The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2256-8

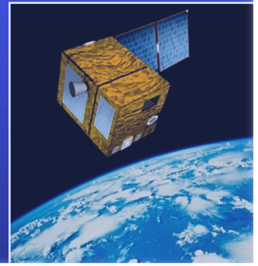
Workshop on Aerosol Impact in the Environment: from Air Pollution to Climate Change

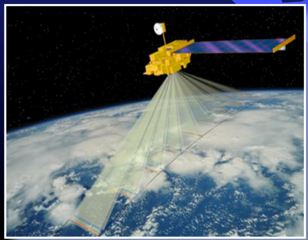
8 - 12 August 2011

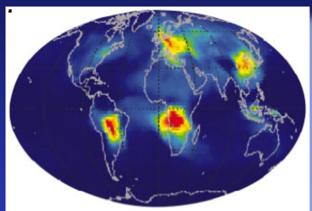
Potential of aerosol properties from enhanced satellite observations

O. Dubovik
Lab. d'Optique Atmospherique, Lille, France

Potential of aerosol remote sensing from space







Oleg Dubovik

Science and Technology University of Lille, CNRS, France

NASA/GSFC, Greenbelt, USA

- ✓ Aerosol retrieval from of the satellite;
- ✓ Inverse modeling
- ✓ Improved POLDER/PARASOL algorithm

Main passive aerosol remote sensing observations

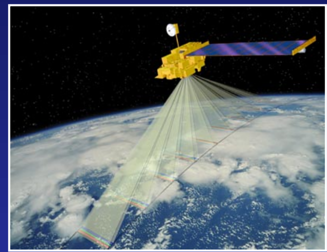
- **MODIS**

Reflectance at
7 channels: 0.47, 0.55, 0.66, 0.87,1.2, 1.6, 2.1

Global Coverage!!!
Good spectral range!

- **MISR**

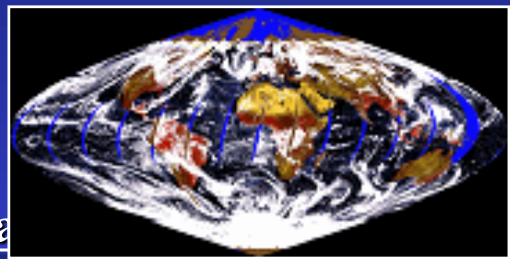
Reflectance at
4 channels: 0.45, 0.55, 0.67, 0.87 mm
9 viewing angles: ±70.5°, ± 60°, ± 45.6°, ± 26.1°, 0°



Sensitive to
Particle shape!!!

- **POLDER**

Reflectance at
8 channels: 0.44, 0.49, 0.56, 0.67,0.76, 0.87, 0.91, 1.02
13 viewing angles
Polarization at: 0.44, 0.67, 0.87



Global Coverage!!!
Sensitive to
Refractive index,
Particle shape.

- **AERONET Ground-based Sun-sky ra**

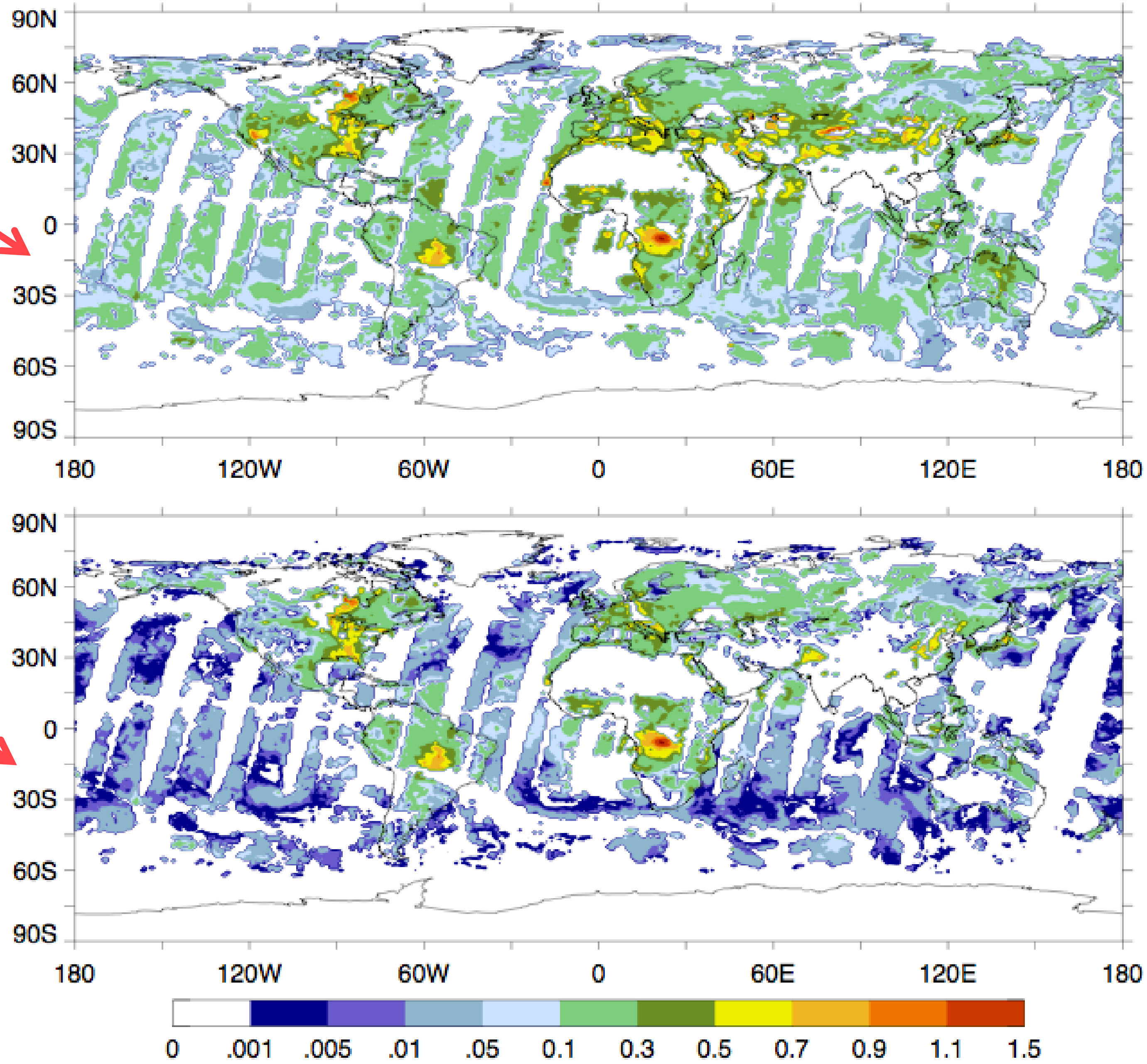
- $\tau(\lambda) \pm 0.02$ at
6 channels: 0.34, 0.38, 0.44, 0.67, 0.87, 1.02, 1.65 μm
- $I(\lambda,\Theta)$ ± 0.05%
6 channels: 0.38, 0.44, 0.67, 0.87, 1.02, 1.65 μm
3° ≤ scattering angles ≤ ~150°
- $P(\lambda,\Theta)$ ± 0.02% at
6 channels: 0.38, 0.44, 0.67, 0.87, 1.02, 1.65 μm

Very Sensitive to
Loading, size,
Particle shape
Absorption !!!

MODIS Aerosol Product for 24 hours

MODIS $\tau_{total}(0.55)$
(Total AOD (degraded to 2^0 x 2.5^0)

MODIS $\tau_{fine}(0.55)$
(Fine Mode AOD (degraded to 2^0 x 2.5^0)



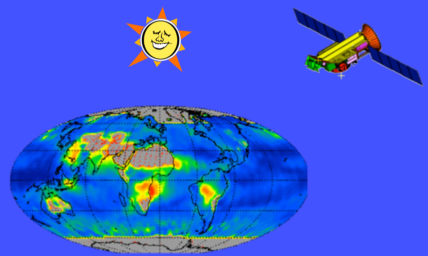
Retrieving aerosol emissions from satellites by GOCART inverse modeling

O. Dubovik, T. Lapyonok, Y. Kaufman , M. Chin,

MODIS/MISR/

PARASOL/CALIPSO:

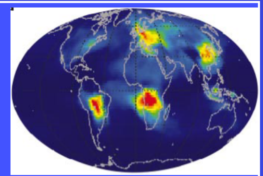
observations of ambient aerosol



INVERSION
via adjoint:

!

GOCART:

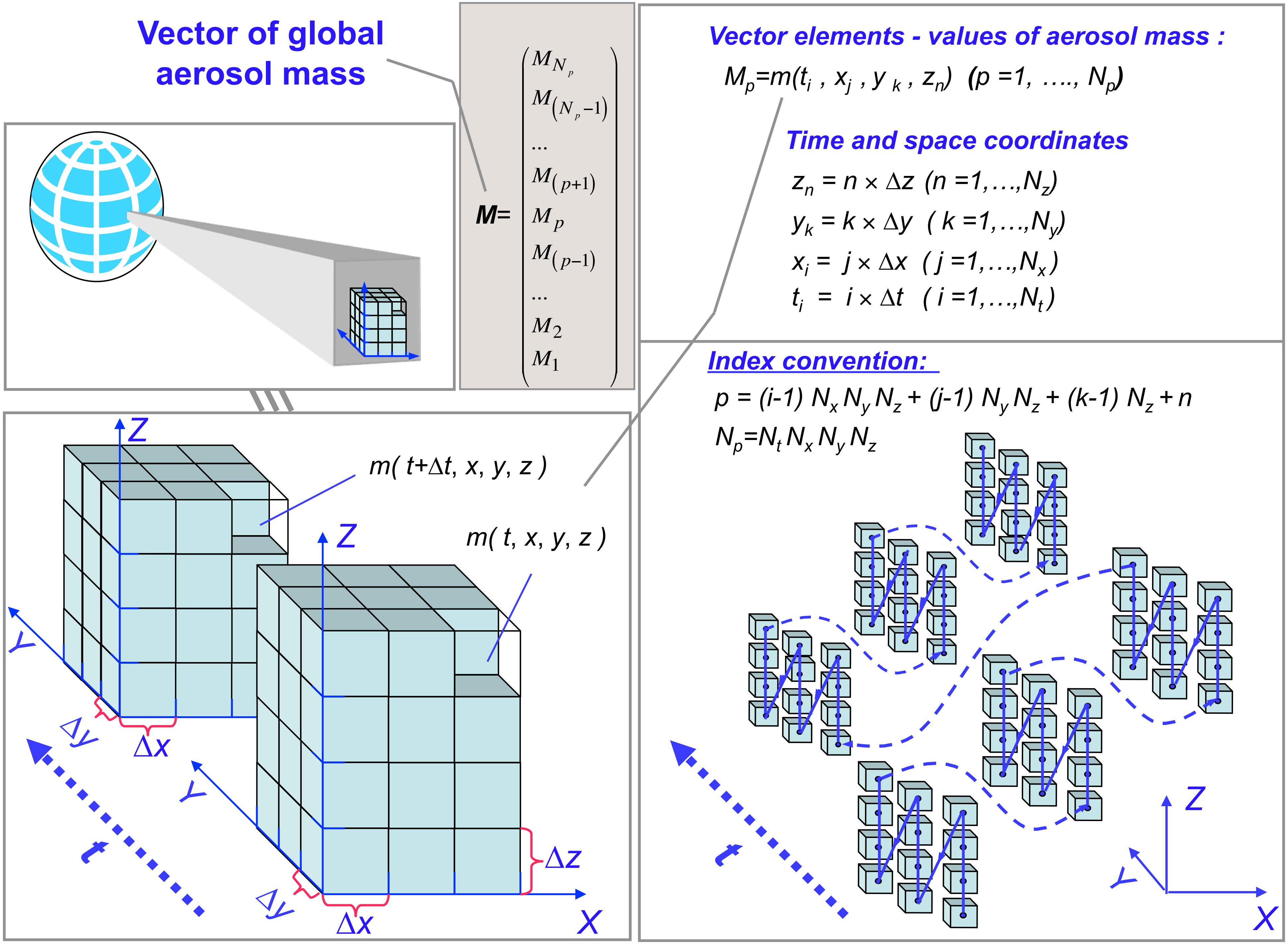


- meteorology
- transport
- chemistry
- removal

-- emissions?

Improved sources (location and strength)

GREAT AGREEMENT of observations and modeling


Vector of global aerosol mass
M=
M_{N_p}
$M_{(N_p-1)}$
...
$M_{(p+1)}$
M_p
$M_{(p-1)}$
...
M_2
M_1
Vector elements - values of aerosol mass :
$M_p = m(t_i, x_j, y_k, z_n)$ $(p = 1, \ldots, N_p)$
Time and space coordinates
$z_n = n \times \Delta z$ $(n = 1, \ldots, N_z)$
$y_k = k \times \Delta y$ $(k = 1, \ldots, N_y)$
$x_j = j \times \Delta x$ $(j = 1, \ldots, N_x)$
$t_i = i \times \Delta t$ $(i = 1, \ldots, N_t)$
Index convention:
$p = (i-1) N_x N_y N_z + (j-1) N_y N_z + (k-1) N_z + n$
$N_p = N_t N_x N_y N_z$
$m(t+\Delta t, x, y, z)$
$m(t, x, y, z)$
Z
Y
X
t
Δx
Δy
Δz

Aerosol Transport:

Basic relationship:

$$M(\mathbf{x},t+\Delta t) = T(\mathbf{x},t)\left(M(\mathbf{x},t) + S(\mathbf{x},t)\right)\Delta t$$

$M(\mathbf{x},t)$ -mass

$S(\mathbf{x},t)$ -emission

Transport processes:

(advection, diffusion, dry deposition,

cloud convection, wet removal, etc.)

$$T(x,t) = T_n T_{n-1} \ldots T_2 T_1$$

Integral form :

$$M(\mathbf{x},t) = \int_{t_0}^{t} T(\mathbf{x},t)\left(M(\mathbf{x},t) + S(\mathbf{x},t)\right)dt$$

Matrix approximation:

$$\mathbf{M}(\mathbf{x},t) = \mathbf{T}(\mathbf{x},t)\left(\mathbf{M}(\mathbf{x},t_0) + \mathbf{S}(\mathbf{x},t)\right)$$

Transport Inversion:

$$\mathbf{M}(\mathbf{x},t) = \mathbf{T}(\mathbf{x},t)\,\mathbf{S}(\mathbf{x},t)$$

Aerosol Mass

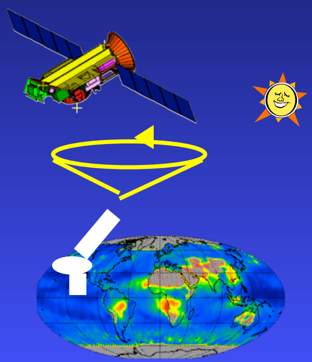
Transport Operator

Source - Aerosol Emission

Least Square Method:

$$\hat{\mathbf{S}} = \left(\mathbf{T}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{T}\right)^{-1}\mathbf{T}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{M}^{*}$$

Measured Aerosol Mass



Dimension of the Problem:

$\mathbf{M}(\mathbf{x},t)$ →

Longitude Points (~144)
X
Latitude Points (~91)
X
Vertical Layers (~30)
X
Time steps (~12 days)
= ~ 5,000,000

$\mathbf{S}(\mathbf{x},t)$ →

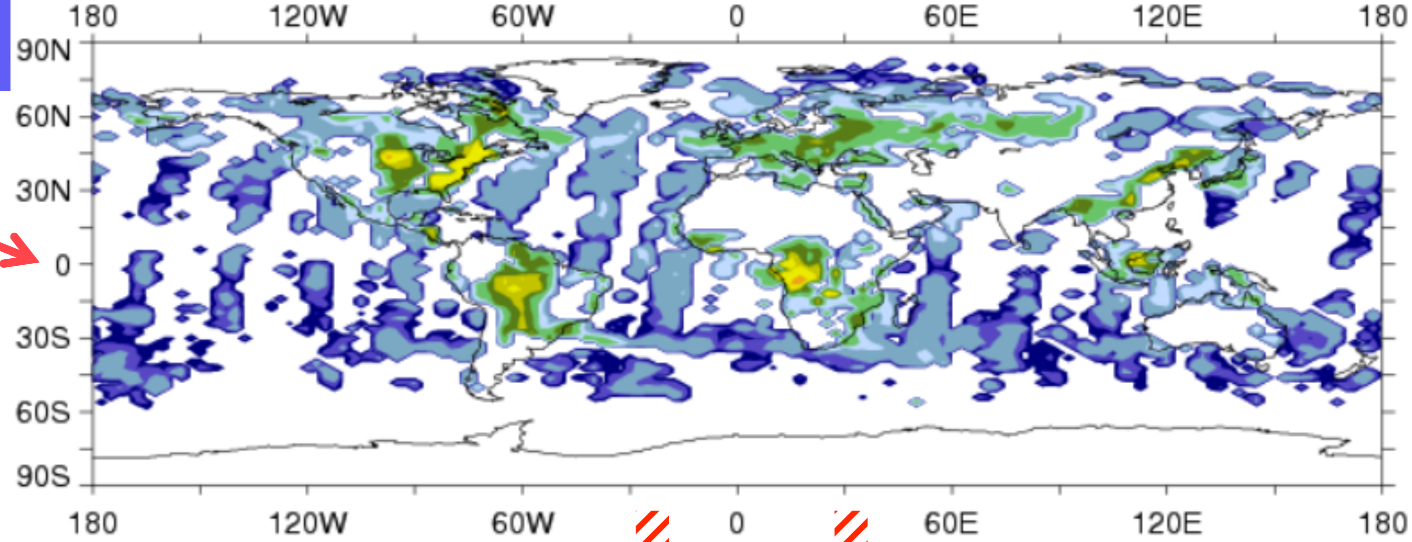
Longitude Points (~144)
X
Latitude Points (~91)
X
Time steps (~12 days)
= ~ 200,000

$\mathbf{T}(\mathbf{x},t)$ → 5,000,000 X 200,000

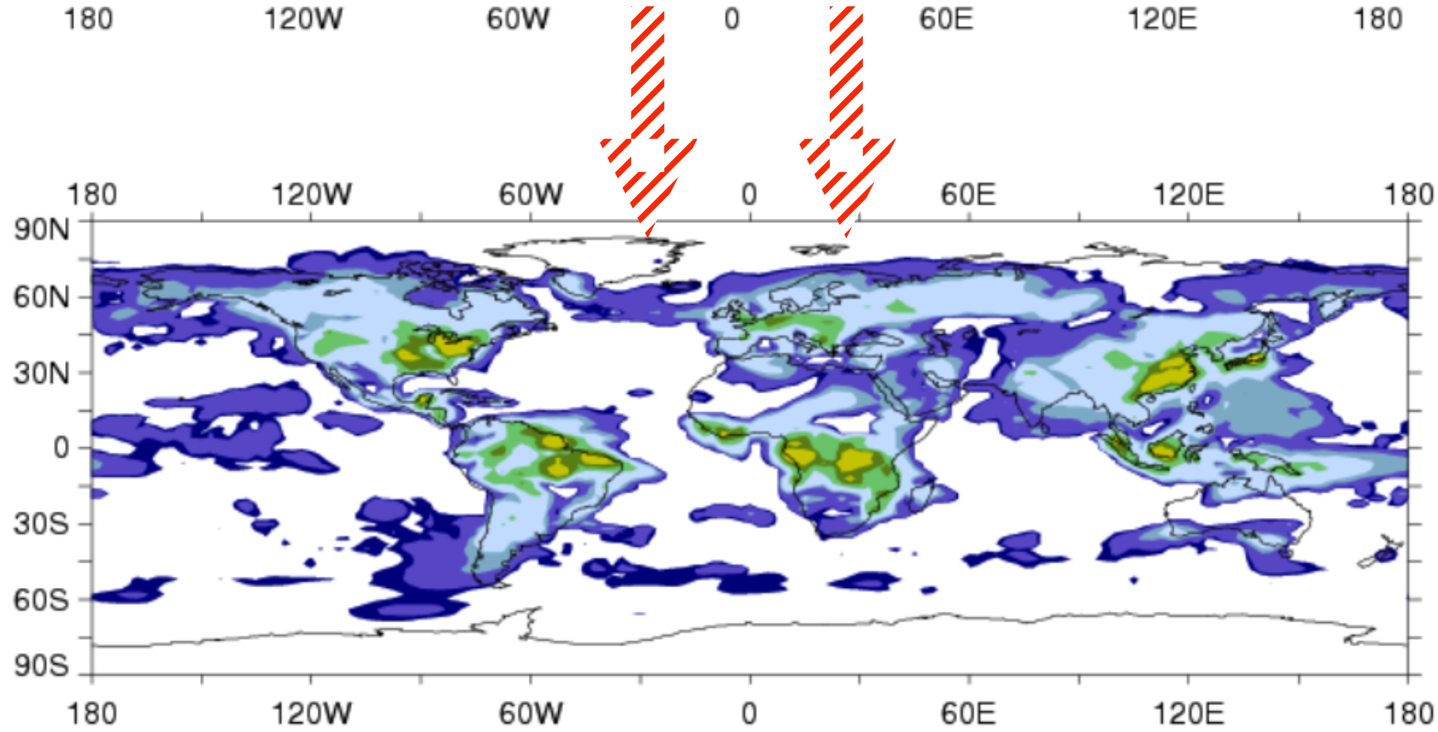
__Fine Mode Aerosol:__
Black Carbon +
Organic Carbon +
Sulfate + …

August 20 - 28, 2000

MODIS+AERONET Observations (opt. thickness)



Retrieved Emission



9 day average, Optical Thickness retrieval is NOT CONSTRAINED to the land

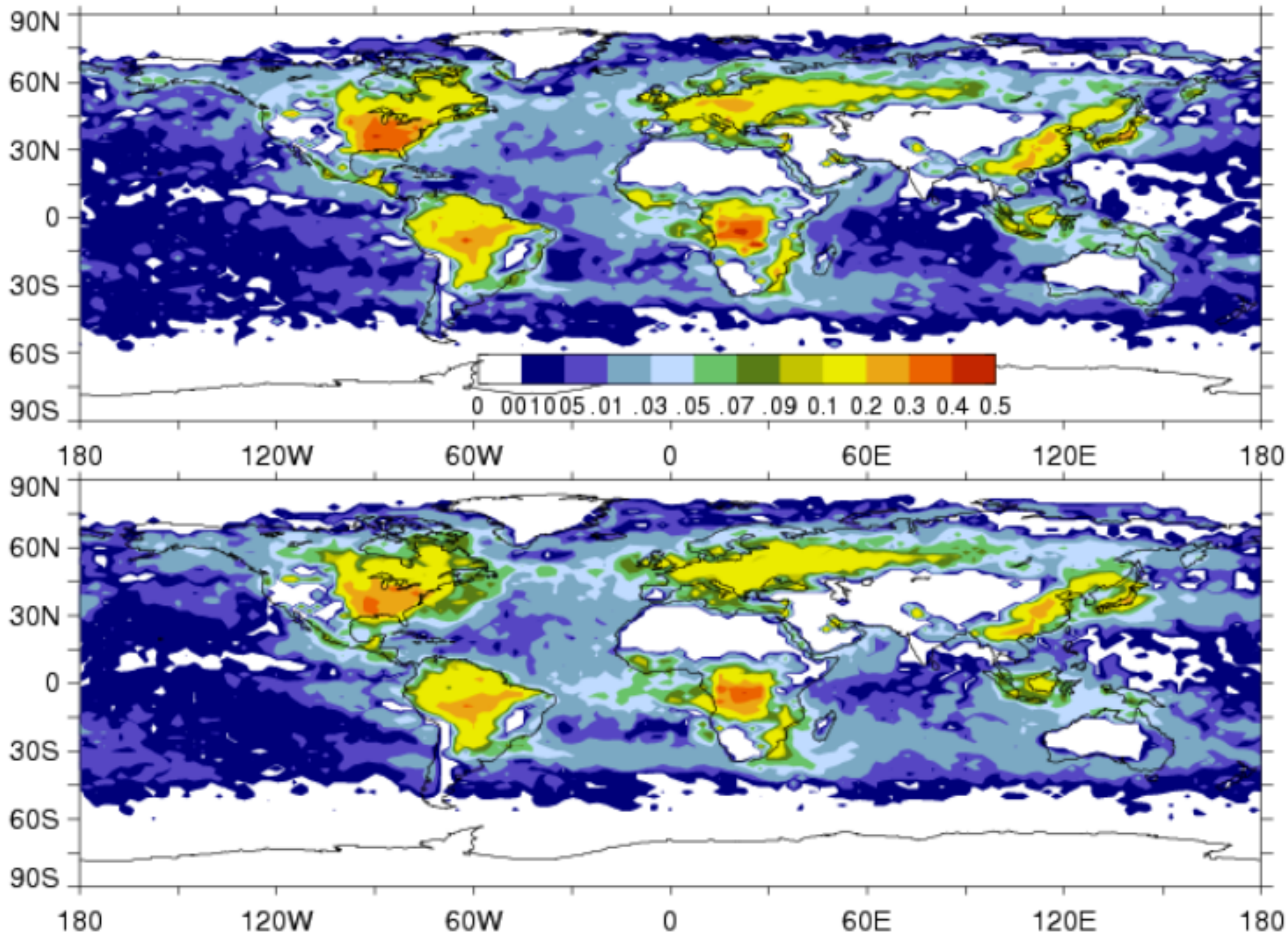
$\sigma_{fit} < \sim 0.04$ (for instantaneous τ values)

Optical Thickness

(August 20-28, 2000)

MODIS+AERONET Observations
(Fine Mode opt. Thickness, (degraded to $2^0 \times 2.5^0$)

Model output using retrieved emission



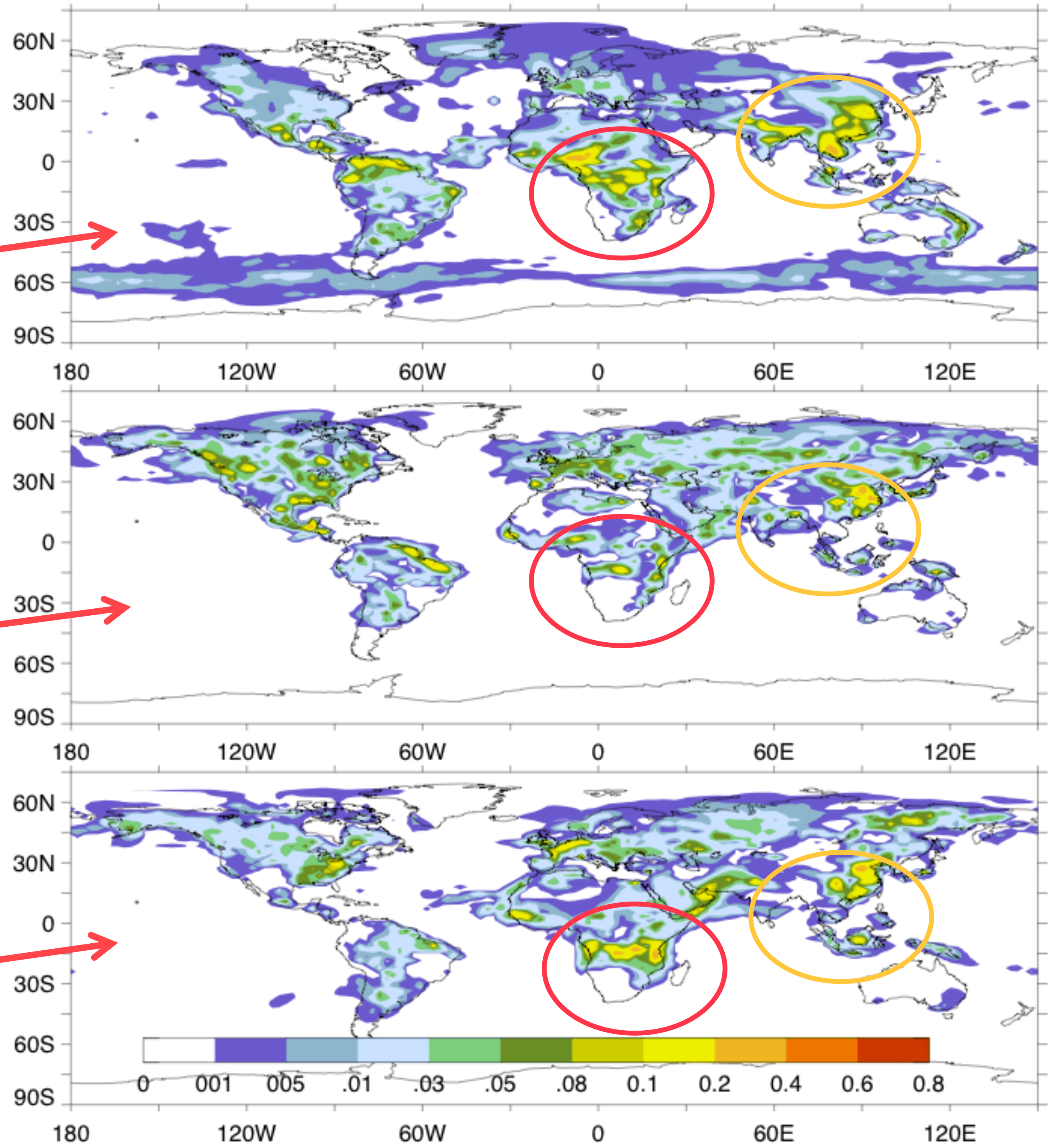
Fine Mode Aerosol:

Monthly retrievals

February 2001

May 2001

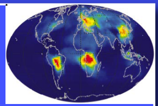
July 2001



Model ≠ Observations

GOCART output

MASS: M(*x*;*y*;*z*;*t*)



$2^o \times 2.5^o$,~20 min

Components:

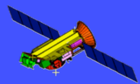
- BC (hydrophilic)
- BC (hydrophobic)
- OC (hydrophilic)(
- OC (hydrophobic)h
- sulfates
- dust (7 sizes) ()
- sea salt(4 sizes)

≠

MODIS products

Aerosol Optical thickness:

$\tau(x;y;t)$



$1^o \times 1^o$,

global coverage in ~2 days

Components:

- $\tau_{fine}(0.55\mu m)$
- $\tau_{coarse}(0.55\mu m)$

→ Better satellite Product is needed !!!

POLDER/PARASOL

- PARASOL (POLDER1&2)
  - Launches Dec., 2004
  - 705km polar orbit, ascending (1:30pm)

- Sensor Characteristics
  - 9 spectral bands ranging from 0.45 to 0.910 µm
  - Wide field of view lens : ± 51 ° along track, ± 43 ° cross track Swath* : 1600 km ; 2100km along track
  - Up to 16 viewing directions
  - Spatial resolution: 5.3 km x 6.2 km

"independent" POLDER/PARASOL measurements :

GLOBAL: every 2 days SPATIAL RESOLUTION: 5.3km × 6.2km

VIEWS: $N_\Theta = 16$: $(80^0 \leq \Theta \leq 180^0)$

INTENSITY: $N^t_\lambda = 6$: (*0.44, 0.49, 0.56, 0.67, 0.865, 1.02* μm)

POLARIZATION: $N^P_\lambda = 3$: (*0.49, 0.67, 0.865* μm)

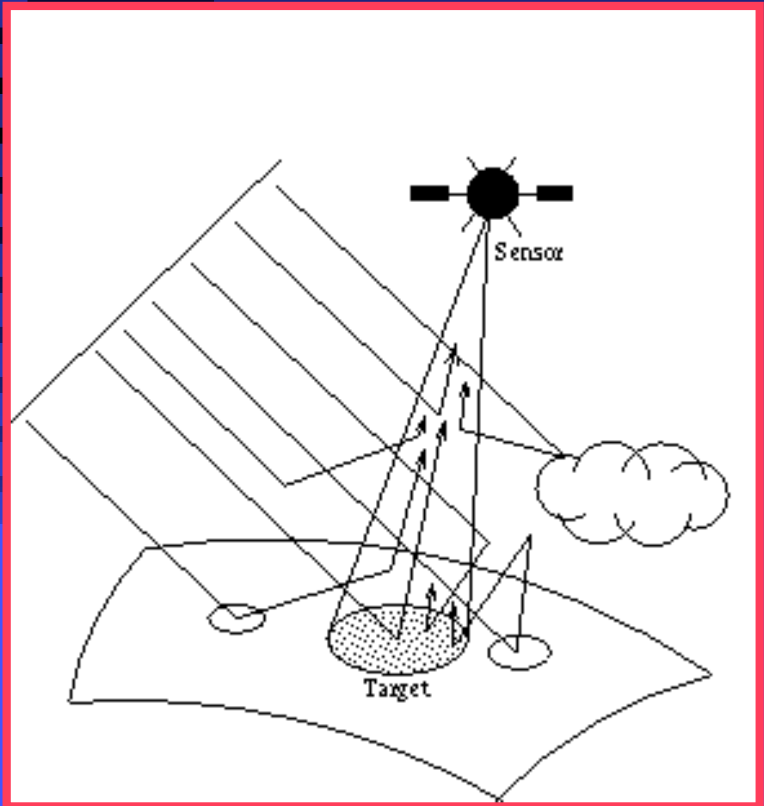
SINGLE OBSERVATION:

a lot !!!

$$(N^t_\lambda + N^P_\lambda) \times N_\Theta = (6+3) \times 16 = 144$$

independent measurements

Look-Up-Table (LUT) – conventional approach for satellite data inversion



ADVANTAGES:

- simple and usually fast;

ISSUES:

- LUT can be too big for comprehensive satellite observations;

- Retrieval results are limited to a selected set of a priori assumed solutions

Present aerosol retrieval from PARASOL:

Over Ocean (Herman et al., 2005):

- *Uses look-up tables*
- *Fits both intensity and polarizations at 0.67 and 0.87 μm*
- *Retrieves:* AOT of fine and coarse mode, size information, non-sphericity, some height information.
- *Issues: does not always provide consistency with other channels*

Over Land (Deuzé et al., 2001):

- *Uses look-up tables*
- *Fits only polarizations at 0.67 and 0.87 μm using look-up tables*
- *Retrieves:*

  AOT of fine mode only , some size information
- *Issues: quite limited*

Concept of optimization of aerosol retrieval from PARASOL:

Strategic principles:

1. *More complete use of PARASOL observation:*

   - always use both intensity and polarization;

   - fit observations from all aerosol informative channels: 0.44, 0.49, 0.55, 0.67, 0.87 and 1.02 μm

2. *Simultaneously retrieve both aerosol and surface (over land)*

3. *Use continues space of solution (i.e. not look up table)*

4. *Use elaborated statistical optimization fitting (e.g. Dubovik 2004):*

   - for each single pixel;

   - multi-pixel retrieval optimization;

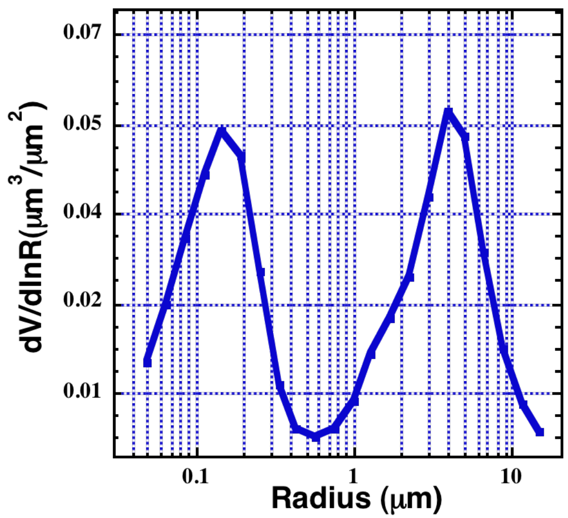
   - multi-instrument retrieval optimization

Aerosol is driven by 30 variables in PARASOL retrieval :

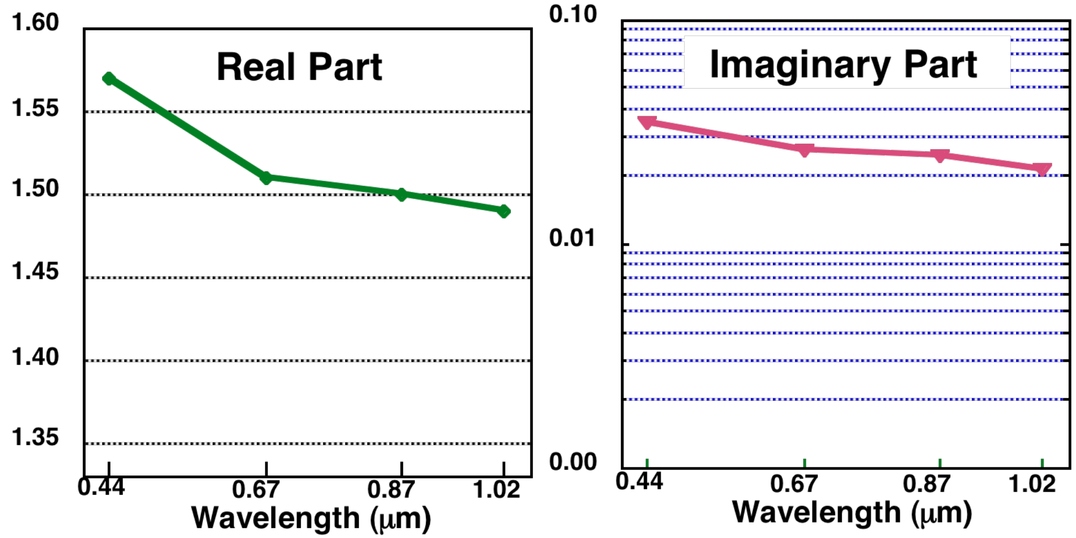
dV/lnr - size distribution (~16 values);
n(λ) and k(λ) - ref. index (6 +6 values)
C_{spher} (%) - spherical fraction (1 value)
h_a – mean aerosol height (1 value)

Similar to AERONET model:

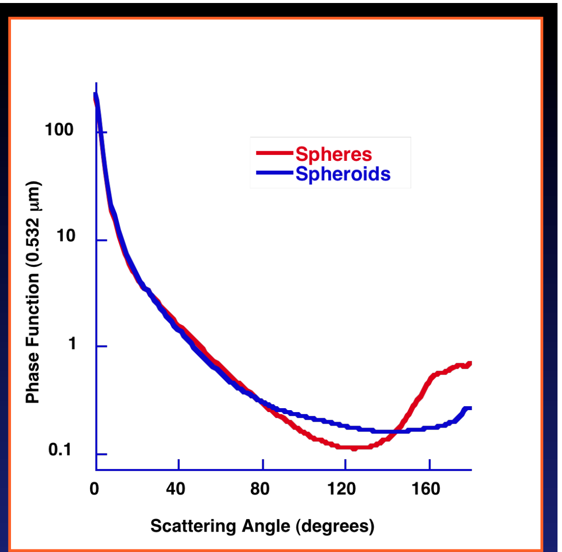
Particle Size Distribution: 0.05 μm ≤ R (22 bins) ≤ 15 μm



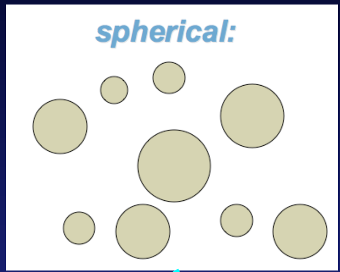
Complex Refractive Index at λ = 0.44; 0.67; 0.87; 1.02 μm

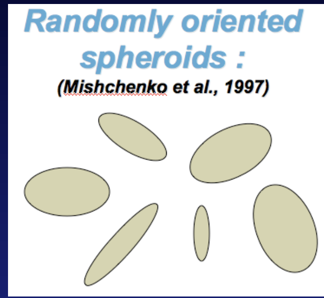


Mixing of particle shapes



retrieved

C × 

+ (1-C) × 

$$\tau(\lambda) = C \int_{r_{min}}^{r_{max}} K_{\tau}^{spherical}(k;n;r)V(r)dr + (1-C)\int_{r_{min}}^{r_{max}}\left(\int_{\varepsilon_{min}}^{\varepsilon_{max}} K_{\tau}^{\varepsilon}(k;n;r,\varepsilon)N(\varepsilon)d\varepsilon\right)V(r)dr$$

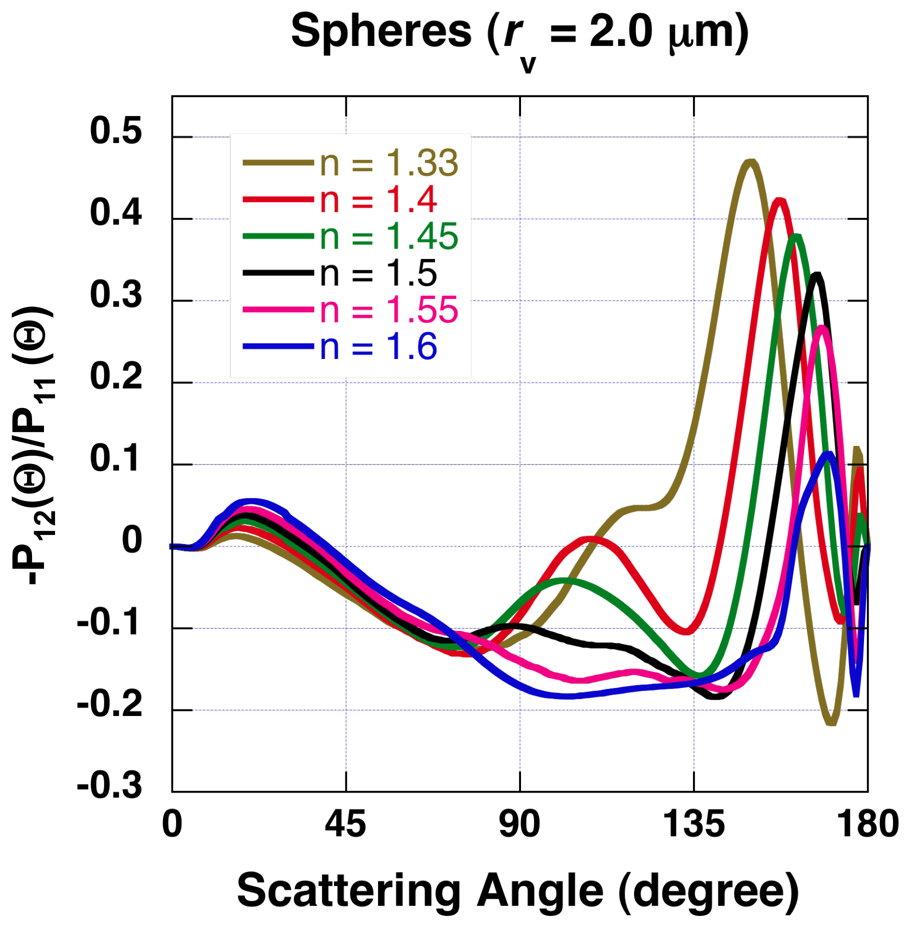
Aspect ratio distr.

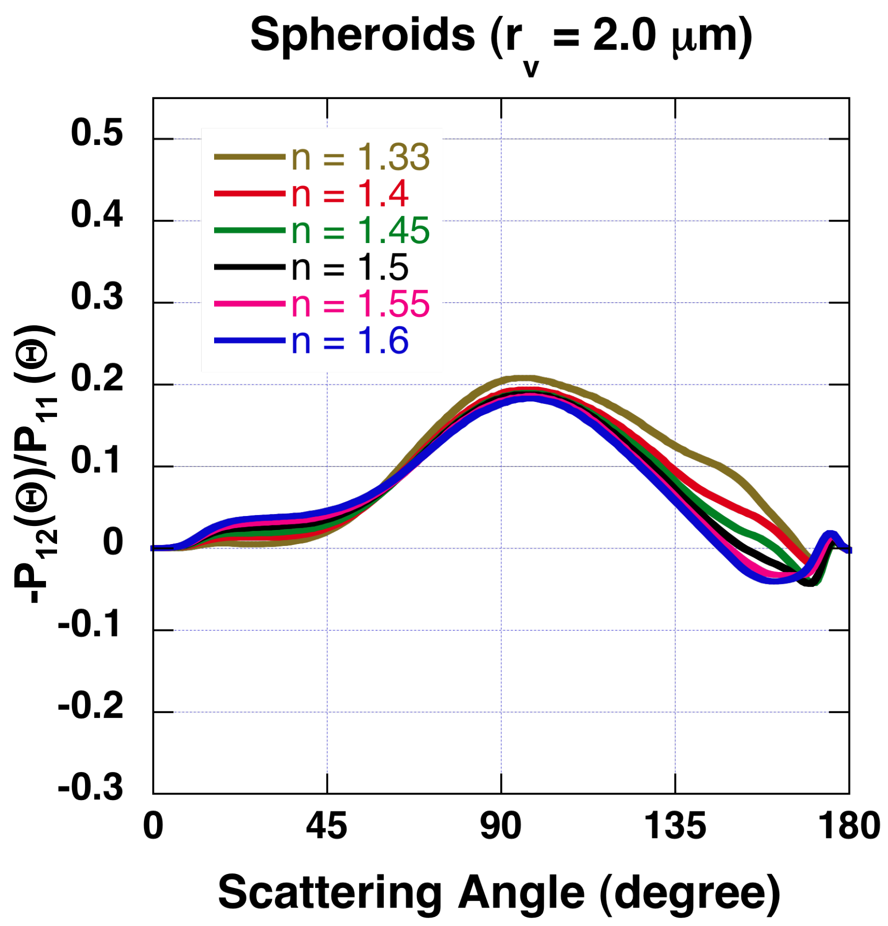
ASSUMPTIONS:

- dV/dlnr - volume size distribution is the same for both components;
- non-spherical - mixture of randomly oriented polydisperse spheroids;
- aspect ratio distribution $N(\varepsilon)$ is fixed to the retrieved by Dubovik et al. 2006

Sensitivity of polarization to particle shape

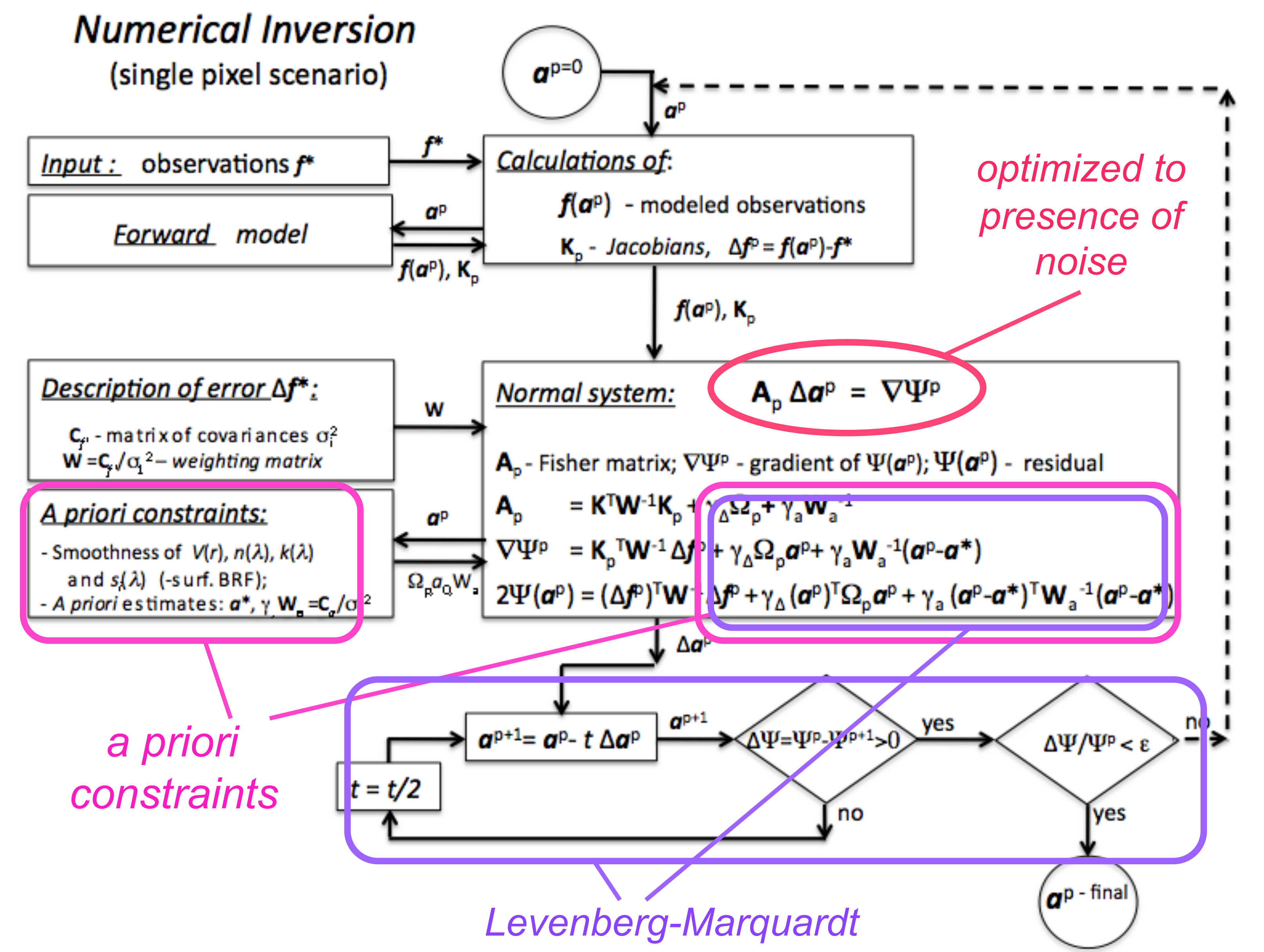
Coarse aerosol





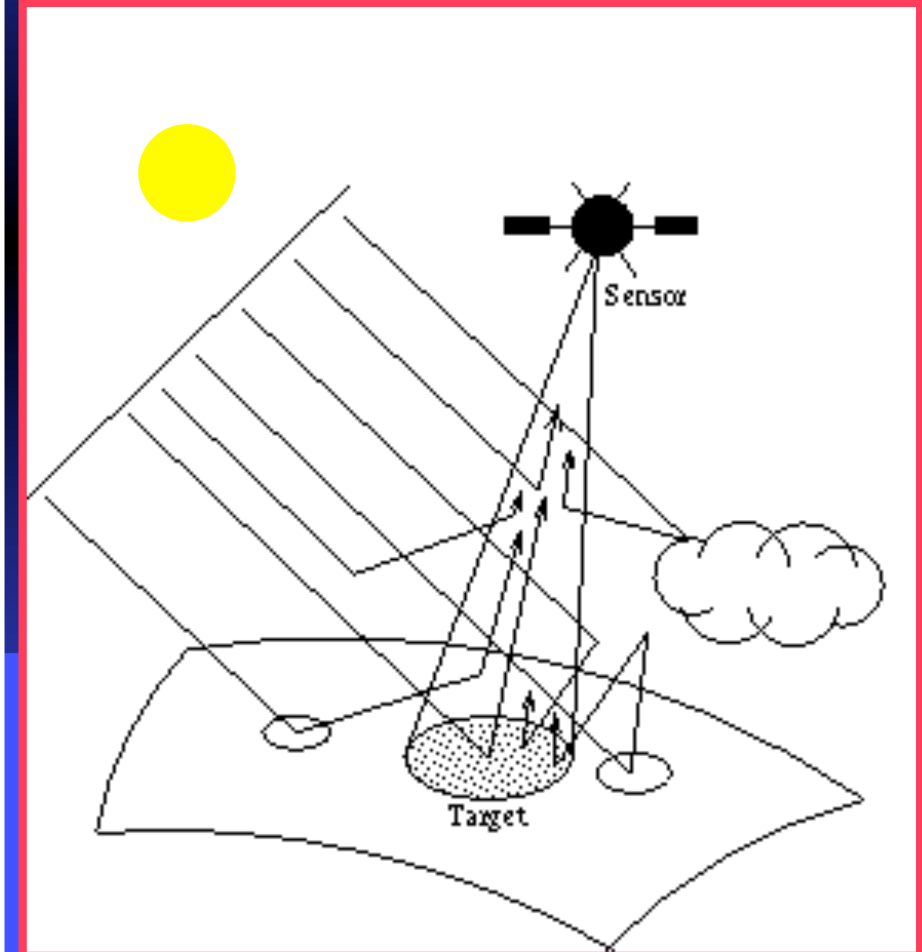
« AERONET like » statistically optimized « no look-up tables » inversion

Dubovik et al., AMT, 2011

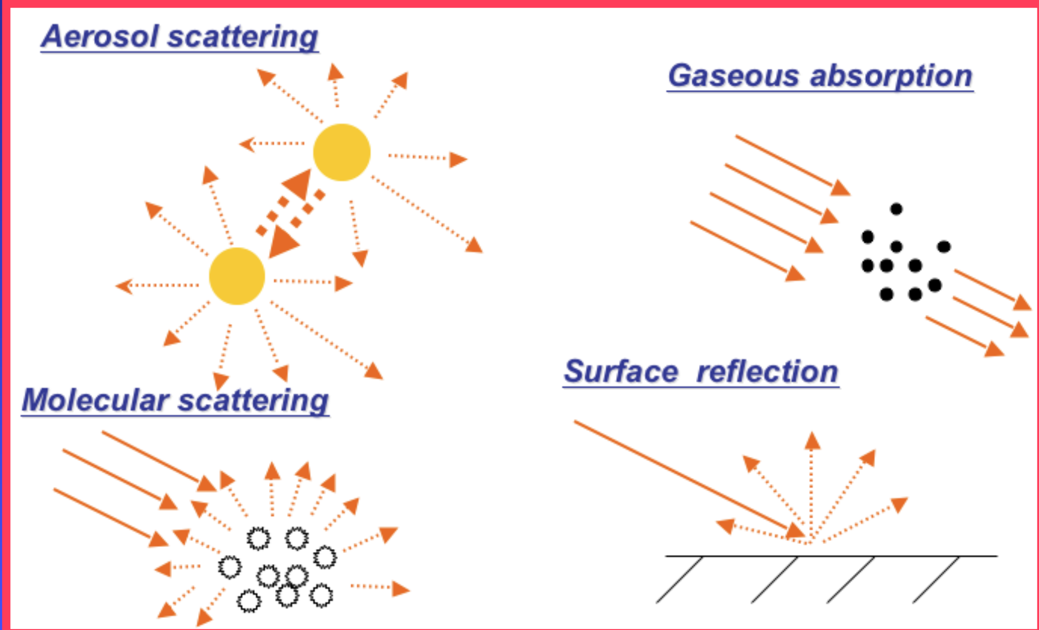


Remote Sensing from Satellite (using the solar spectrum)

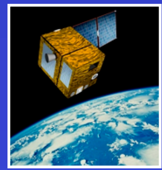
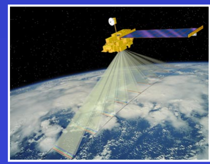
ISSUE: to distinguish aerosol contributions

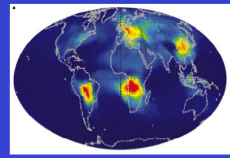


Multiple scattering



Forward Model



Vector of retrieved parameters :

$\boldsymbol{a}^{aer}$ - *aerosol properties*

$\boldsymbol{a}^{surf}$ - *surface properties*

$\boldsymbol{a}^{aer}$ ↓ $\boldsymbol{a}^{surf}$ ↓

Aerosol single scattering :

Provides: $\tau(\lambda)$, $\omega_0(\lambda)$, $P_{ii}(\lambda,\Theta)$

Surface reflectance :

Provides: Bi-directional Reflection Function (BRF) Bi-directional Polarized Reflection Function (BPRF)

τ, ω_0, $P_{ii}(\ldots)$ ↓

BRDF, BPRF ↓

Full radiative transfer model :

Calculates detailed distribution of atmospheric radiances: $F(\lambda,\Theta,\ldots)$

fixed a priori :

- *molecular scattering;*
- *gaseous absorption;*
- *vertical profile of aerosol*

↓

Simulated satellite observations: $f(\boldsymbol{a}^p)$

« Blind » Test of aerosol retrieval over dark surface

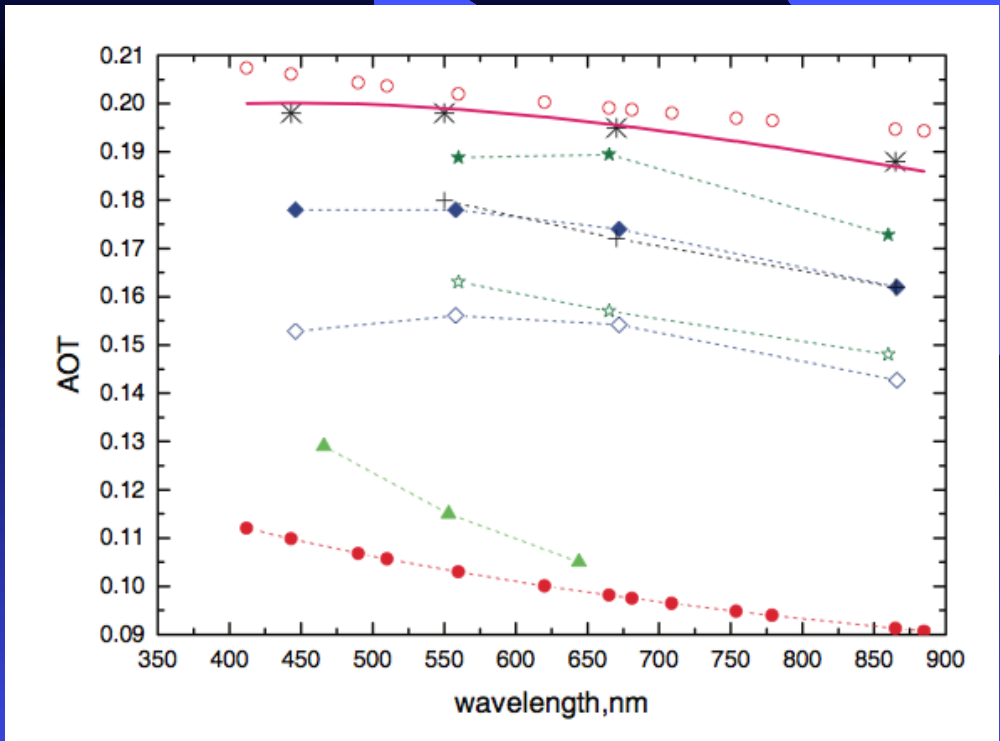
Kokhanovsky, et al, The inter-comparison of major satellite aerosol retrieval …., Atmos. Meas. Tech., 3, 909–932, 2010.

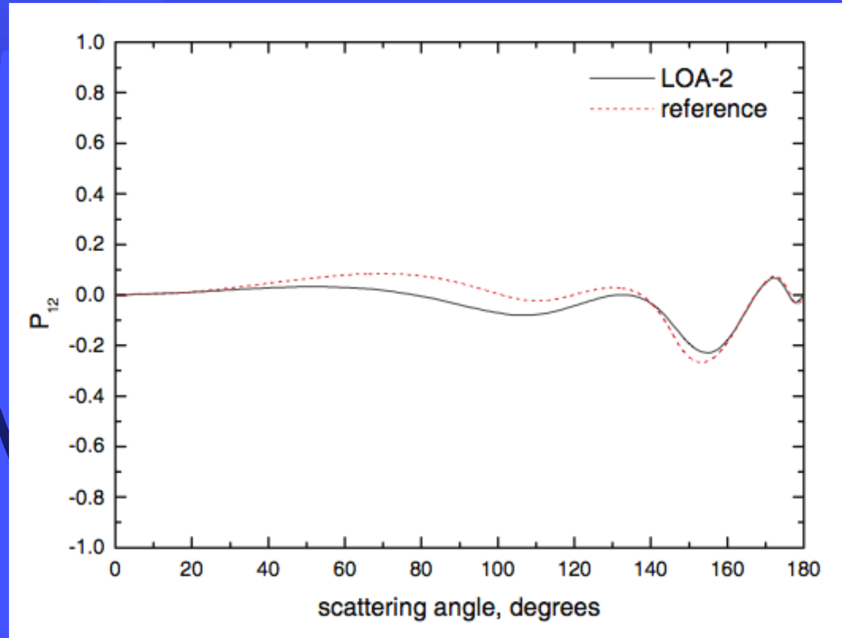
8 algorithms/5 instruments

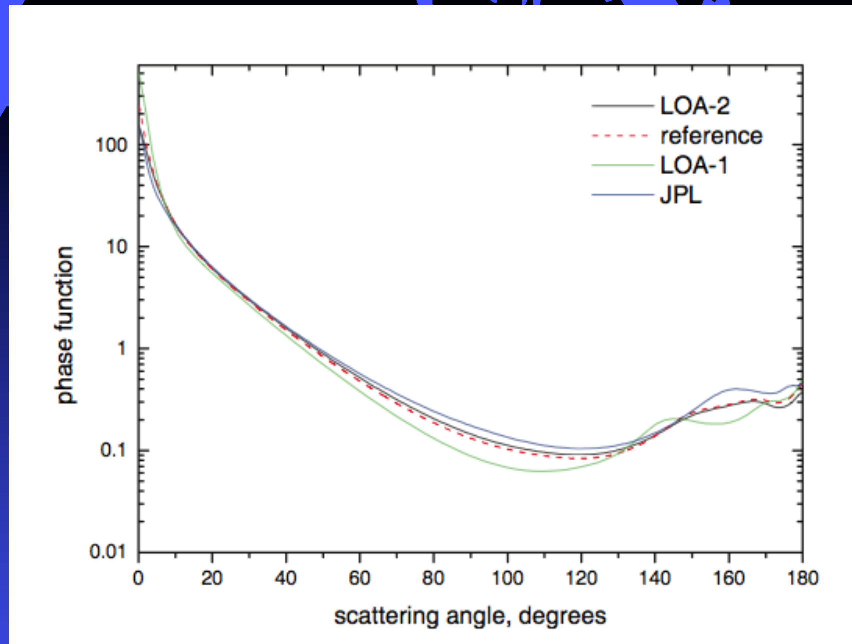
NASA/MODIS	USA	LUT
NASB/MERIS	Belarus	RT
Swansea/AATSR	UK	RT
Oxford/AATSR	UK	LUT
JPL/MISR	USA	LUT
PSI/MISR	Switzerland	LUT
LOA-1/POLDER	France	LUT
LOA-2/POLDER	France	RT

Tests over dark surface
(« *Blind* » *Test*)

Kokhanovsky, et al, The inter-comparison of major satellite aerosol retrieval …., Atmos. Meas. Tech., 3, 909–932, 2010.







Rahman-Pinty-Verstraete (RPV) model ***(Rahman et al., 1993)***

MISR (Martonchik et al. 1998)
SEVIRI (Govaerts et al. 2010)

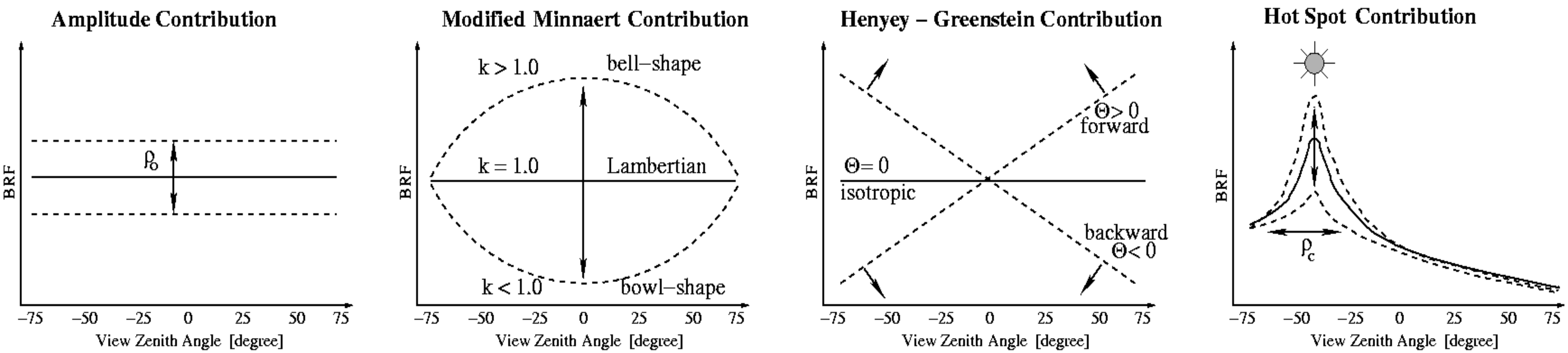
Bi-Directional Surface Reflectance

$$\rho_{sfc}(\vartheta_1,\varphi_1;\vartheta_2,\varphi_2) = \rho_0 M_i(k) F_{HG}(\Theta) H(h)$$

To be retrieved in each wavelength

- ρ_0 - controls amplitude level
- k - controls bowl/bell shape
- Θ - controls forward/backward scattering
- h - controls hot spot peak

ρ_0 k Θ h

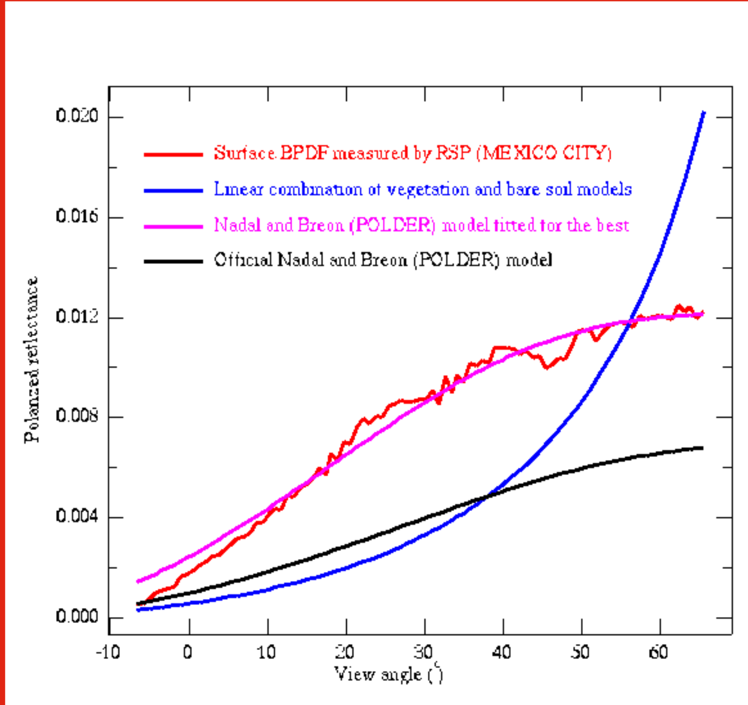


Polarized Reflectance of the Surface:

1. Nadal and Bréon, (1999):

$$R_p^{surf}(\theta_s,\theta_v,\varphi_r) = \alpha\left[1-\exp\left(-\beta\frac{F_p(\gamma)}{\mu_s+\mu_v}\right)\right]$$

(α and β - empirical parameters)



F. Waquet

2. Maignan et al., (2009):

$$R_p^{surf}(\theta_s,\theta_v,\varphi_r) = \frac{B\exp(-\tan(\alpha_i))\exp(-v)\,F_p(\gamma)}{4(\mu_0+\mu_1)}$$

Spectrally independent !!!

(B - empirical parameter)

parameters to retrieve:

AEROSOL:

- *dV(r)/dlnr (16 bins from 0.07 to 10 mm);* $N_r = 16$
- $n(\lambda)$ $N_\lambda = 6$
- $k(\lambda)$ $N_\lambda = 6$
- *Fraction of spherical particles* $N_\lambda = 1$
- *Aerosol height* $N_\lambda = 1$

SURFACE:

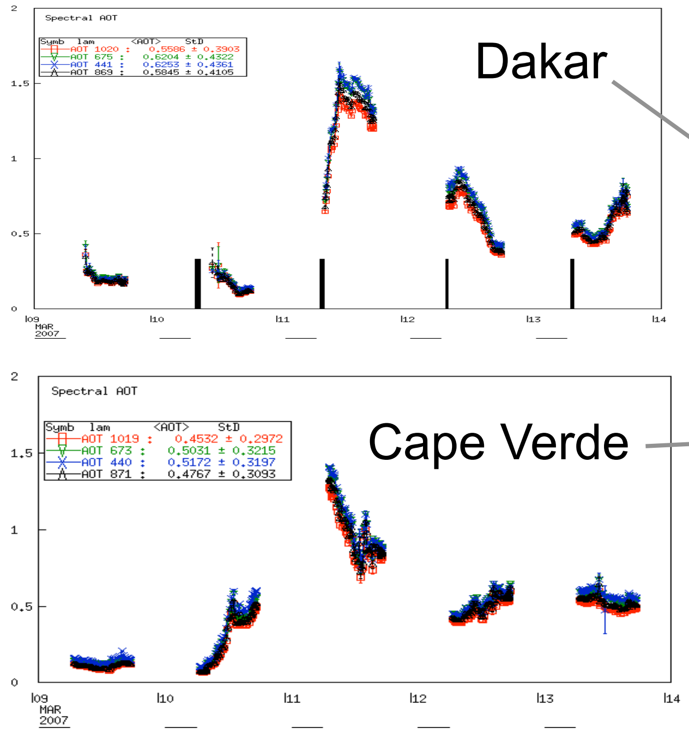
- *BRF (3 parameters for each* λ*)* $N = 3 \times 6 = 18$
- *BPRF (parameters for each)* $N_\lambda = 6$

TOTAL = 54

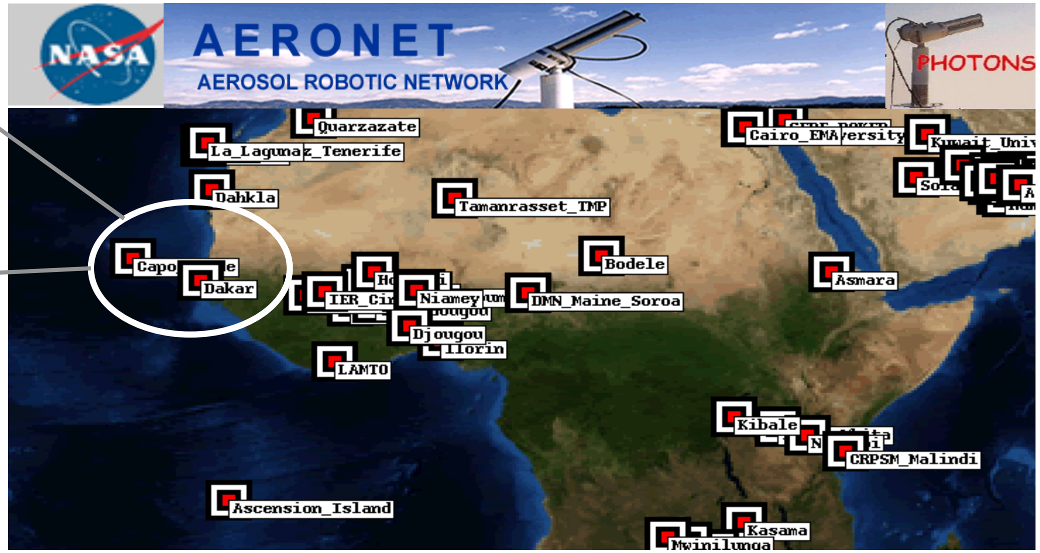
Satellite aerosol retrievals have some fundamental limitations, especially in some "difficult conditions" e.g. over bright surfaces.

↓

Some additional constraint on the retrieval could do good…

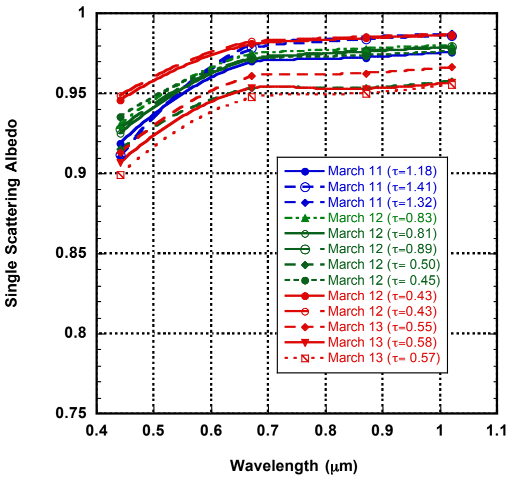


Saharan dust outbreak observed by August 9 -13, 2007

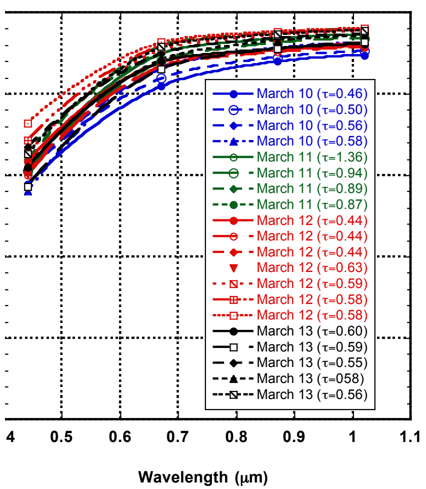


AERONET retrievals over Dakar and Cape Verde during August 9 -13, 2007

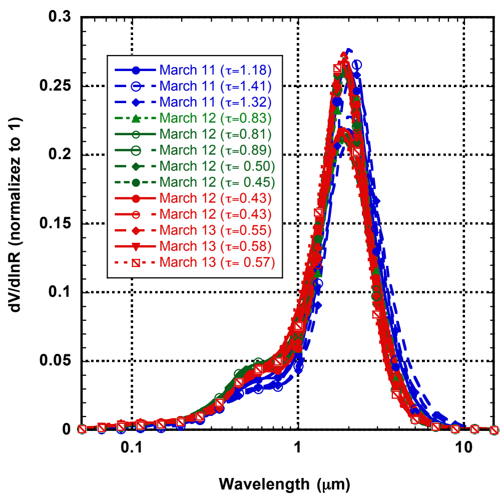
Retrieved Single Scattering Albedo
(March 11-13, 2007, Cape-Verde)



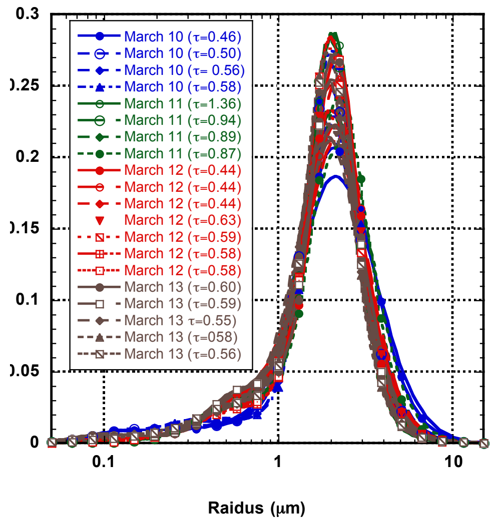
Retrieved Single Scattering Albedo
(March 10-13, 2007, Dakar)



Retrieved Size Distribution
(March 11-13, 2007, Cape-Verde)



Retrieved Size DIstribtuion
(March 10-13, 2007, Dakar)



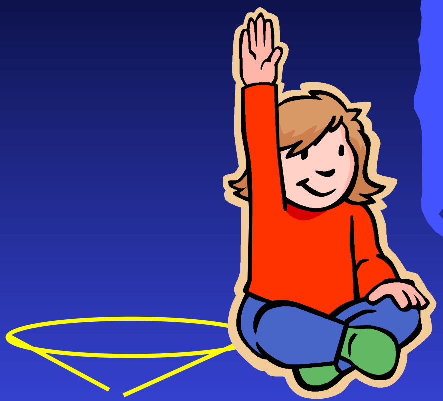
• Surface reflectance variability is limited;

• AERONET and other observations suggest aerosol properties are stable within:

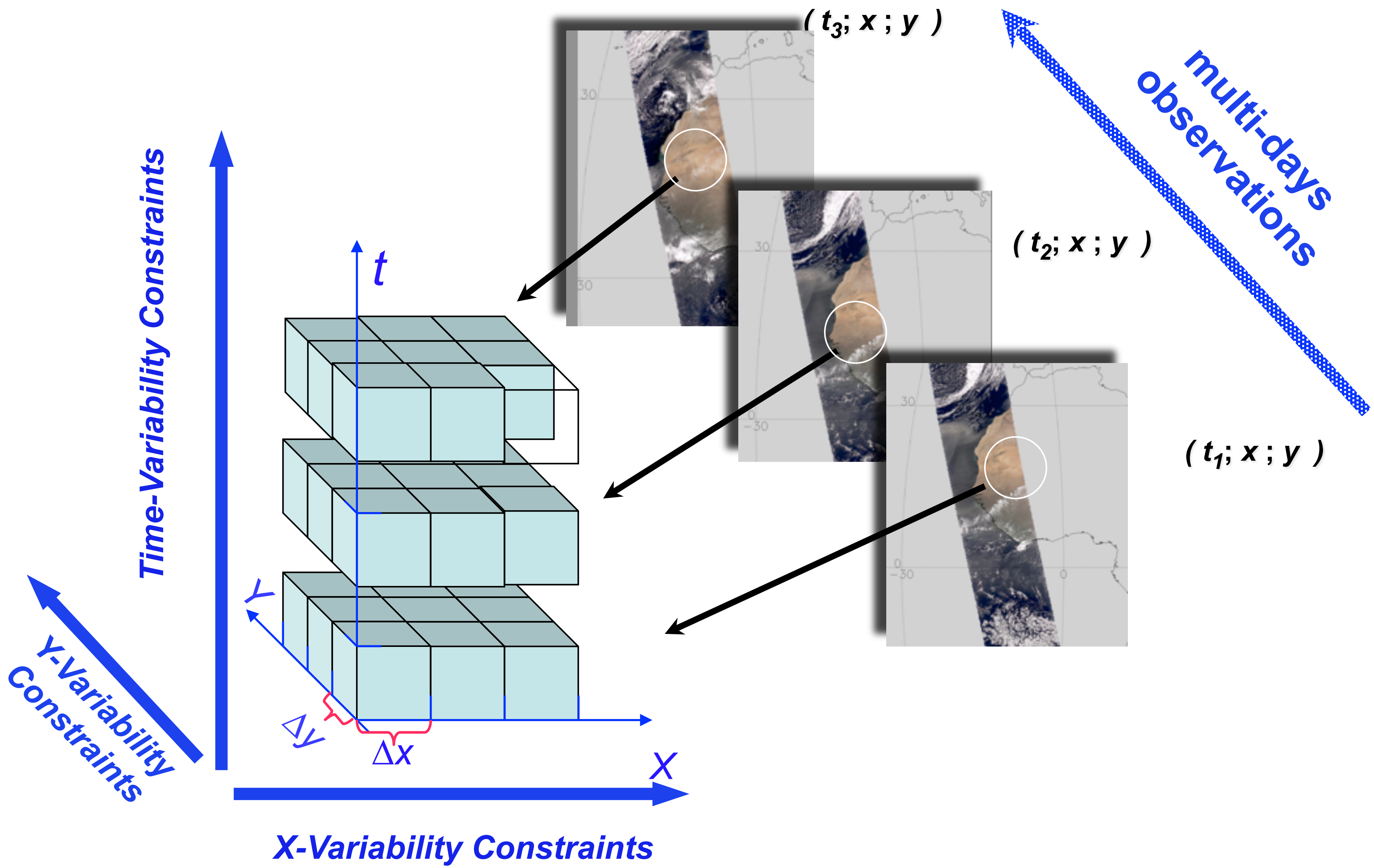
- $\tau(\lambda)$	- 30 min - 1 hour;
- size distribution shape	- hours - days;
- $\omega_0(\lambda)$, $n(\lambda)$, $k(\lambda)$	- hours - days;

↓

This can be used as extra information/constrain in the retrieval



The concept of multi-pixel retrieval



Single - Pixel Retrieval:

O. Dubovik
M. Herman
J.-L. Deuzé
F. Ducos
D. Tanré

f_j^* - PARASOL data:

Angular measurements (~15 angles) of

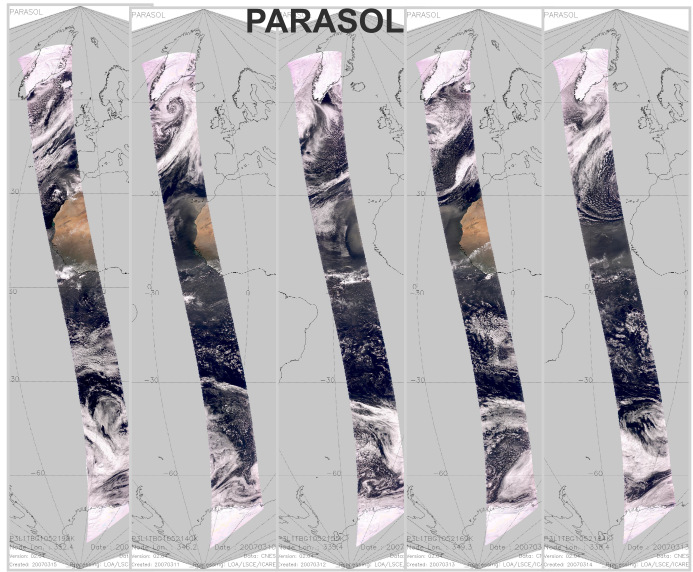
- ***Intensity*** (λ = 0.49; 0.67; 0.87; 1.02 μm)
- ***Polarization*** (λ = 0.49; 0.67; 0.87 μm)

a_j - Parameters to be retrieved:

-***Aerosol*** propeties:
- size distribution; - real refractive index
- imaginary refractive index; - particle shape

-***Surface*** properties (***over land***):
- BRF parameters; - BPRF parameters

$$\begin{cases} f_j^* \\ 0_j^* \end{cases} = \begin{pmatrix} \mathbf{F}_j \\ \mathbf{D}_j \end{pmatrix} \mathbf{a}_j + \begin{matrix} \Delta_j^m \\ \Delta_j^a \end{matrix}$$



A Priori Constraints limiting derivatives (e.g. *Dubovik 2004*) of

- for aerosols (e.g. in AERONET, *Dubovik and King 2000) :*
- aerosol size distribution variability over size range;
- spectral variability of complex refractive index;

- for surface (e.g. in AERONET/satellite retrievals, *Sinuyk et al. 2007) :*
- spectral variability of BRF/ PBRF parameters.

Multi-term LSM statistically optimized ***Solution*** *(Dubovik and King 2000, Dubovik 2004)* **:**

$$\mathbf{a}_j = \left(\mathbf{F}_j^T \mathbf{W}_j^{-1} \mathbf{F}_j + \gamma_j \Omega_j\right)^{-1} \left(\mathbf{F}_j^T \mathbf{W}_j^{-1} \mathbf{f}_j^*\right)$$

,where $\Omega_j = \mathbf{D}_j^T \mathbf{D}_j; \; \mathbf{W}_i = \frac{1}{\varepsilon_f^2} \mathbf{C}_f; \quad \gamma_j = \frac{\varepsilon_f^2}{\varepsilon_a^2}$

Multi - Pixel Retrieval:

$$\begin{cases} \begin{pmatrix} \begin{pmatrix} f_1^* \\ o_1^* \end{pmatrix} \\ \begin{pmatrix} f_2^* \\ o_2^* \end{pmatrix} \\ \begin{pmatrix} f_3^* \\ o_3^* \end{pmatrix} \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} \mathbf{F}_1 \\ \mathbf{D}_1 \end{pmatrix} & 0 & 0 \\ 0 & \begin{pmatrix} \mathbf{F}_2 \\ \mathbf{D}_2 \end{pmatrix} & 0 \\ 0 & 0 & \begin{pmatrix} \mathbf{F}_3 \\ \mathbf{D}_3 \end{pmatrix} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} + \begin{pmatrix} \begin{pmatrix} \Delta_1^m \\ \Delta_1^a \end{pmatrix} \\ \begin{pmatrix} \Delta_2^m \\ \Delta_2^a \end{pmatrix} \\ \begin{pmatrix} \Delta_3^m \\ \Delta_3^a \end{pmatrix} \end{pmatrix} \\ \cdots \\ \begin{pmatrix} O_t^* \\ O_x^* \\ O_y^* \end{pmatrix} = \begin{pmatrix} \mathbf{D}_{t,1} & \mathbf{D}_{t,2} & \mathbf{D}_{t,2} \\ \mathbf{D}_{x,1} & \mathbf{D}_{x,2} & \mathbf{D}_{x,3} \\ \mathbf{D}_{y,1} & \mathbf{D}_{y,2} & \mathbf{D}_{y,3} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} + \begin{pmatrix} \Delta_t^a \\ \Delta_x^a \\ \Delta_y^a \end{pmatrix} \end{cases}$$

Single-Pixel Data (PARASOL measurements and physical a priori constraints) ***are used by the same way as in Single-Pixel retrieval.***

Multi-Pixel a priori constraints (*e.g.Dubovik et al. 2008*):

- limited ***spatial*** variability of each aerosol /surface parameter
- limited ***temporal*** variability of each aerosol /surface parameter

NOTE: *degree of variability constraints (smoothnes) can be different and adequately chosen for each parameter*

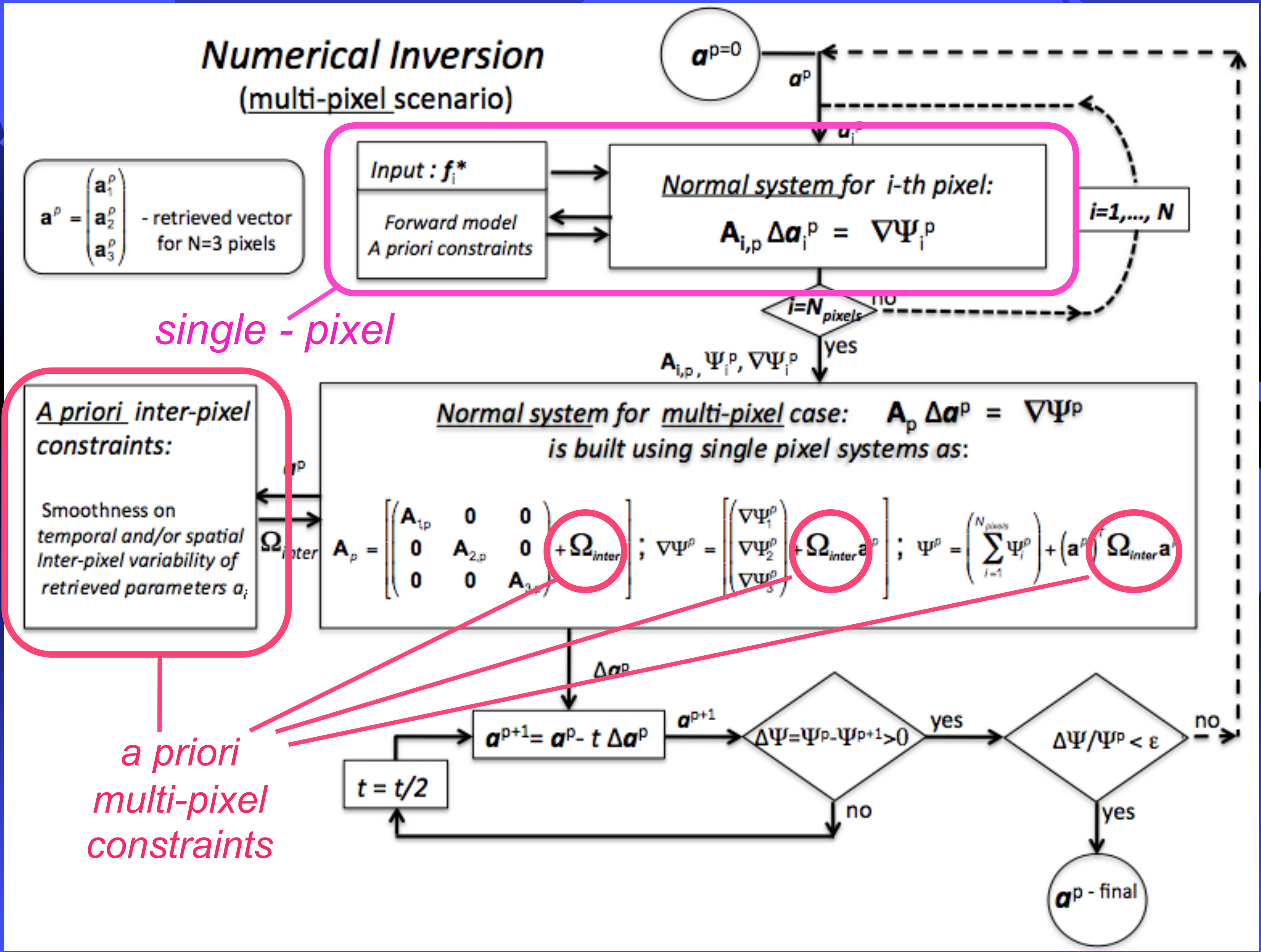
Multi-term LSM ***Multi-Pixel Solution:***

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} = \left[\begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \mathbf{F}_1 & 0 & 0 \\ 0 & \mathbf{F}_2^T \mathbf{W}_2^{-1} \mathbf{F}_2 & 0 \\ 0 & 0 & \mathbf{F}_3^T \mathbf{W}_3^{-1} \mathbf{F}_3 \end{pmatrix} + \begin{pmatrix} \gamma_1 \Omega_1 & 0 & 0 \\ 0 & \gamma_2 \Omega_2 & 0 \\ 0 & 0 & \gamma_3 \Omega_3 \end{pmatrix} + \gamma_x \Omega_x + \gamma_y \Omega_y + \gamma_t \Omega_t \right]^{-1} \begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \Delta f_1^p \\ \mathbf{F}_2^T \mathbf{W}_2^{-1} \Delta f_2^p \\ \mathbf{F}_3^T \mathbf{W}_3^{-1} \Delta f_3^p \end{pmatrix}$$

,where $\Omega_x = \mathbf{D}_x^T \mathbf{D}_x;\ \Omega_y = \mathbf{D}_y^T \mathbf{D}_y;\ \Omega_t = \mathbf{D}_t^T \mathbf{D}_t;\ \gamma_x = \frac{\varepsilon_f^2}{\varepsilon_x^2};\ \gamma_y = \frac{\varepsilon_f^2}{\varepsilon_y^2};\ \gamma_t = \frac{\varepsilon_f^2}{\varepsilon_t^2}$

« PARASOL » statistically optimized « no look-up tables » *multi-pixel* inversion

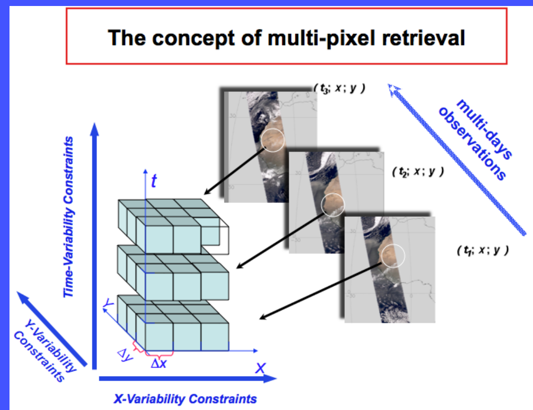
Dubovik et al., AMT, 2011



Observational conditions:

- Geometry is the same as for PARASOL over Banizoumbu (as in the example for actual PARASOL inversions)
- Surface is bright;
- Aerosol loadings: 16 cases for $\tau(0.44) = 0.01 – 4$;
- Aerosol types: Dust, Biomass Burning (original from AERONET)
- Aerosol height – 3 km

Retrieved parameters:



AEROSOL:

- dV(r)/dlnr (16 bins from 0.07 to 10 μm);
- $n(\lambda)$, $k(\lambda)$, $\omega_0(\lambda)$
- Aerosol height
- Fraction of spherical particles

SURFACE:

- BRF 3 parameters for each λ);
- BPRF (1 parameter for each λ)

SPATIAL – TEMPORAL:

- 4 pixels for each of 4 days

Stringent test conditions:

-The same initial guess for all retrievals:

- no a priori information about surface type;
- no a priori information about aerosol type
- no a priori information about aerosol loading;

- The test were also done for vegetated surface;
- The synthetic data are calculated using original non-simplified AERONET data;
- Random noise: 1% for intensity, 0.5% for degree of linear polarization.

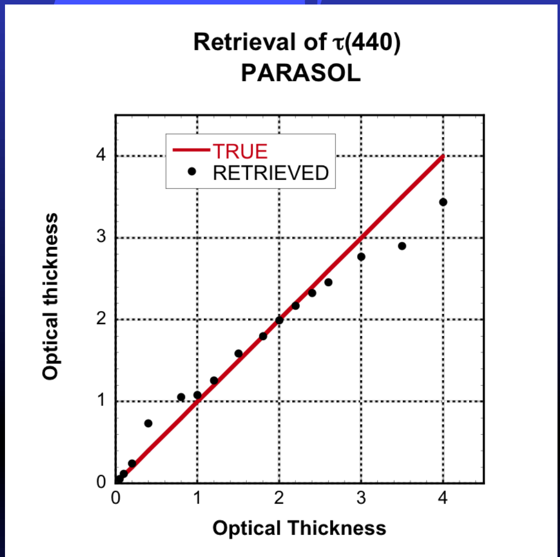
Single Initial Guess:

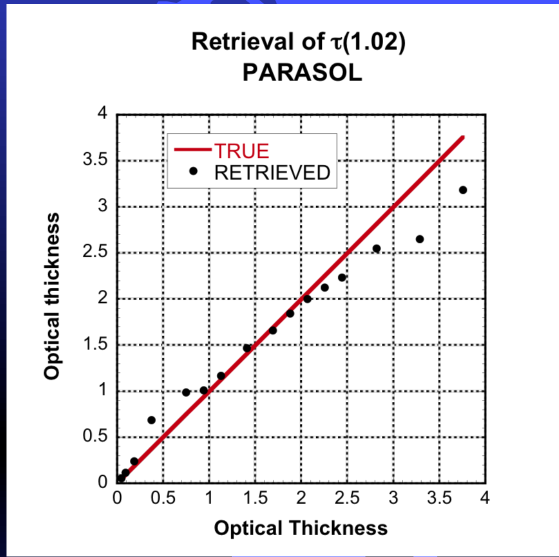
Aerosol Properties	Surface Reflectance
$C_V = C_0$ (corresponding to the value of τ_{aer} (0.44)~0.05);	$\rho_0(\lambda_i) = 0.05$ $(i = 1, ..., N_\lambda)$
$dV(r_i)/d\ln r = 0.1$; $(i = 1, ..., N_r)$	$\kappa(\lambda_i) = 0.75$ $(i = 1, ..., N_\lambda)$
$C_{sph} = 0.7$	$\theta(\lambda_i) = -0.1$ $(i = 1, ..., N_\lambda)$
$n(\lambda_i) = 1.4$ $(i = 1, ..., N_\lambda)$	$h_0(\lambda_i) = \rho_0(\lambda_i)$ $(i = 1, ..., N_\lambda)$
$k(\lambda_i) = 0.005$ $(i = 1, ..., N_\lambda)$	$B(\lambda_i) = 0.03$ $(i = 1, ..., N_\lambda)$

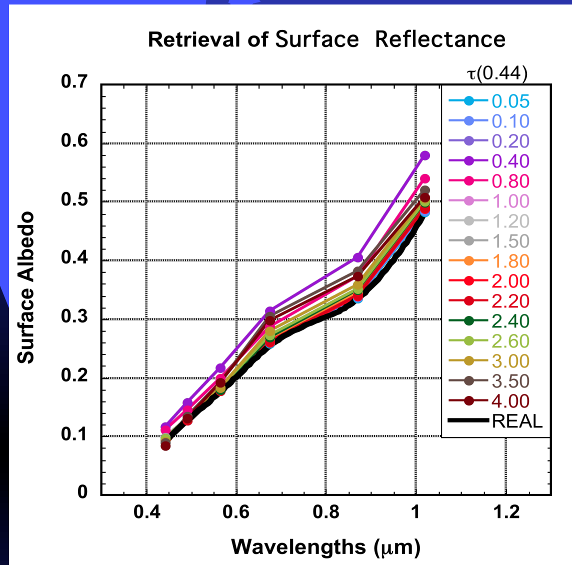
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

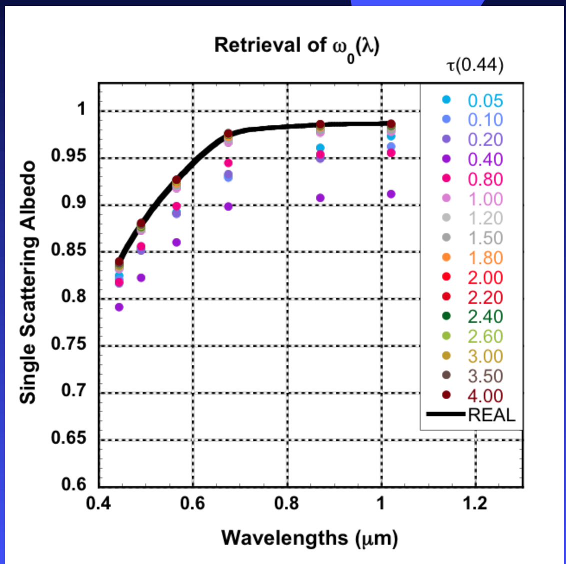
NO NOISE ADDED !!! (minor noise is always present)

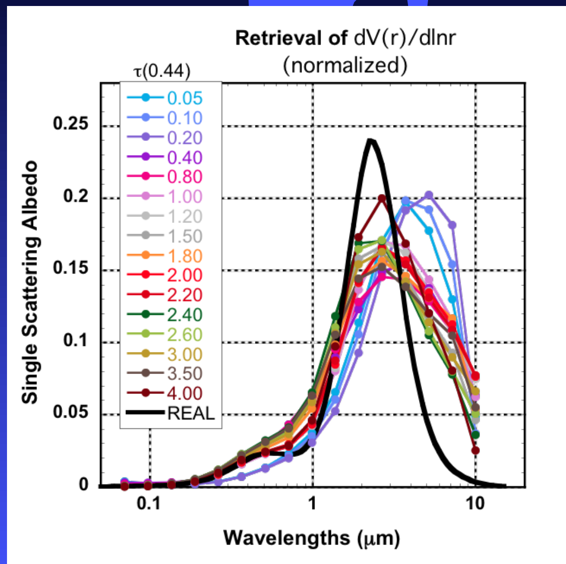
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

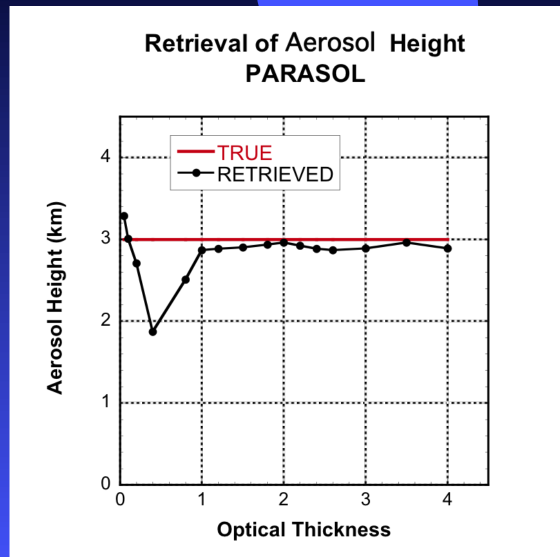








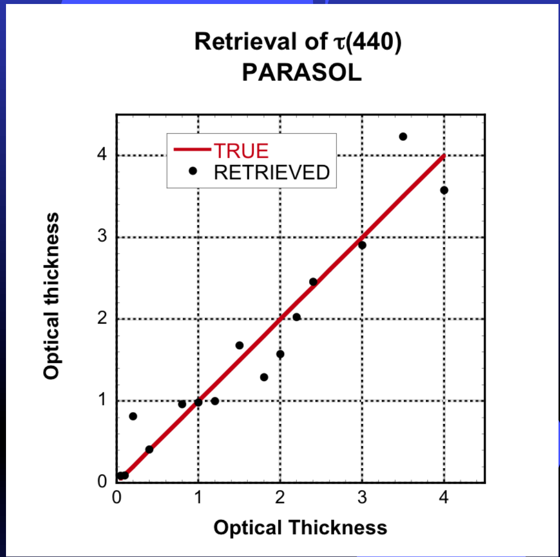


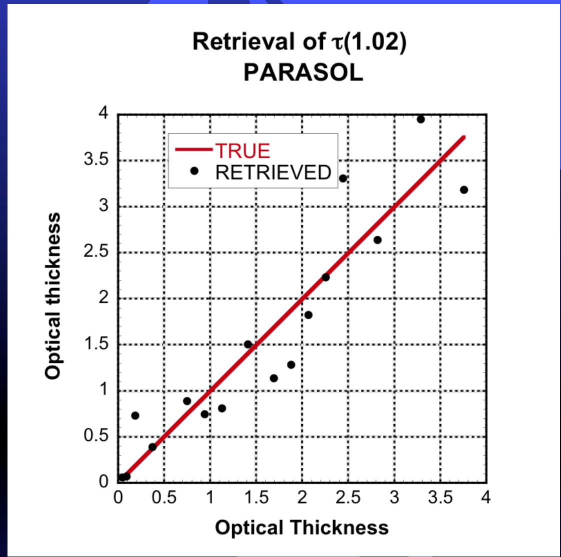


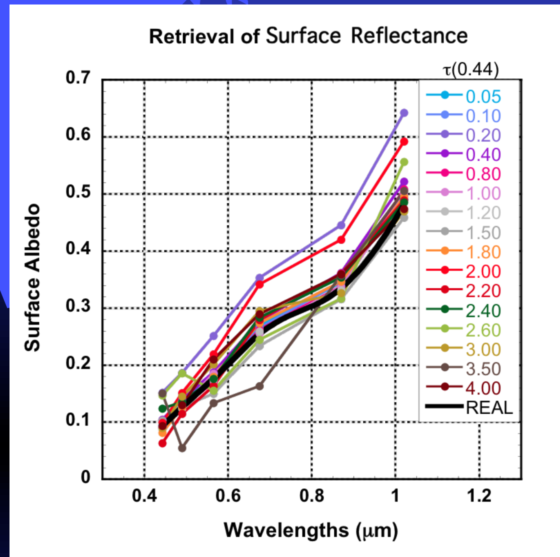
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

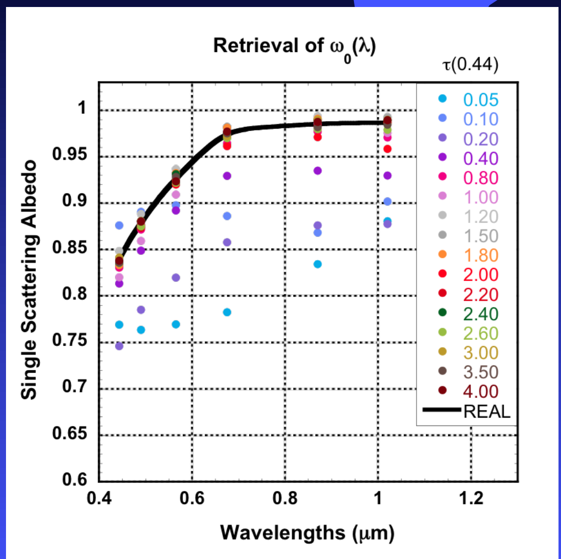
NOISE ADDED: 1% for I(λ), 0.005 for Q(λ)/I(λ) and U(λ)/I(λ) !!!

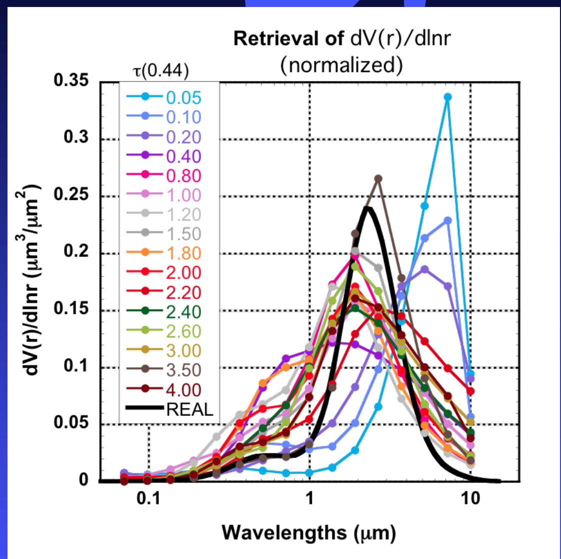
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

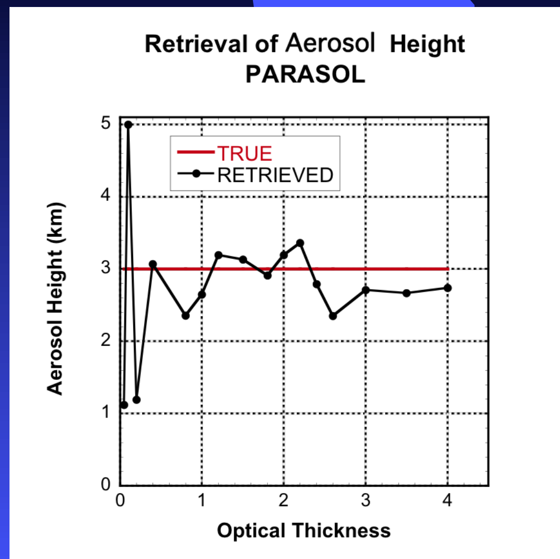










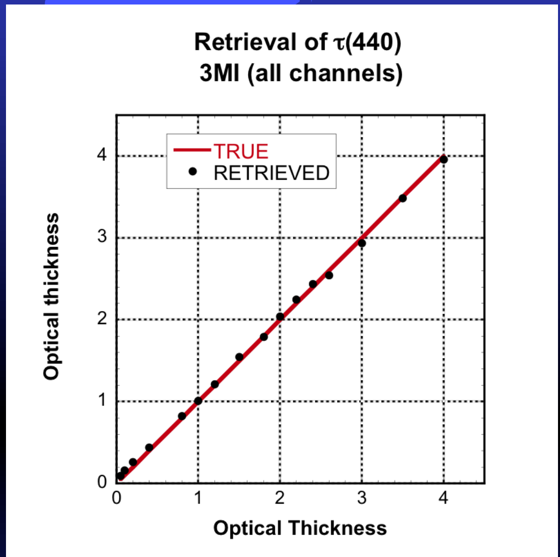


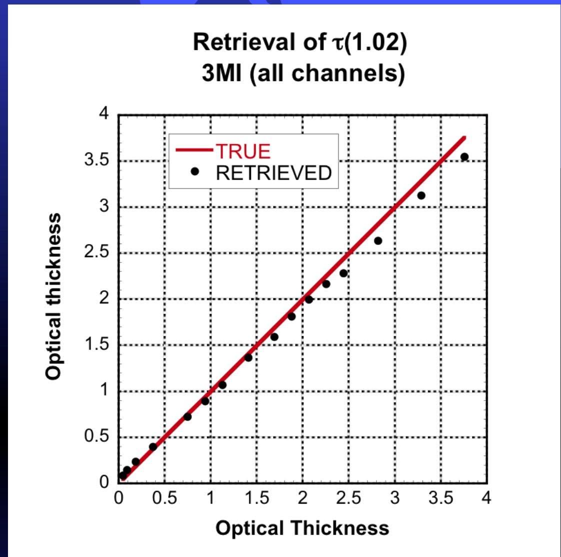
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

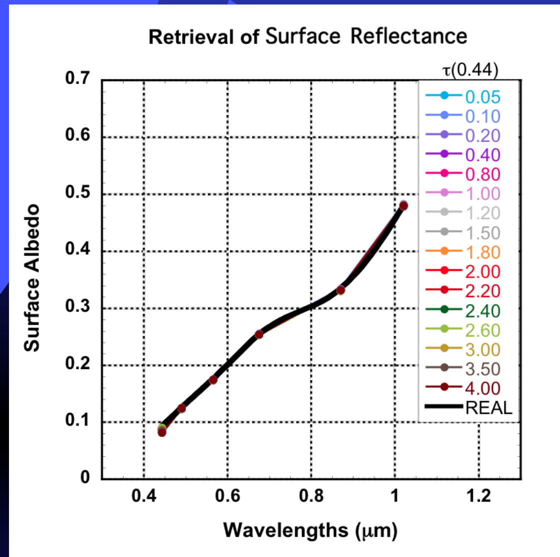
NOISE ADDED: 1% for I(λ), 0.005 for Q(λ)/I(λ) and U(λ)/I(λ) !!!

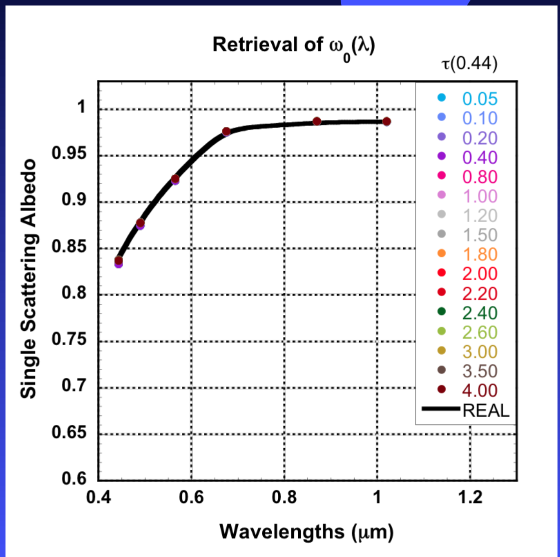
Multi-Pixel Retrieval (i.e. temporal and spatial variability of surface and aerosol is limited)

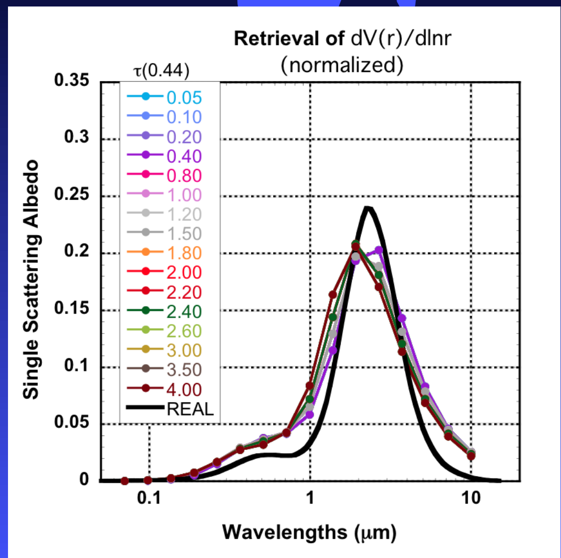
Desert Dust aerosol (non-spherical!!!)

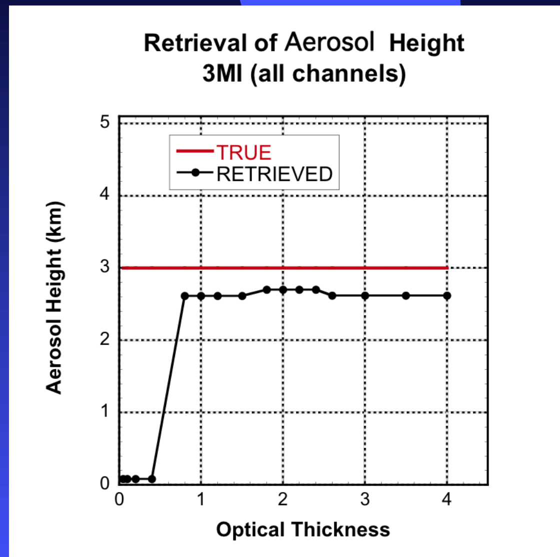






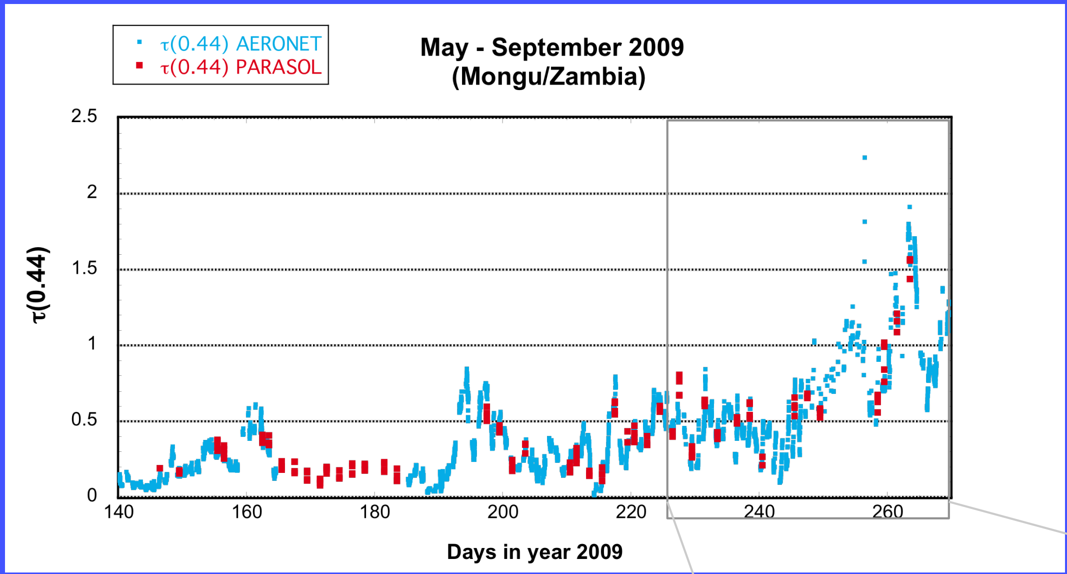


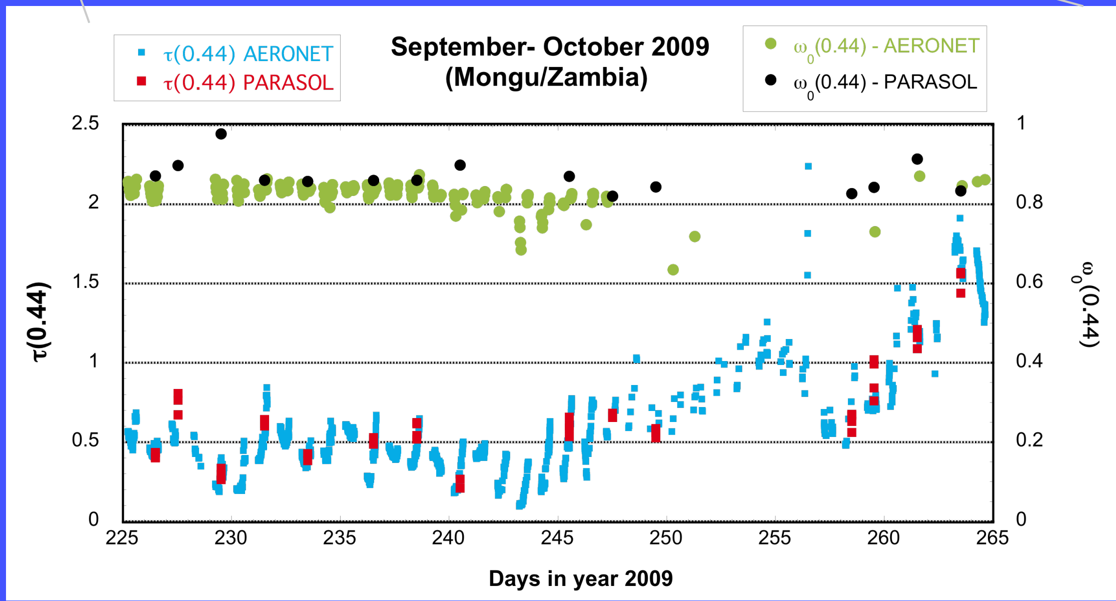




Inversion of real PARASOL data

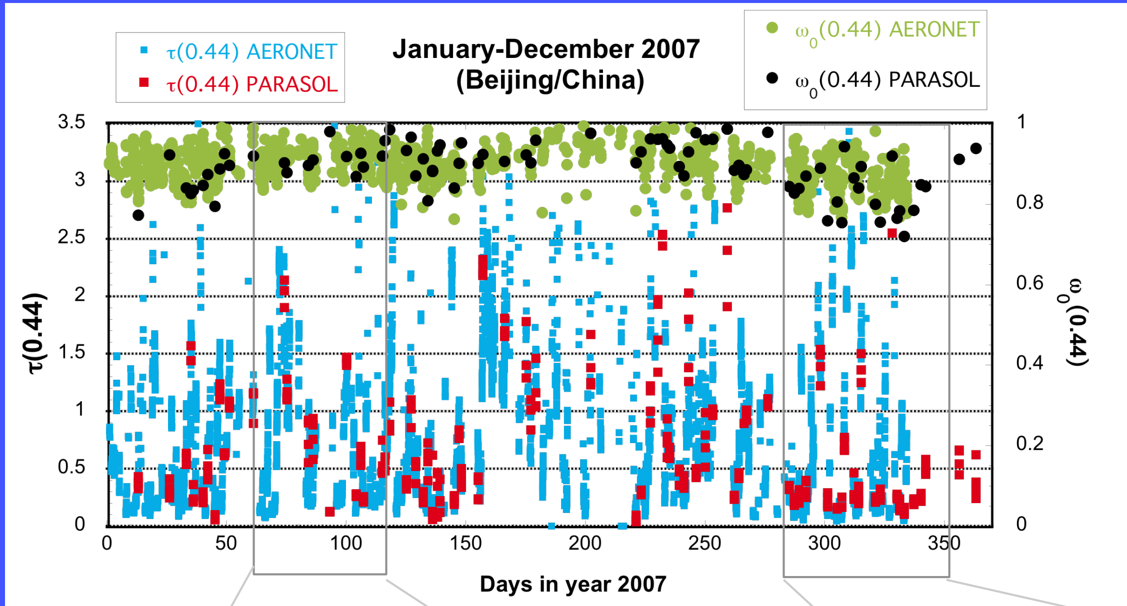
Biomass aerosol
Mongu/Zambia

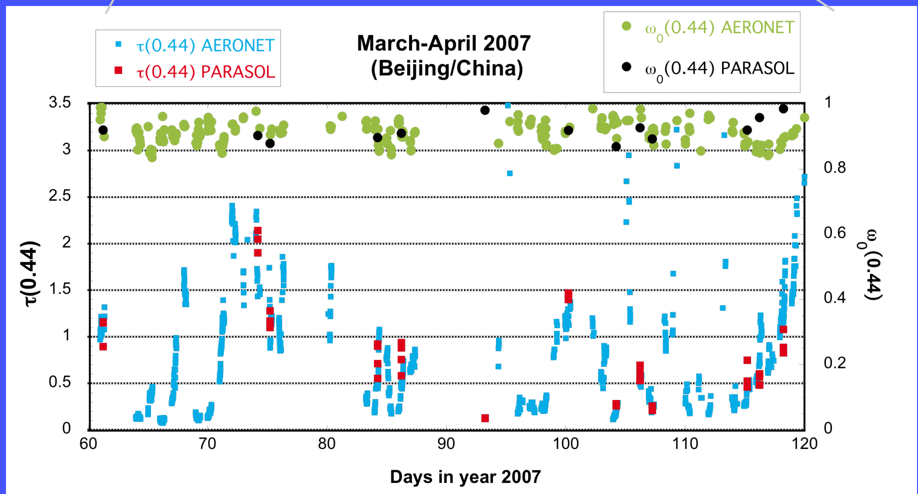


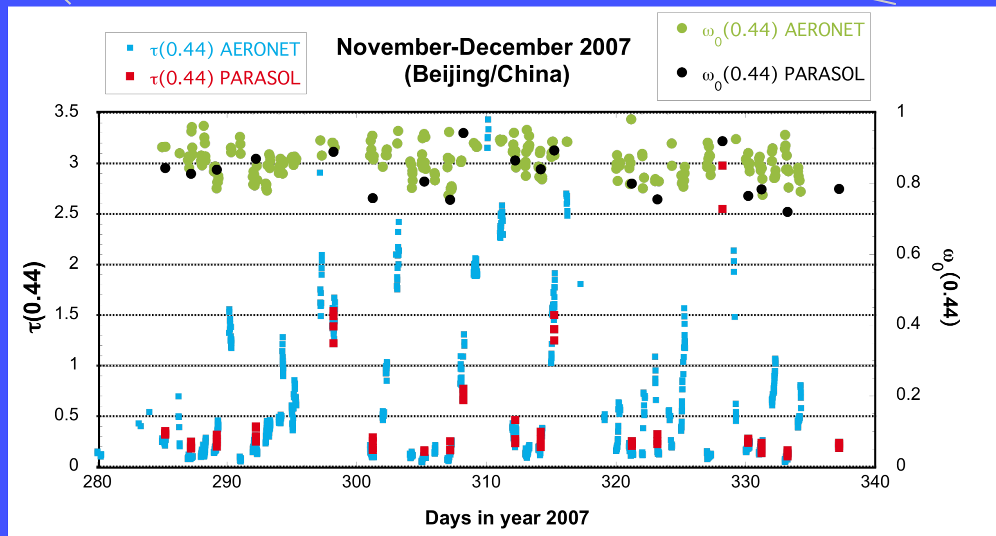


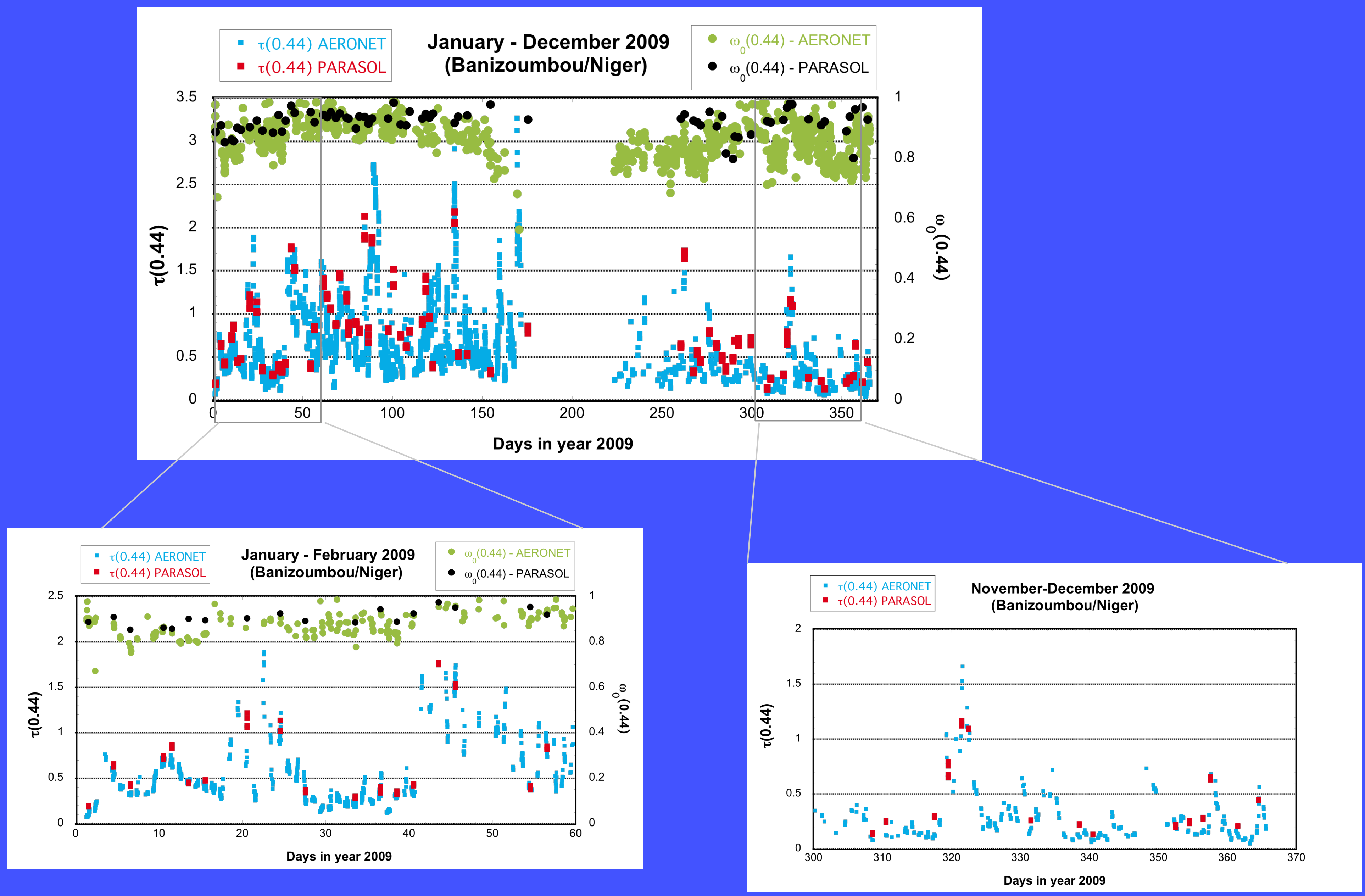
Inversion of real PARASOL data

(urban/industrial aerosol Beijing/China)









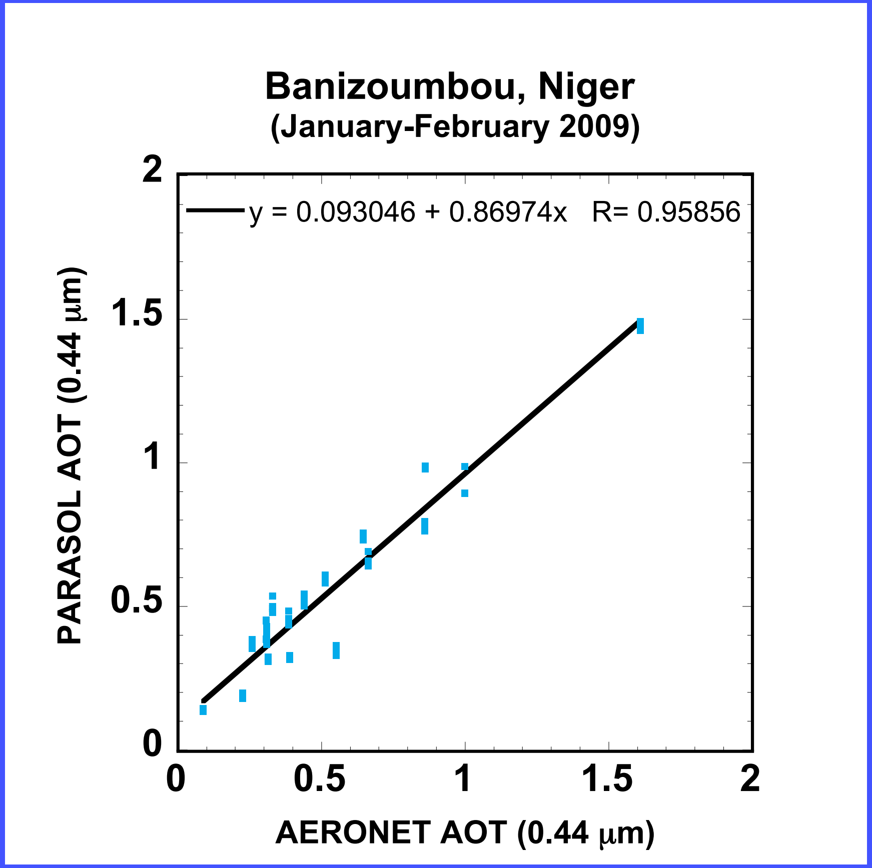
Inversion of real PARASOL data

Dust and biomass
Banizoumbu/Niger

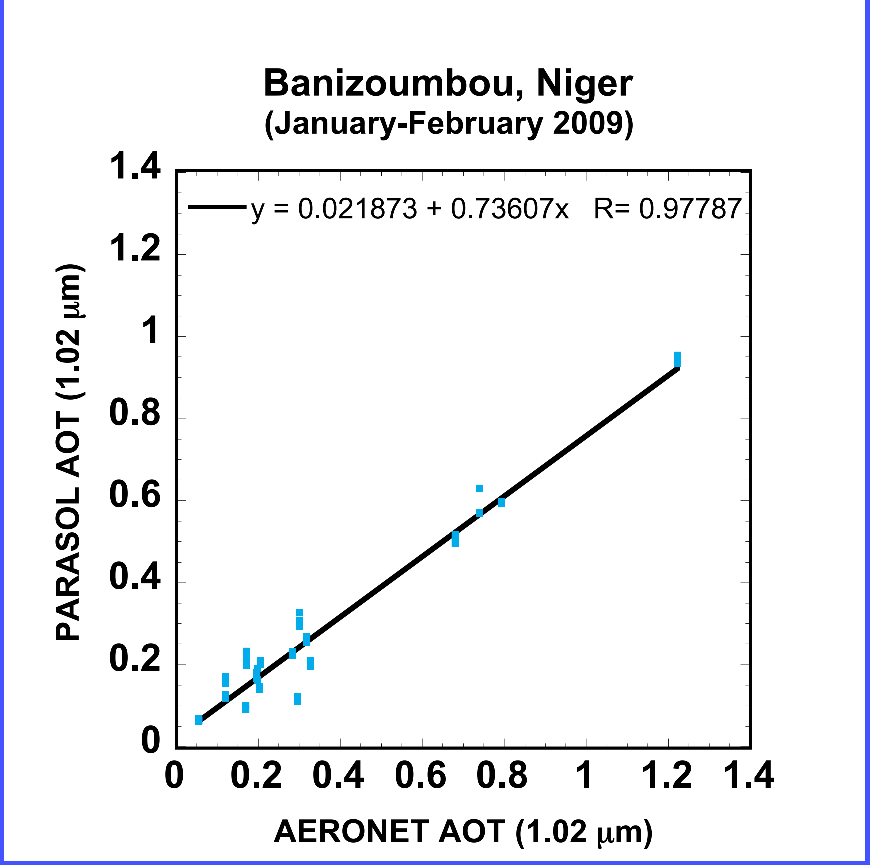
Optical Thickness

PARASOL versus AERONET

0.44 μm



1.02 μm

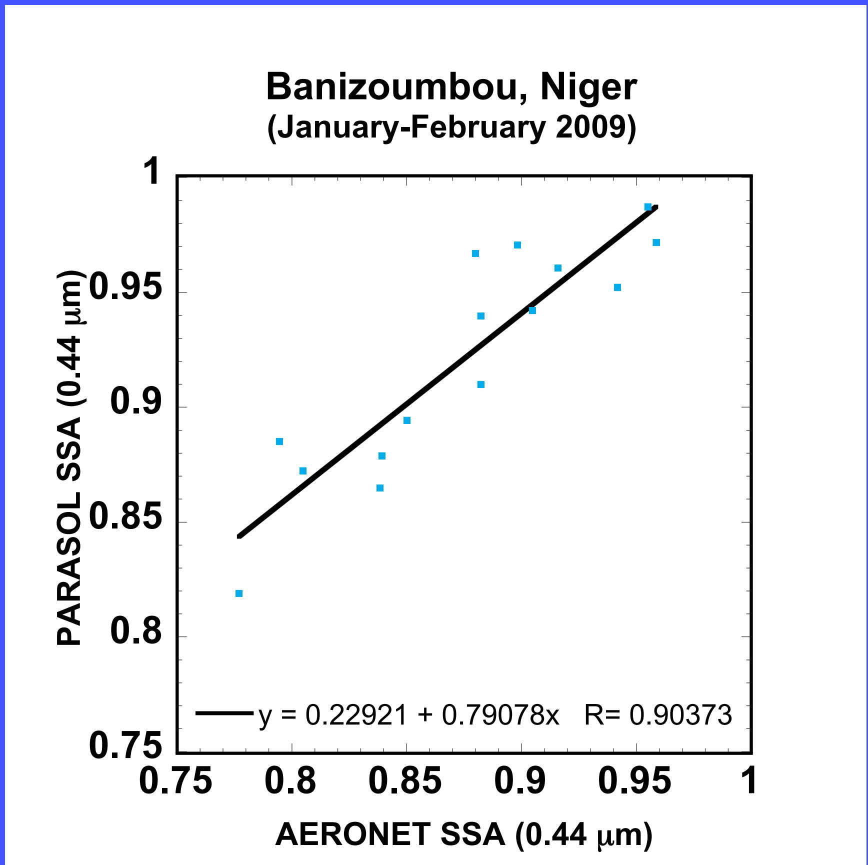


Dust and biomass
Banizoumbu/Niger

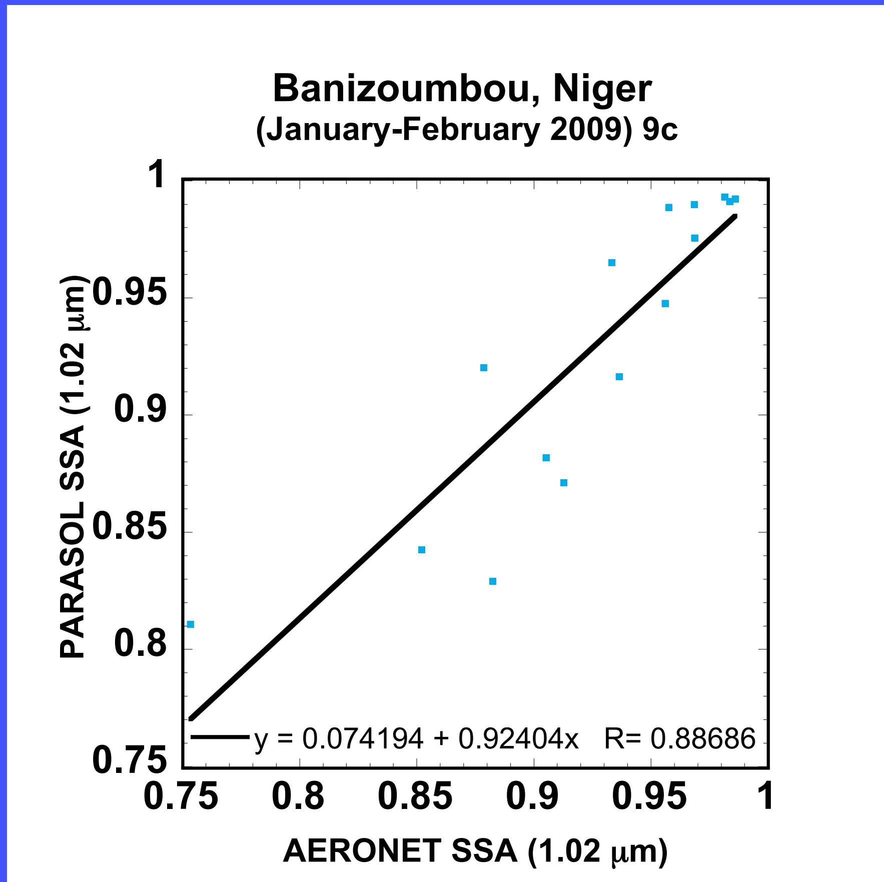
Single Scattering Albedo

PARASOL versus AERONET

0.44 μm

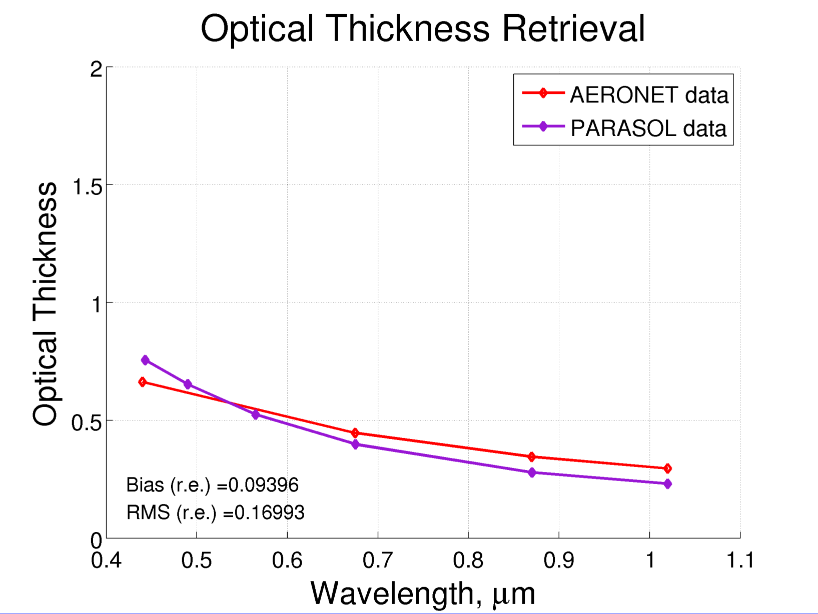


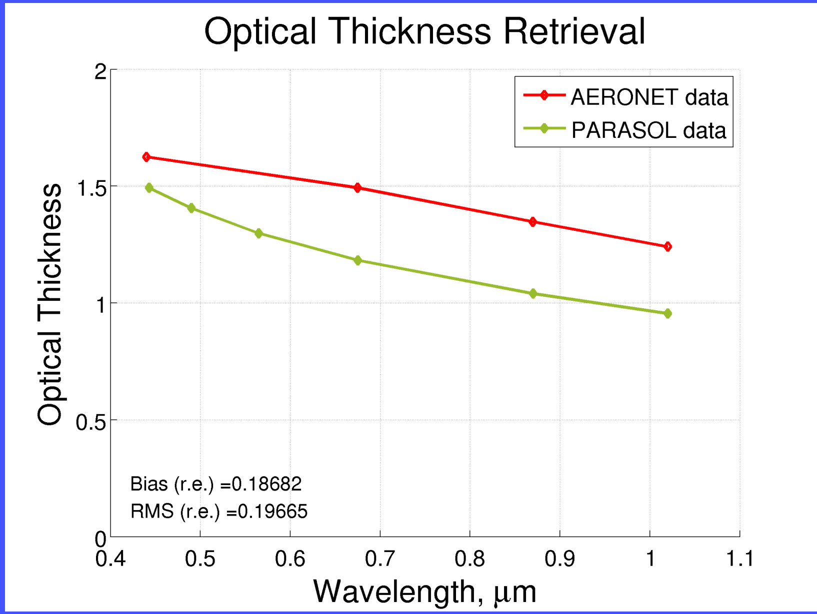
1.02 μm

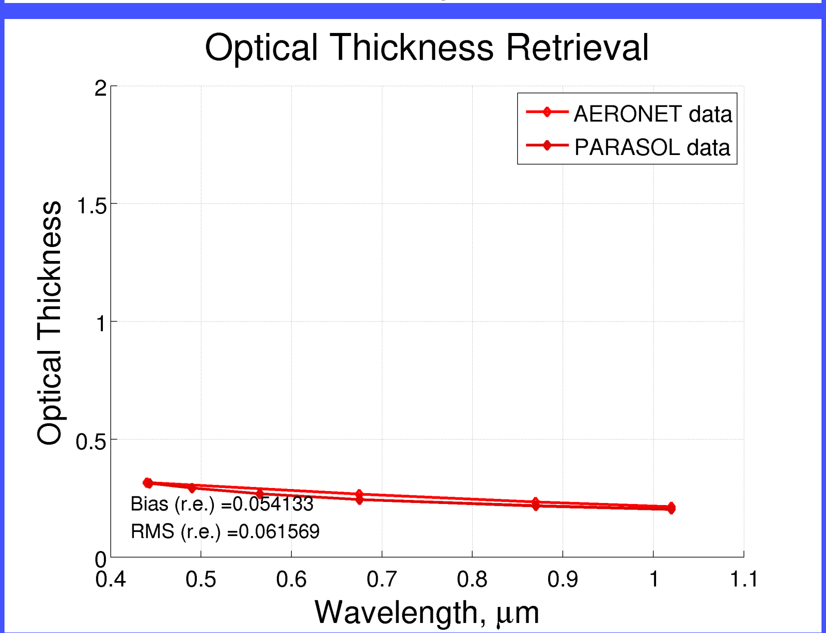


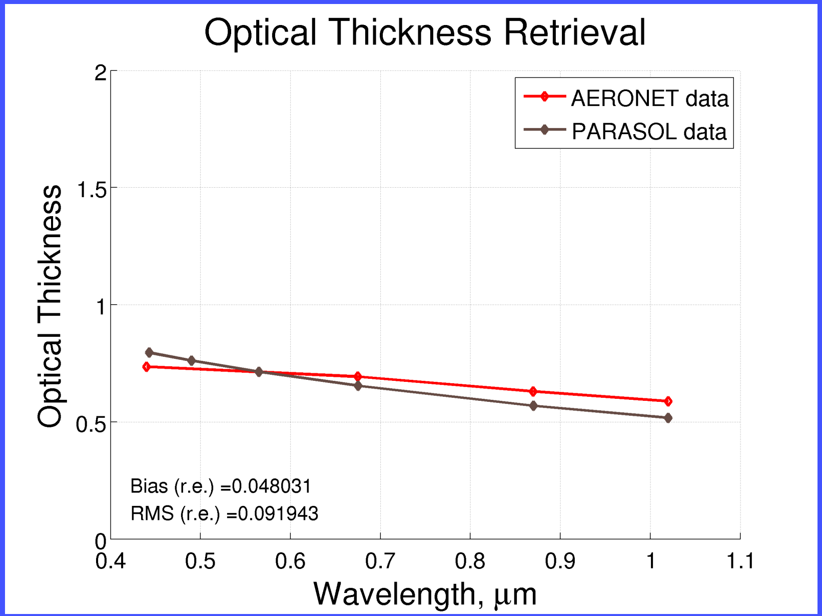
PARASOL versus AERONET

Dust and biomass
Banizoumbu/Niger



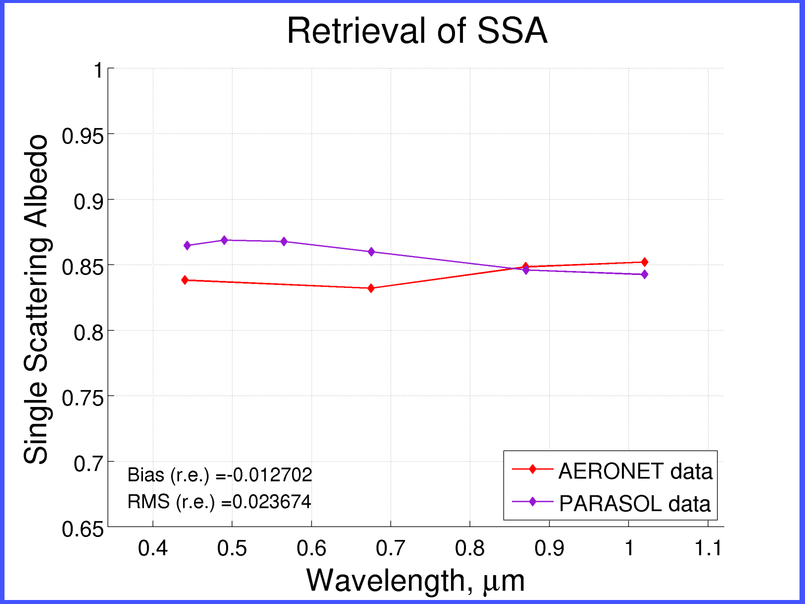


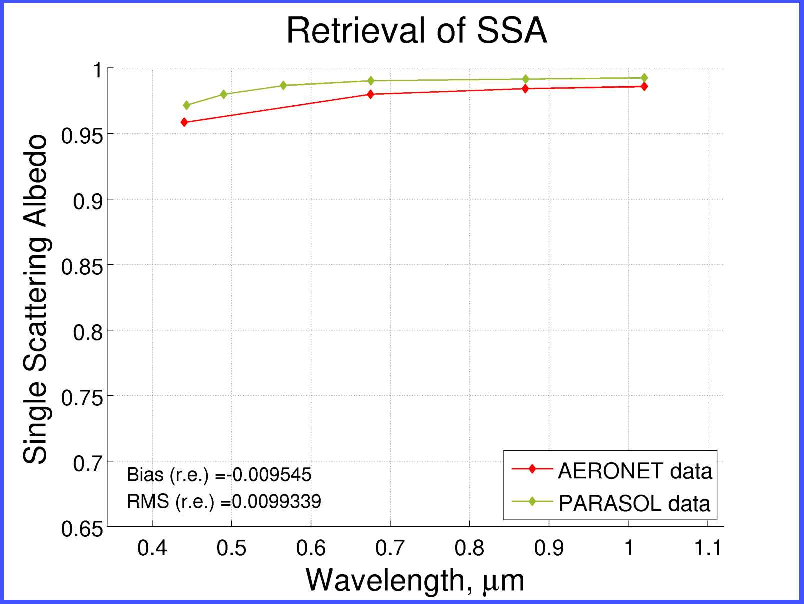


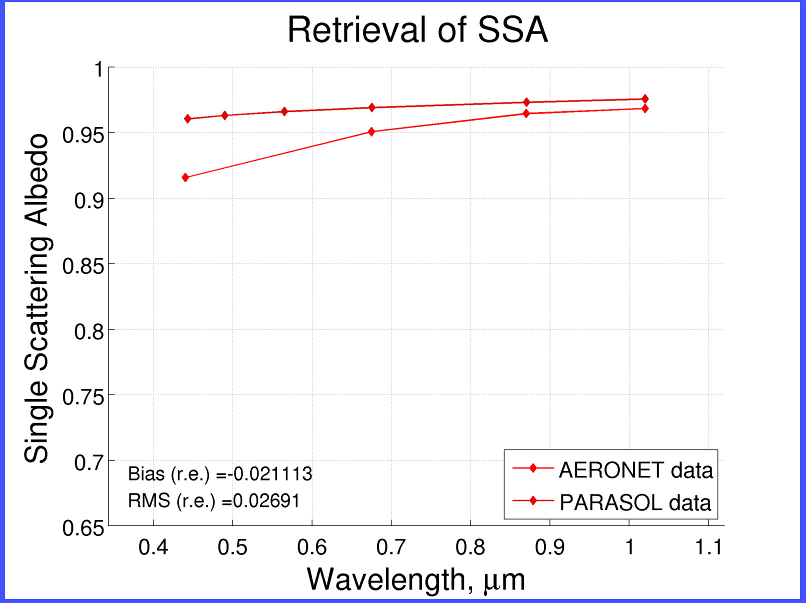


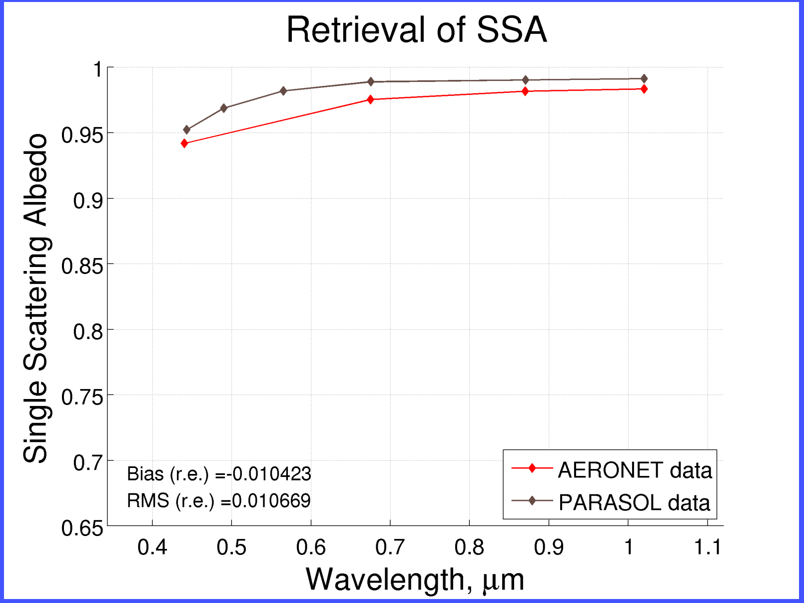
PARASOL versus AERONET

Dust and biomass
Banizoumbu/Niger



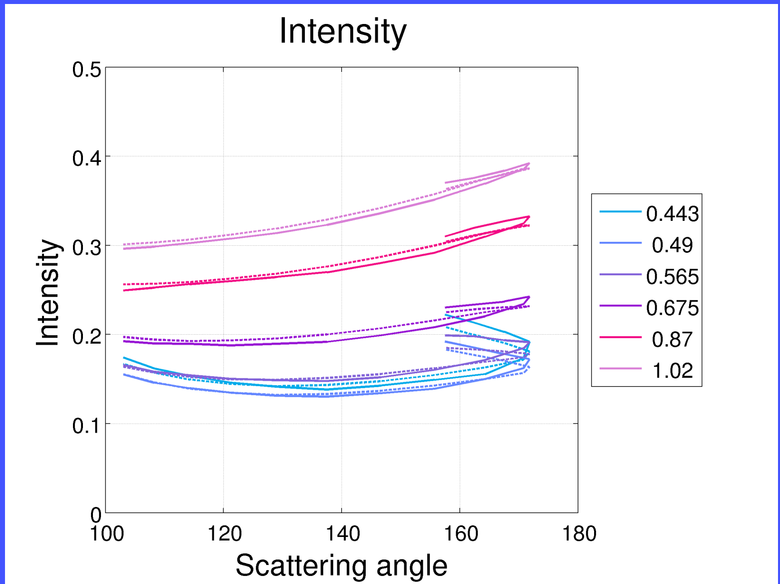


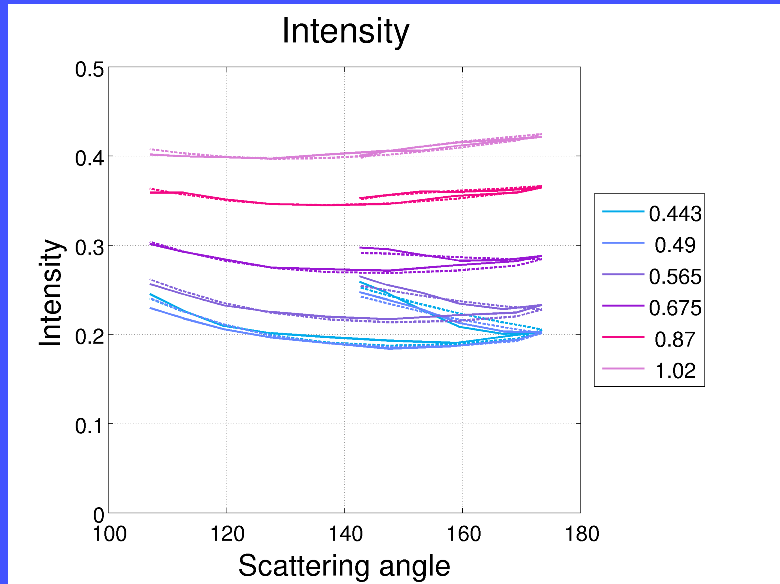


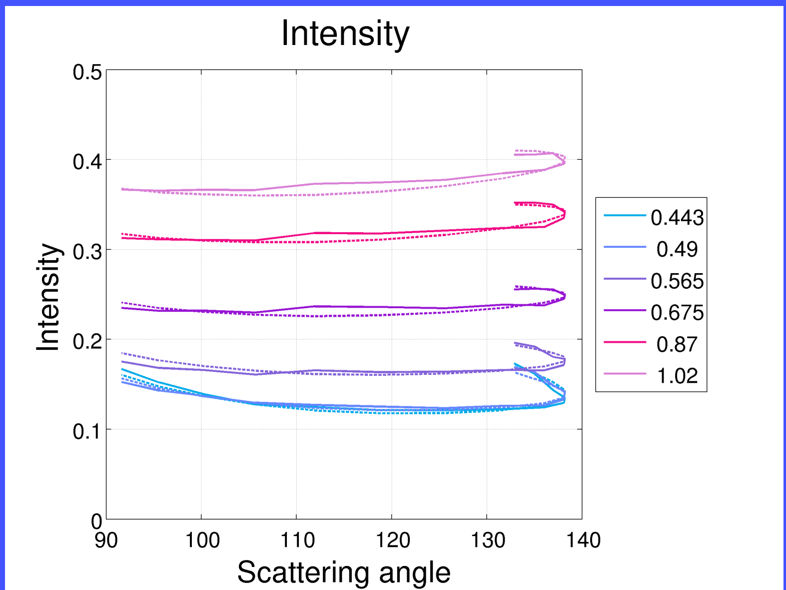


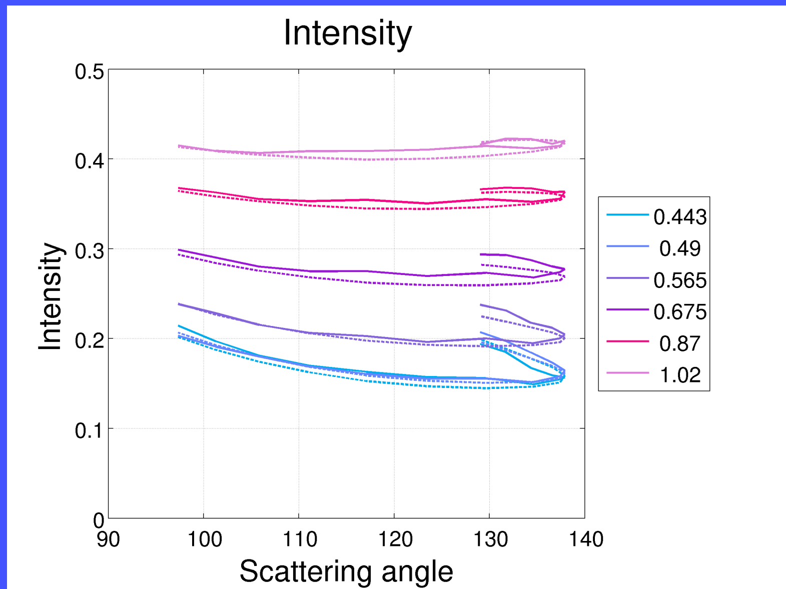
Fit of PARASOL observations

Dust and biomass
Banizoumbu/Niger





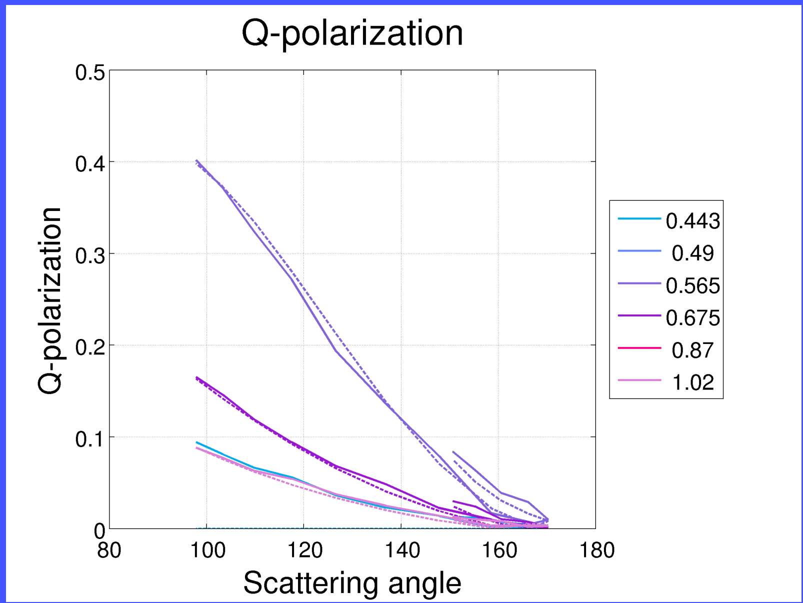


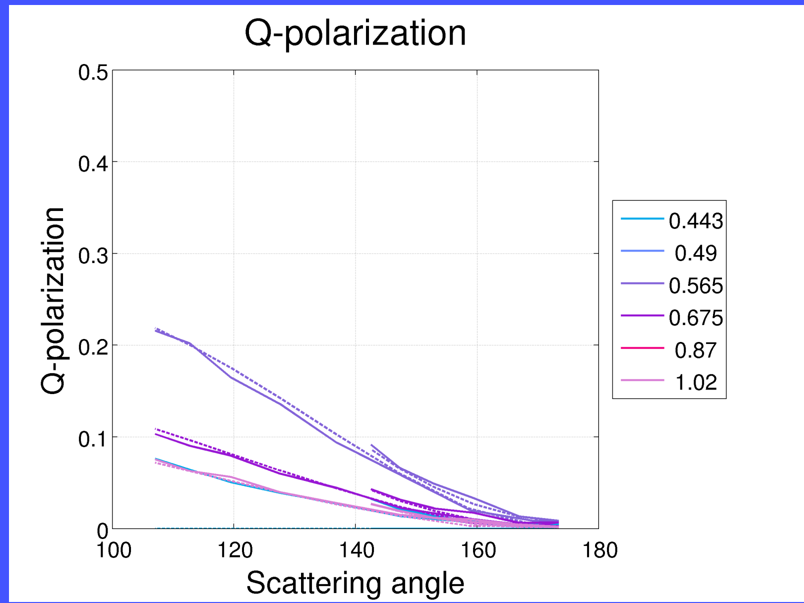


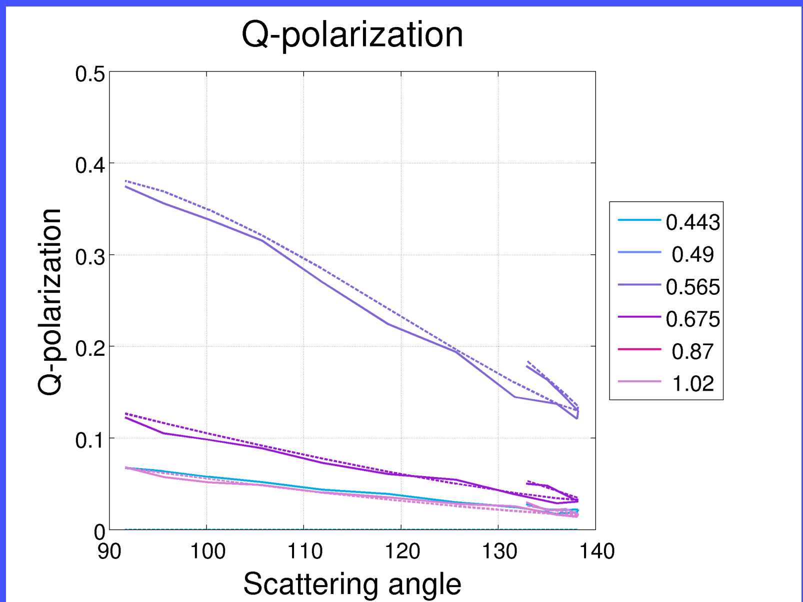
Fit of PARASOL observations

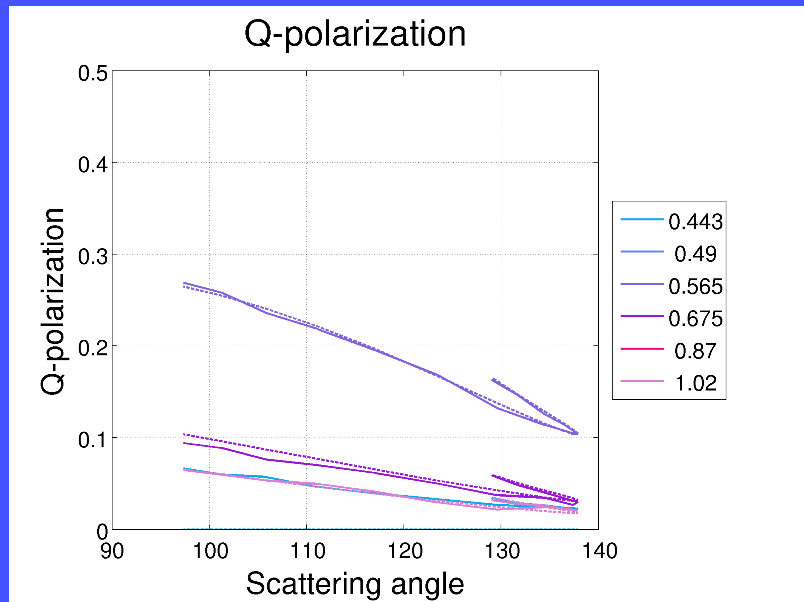
(Q/I in plane of scattering)

Dust and biomass Banizoumbu/Niger









Conclusions/Perspectives:

1. Inverse modeling – *promising approach for synergy of modeling and remote sensing*

   Potential for improvement:

   - using enhanced products from advanced satellite sensors retrievals

2. New PARASOL algorithm – *promising*

   Potential for improvement:

   - producing global aerosol products
   - multi-sensor retrieval: