Update on MODIS DT Pixel-Level Uncertainties

6th AeroSAT Workshop
19 – 20 October, 2018

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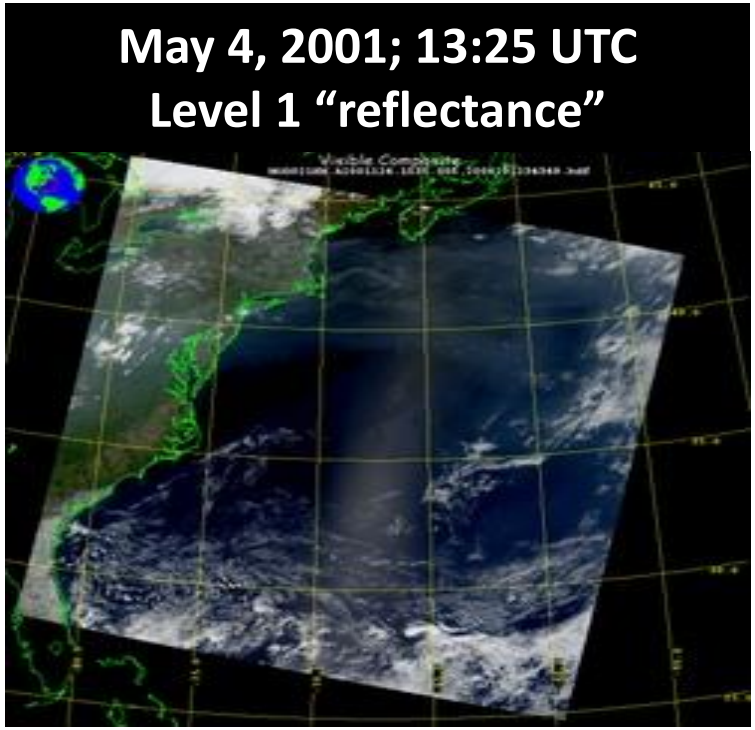
Outline

- **DT Aerosol Retrieval**
- **Retrieval Challenges / Sources of Uncertainty**
- **Approaches to estimate uncertainty**
- **MODIS DT uncertainties**
- **Summary**

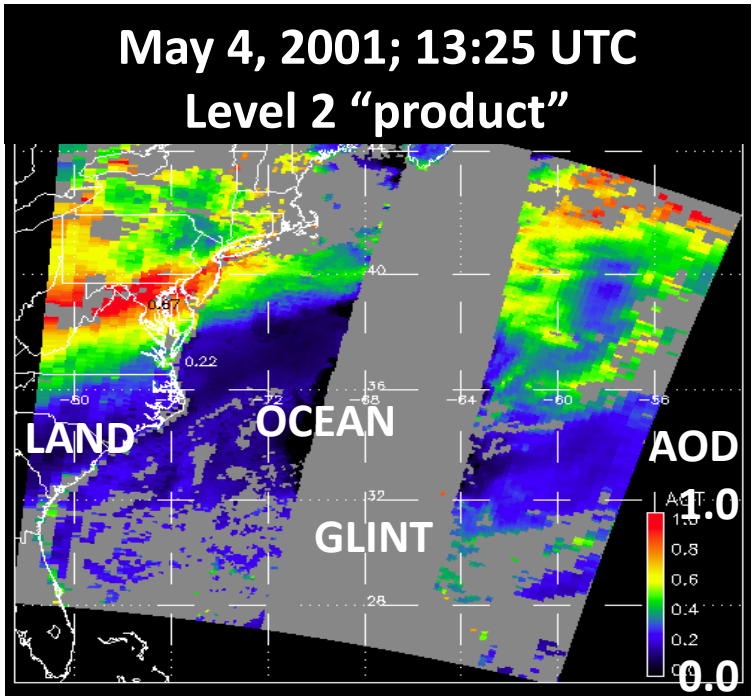
Aerosol retrieval from MODIS

What MODIS observes



LUT

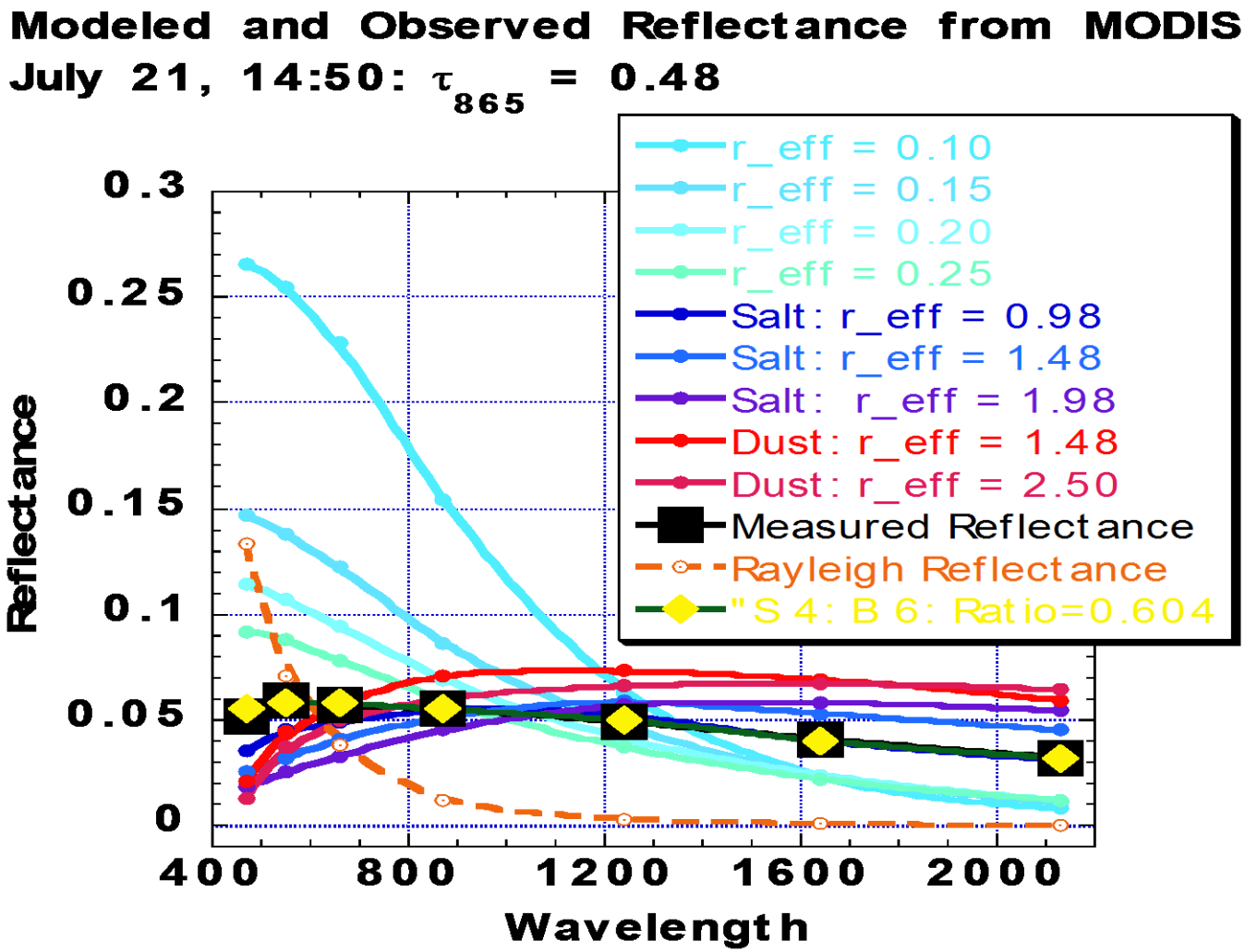
Attributed to aerosol (AOD)



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

1. Dark Target ("DT" ocean and land; Levy, Mattoo, 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)

The Retrieval Challenge

Obtain estimates of geophysical/optical quantities

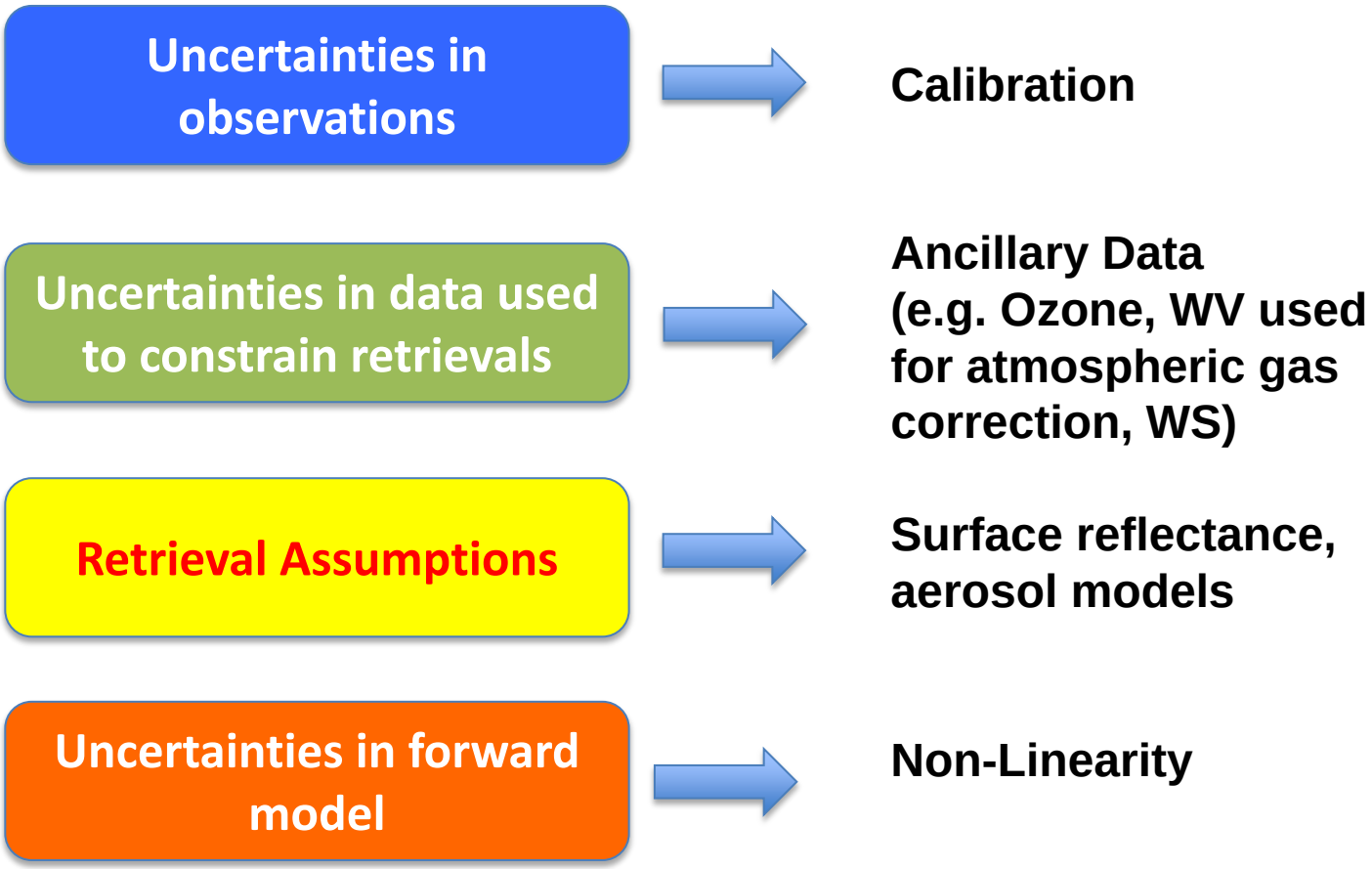
Invert Observations (with noise)

Using RT / forward models (that are not perfect)

And with (imperfect) prior knowledge

Further complicated by non-unique solutions

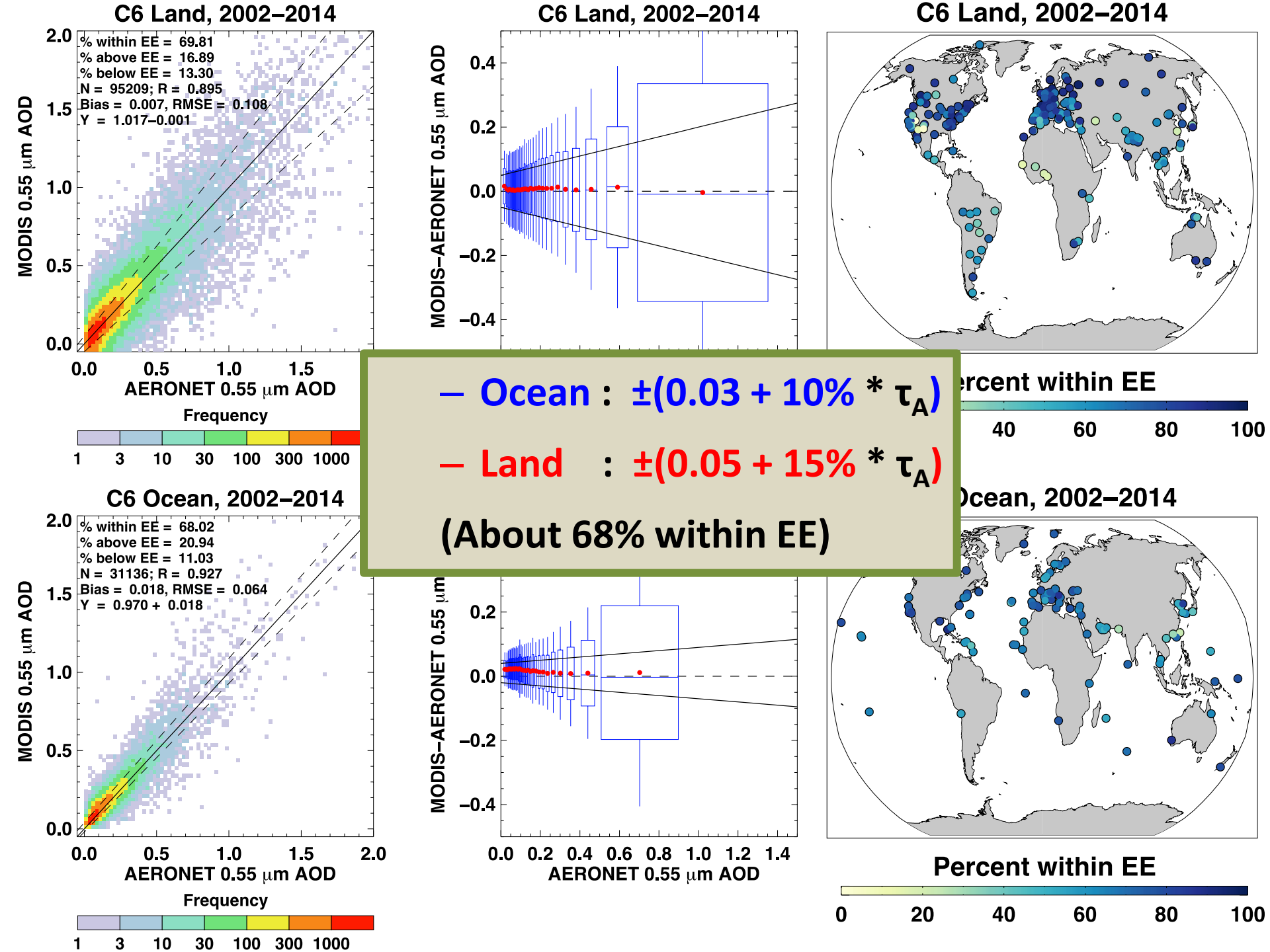
Major sources of uncertainties



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 ?**

Validation (Error 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
ercent 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

Error Propagation

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:

$$\Delta t_{/} = \frac{\partial t}{\partial R1}\Big|_{R2} \frac{dR1}{da}\Delta a + \frac{\partial t}{\partial R2}\Big|_{R1} \frac{dR2}{da}\Delta a + \ldots\ldots \qquad \ldots\ldots \textbf{(1)}$$

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 :

$$\Delta t_{/} = \frac{\partial t}{\partial R1}\Big|_{R2} \Delta R1 + \frac{\partial t}{\partial R2}\Big|_{R1} \Delta R2 + \ldots\ldots \qquad \ldots\ldots \textbf{(2)}$$

ΔR can be calculated for various error sources

Definitions and Methodology

The Retrieval Error can be written in Matrix Form as : $K^{-1}\ O\ (K^{-1})^T$ **OR** $S\ O\ S^T$

where ,

S = K^{-1}

K = Partial derivative $\left(\frac{\partial t}{\partial R}\right)$

O = Uncertainty Covariance (ΔR) Matrix

For 7-Channel MODIS-DT Over Ocean Retrieval,

$$S = \begin{bmatrix} \frac{\partial R1}{\partial t} \\ \frac{\partial R2}{\partial t} \\ . \\ . \\ . \\ \frac{\partial R7}{\partial t} \end{bmatrix}$$

$$O_{atmos\_error} = \begin{bmatrix} S^2_{DR1} & \cdots\cdots & S_{DR1DR7} \\ . & & . \\ . & S^2_{DR2} & . \\ . & & . \\ S_{DR1DR7} & \cdots\cdots & S^2_{DR7} \end{bmatrix}$$

Brute Force Calculations

Brute Force Approach

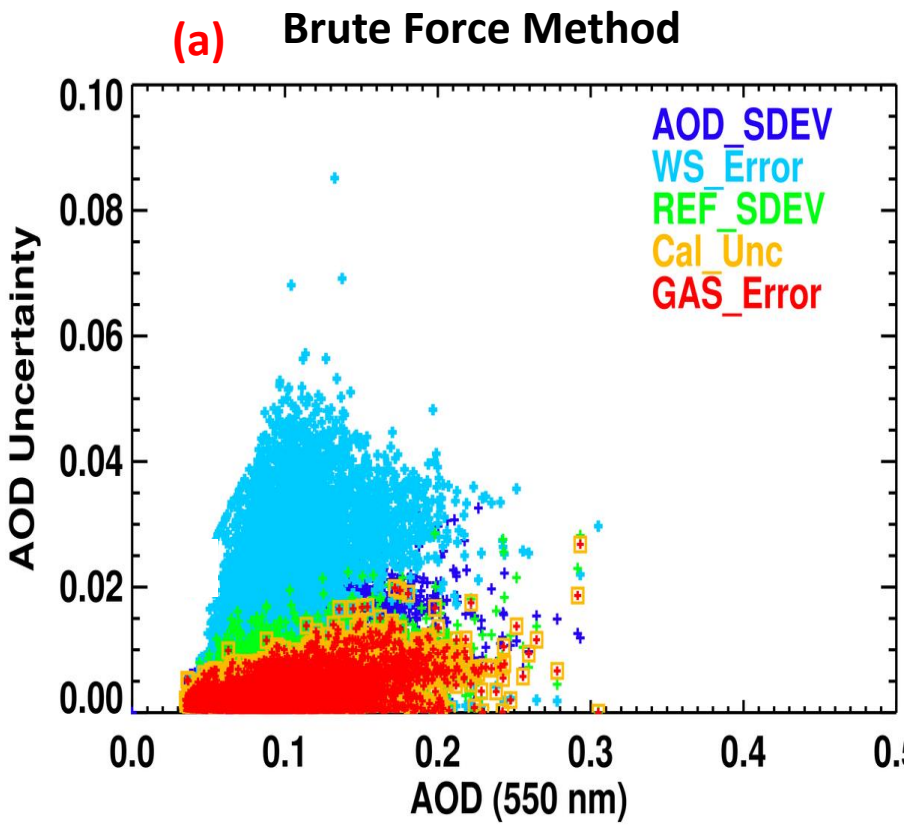
Retrieve AOD Three times using (3 Runs)

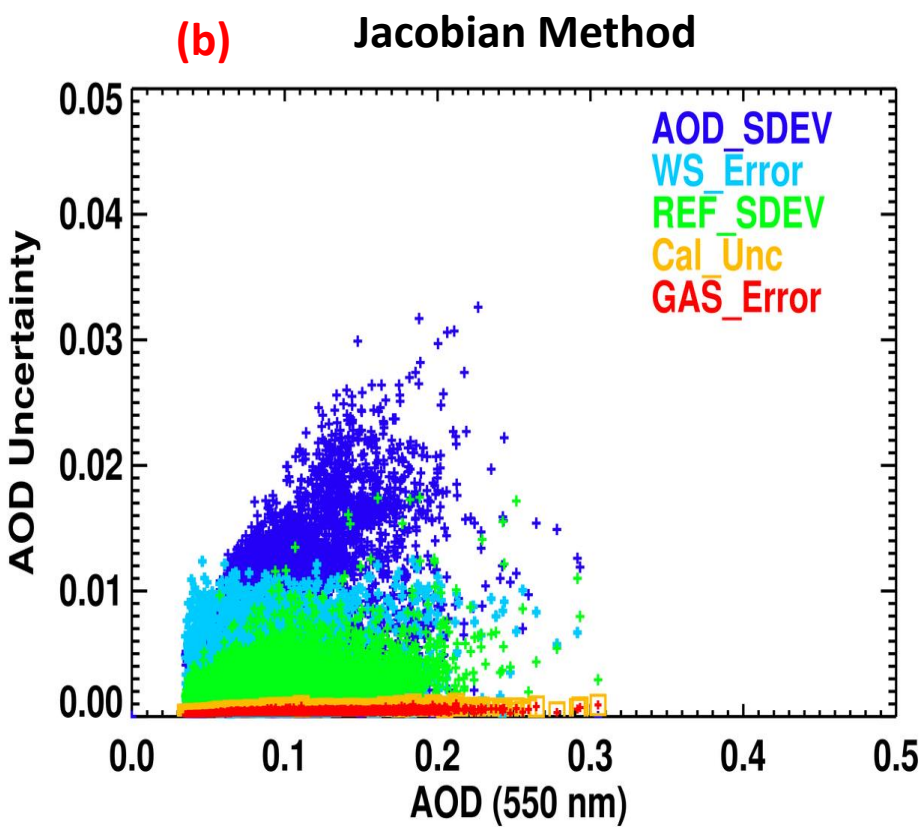
For Example:

(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

Summary Plot : Uncertainty in AOD retrieval





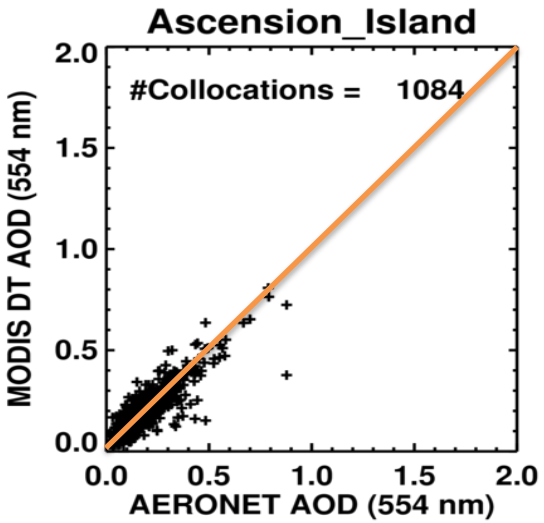
- Uncertainty from the aerosol models (AOD_SDEV) dominates (Jacobian)
- Atmospheric gas correction errors lowest
- What do these uncertainty numbers mean? How do magnitudes compare with EE ? (<15%)

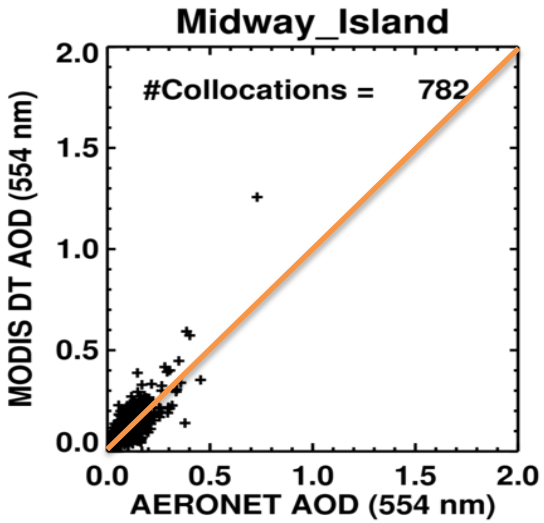
Asking this question ……

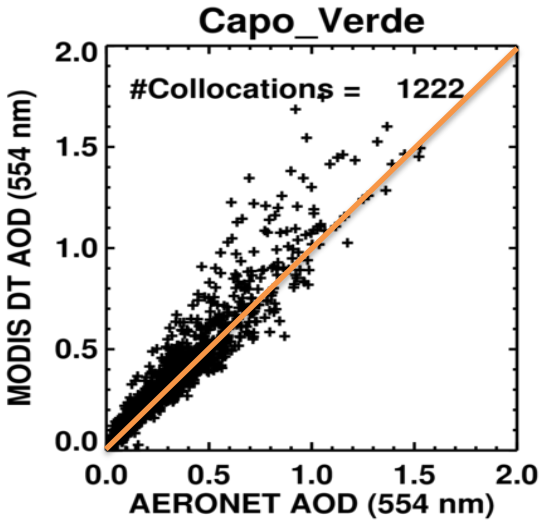
Do AOD uncertainties from different approaches converge within the error / uncertainty envelopes ? [if errors are calculated in a consistent way?]

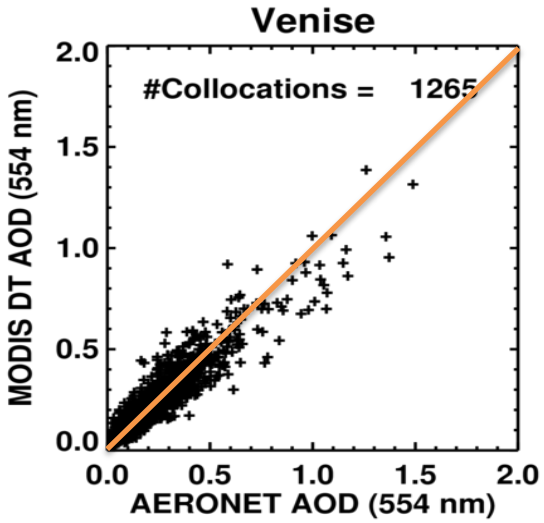
Inter-compare Uncertainty in DT AOD retrieval : The 3 approaches

MODIS DT C6 AOD (Terra+Aqua) over 4 Ocean Sites : 2000 – 2017





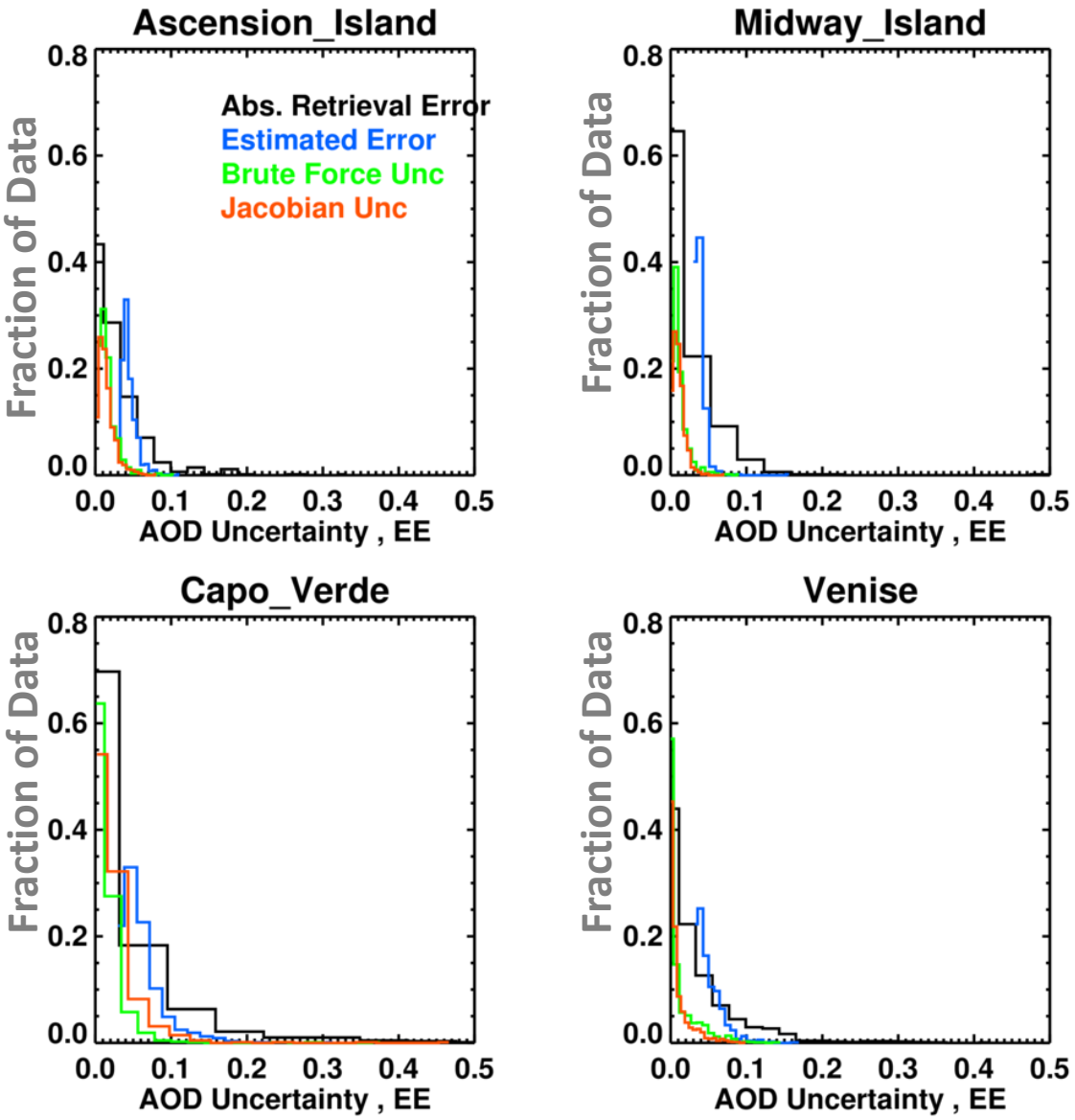




Collocation Criteria

- Nearest retrieval within 25 km of site
- Atleast 5 retrievals in one year

Comparison of Uncertainty in DT AOD retrieval with Retrieval Error



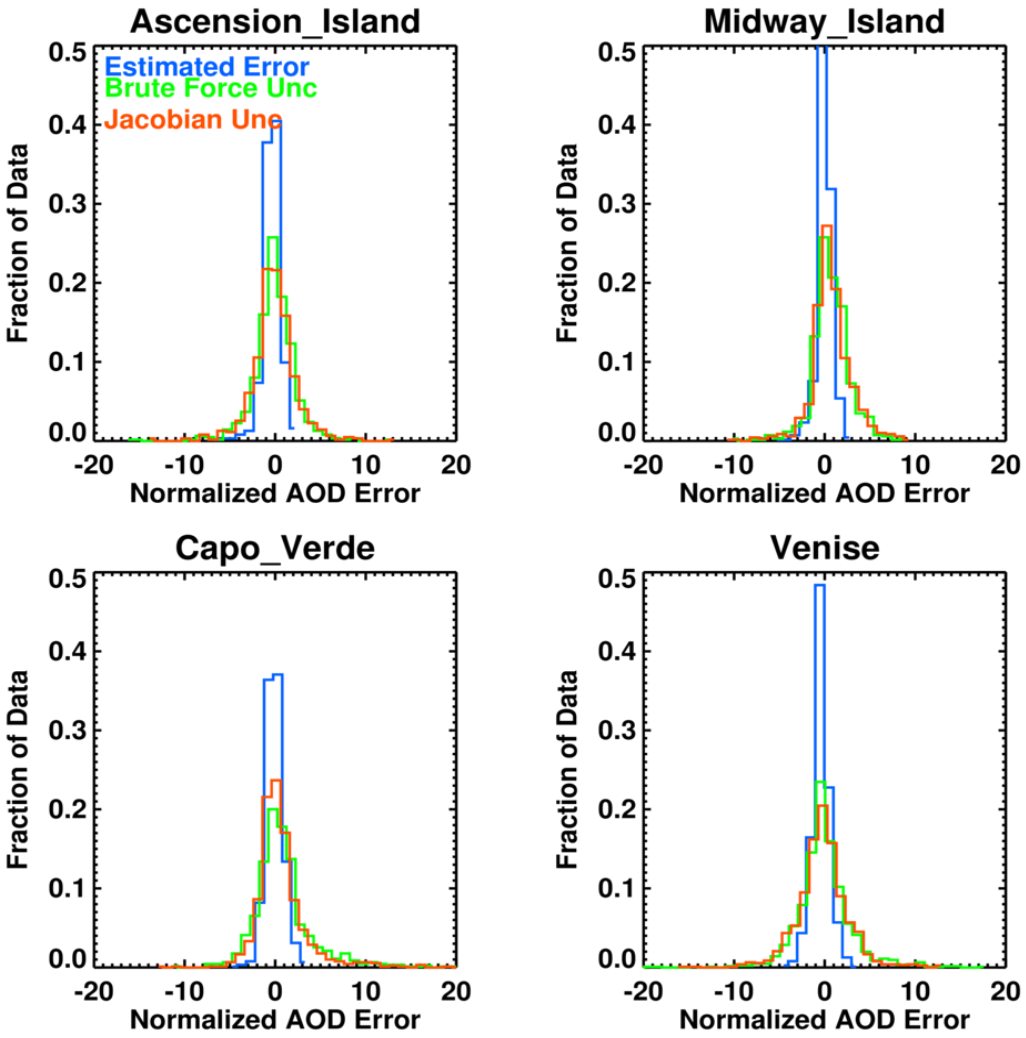
Retrieval Error = MODIS - AERONET AODs

Estimated Error = $\pm(0.03 + 10\% * \tau_A)$

Error Propagation < Retrieval Error

Although site dependent, uncertainties computed from error propagation or ensemble of retrievals are smaller than the retrieval error

Normalized Errors : Both AERONET & Retrieval Uncertainty



Normalized Error = Retrieval Error / Estimated Difference (ED)

ED = [(retrieval uncertainty)^2. + (AERONET uncertainty)^2.]

- **Retrieval Error larger than Brute force , Jacobian Uncertainties**
- **Error propogation (with known error sources) helps define the precision of retrievals**
- **Understanding the sources of (in)accuracy of retrieval requires in-situ observations**

Retrievals in cloud vicinity compromises the comparisons against AERONET

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.