Pixel Level "Uncertainty" in MODIS AOD from Dark Target Algorithm (Over Ocean Only)

3rd AeroSAT Workshop , Frascati, Italy

8 – 9 October 2015

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AeroSAT Goals & Questions

- What model needs and what satellite provides
- Consistent "definition" required (e.g. error vs. uncertainty)
- How does model use "quantitative" information of uncertainty?
- Methodology to calculate uncertainties – satellite community
- Complexity / Simplicity desirable? Accuracy of uncertainty?
- Are requirements of climate and other numerical global models same ?

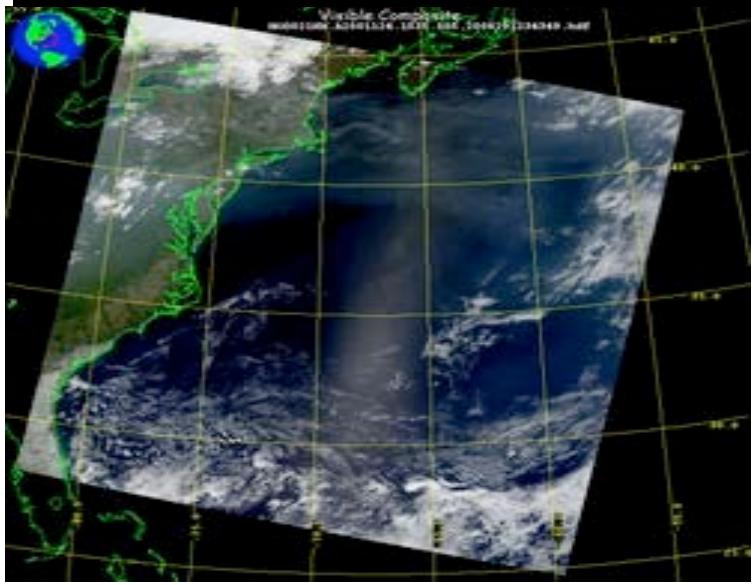
Multiple Approaches exist

- **Validation (Error Envelope) – ground truth**
- **Per-pixel level uncertainty (error propagation)**
- **Ensemble retrievals to calculate dispersion in AOD**
  - **Which one makes sense for model?**
  - **Which one suffices ?**

Aerosol retrieval from MODIS

What MODIS observes

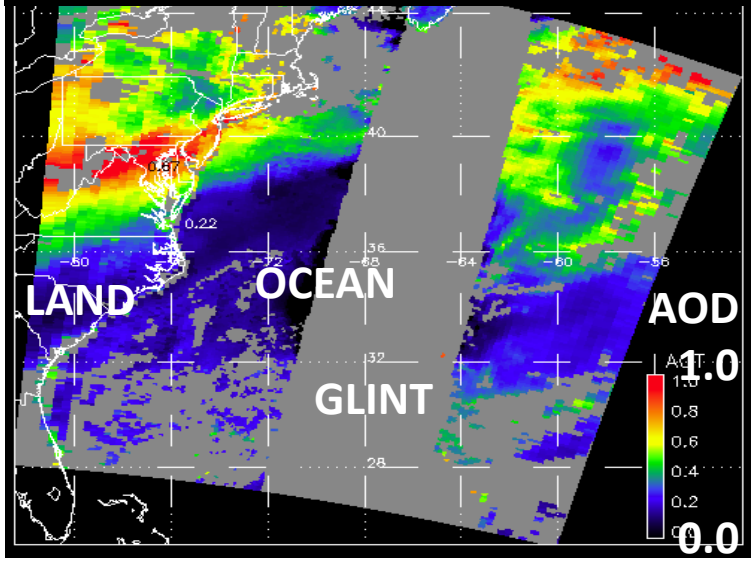
May 4, 2001; 13:25 UTC
Level 1 "reflectance"



LUT

Attributed to aerosol (AOD)

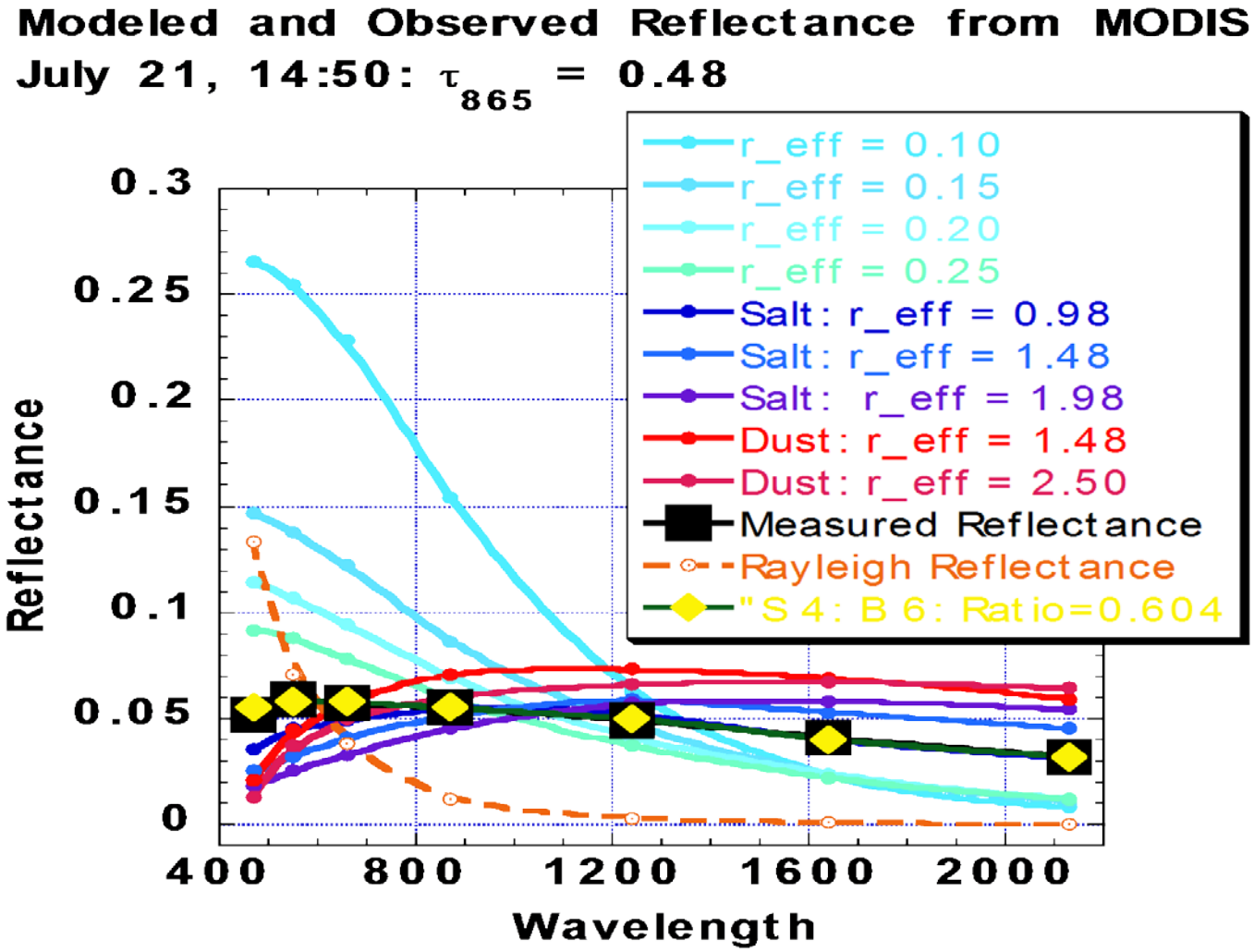
May 4, 2001; 13:25 UTC
Level 2 "product"



There are many different "algorithms" to retrieve aerosol from MODIS

1. Dark Target ("DT" ocean and land; Levy, Mattoo, Munchak, Remer, Tanré, Kaufman)
2. Deep Blue ("DB" desert and beyond; Hsu, Bettenhousen, Sayer,..)
3. MAIAC (coupled with land surface everywhere; Lyapustin, Wang, Korkin,…)
4. Ocean color/atmospheric correction (McClain, Ahmad, …)
5. Etc (neural net, model assimilation, statistical, …)
6. Your own algorithm (many groups around the world)

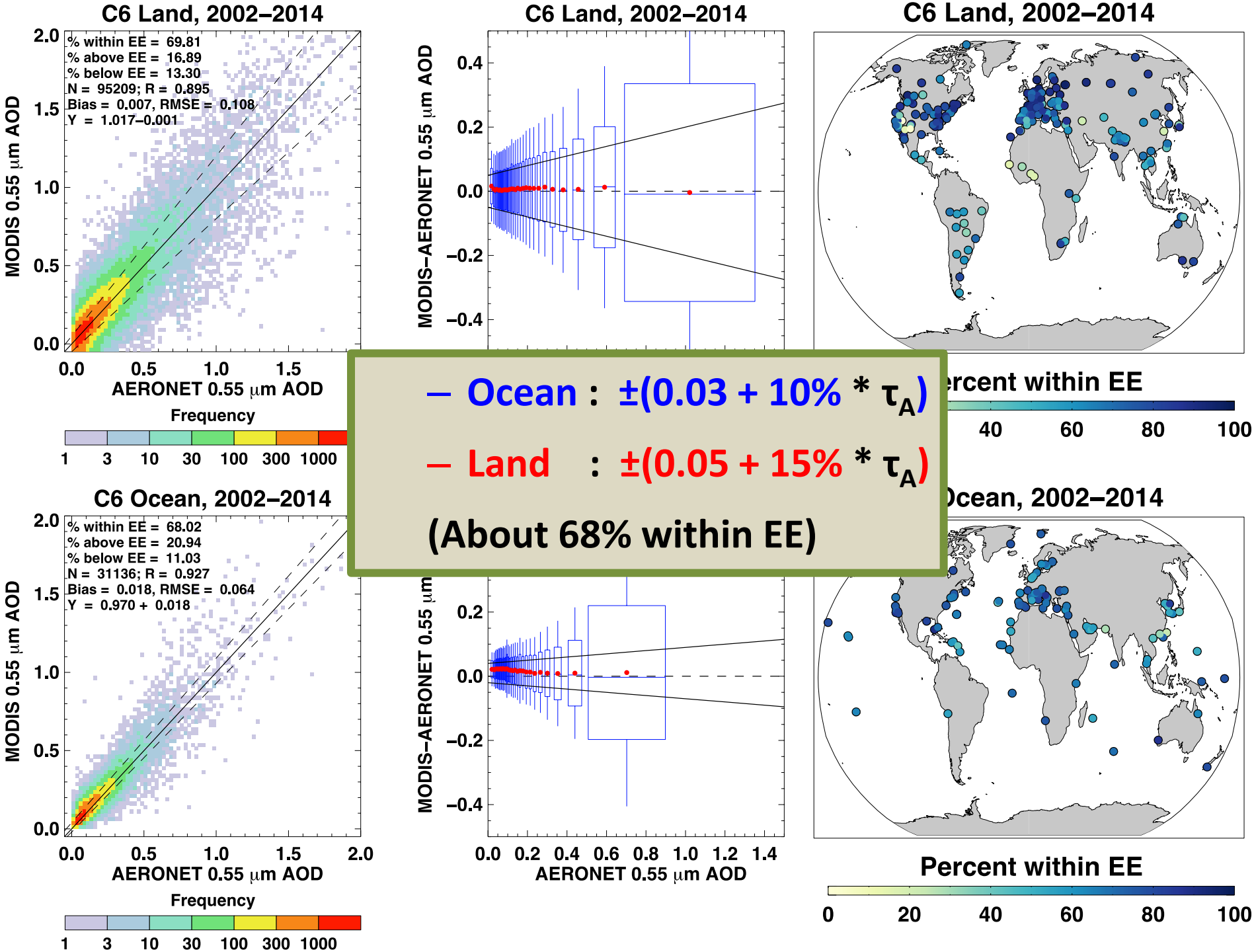
MODIS Aerosol Retrieval – LUT Approach



- Find a solution in the LUT that best matches the TOA spectral reflectance
- Then infer the aerosol conditions that produced the scene (e.g. AOD and size)

Pre-launch estimate of error (e.g. Tanré et al., 1997)

- This was primarily a "sensitivity" study:
- Derived "**Expected Error (EE) envelope**" for the MODIS aerosol product:
  - **Ocean : ±(0.05 + 5%)**
  - **Land : ±(0.05 + 20%)**
- MODIS was launched in 1999
- How to "validate" this EE envelope?


C6 Land, 2002–2014
% within EE = 69.81
% above EE = 16.89
% below EE = 13.30
N = 95209; R = 0.895
Bias = 0.007, RMSE = 0.108
Y = 1.017–0.001
MODIS 0.55 μm AOD
AERONET 0.55 μm AOD
Frequency
1 3 10 30 100 300 1000
C6 Land, 2002–2014
MODIS–AERONET 0.55 μm AOD
C6 Land, 2002–2014
Percent within EE
40 60 80 100
– Ocean : ±(0.03 + 10% * τA)
– Land : ±(0.05 + 15% * τA)
(About 68% within EE)
C6 Ocean, 2002–2014
% within EE = 68.02
% above EE = 20.94
% below EE = 11.03
N = 31136; R = 0.927
Bias = 0.018, RMSE = 0.064
Y = 0.970 + 0.018
MODIS 0.55 μm AOD
AERONET 0.55 μm AOD
Frequency
1 3 10 30 100 300 1000
MODIS–AERONET 0.55 μm
AERONET 0.55 μm AOD
Ocean, 2002–2014
Percent within EE
0 20 40 60 80 100

Per-pixel Uncertainty

Quantify the per-pixel level uncertainty in Aerosol Optical Depth

(1) Using Jacobians

Uncertainty in Aerosol Optical Depth Retrieval

There are two broad uncertainty sources :

1. Measurement / Input Uncertainties

- **Calibration Uncertainty [1 – 2%]**
- **Standard Deviation of reflectance in 10 x 10 km retrieval box [~2%]**
- **Uncertainty in the Ancillary data used for atmospheric correction [~0.1 - 0.5%]**
- **Cloud contamination [±0.05] (preliminary)**

  [τ Bias of +0.04 (Terra) and +0.01 (Aqua), *Hyer et al.,2011*]
- **Snow contamination ?**

2. Retrieval Assumptions

- **Surface reflectance – Δwind speed over ocean**
- **Aerosol models – variance of all solutions/ AODs used in average solution**

- **The numbers in red are derived from ocean analysis shown in following slides**

Generic Formulation

$$\Delta\tau_{\lambda} = \frac{\partial\tau}{\partial xi}(\Delta xi)$$

→

$$(\Delta y)i = \frac{\partial f}{\partial xi}(\Delta xi)$$

x = reflectance

Sensitivity

Small Change in Input

The partial derivatives are estimated by :

$$\frac{\partial f}{\partial xi} = \frac{\partial f}{\partial Xi}\Big|_{x1,x2,x3.....,xN}$$

Definitions and Methodology

For a 2-channel retrieval scheme, the change in retrieved aerosol optical depth due to change in some parameter '**a**' can be written as:

$$\Delta\tau_\lambda = \frac{\partial\tau}{\partial R1}\Big|_{R2}\frac{dR1}{da}\Delta a + \frac{\partial\tau}{\partial R2}\Big|_{R1}\frac{dR2}{da}\Delta a + \ldots\ldots \qquad \ldots\ldots (1)$$

where :

* R1 and R2 = TOA aerosol reflectance in two spectral channels
* **a** = the source of uncertainty i.e. measurement / calibration error, atmospheric correction error, surface reflectance error etc.
* Partial derivative of τ = the retrieval sensitivity of τ [can be compute from LUT]

Equation (1) can be written as :

$$\Delta\tau_\lambda = \frac{\partial\tau}{\partial R1}\Big|_{R2}\Delta R1 + \frac{\partial\tau}{\partial R2}\Big|_{R1}\Delta R2 + \ldots\ldots \qquad \ldots\ldots (2)$$

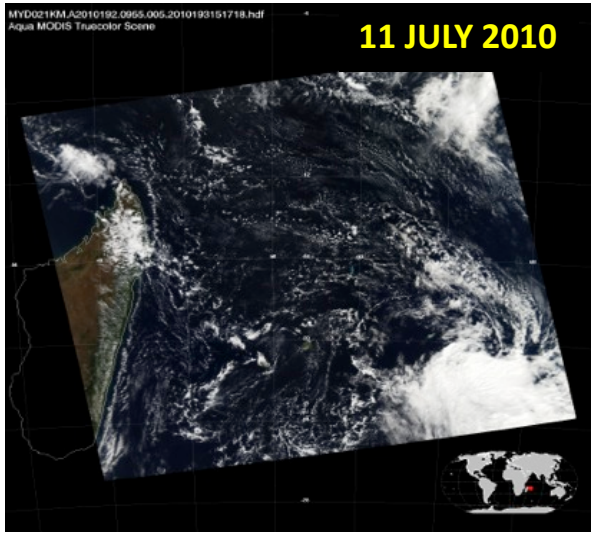
ΔR can be calculated for various error sources

Assumptions

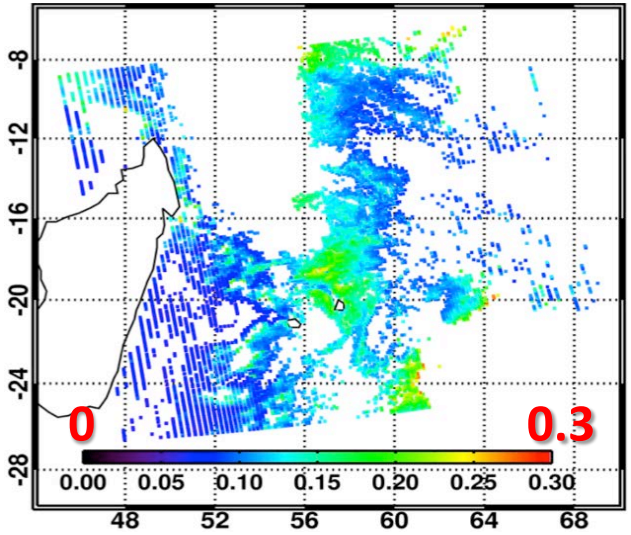
- Errors are uncorrelated spectrally
- Errors distribution is gaussian

Example to demonstrate our AOD Uncertainty Estimation (Over Ocean)

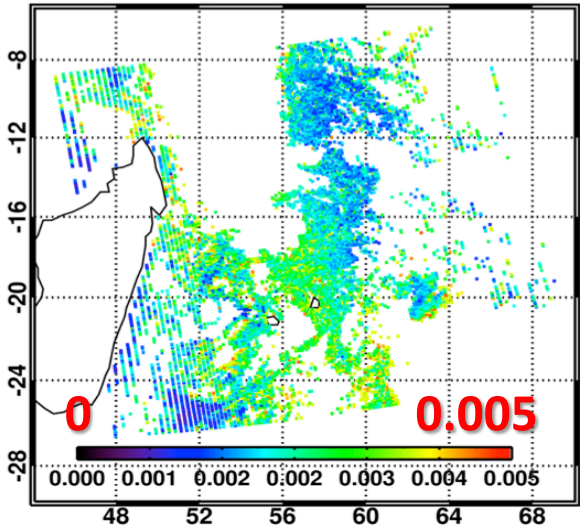
L1B RGB Image to East of Africa



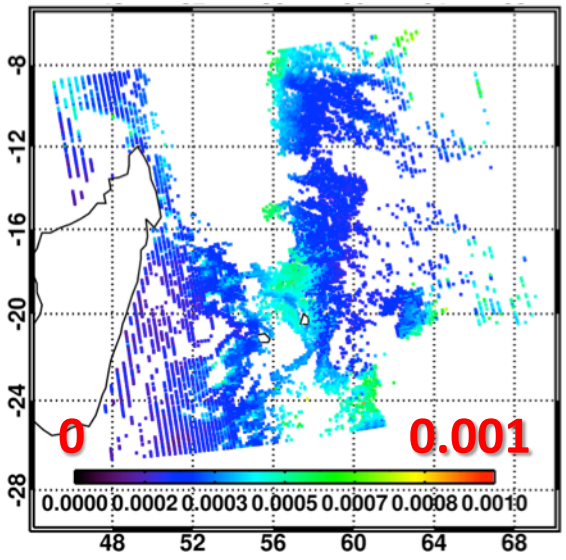
AOD (554 nm)



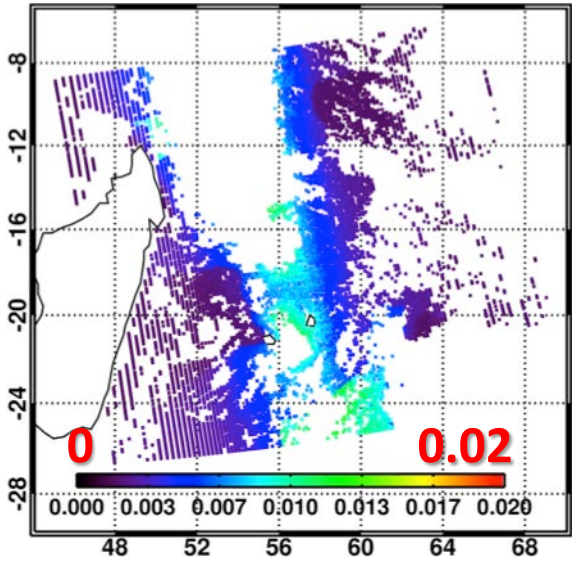
AOD Uncertainty (REF_SDEV)



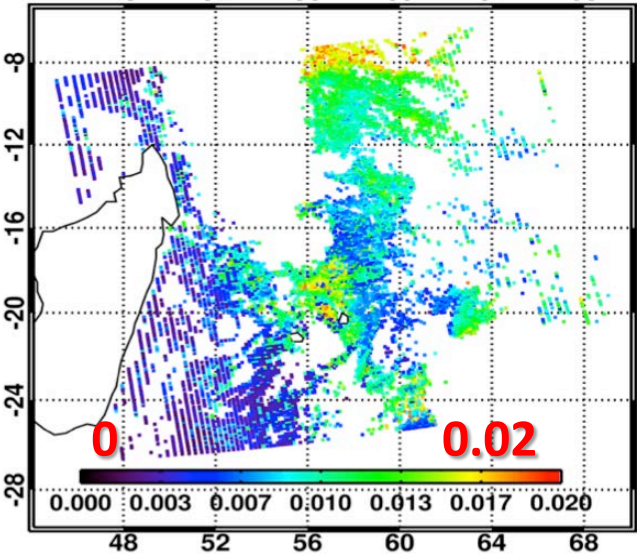
AOD Uncertainty (Gas)



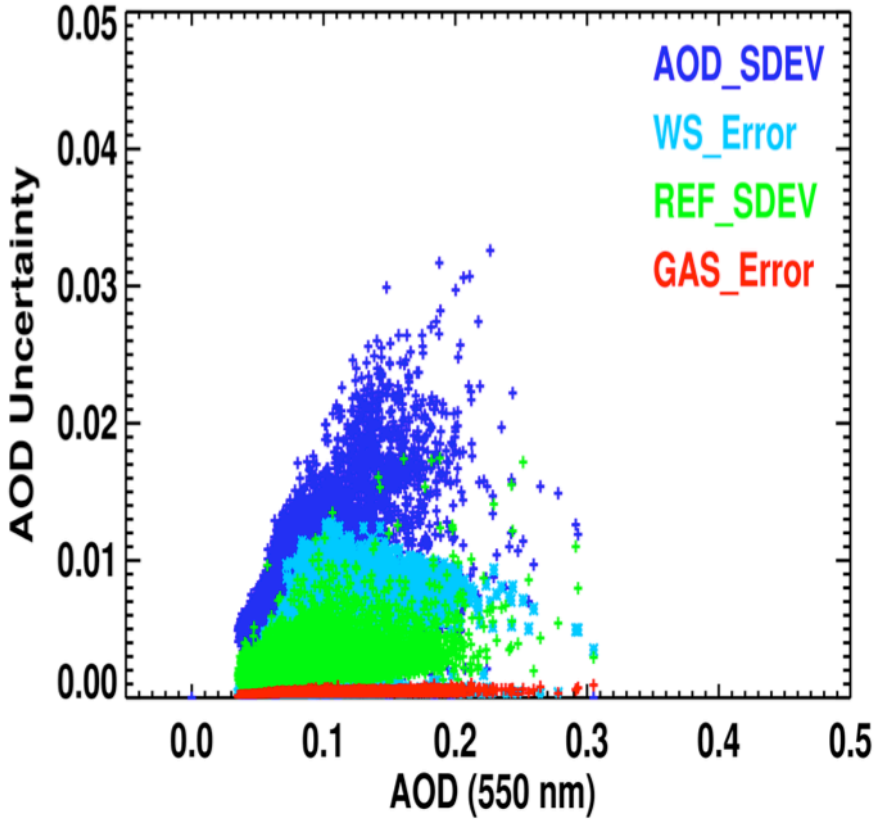
AOD Uncertainty (Wind Speed)

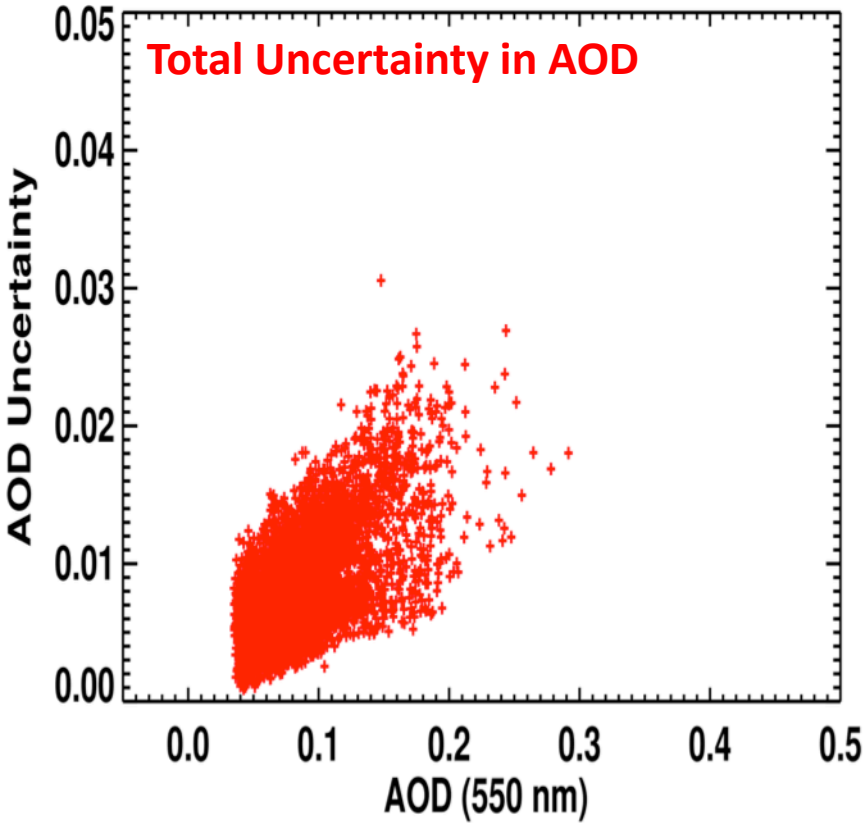


AOD Standard Deviation (Avg Sols)



Summary Plot : Uncertainty in AOD retrieval

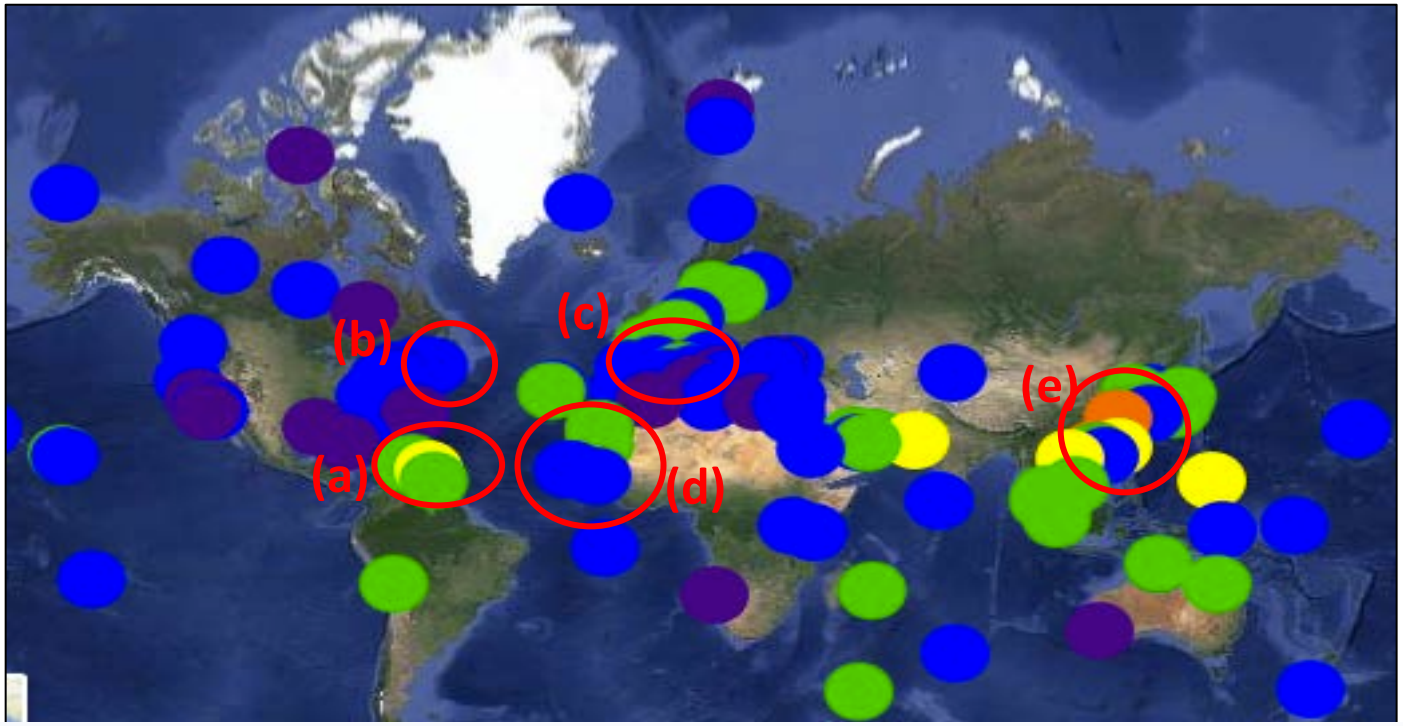




- Uncertainty from the aerosol models (AOD_SDEV) dominates
- Atmospheric gas correction errors lowest
- What do these uncertainty numbers mean? Are the magnitudes reasonable ? (<15%)

Validation of Uncertainty?

Validation of Uncertainty Estimates



Percent of collocations within expected error

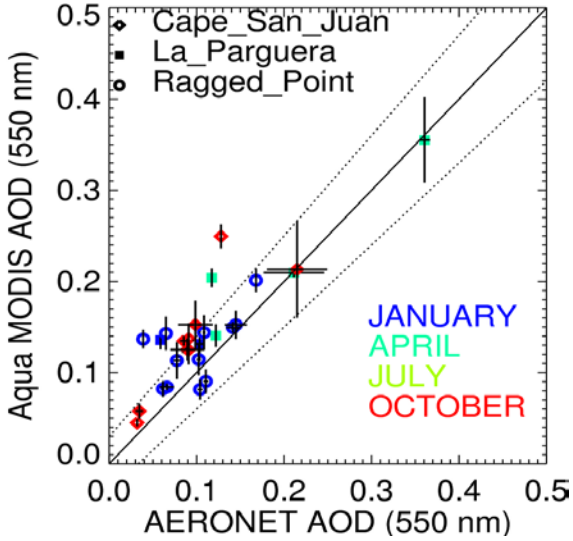
0-16.6%	16.6 – 33.3%	33.3-50%	50-66.6%	66.6-83.3%	83.3-100%

Figure shows the global performance of MODIS Dark Target Ocean retrieval algorithm.

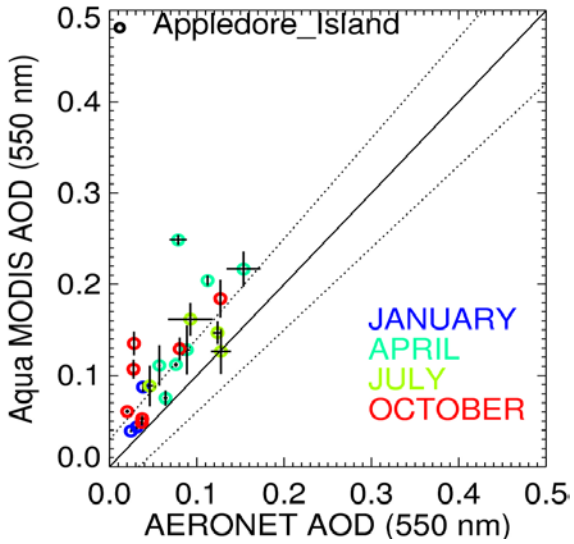
This is available at http://darktarget.gsfc.nasa.gov/validation/maps

Validation of Uncertainty Estimates

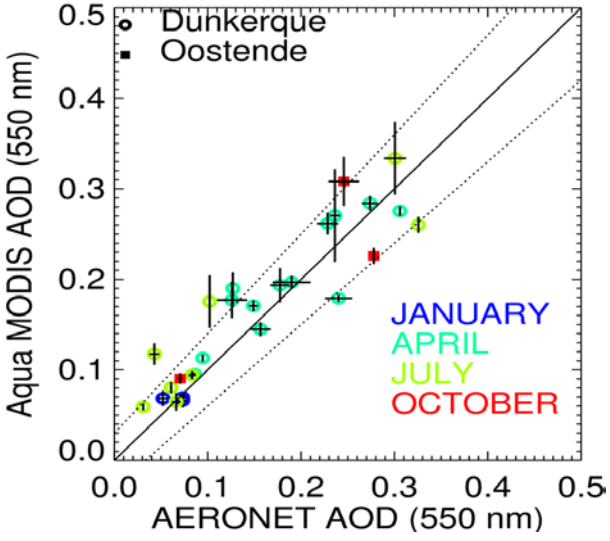
The Caribbean Region



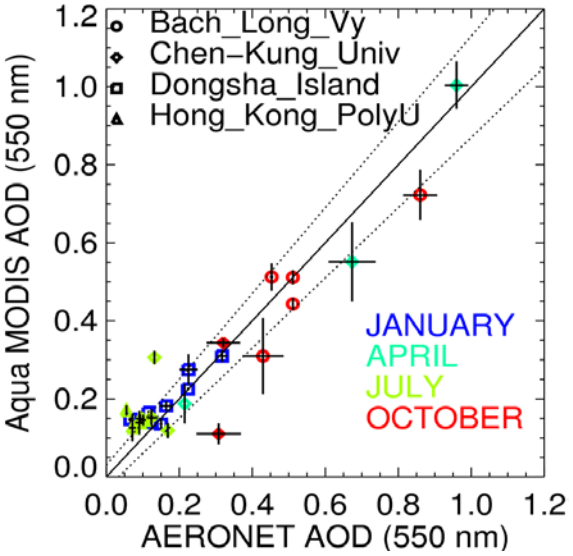
Eastern US



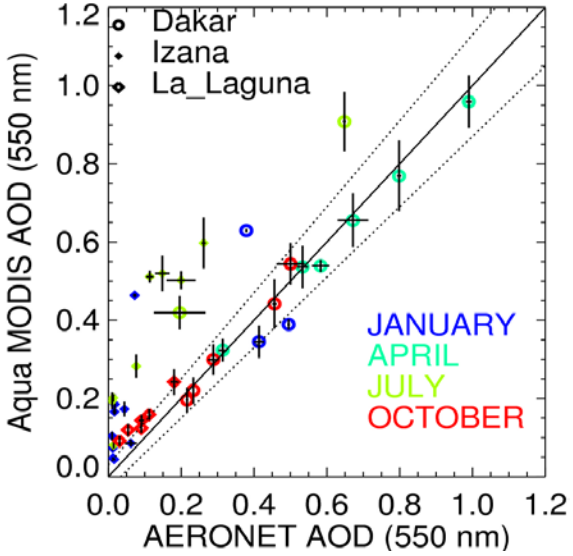
Eastern Europe



East of China



West Africa



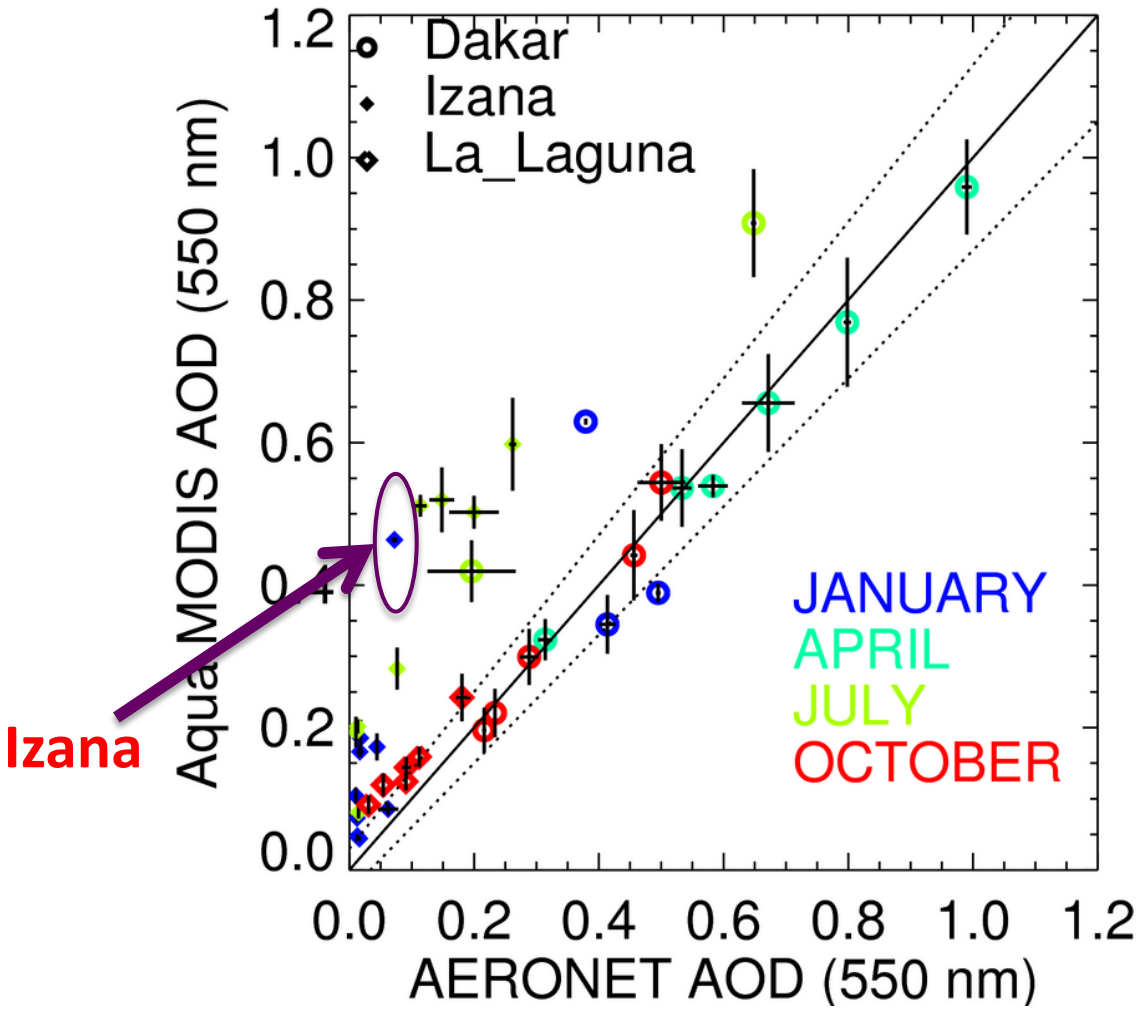
On each data point, the

Vertical Lines = ± Absolute Uncertainty

Horizontal lines = ± Aeronet AOD STD

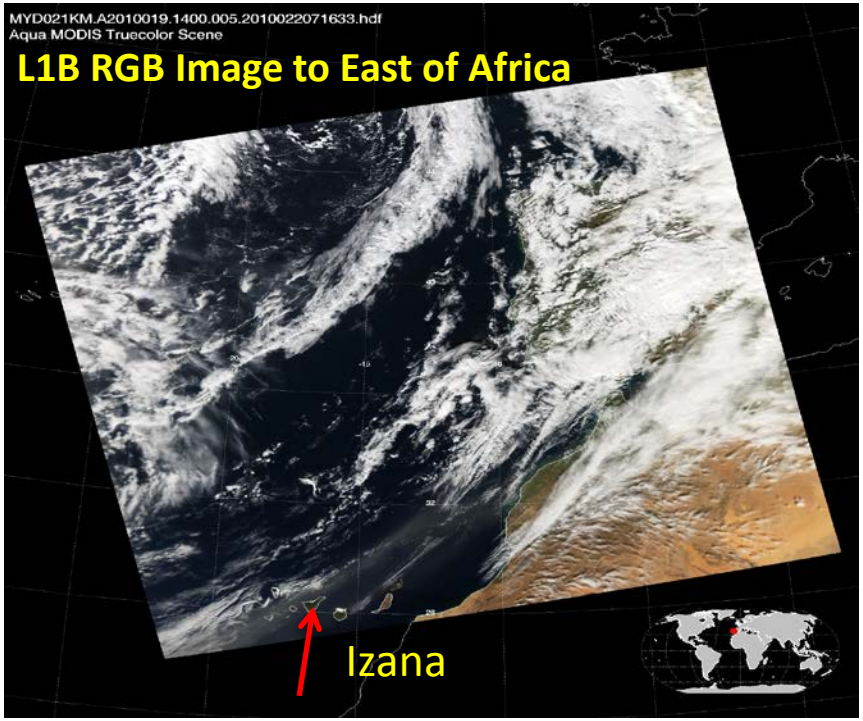
Validation of Uncertainty Estimates

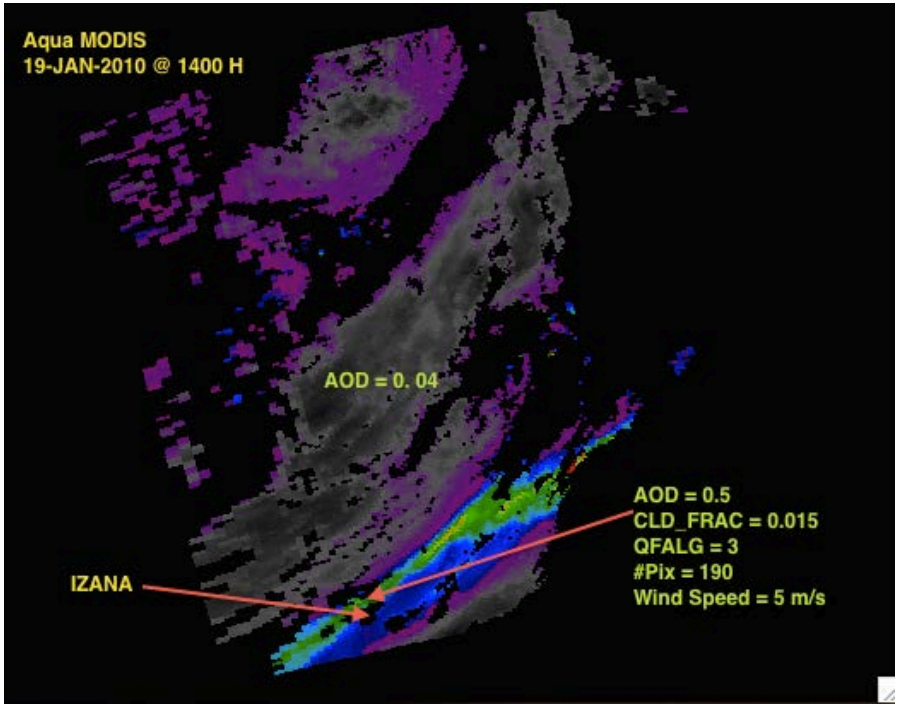
West Africa



- Is uncertainty within Expected Error envelope (dashed line)?
- Is uncertainty small for good agreement?
- Do outliers have large uncertainty ?

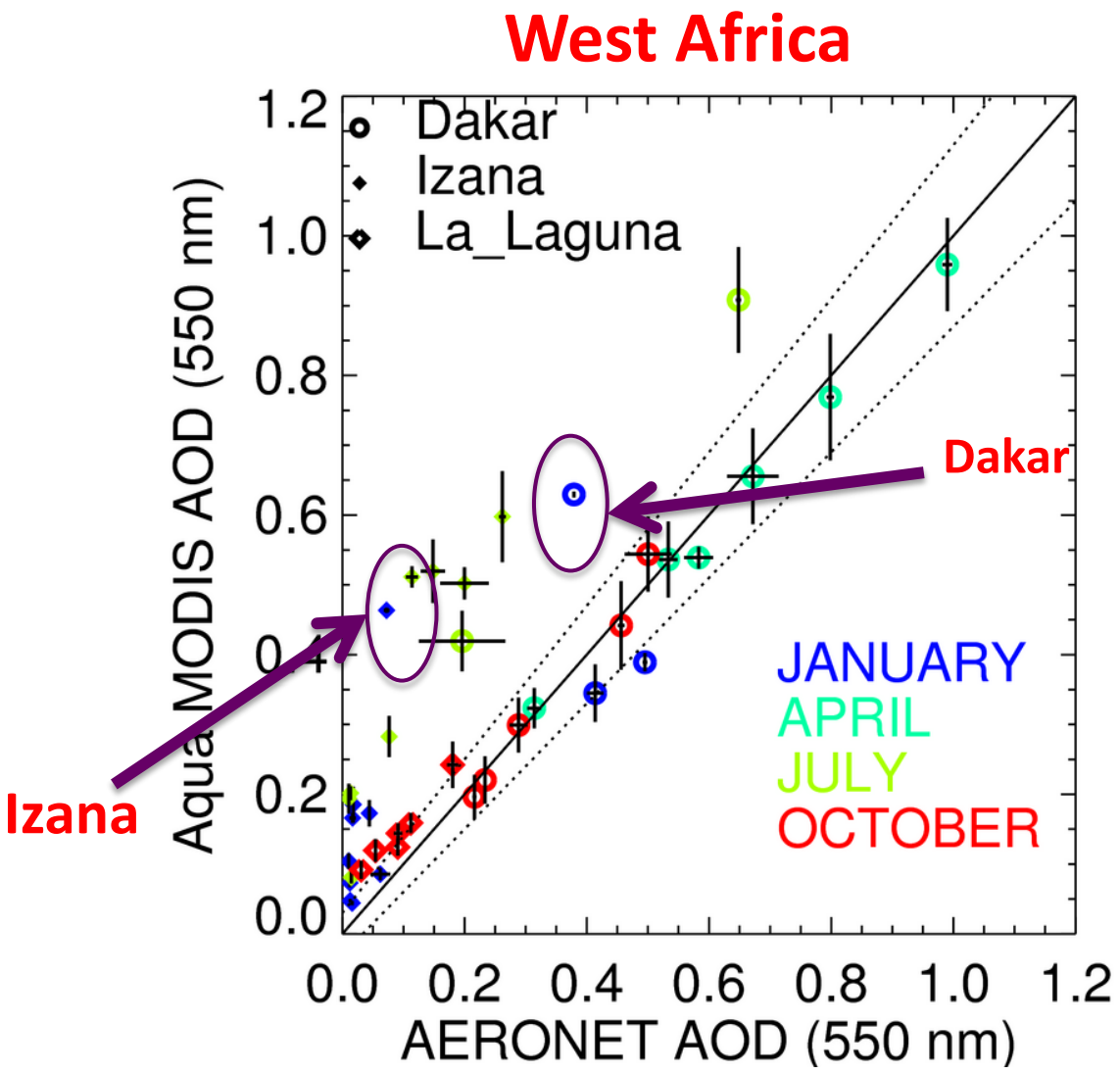
Validation of Uncertainty Estimates





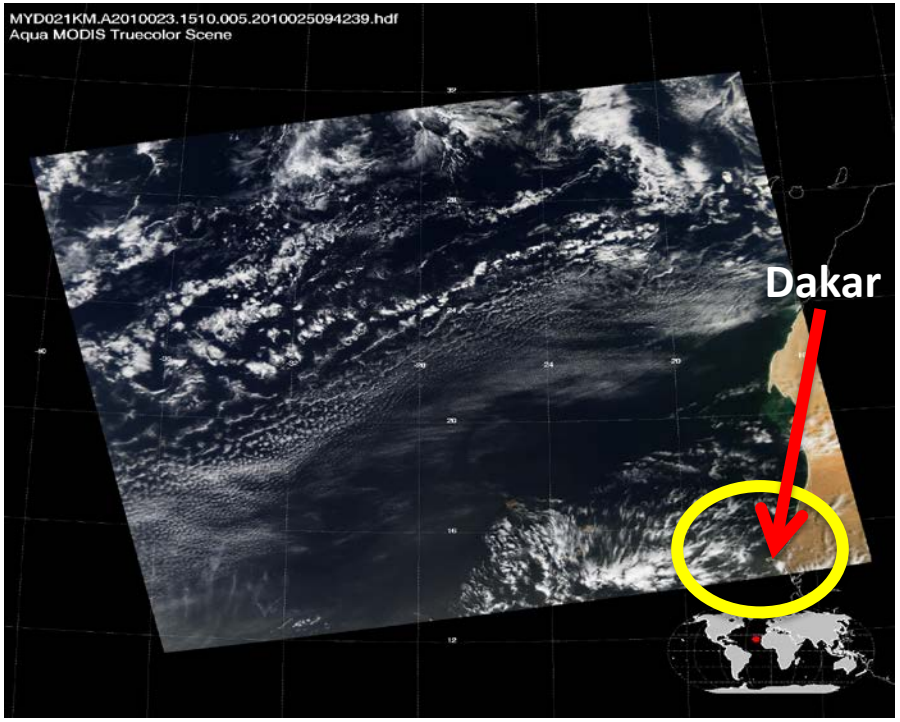
- High Altitude Station (AOD ~ 0.2)
- Thick plume misses the station
- MODIS AOD retrieval High Quality (= 3); Cloud Fraction = 0.015
- Disagreement with AERONET ≠ bad retrieval (spatial variability / collocation problem)

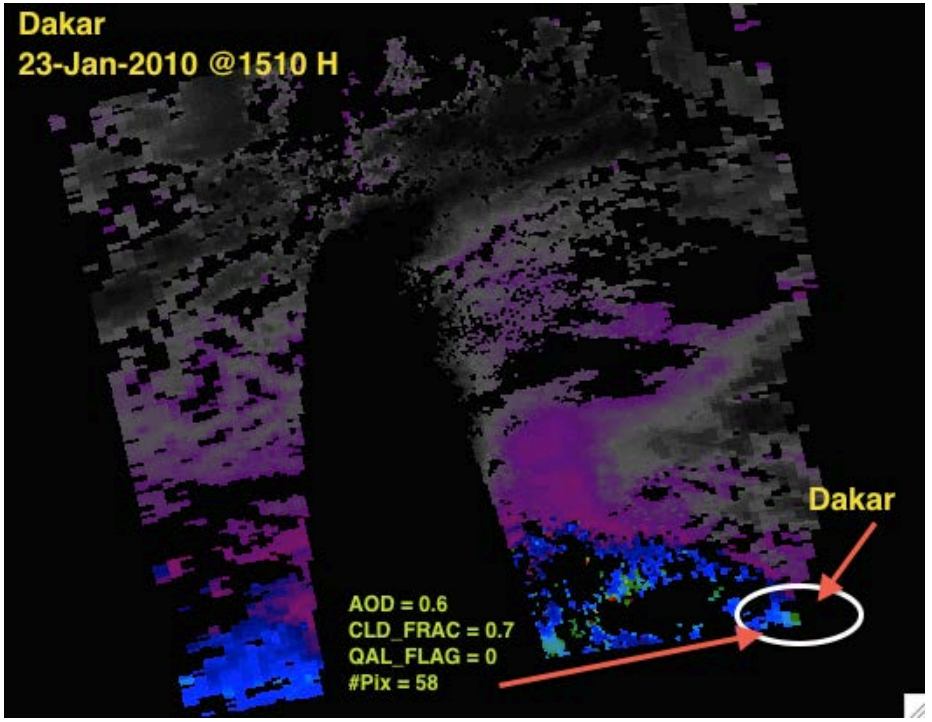
Validation of Uncertainty Estimates



- **Is uncertainty within Expected Error envelope (dashed line)?**
- **Is uncertainty small for good agreement?**
- **Do outliers have large uncertainty ?**

Validation of Uncertainty Estimates

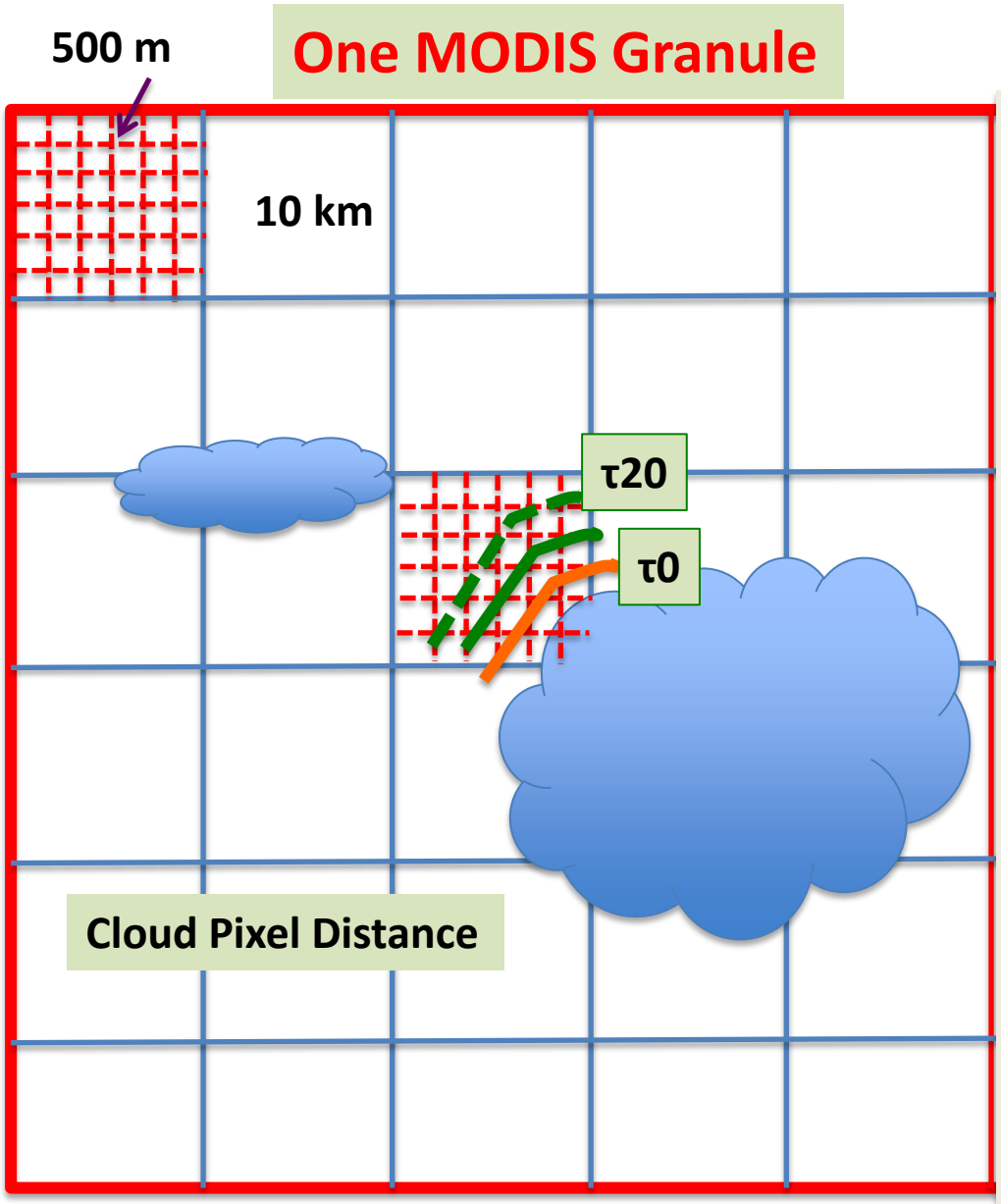




- Dust seen around the station
- Broken cloud fields co-exist
- MODIS AOD retrieval Low Quality (= 0) ; Cloud Fraction = 0.7
- Cloud Contamination ? Precise but Inaccurate / Baised ?

Clouds and Contamination ?

Cloud Contamination Issue



τ0 : AOD from ALL pixels (C6)

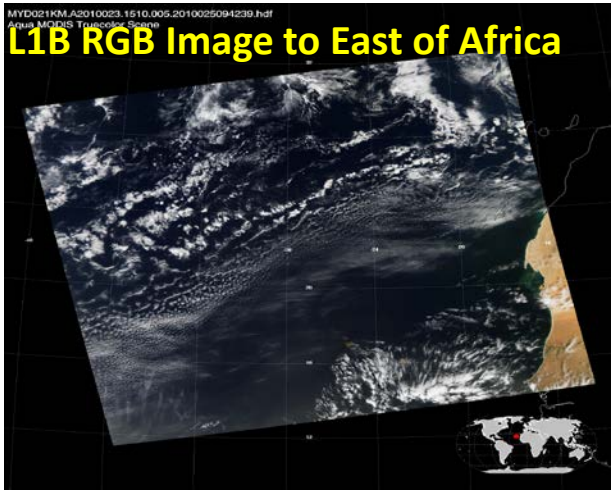
τ20 : AOD from pixels with cloud pixel distance > 20

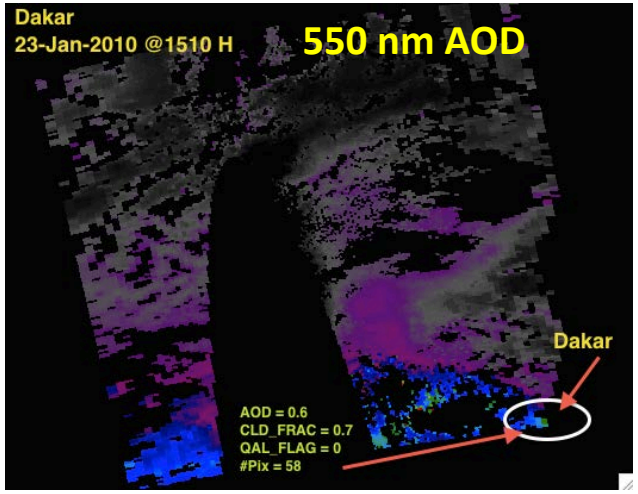
Hypothesis :

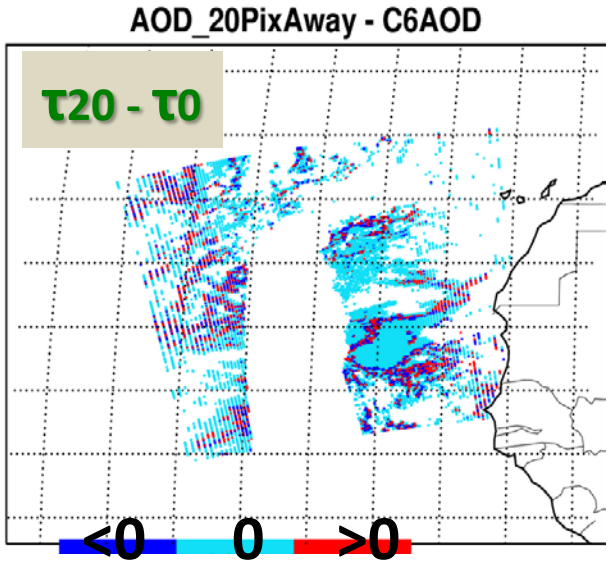
If C6 AOD retrieval has cloud contamination :

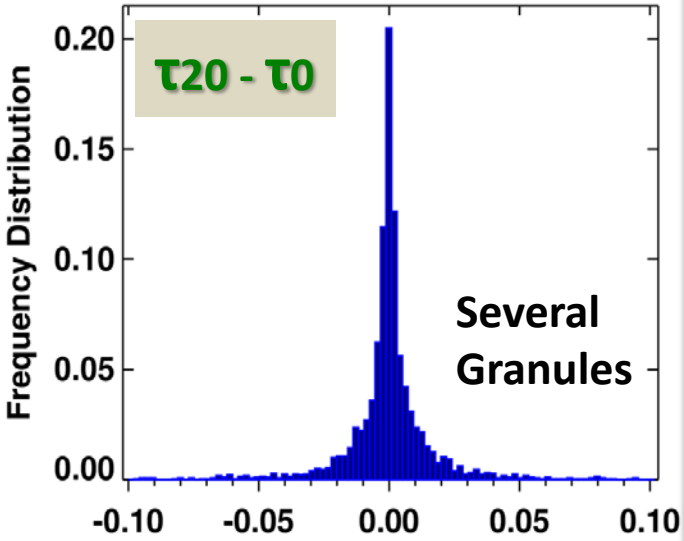
τ20 - τ0 = Negative

Cloud Contamination Issue









- Surprise! Both blues and reds
- Histogram shows
  - Gaussian
  - $\Delta\tau \approx \pm 0.05$
- Most differences within ± 0.01
- => Reasonable overall cloud screening
- Low Quality flags => Clouds contamination
- Work in Progress

Per-pixel Uncertainty

Quantify the per-pixel level uncertainty in Aerosol Optical Depth

(2) Using Ensemble of retrievals

Uncertainty can be calculated using 2 approaches

For Example:

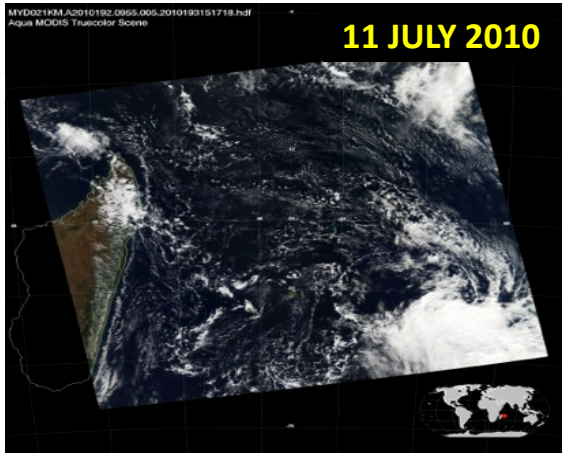
Approach One: Calculate uncertainty using Jacobian method

Approach Two: Brute Force = Retrieve AOD Three times using (3 Runs)

(a) 10 km mean reflectance (ρ_λ) used in standard retrieval
(b) ρ_λ plus standard deviation in 10 km reflectance [$\rho_\lambda + \sigma_\lambda$]
(c) ρ_λ minus standard deviation in 10 km reflectance [$\rho_\lambda - \sigma_\lambda$]

Calculate uncertainty / standard deviation in AOD from these 3 calculations

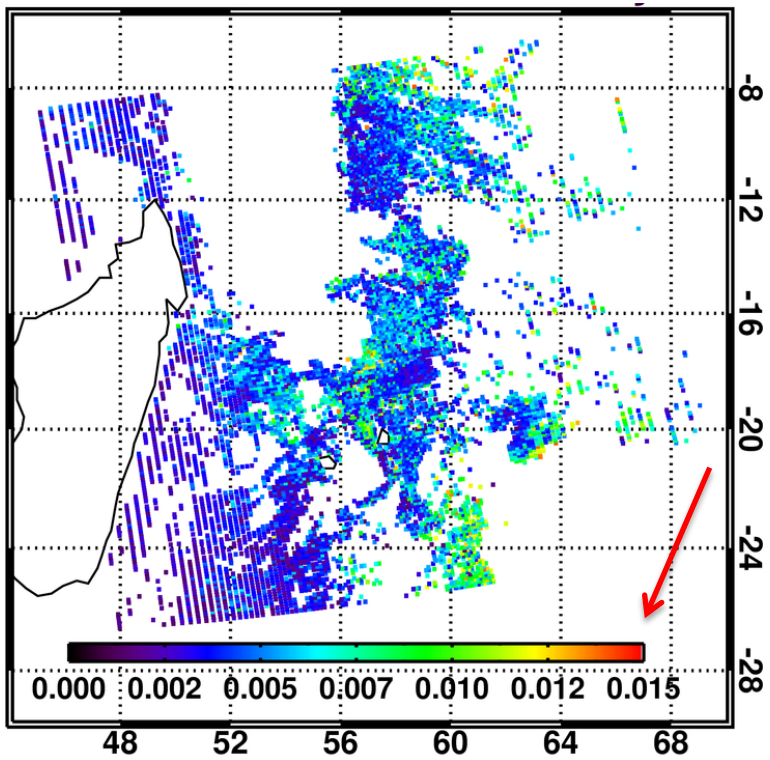
Uncertainty from Reflectance Standard Deviation



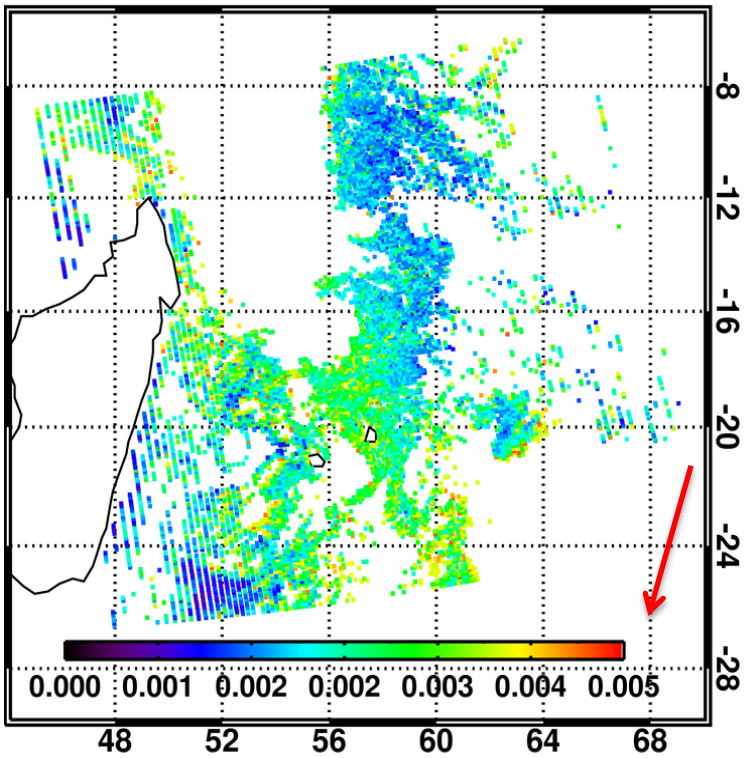
- AOD Uncertainty magnitudes differ
- Spatial patterns don't necessarily match

Which one is the actual / true representation of AOD Uncertainty here ?

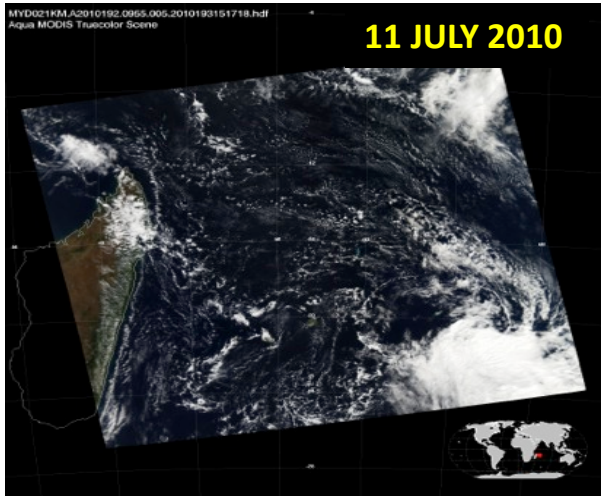
Brute Force



Jacobian



Uncertainty from Wind Speed Error



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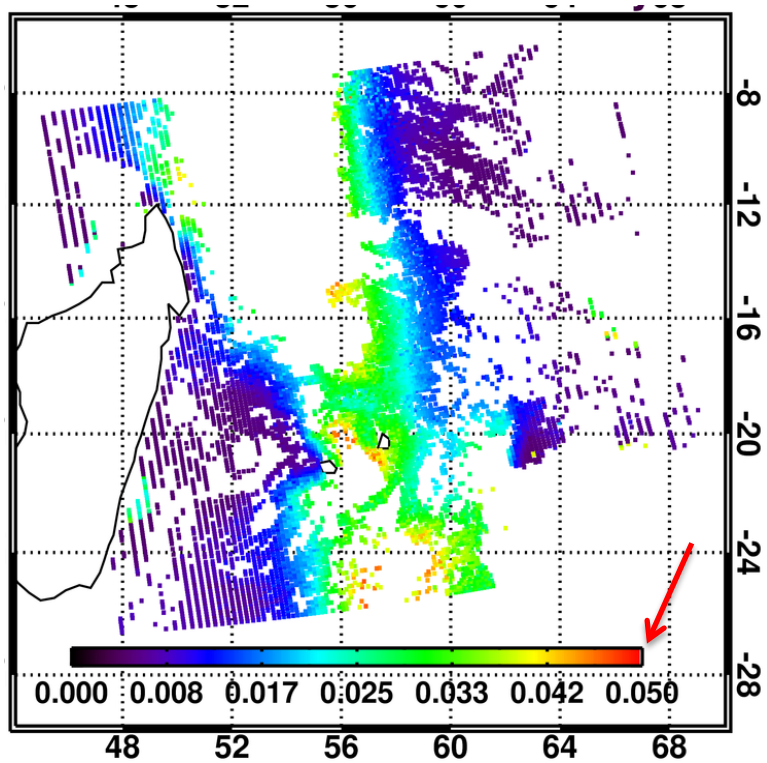
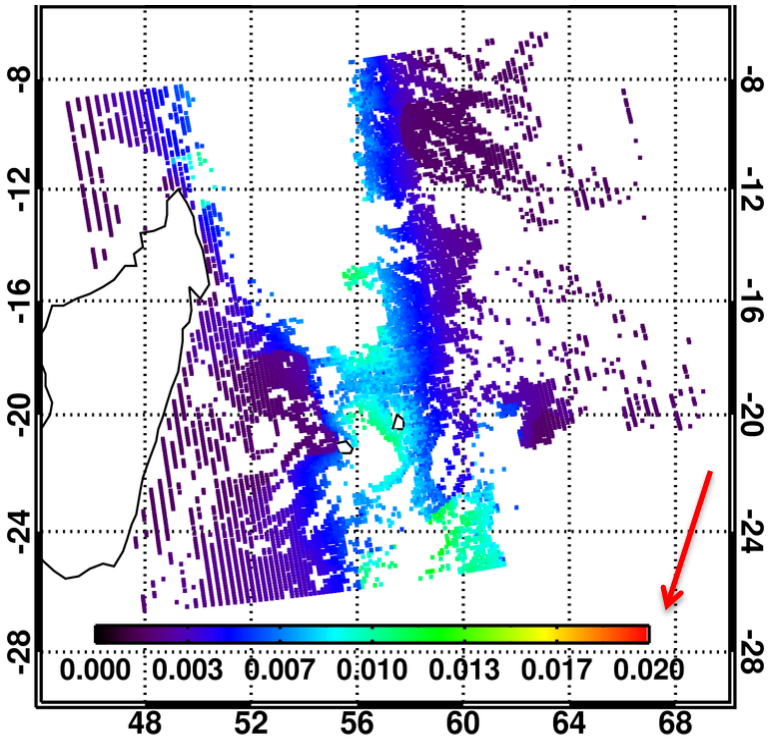
Which one is the actual / true representation of AOD Uncertainty here ?

Brute Force



Jacobian



Conclusion/Summary

- The MODIS dark-target aerosol retrieval and products is maturing
- Prior to MODIS launch, we performed sensitivity tests to derive expected error (EE) envelopes
- Post launch, these EE envelopes for AOD was “validated” by comparing to sun-photometer data
- Later on, as N increased, new sites with new surface and aerosol characteristics were added
- The EE envelope was revised to meet the performance compared to all global sites
- But some retrievals are better or worse than EE
- We know that
- Quality flags (=1,2,3 Ocean) gives best retrieval – to increase N, quantitative uncertainty estimates can be helpful
- Hopefully we can work with AeroSAT & CCI project and do this consistently.

Back to Questions

- Ensemble vs. Jacobian Uncertainty envelope not the same
- Do AODs from different approaches converge within the error / uncertainty envelopes ? [if errors are calculated in a consistent way?]
- Consistent Definition & Methodology (satellite + model community)
- What is the Accuracy of uncertainty estimates that model needs ?
- Different for Climate and Numerical models? How much?
- How much does data frequency matter for models?

Thank You!