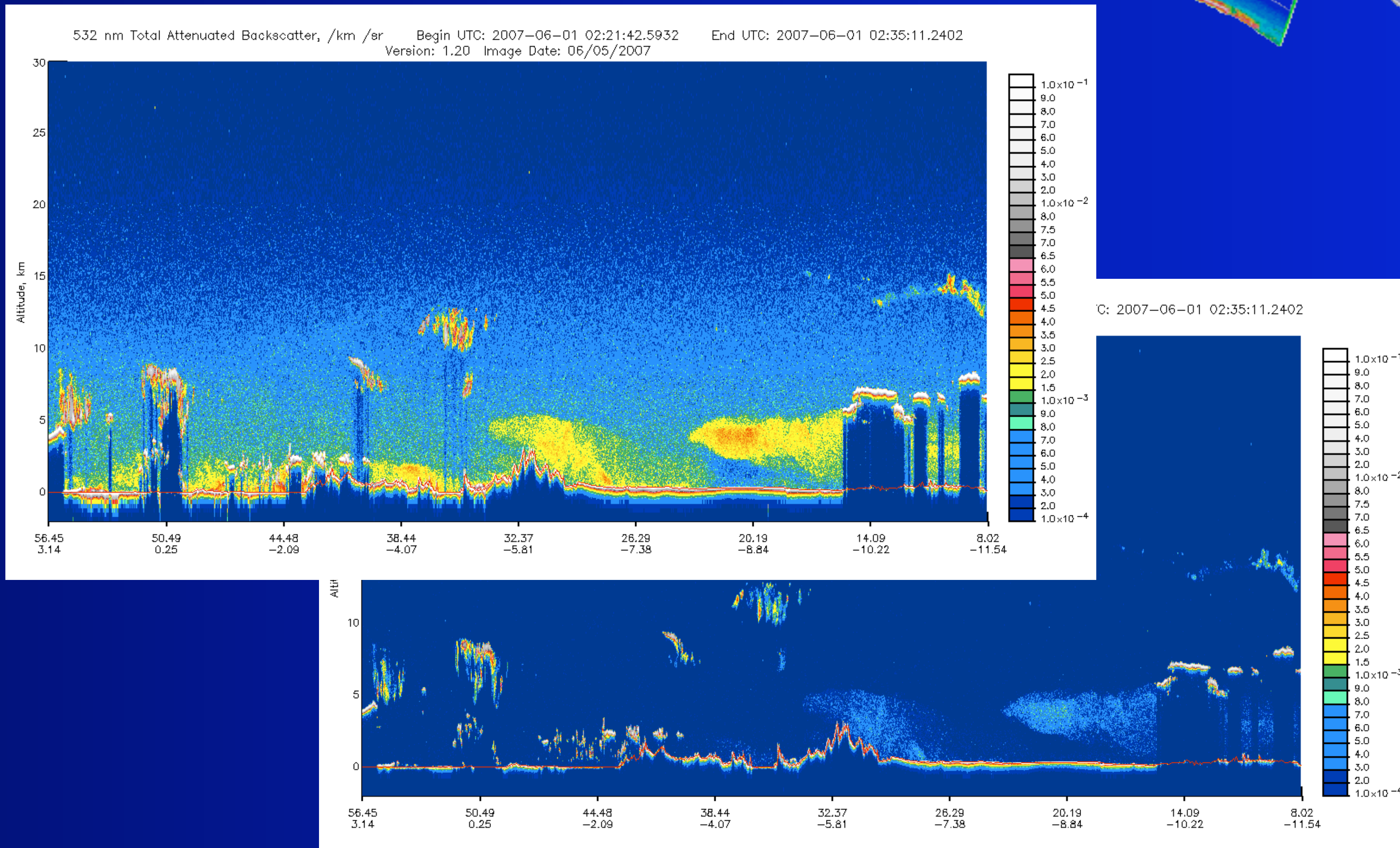
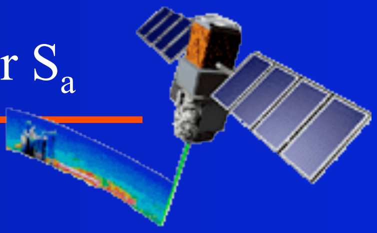
CRAM Saharan Dust Investigations/Model Modifications



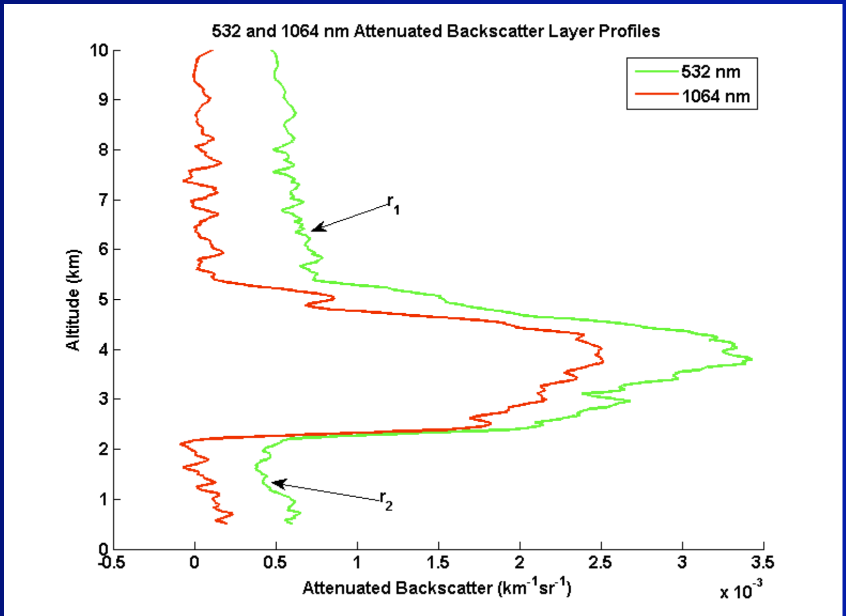


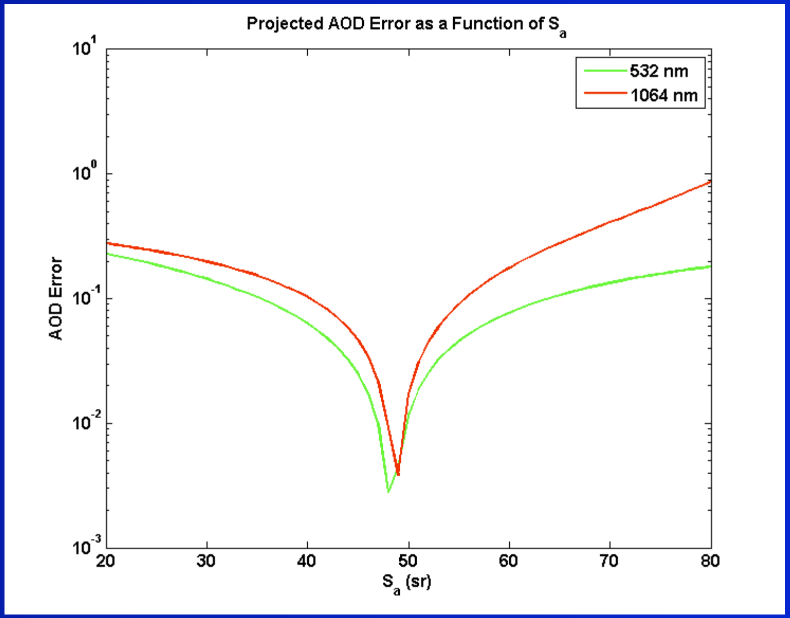
Application of Direct Transmittance to Retrieve Layer S_a



1. Determine layer optical depth

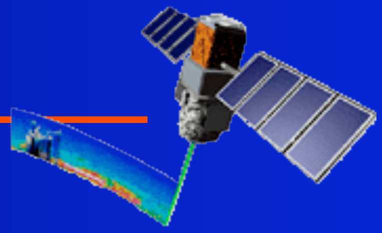
$$\tau_l = -\frac{1}{2}\left[\ln\left(\frac{X(r_2)}{X(r_1)}\right) + \ln\left(\frac{\beta_R(r_1)}{\beta_R(r_2)}\right) + \ln\left(\frac{T_R^2(r_1)}{T_R^2(r_2)}\right)\right]$$





2. Iterate over aerosol solutions (S_a values) to determine a solution matching the optical depth constraint

Direct Transmittance Results



•6 cases thought to provide reliable solutions at 532 nm, 5 at 1064 nm, yielding:

532 nm: $S_a = 45.3 \pm 5$ sr

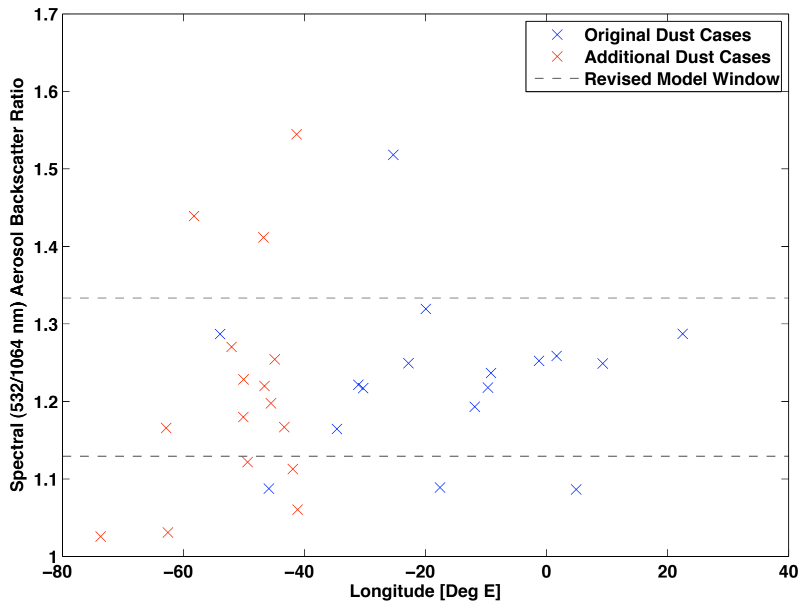
S_a ratio = 1.05 ± 0.2

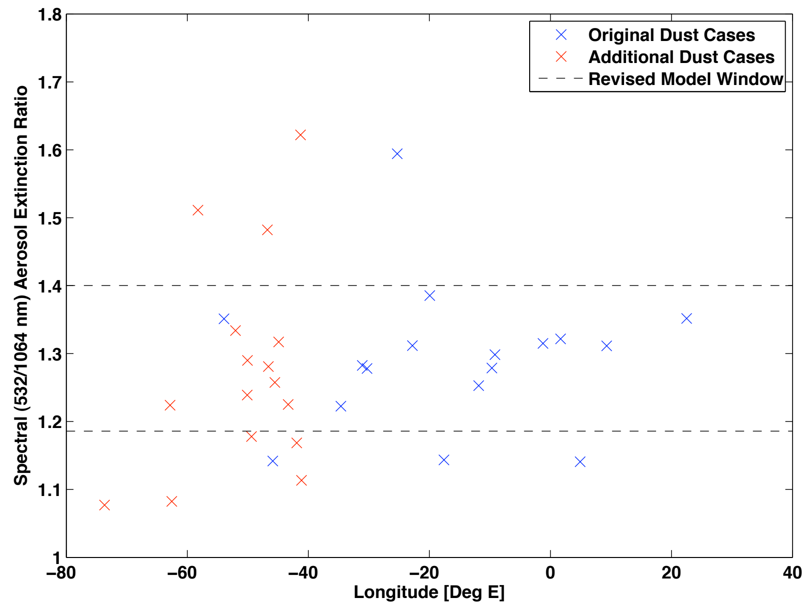
1064 nm: $S_a = 43 \pm 9$ sr

Good agreement at 532 nm, but S_a ratio different from dust model (1.2 ± 0.1)

•Use 532 nm S_a and modified S_a ratio (1.05) to statistically assess numerous dust cases and define modified model spectral σ_a and β_a ratios

Ensemble Dust Observations Within the Modified Dust Model

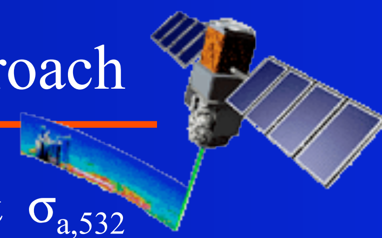




	Lidar Ratios @ 550 nm		550 to 1020 nm Ratios		
Aerosol Type	Reported in Literature	AERONET Modeled $S_a \pm$ SD	S_a ratio	β ratio	σ ratio
Dust (spheroids)	46 ± 6	42 ± 4	1.2 ± 0.1	0.9 ± 0.1	1.2 ± 0.1
Dust (Revised)	n/a	45 ± 5	1.05 ± 0.2	1.23 ± 0.10	1.29 ± 0.11

SD = Standard Deviation of Gaussian fit

Model Modification/Confirmation by E-CRAM Approach



- Start with 532 nm knowns of $S_{a,532}$ and vertical profiles of $\beta_{a,532}$ & $\sigma_{a,532}$ as provided by HSRL or from a known aerosol layer transmittance.
- For 1064 nm can reasonably assume:

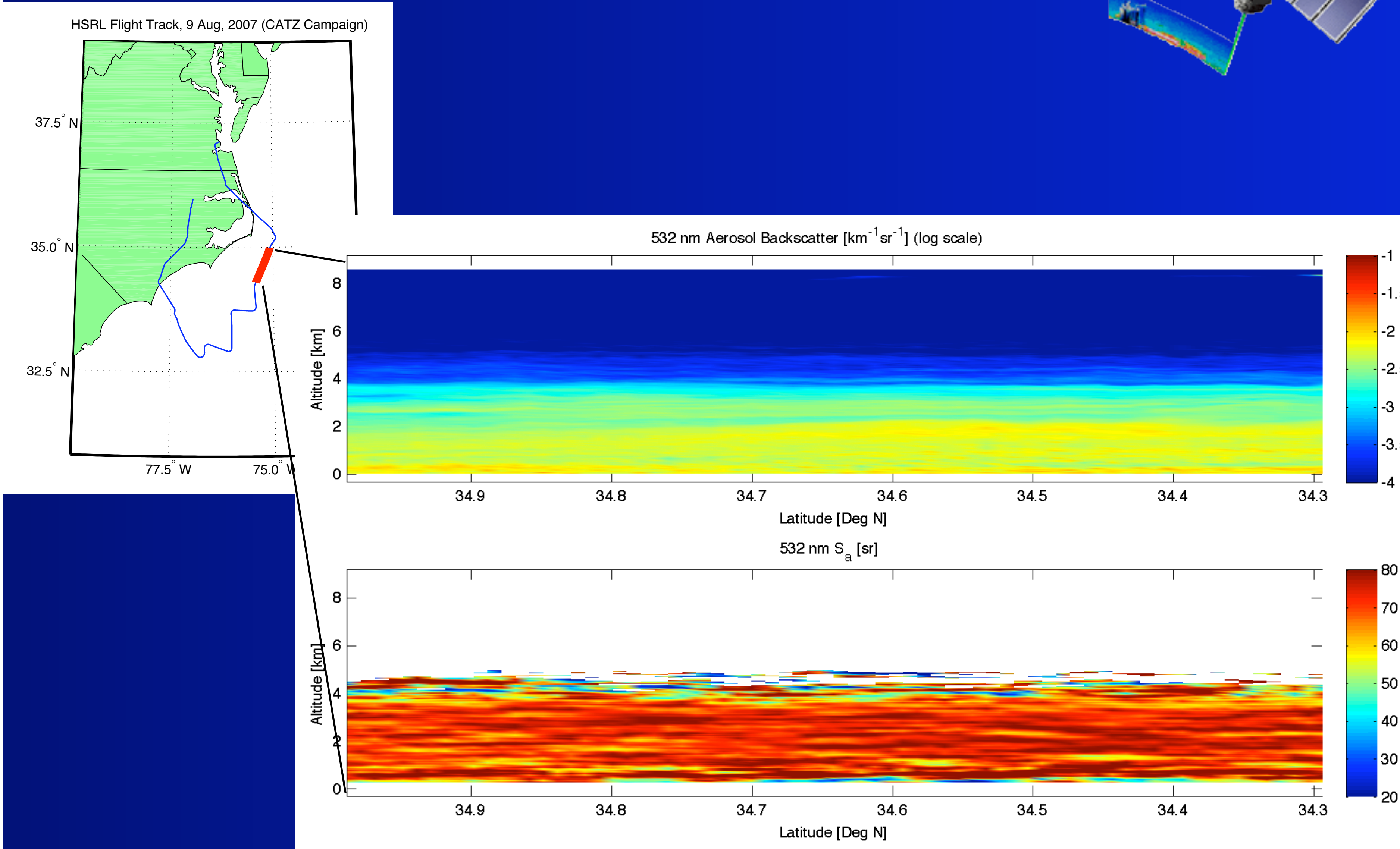
$$S_{a,1064} = K_1 S_{a,532} \qquad K_1 = \text{a constant}$$

$$\beta_{a,1064} = K_2 \beta_{a,532} \qquad K_2 = \text{a constant}$$

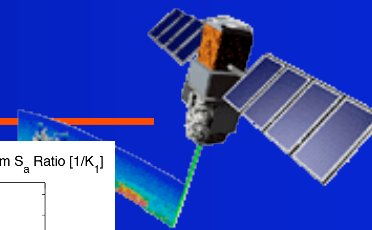
- Solve by least-squares minimization for the K_1 value which minimizes the spatial (vertical) variability of K_2.
- With K_1 determined, thus have $S_{a,1064}$ for retrievals of $\beta_{a,1064}$ & $\sigma_{a,1064}$
- Also, with 532nm knowns, then have the CRAM spectral parameters which can either confirm existing CRAM models or define new models:

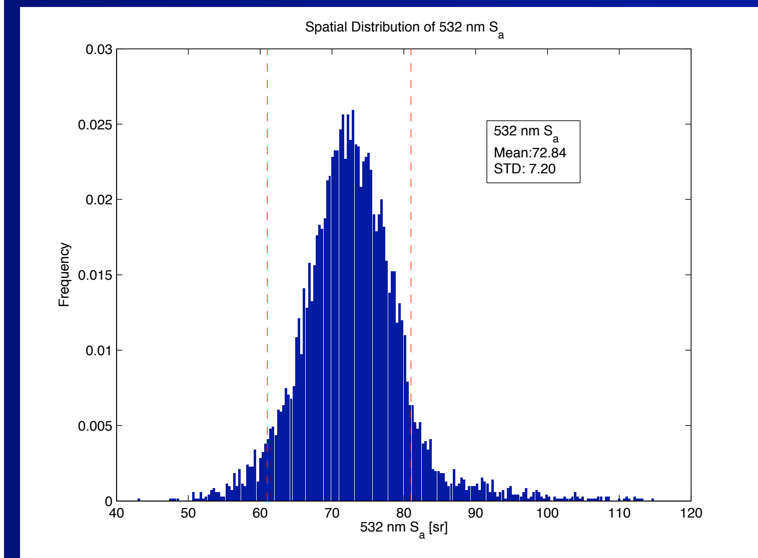
$$\frac{S_{a,532}}{S_{a,1064}} = \frac{1}{K_1} \qquad \frac{\beta_{a,532}}{\beta_{a,1064}} = \frac{1}{K_2} \qquad \frac{\sigma_{a,532}}{\sigma_{a,1064}} = \frac{1}{K_1 K_2}$$

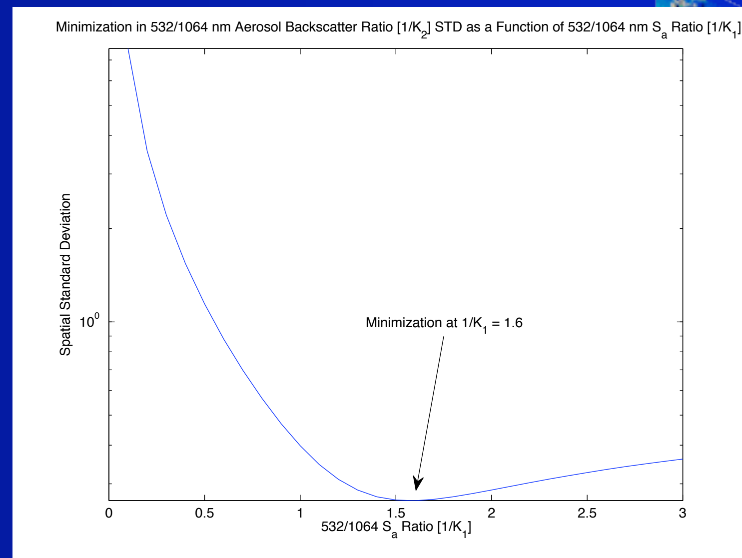
HSRL E-CRAM Example (9 August, 2007)

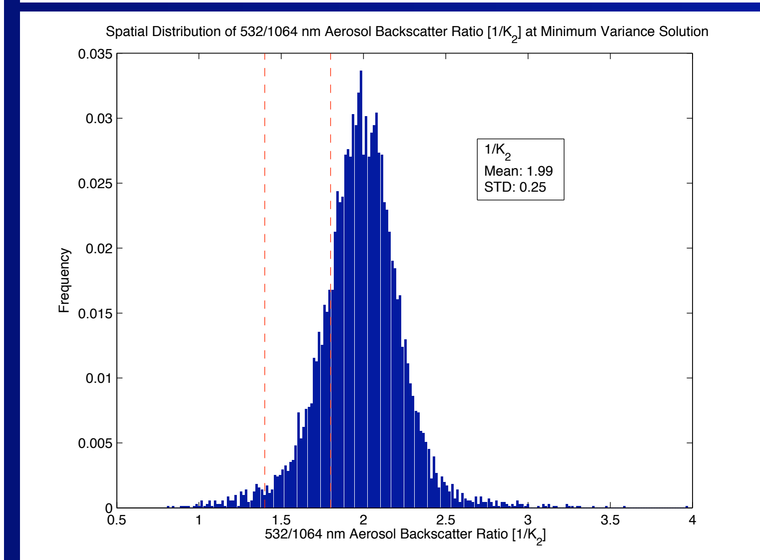


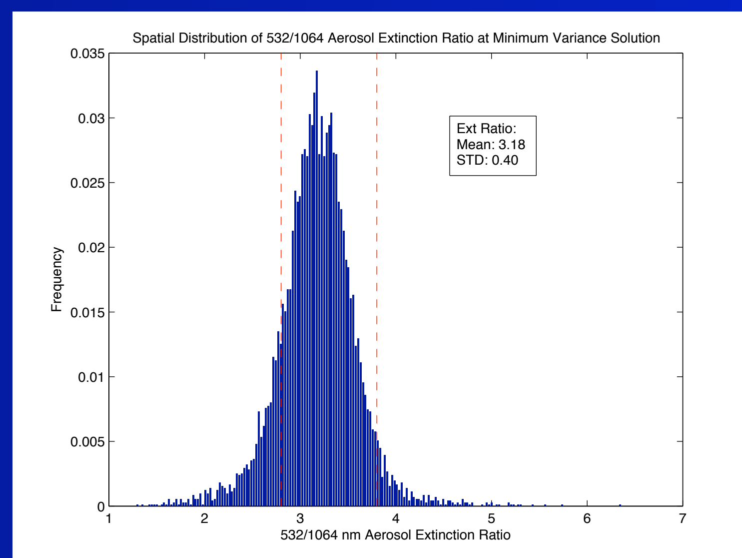
HSRL E-CRAM Example (9 August, 2007)





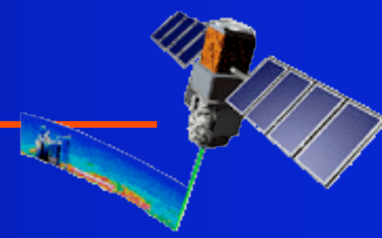






(Present CRAM model parameters bracketed in red)

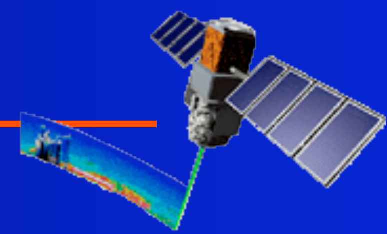
HSRL E-CRAM Potential U/I Revised Model



	Lidar Ratios @ 550 nm		550 to 1020 nm Ratios		
Aerosol Type	Reported in Literature	AERONET Modeled $S_a \pm$ SD	S_a ratio	β ratio	σ ratio
Urban/Industrial	65 ± 4	71 ± 10	1.9 ± 0.3	1.6 ± 0.2	3.3 ± 0.5
Urban/Industrial (E-CRAM Revised)	n/a	73 ± 7	1.6	2 ± 0.3	3.2 ± 0.4

SD = Standard Deviation of Gaussian fit

Conclusions



- HSRL S_a retrievals show that, while S_a is not truly spatially constant, the variations tend to be normally distributed with rather small standard deviations, <~15%. Optical depth and extinction retrievals on CALIPSO data using mean S_a HSRL values yield results typically close to the HSRL determinations.
- CRAM retrieved extinction and backscatter spectral ratios (assuming spatially constant S_a), while also not spatially constant, are typically fairly normally distributed and their mean values work very well for CRAM retrievals.
- CRAM models typically yielded good to very good fits to CALIPSO data, and the extinction profiles and optical depths from these fits were found to be in good to very good agreement with the HSRL determinations.
- CRAM dust model successfully modified to yield improved dust layer retrievals by using a combination of direct-transmittance solutions and statistical assessment of numerous CALIPSO dust layer observations.
- E-CRAM applied to HSRL data found to be a promising approach for confirming/ modifying CRAM models – will be a major thrust for future investigations.