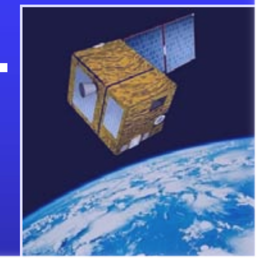
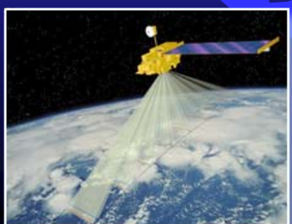
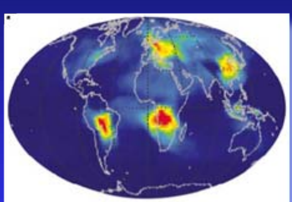
Development of the enhanced retrieval of aerosol from multi-anlge polarimetric PARASOL observations.







O. Dubovik, M. Herman, A. Holdak, T. Lapyonok, D. Tanré, J.-L. Duzé and F. Ducos

Science and Technology University of Lille, CNRS, France

- ✓ the concept of the algorithm;
- ✓ testing of the algorithm;
- ✓ application to the POLDER/PARASOL data

PARASOL/A-Train

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

- Sensor Characteristics
  - 9 spectral bands ranging from 0.45 to 1.02 µm
  - 3 (0.49, 0.67, 0.87) - polarized
  - Wide field of view lens : ± 51 ° along track, ± 43 ° cross track Swath* : 1600 km ; 2100km along track
  - Spatial resolution: 5.3 km x 6.2 km
  - up to 14 viewing directions

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"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 !!!** – as much as AERONET*

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

independent measurements

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:*

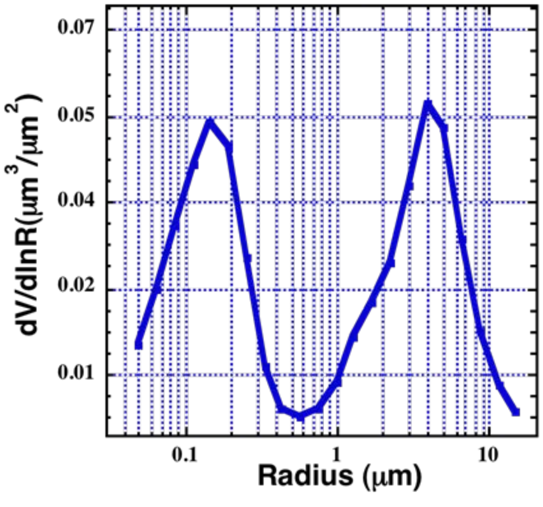
AOT of fine mode only , some size information

- *Issues: quite limited*

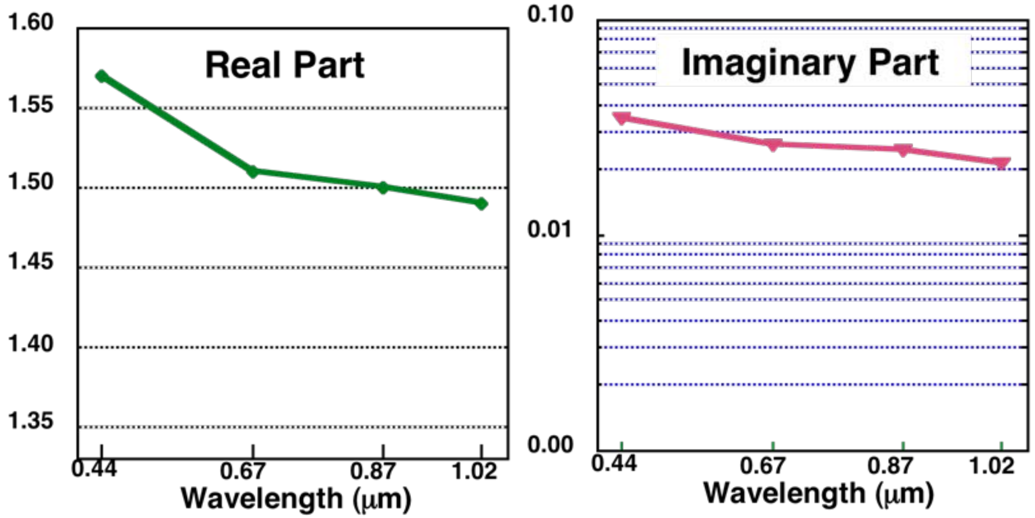
AERONET retrievals are driven by 31 variables :

dV/lnr - size distribution (22 values);
n(λ) and k(λ) - ref. index (4 +4 values)
C_{spher} (%) - spherical fraction (1 value)

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



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*** propetries:
- size distribution; - real refractive index
- imaginary refractive index; - particle shape, - height

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

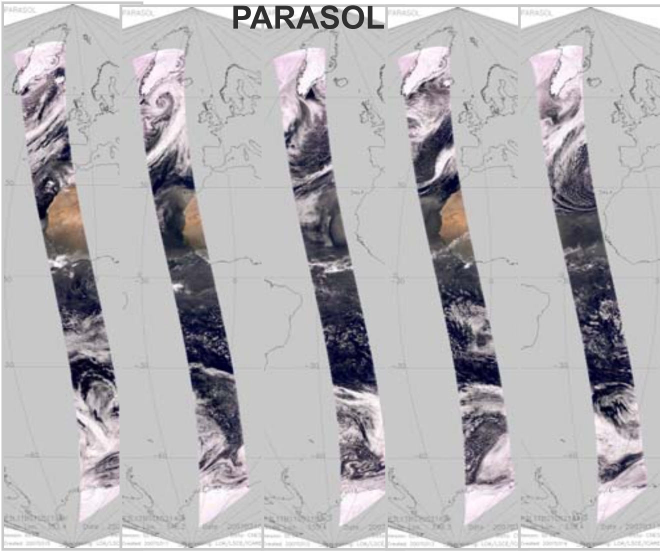
!!!

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

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

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

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

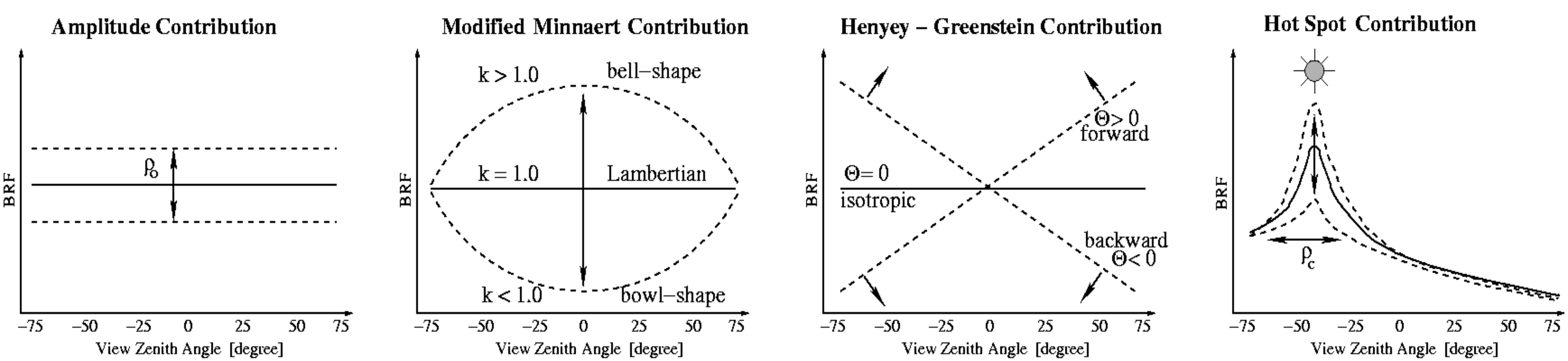
Bi-Directional Surface Reflectance

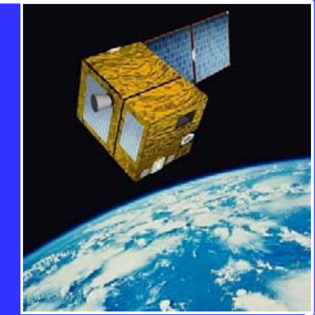
$$\rho_{sfc}(\vartheta_1,\varphi_1;\vartheta_2,\varphi_2) = \rho_0 M_i(k) F_{HG}(\Theta) H(h)$$

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





parameters to retrieve:

AEROSOL:

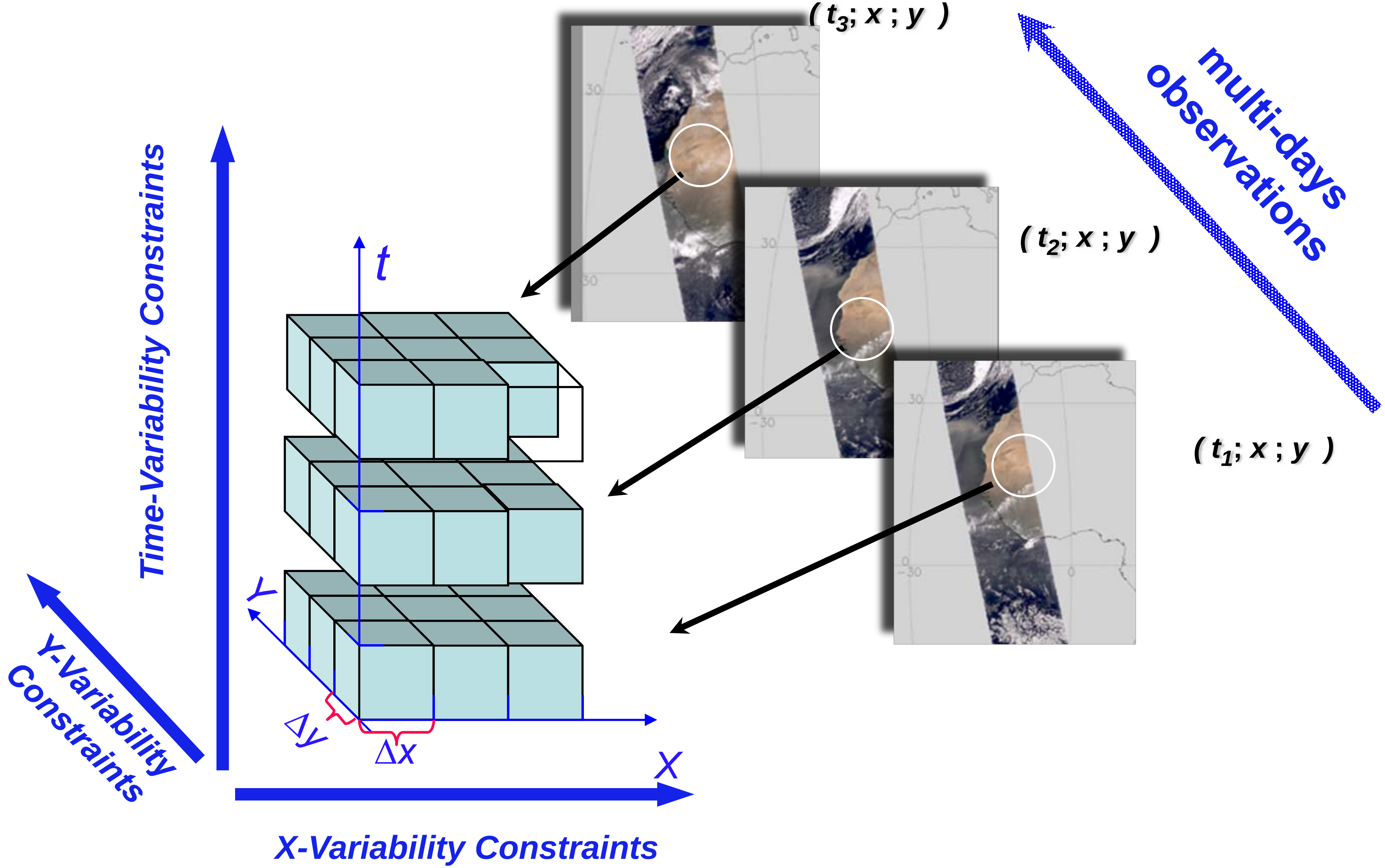
- *dV(r)/dlnr (16 bins from 0.07 to 10 mm);* $N_r = 16$
- *n(λ)* $N_\lambda = 6$
- *k(λ)* $N_\lambda = 6$
- *Fraction of spherical particles* $N_\lambda = 1$
- *Aerosol height* $N_\lambda = 1$

SURFACE:

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

TOTAL = 54

The concept of multi-pixel retrieval



Multi - Pixel Retrieval:

$$
\left\{
\begin{pmatrix} \begin{pmatrix} \mathbf{f}_1^* \\ 0_1^* \end{pmatrix} \\ \begin{pmatrix} \mathbf{f}_2^* \\ 0_2^* \end{pmatrix} \\ \begin{pmatrix} \mathbf{f}_3^* \\ 0_3^* \end{pmatrix} \\ \dots \\ 0_t^* \\ 0_x^* \\ 0_y^* \end{pmatrix}
=
\begin{pmatrix}
\begin{pmatrix} \mathbf{F}_1 \\ \mathbf{D}_1 \end{pmatrix} & \begin{matrix} 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} \\
\begin{matrix} 0 \\ 0 \end{matrix} & \begin{pmatrix} \mathbf{F}_2 \\ \mathbf{D}_2 \end{pmatrix} & \begin{matrix} 0 \\ 0 \end{matrix} \\
\begin{matrix} 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} & \begin{pmatrix} \mathbf{F}_3 \\ \mathbf{D}_3 \end{pmatrix} \\
\dots & \dots & \dots \\
\mathbf{D}_{t,1} & \mathbf{D}_{t,2} & \mathbf{D}_{t,2} \\
\mathbf{D}_{x,1} & \mathbf{D}_{x,2} & \mathbf{D}_{x,3} \\
\mathbf{D}_{y,1} & \mathbf{D}_{y,2} & \mathbf{D}_{y,3}
\end{pmatrix}
\begin{pmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix}
+
\begin{pmatrix} \begin{pmatrix} \Delta_1^m \\ \Delta_1^a \end{pmatrix} \\ \begin{pmatrix} \Delta_2^m \\ \Delta_2^a \end{pmatrix} \\ \begin{pmatrix} \Delta_3^m \\ \Delta_3^a \end{pmatrix} \\ \Delta_t^a \\ \Delta_x^a \\ \Delta_y^a \end{pmatrix}
\right.
$$

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:***

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

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

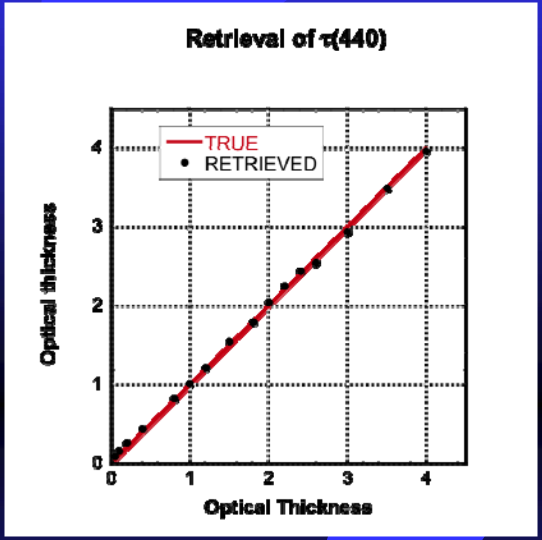
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

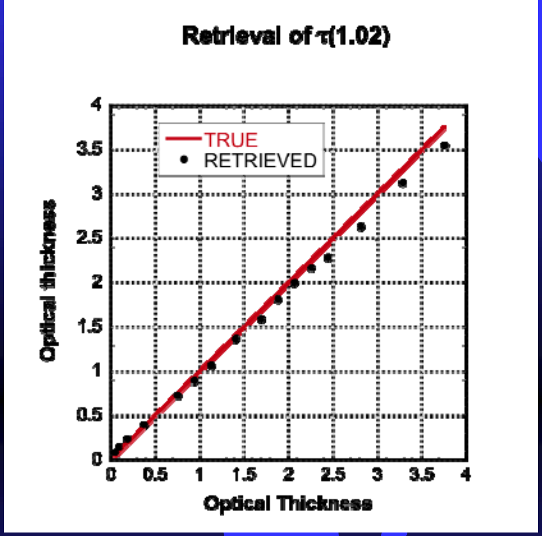
NOISE ADDED: 1% for I(λ), 0.5% for Q(λ)/I(λ) and U(λ)/I(λ) !!!

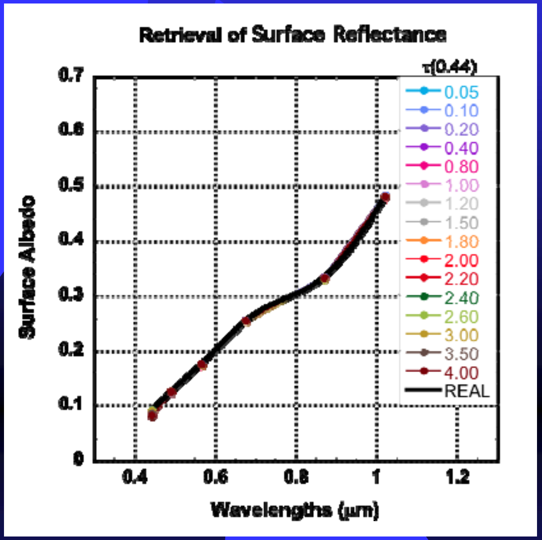
Multi-Pixel Retrieval (i.e. temporal and spatial variability of surface and aerosol is limited)

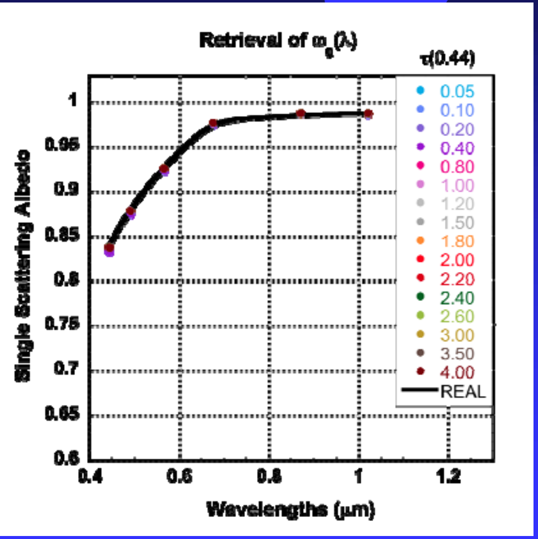
Desert Dust aerosol (non-spherical!!!)

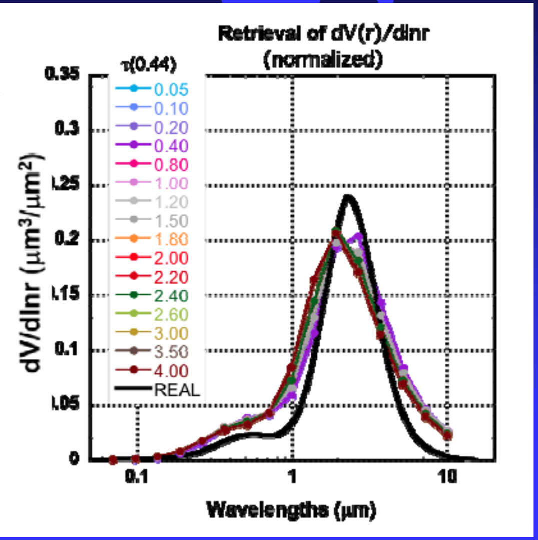
Dubovik et al. AMT, 2011

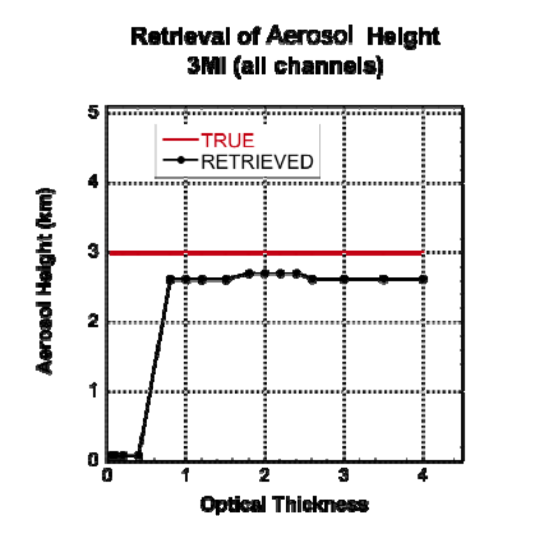












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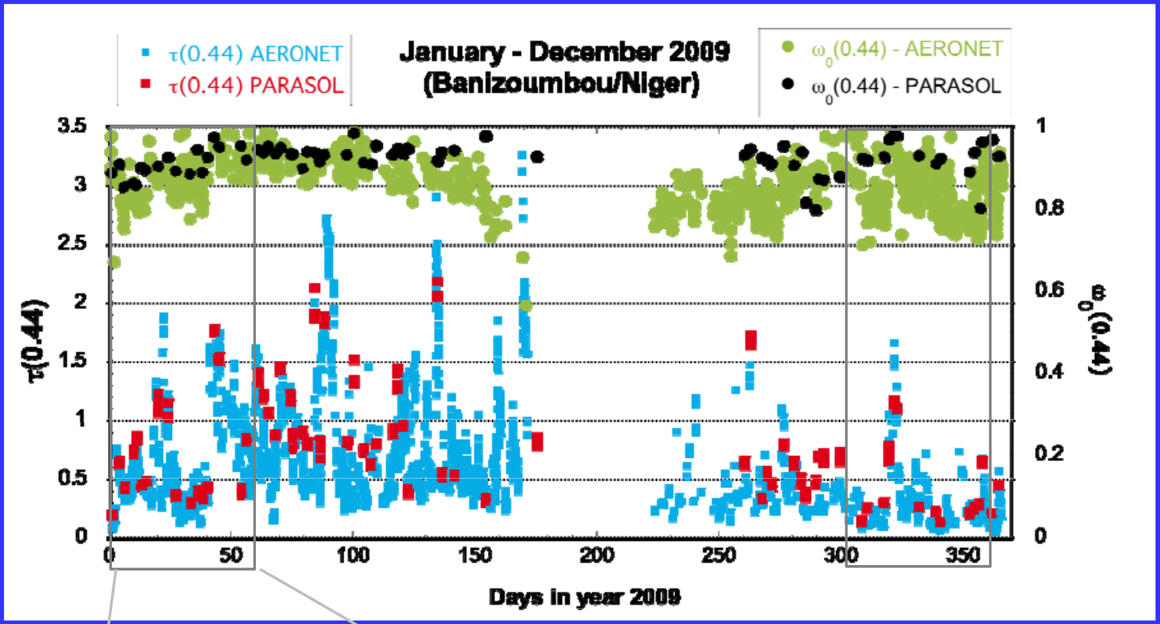
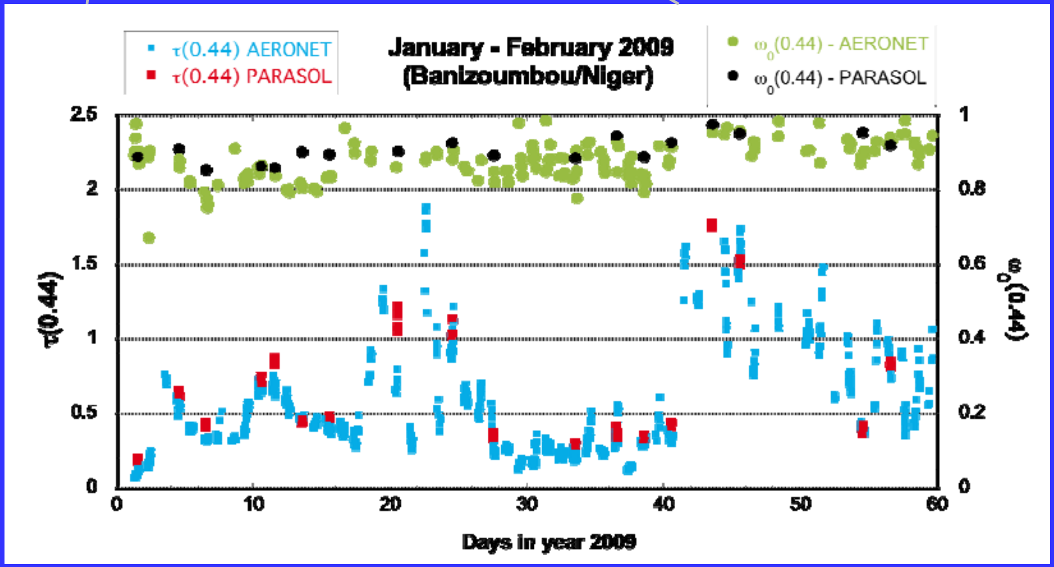
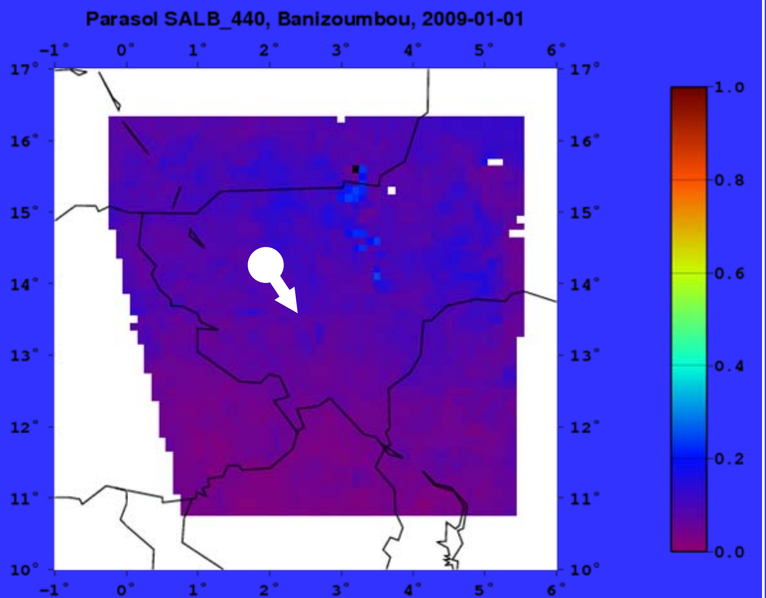




0.44



Surface Albedo

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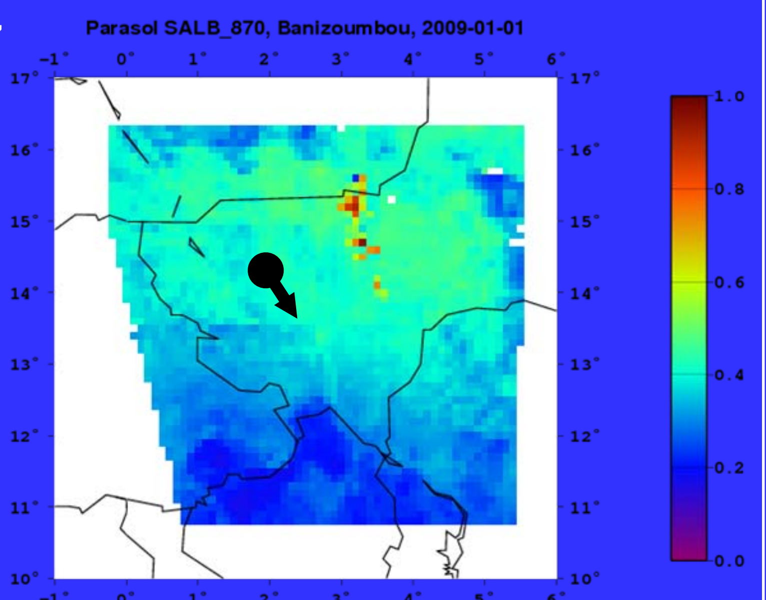
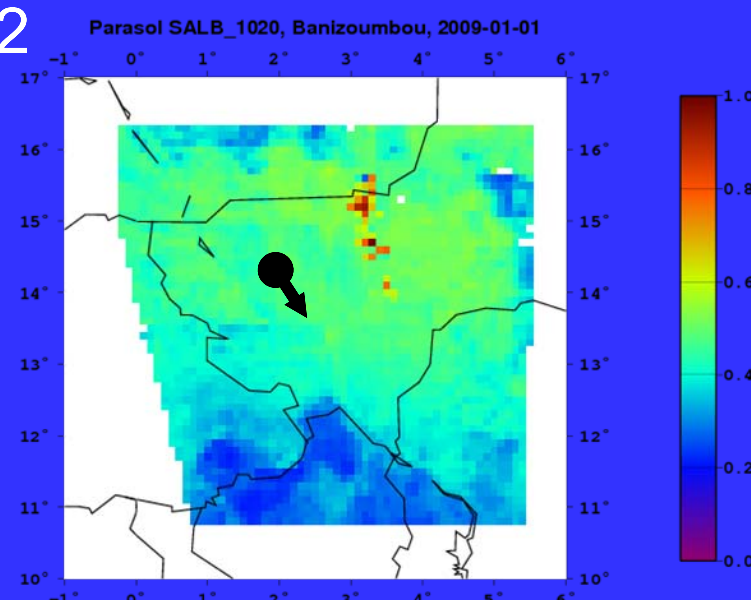
0.87



1.02



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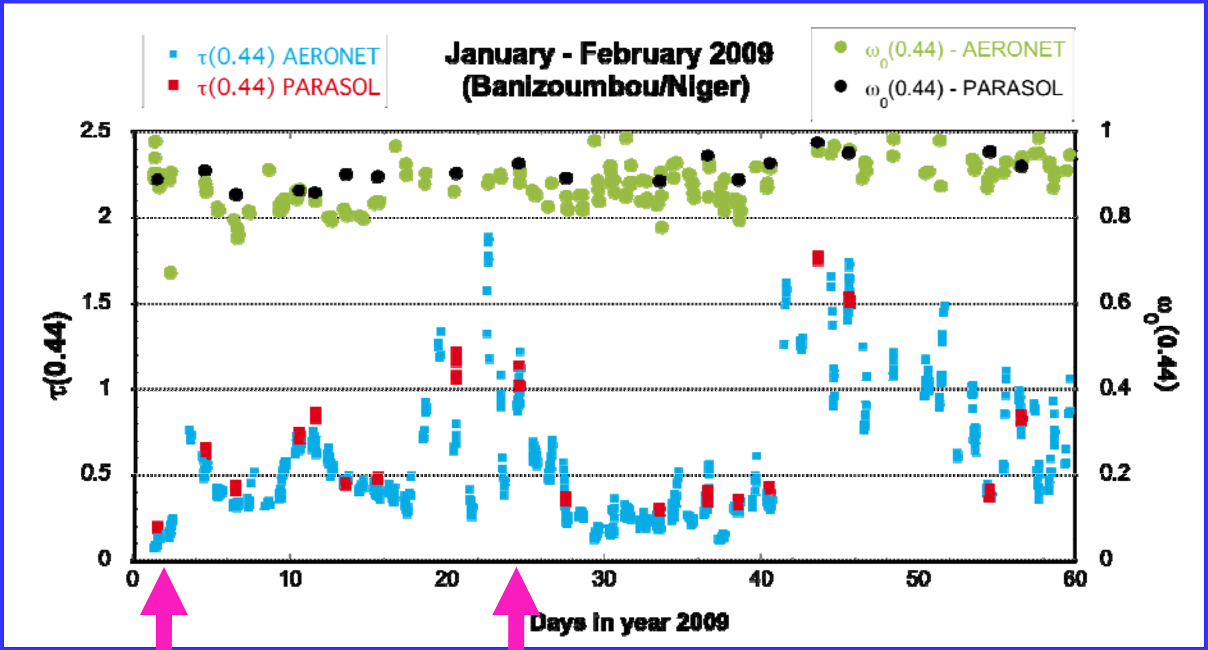
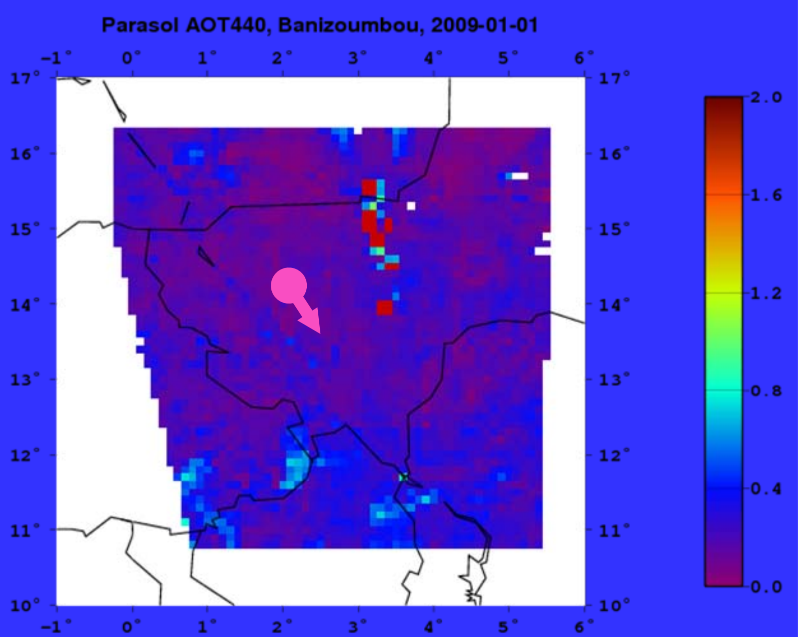
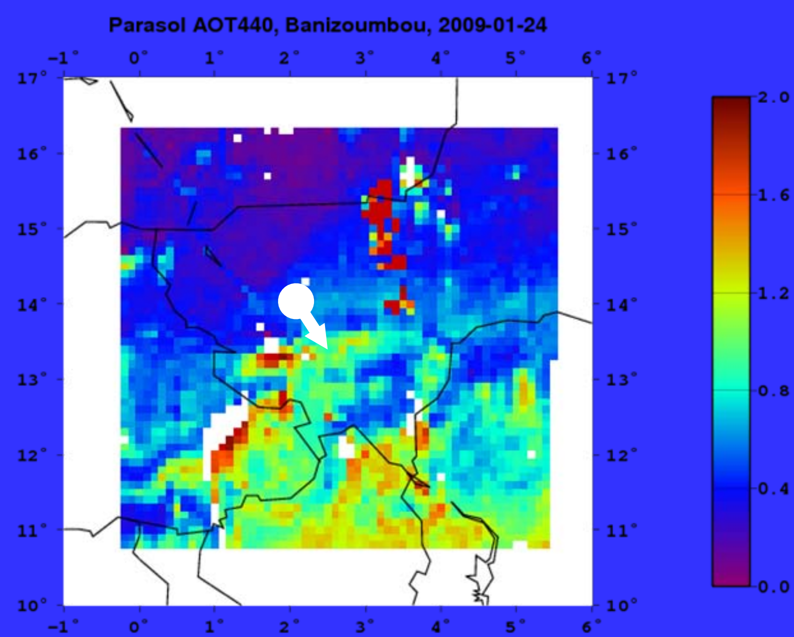
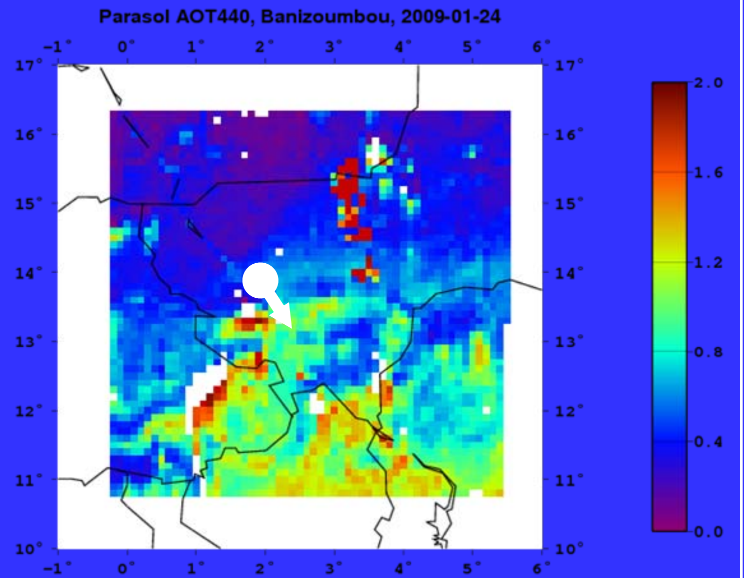






$\tau(0.44)$



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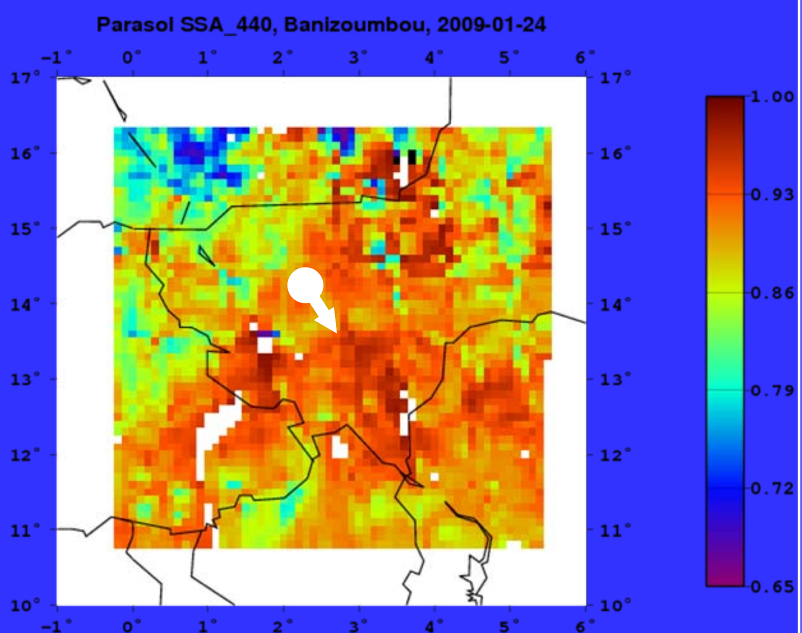
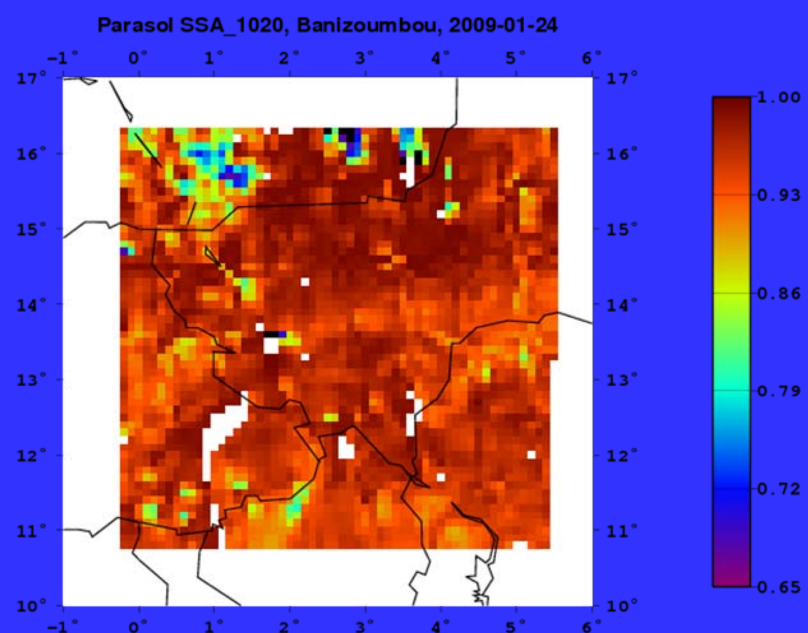
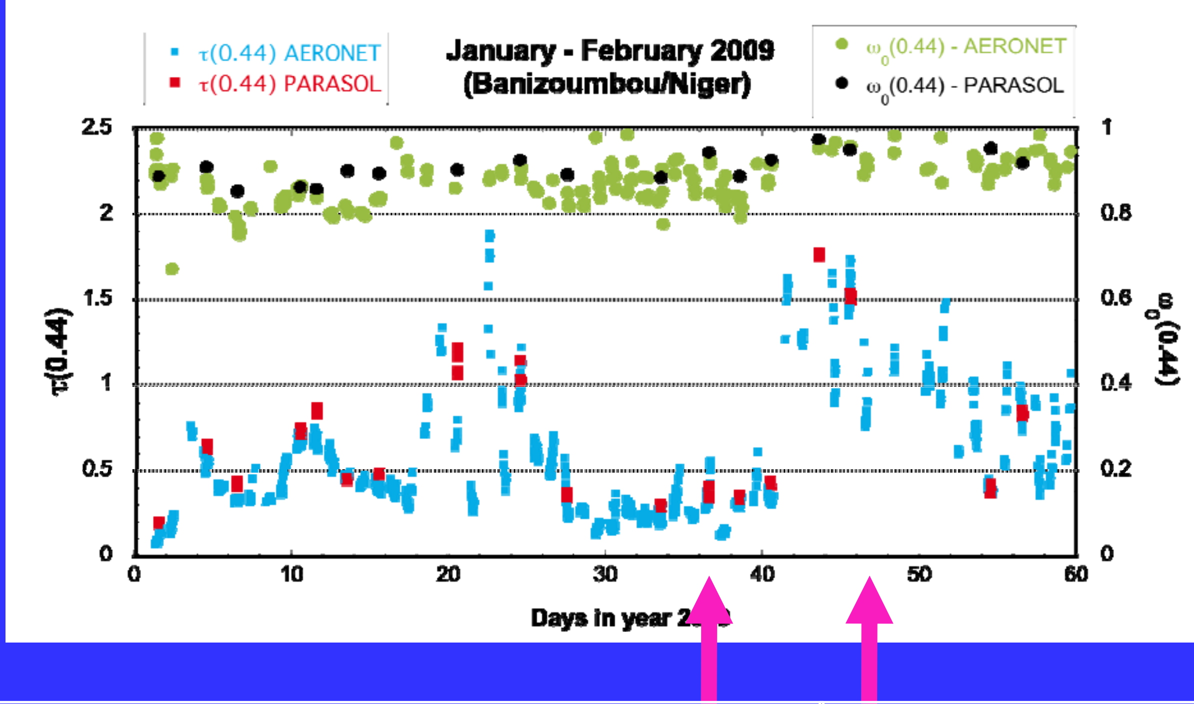
$\omega_0(0.44)$

$\omega_0(1.02)$







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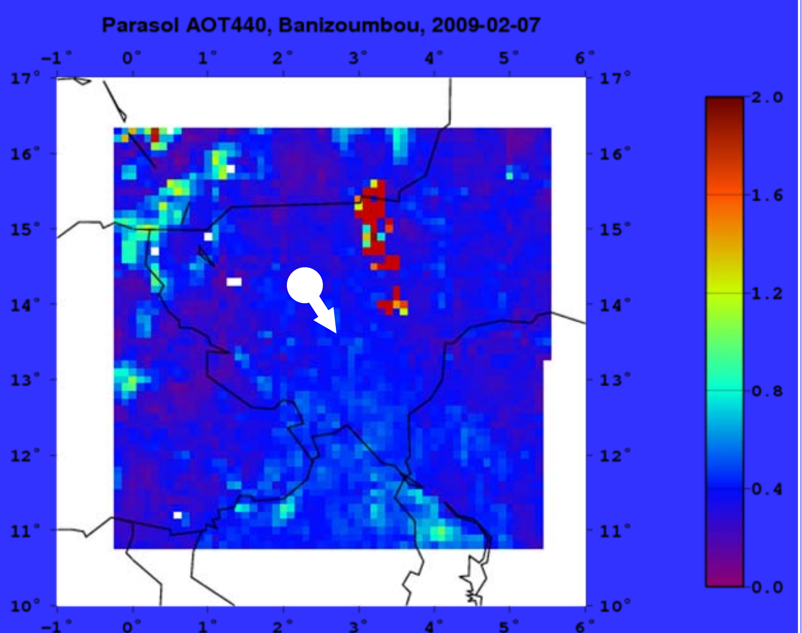
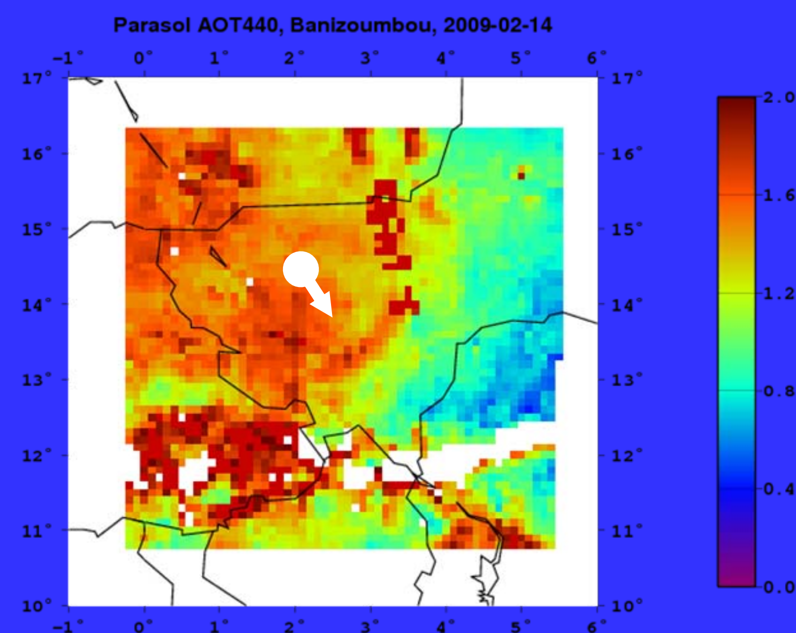
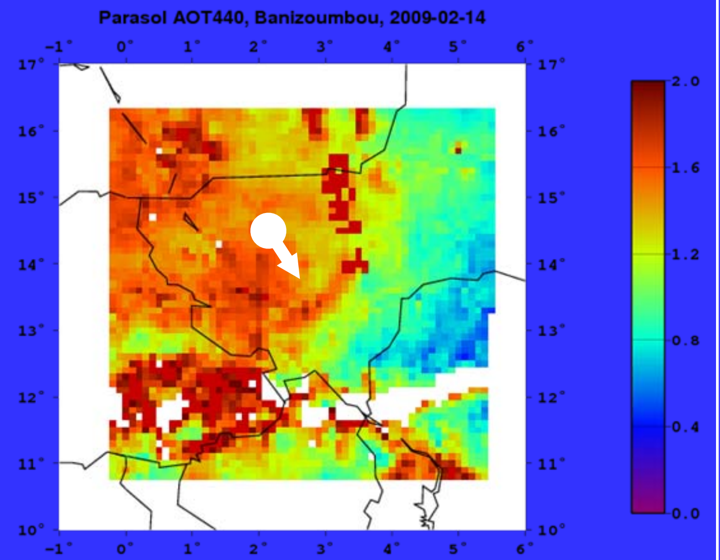




$\tau(0.44)$



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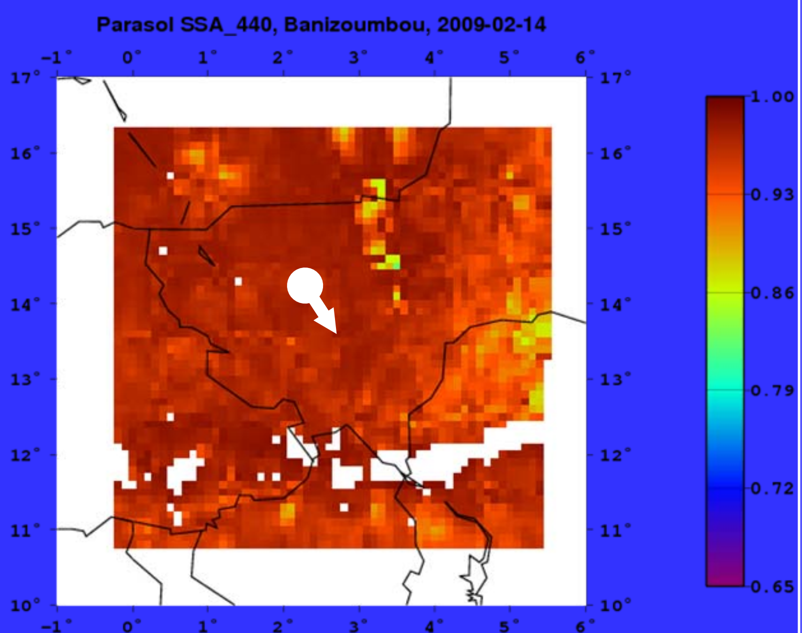
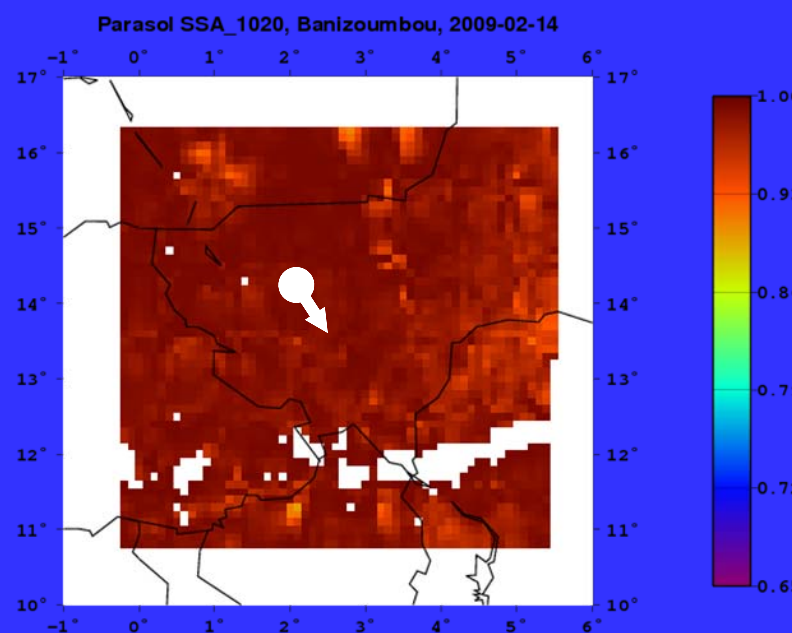
$\omega_0(0.44)$

$\omega_0(1.02)$

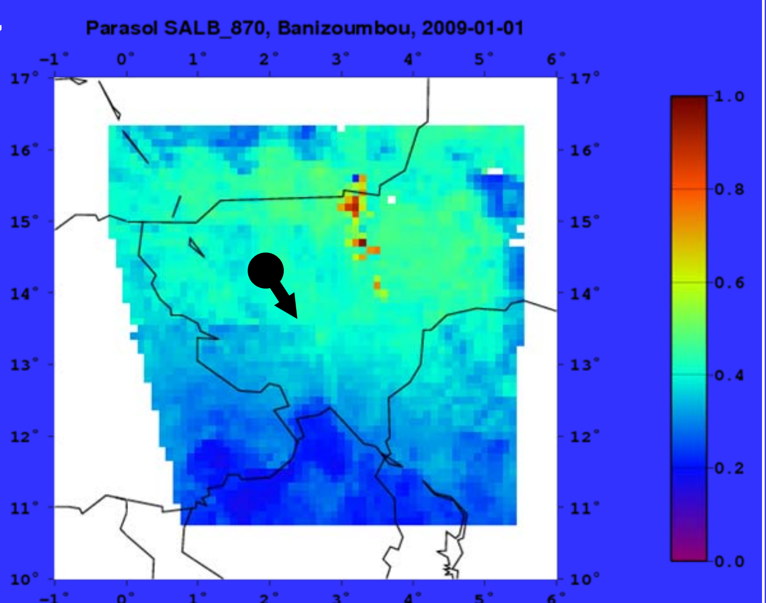




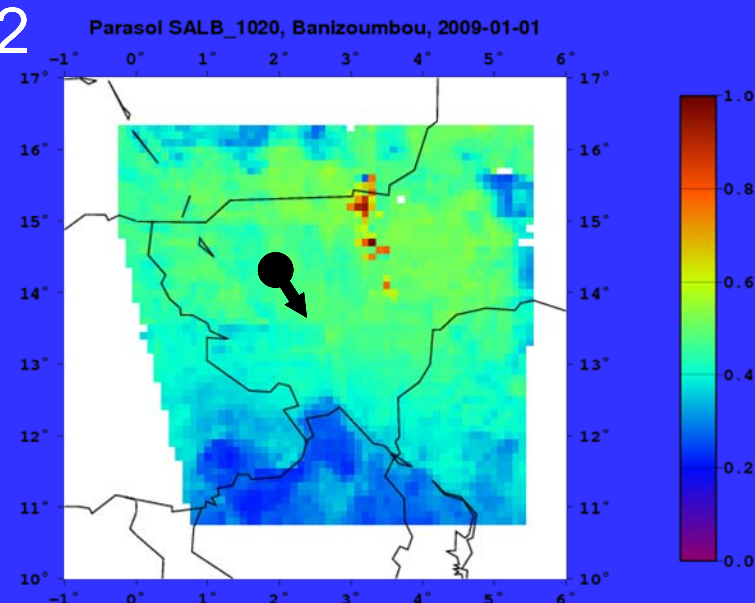
Surface Albedo

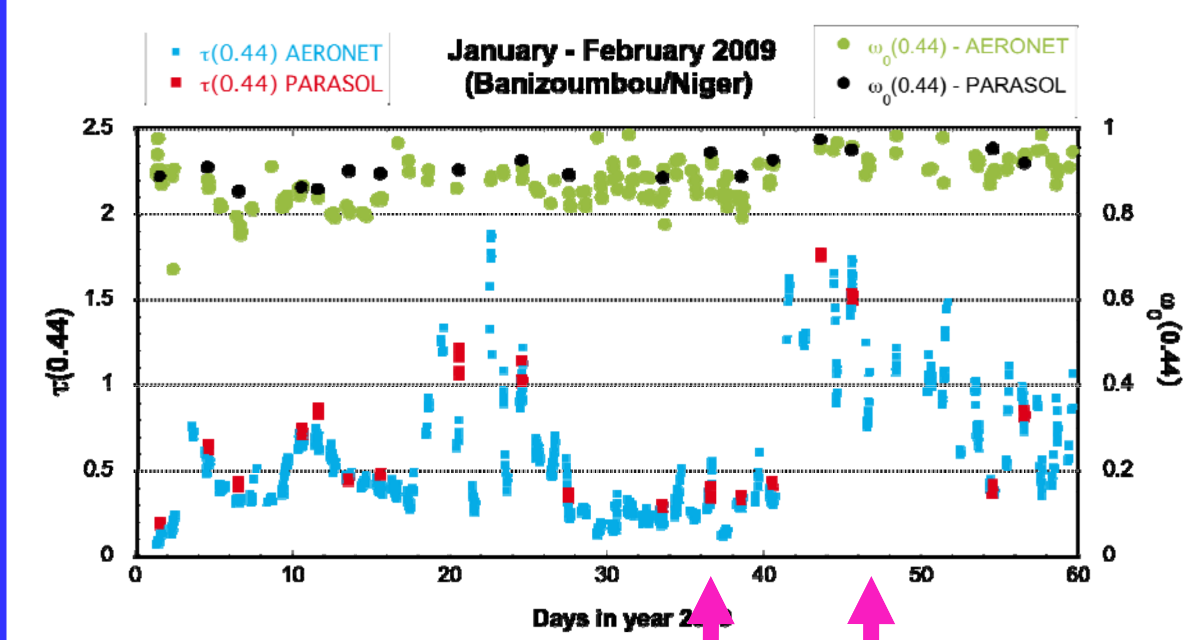
Banizoumbou
NIGER

0.87

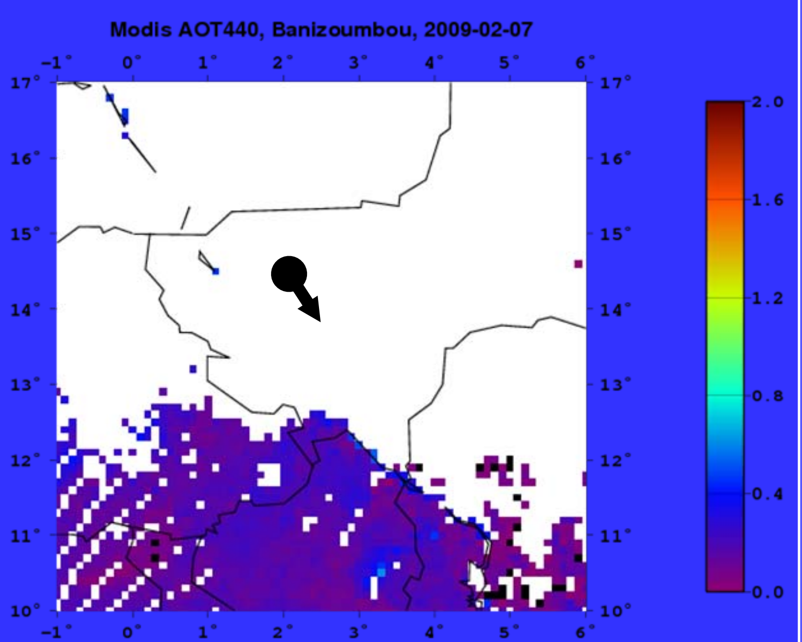


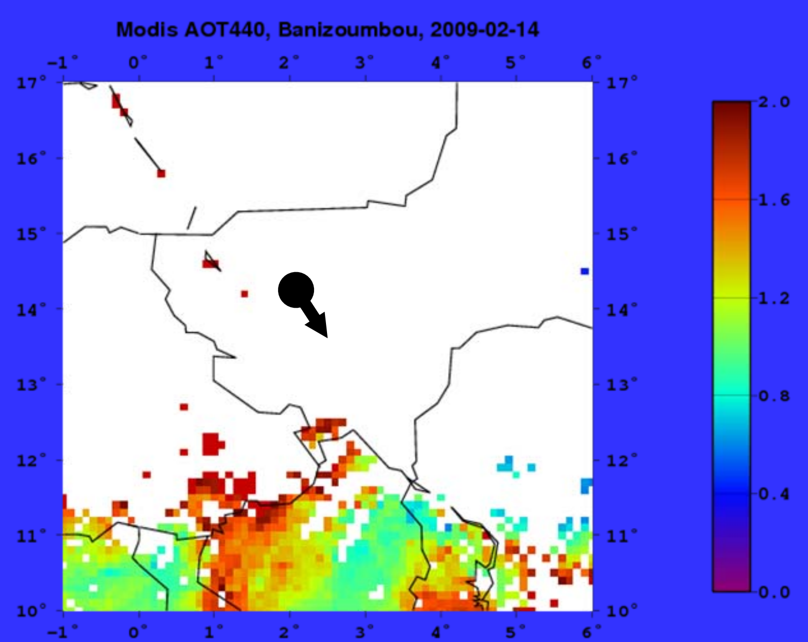
1.02





MODIS (dark target)



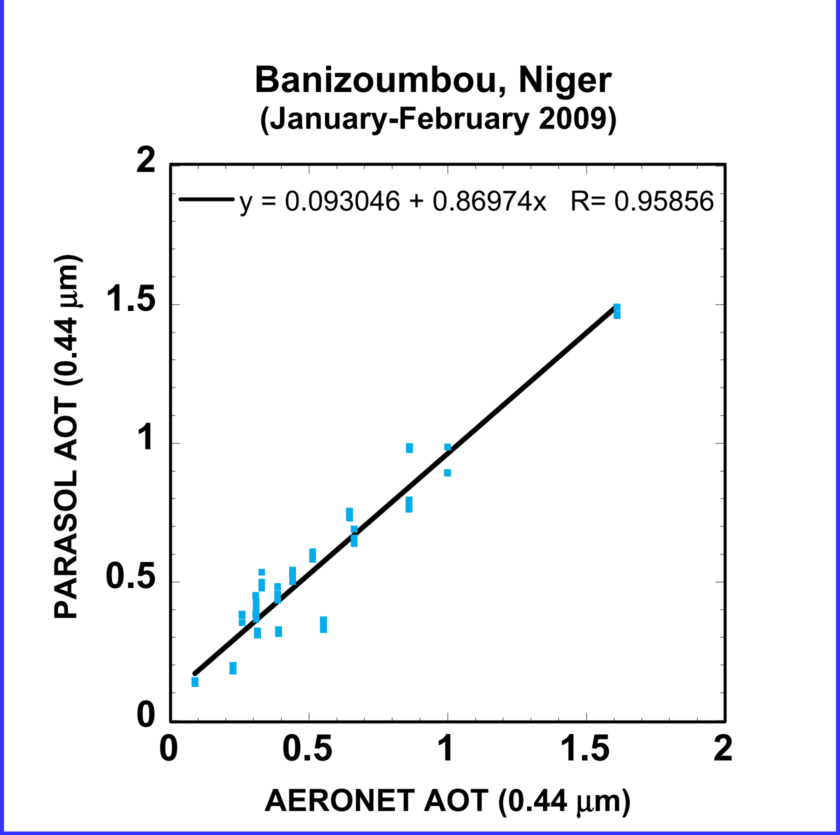


Dust and biomass
Banizoumbu/Niger

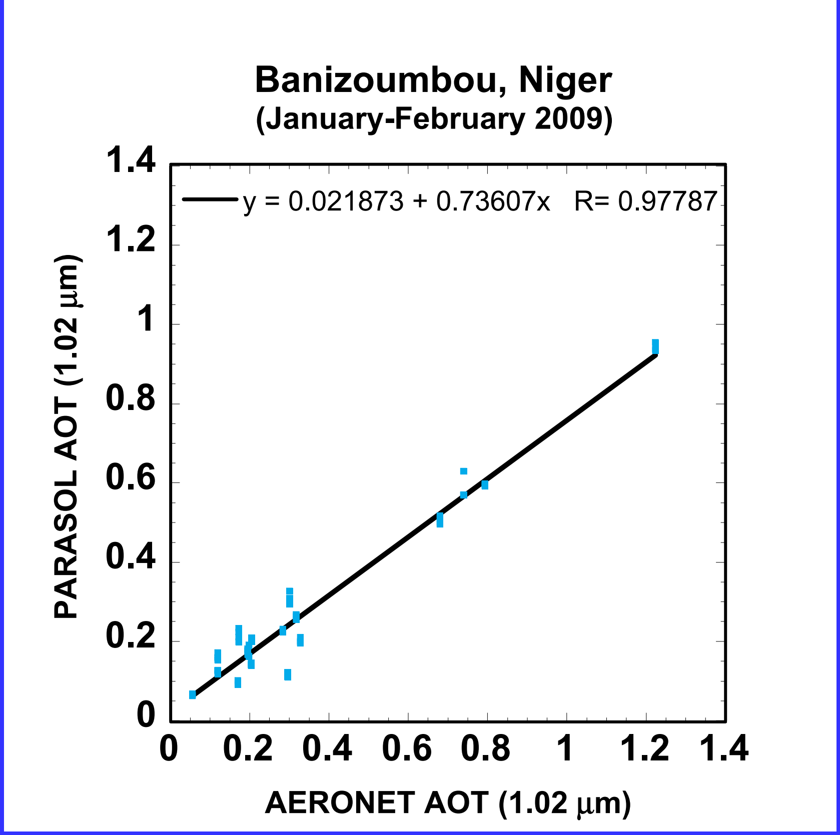
Optical Thickness

PARASOL versus AERONET

0.44 µm



1.02 µm

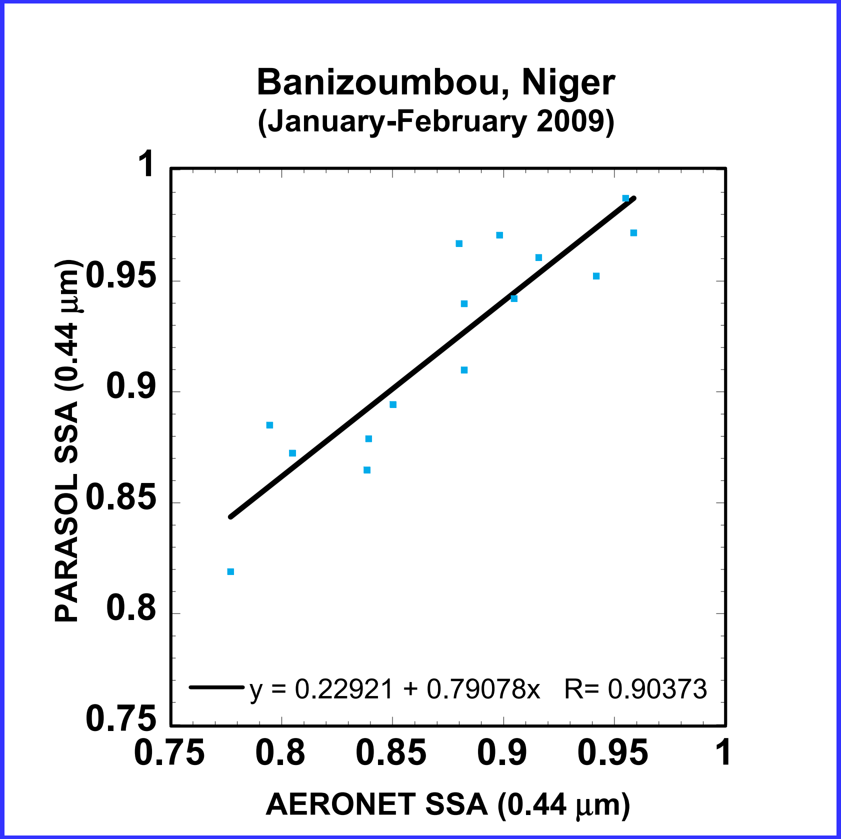


Dust and biomass
Banizoumbu/Niger

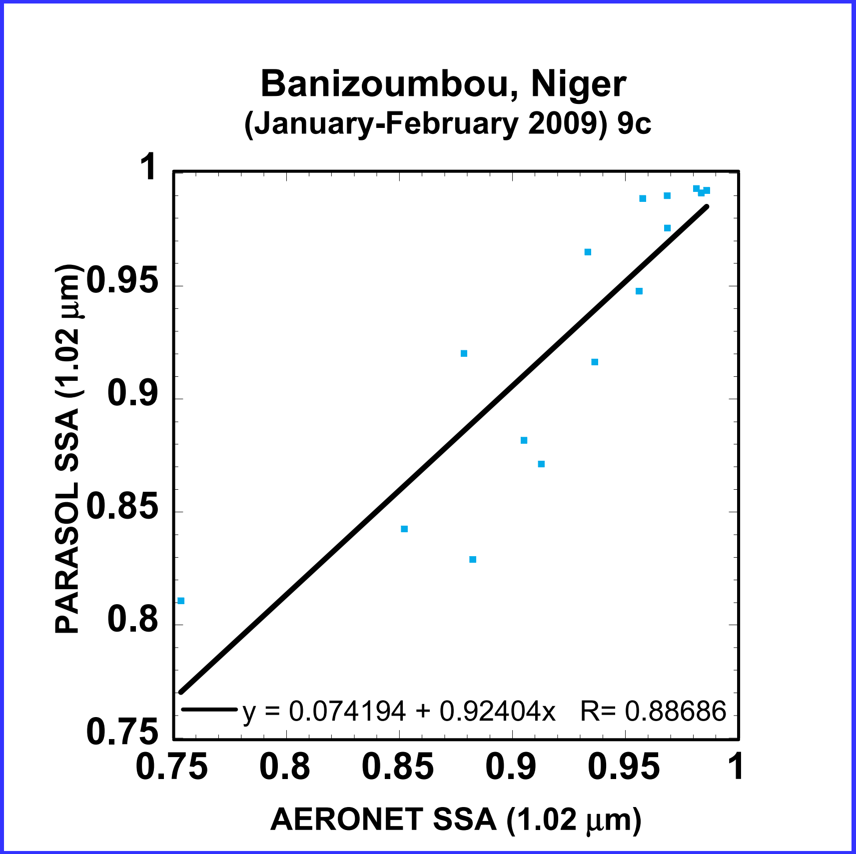
Single Scattering Albedo

PARASOL versus AERONET

0.44 μm

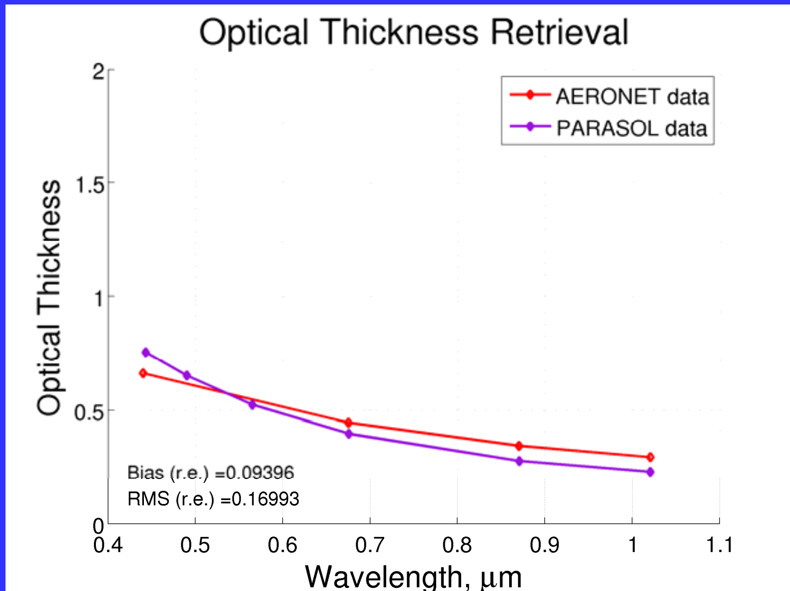


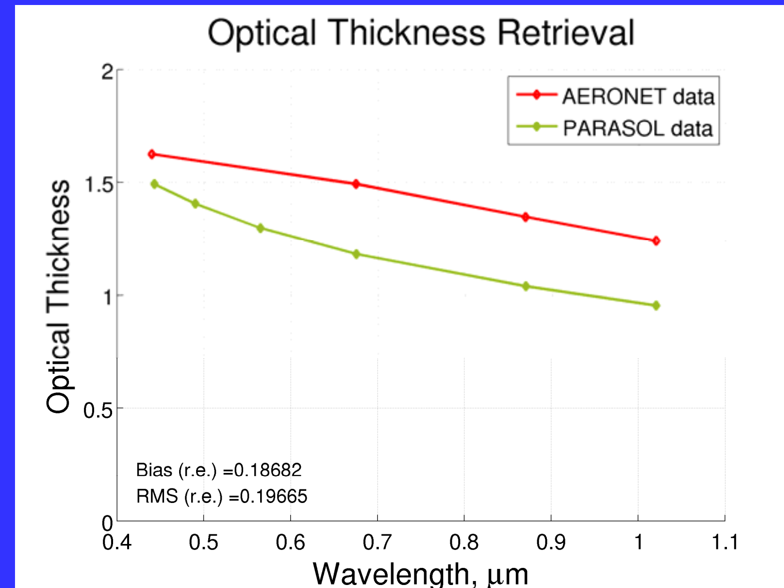
1.02 μm

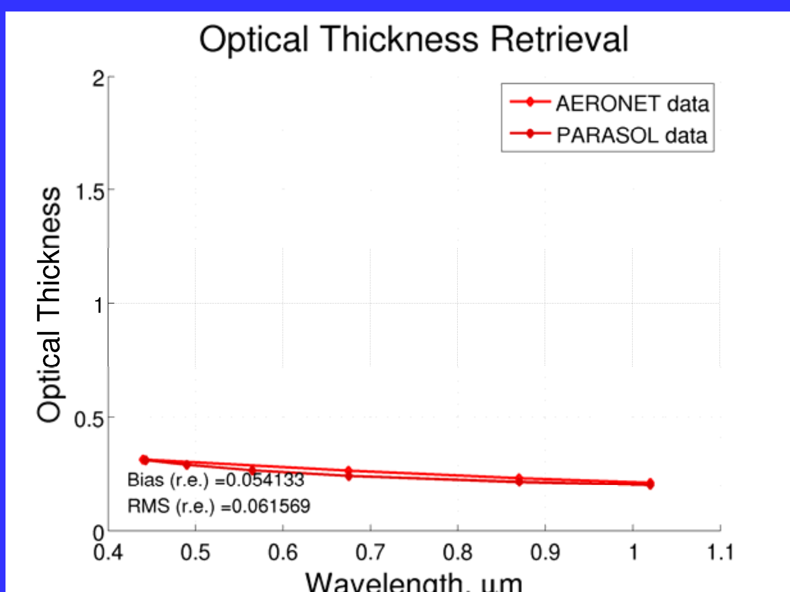


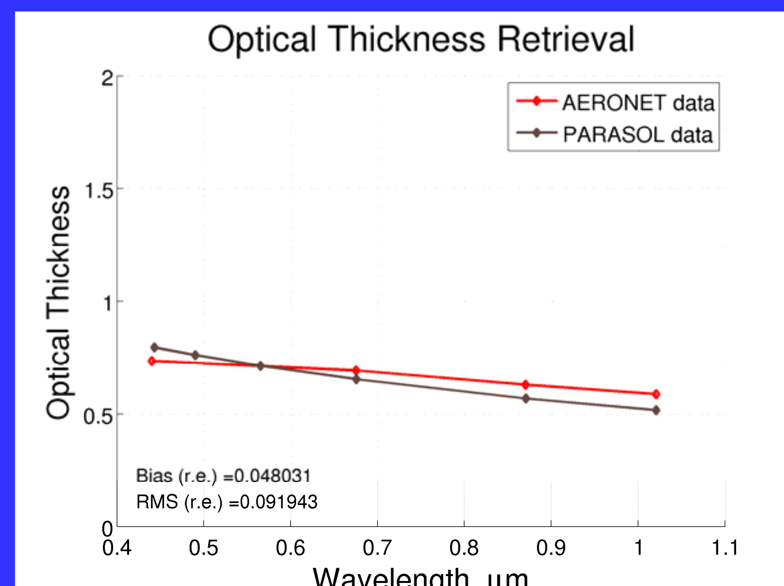
PARASOL versus AERONET

Dust and biomass
Banizoumbu/Niger



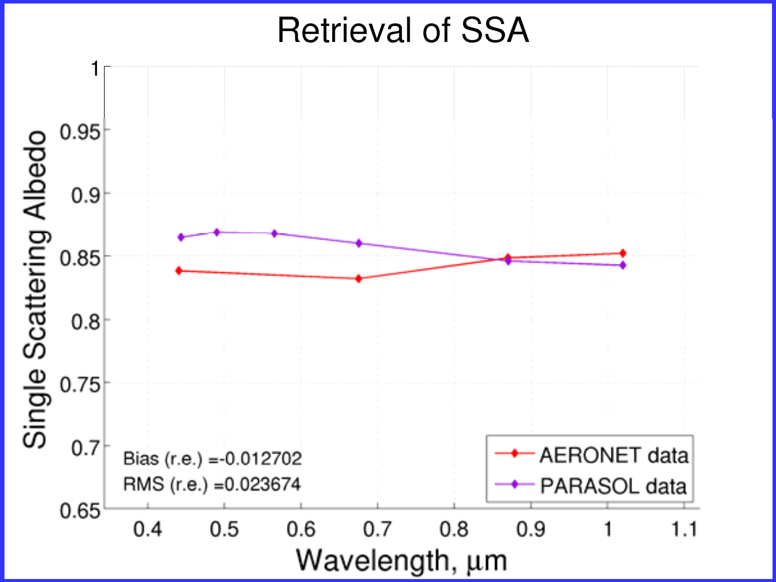


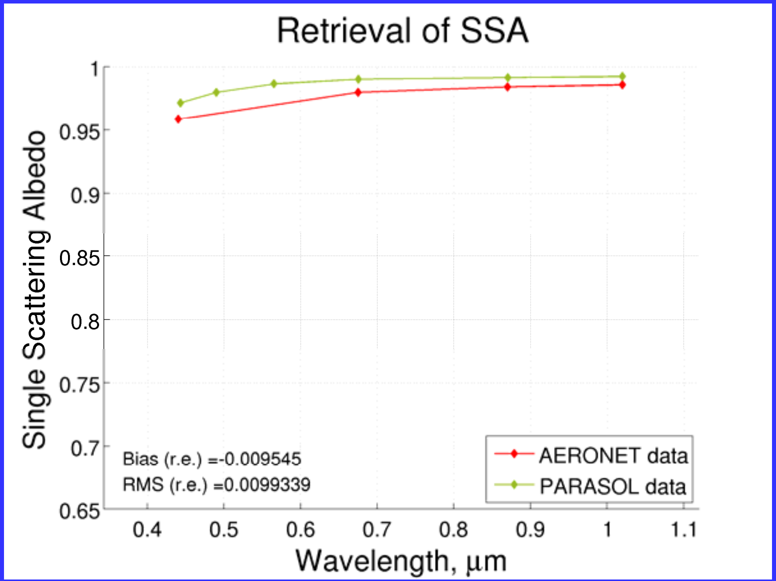


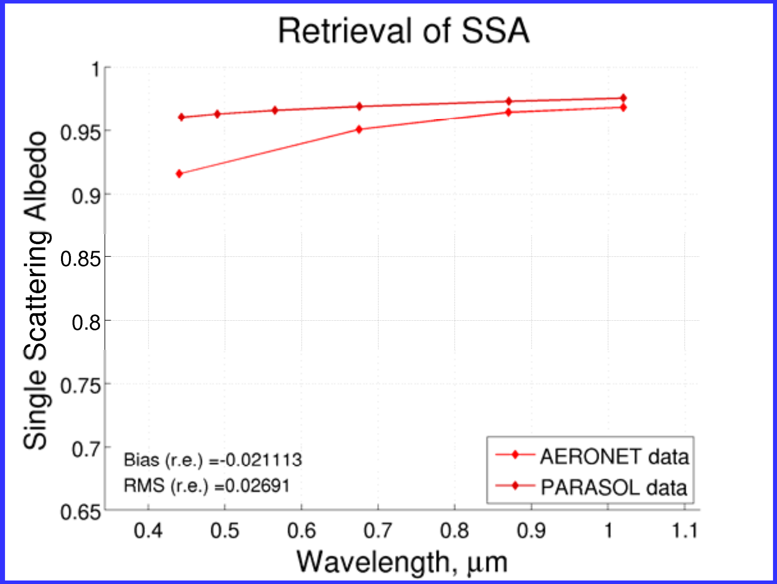


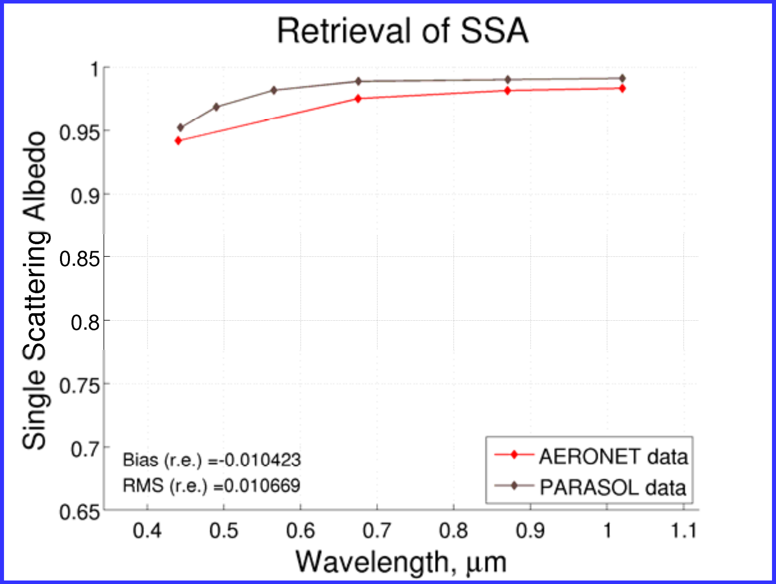
PARASOL versus AERONET

Dust and biomass
Banizoumbu/Niger



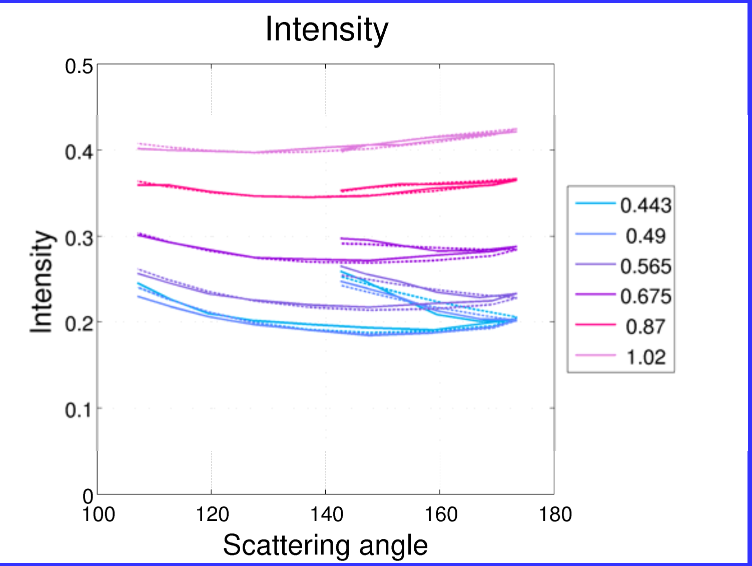


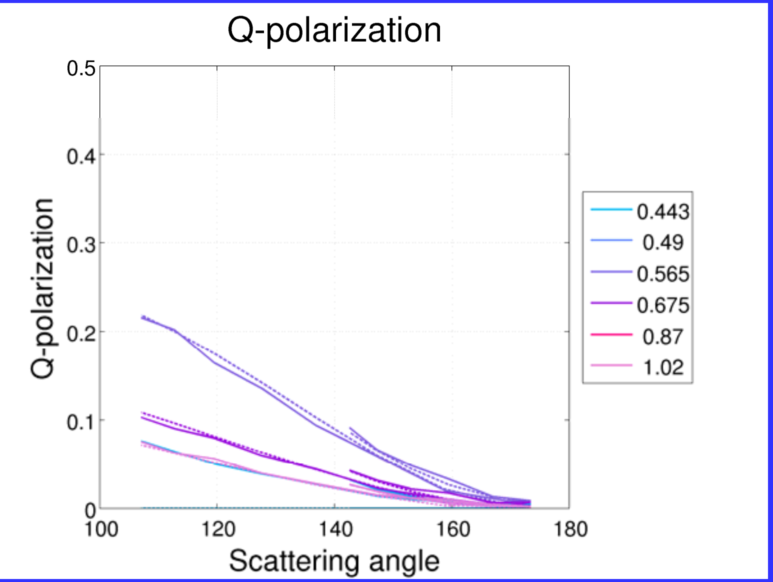


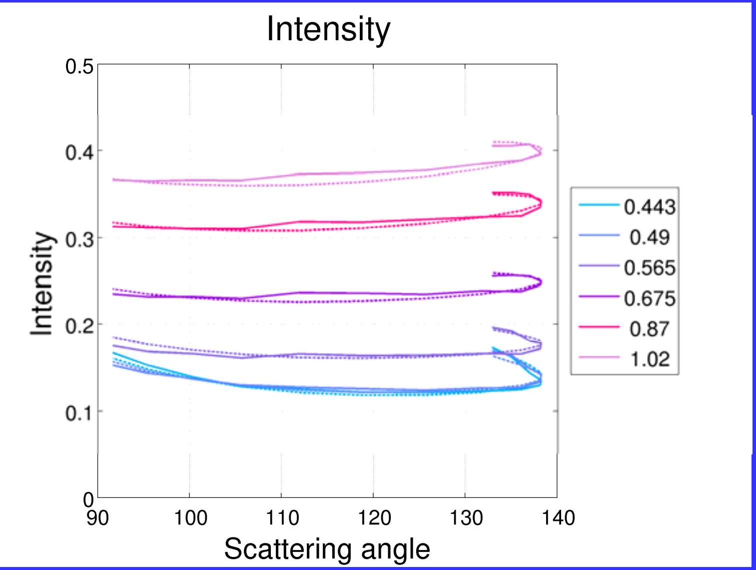


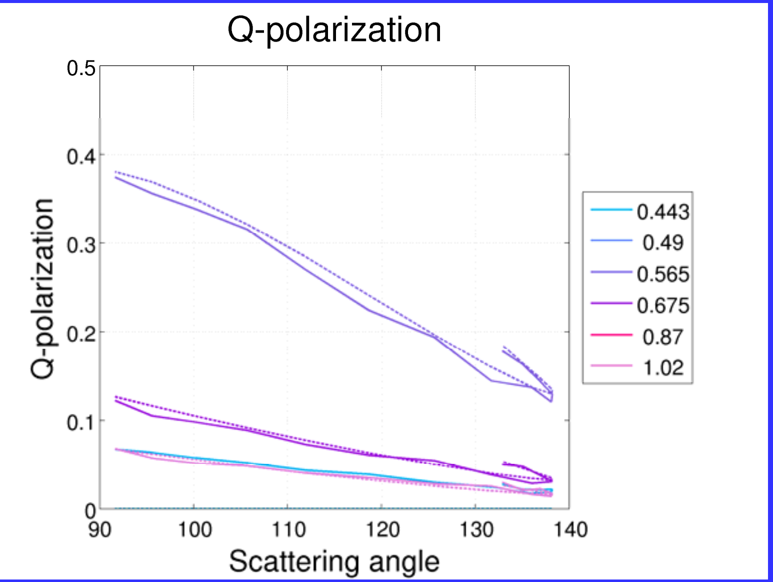
Fit of PARASOL observations

Dust and biomass
Banizoumbu/Niger

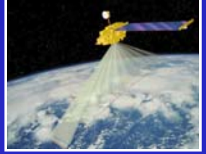


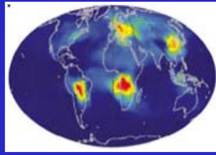






Described in Dubovik et al., AMT, 2011





Algorithm Status:

1. <u>**Core Algorithm is developed and performs well:**</u>

- **uses very elaborated aerosol and RT models;**
- **based on rigorous statistical optimization;**
- ***performs well in numerical test*** *(Dubovik et al. 2011, Kokhanovsky et al. 2010);*
- ***has a lot of flexibility for constraining retrieval: both for single-pixel and/or multi-pixel scenarios)***

2. <u>**Issues:**</u>

- **too long - 10 sec per 1 pixel!!!**
- **needs to be optimally set for operational processing**
- **cloud – screening – need to be improved !!!**

<u>***Main Objective:***</u>

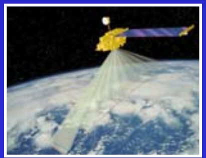
to make algorithm operational

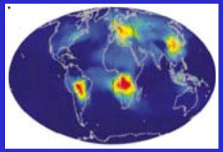
Conclusions/Perspectives:

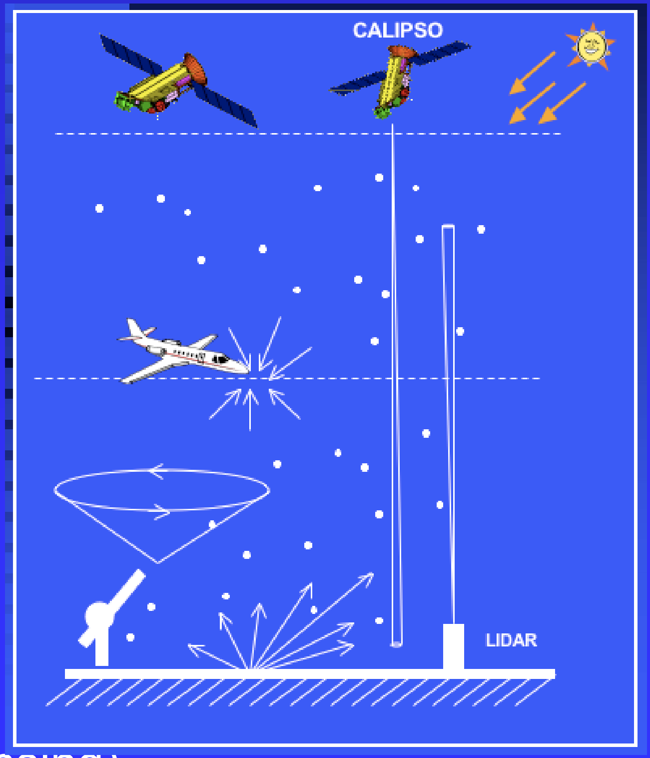
1. New Algorithm – *promising*

Potential for improvement:

- optimizing BRDF and BPDF models
- optimizing aerosol model
- including chemistry parameters into retrievals
- tuning a priori constraints settings







2. Issues:

- 10 sec per 1 pixel – too long !!!
- spectral dependence – moderate accuracy !!!
- cloud – screening – need to be improved !!!

3. Potential:

- multi-sensor retrieval:
  PARASOL + MODIS
  PARASOL + CALIPSO, GLORY, etc.)
- inverse modeling (tuning the models by remote sensing)

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;

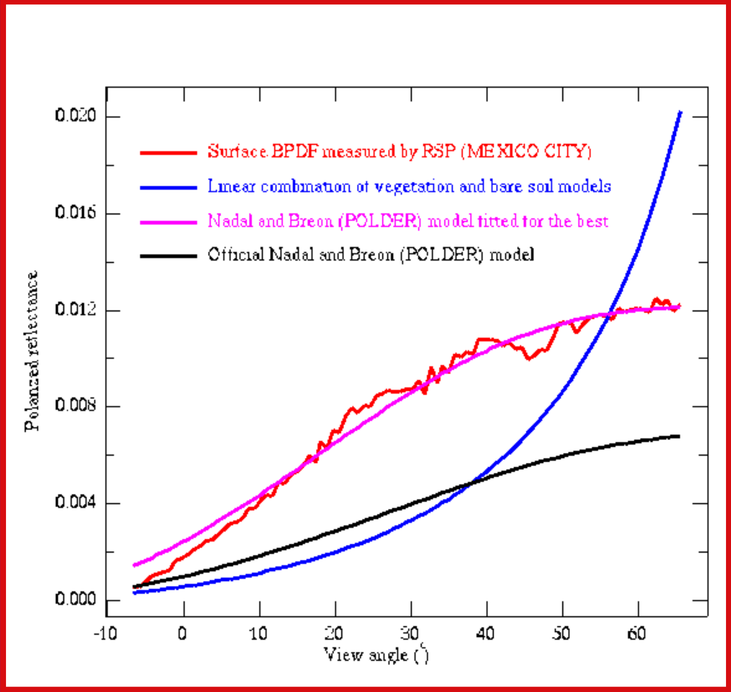
   - multi-instrument retrieval optimization

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)

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.

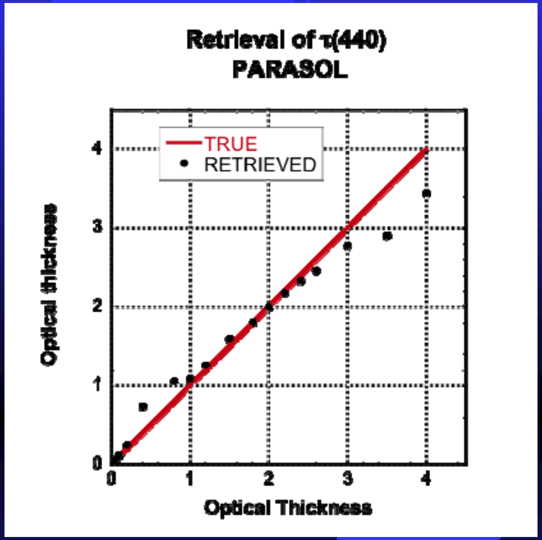
Single Initial Guess:

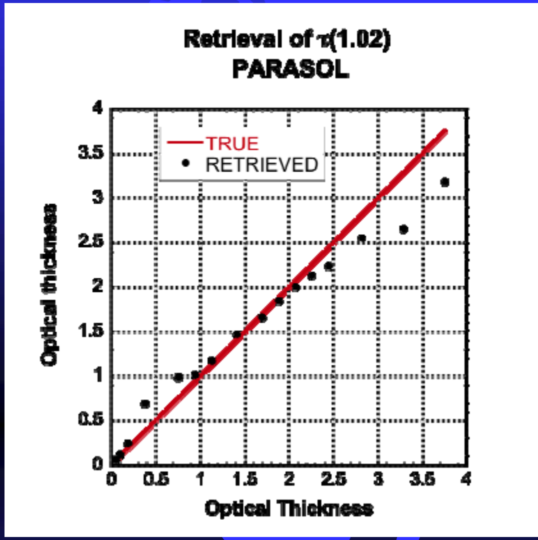
Aerosol Properties	Surface Reflectance
$C_v = C_0$ (corresponding to the value of τ_{aer} (0.44)~0.05);	$\rho_o(\lambda_i) = 0.05$ $(i = 1, ..., N_\lambda)$
$dV(r_i)/d\ln r = 0.1$; $(i = 1, ..., N_r)$	$\kappa(\lambda_i) = 0.75$ $(i = 1, ..., N_\lambda)$
$C_{sph} = 0.7$	$\theta(\lambda_i) = -0.1$ $(i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

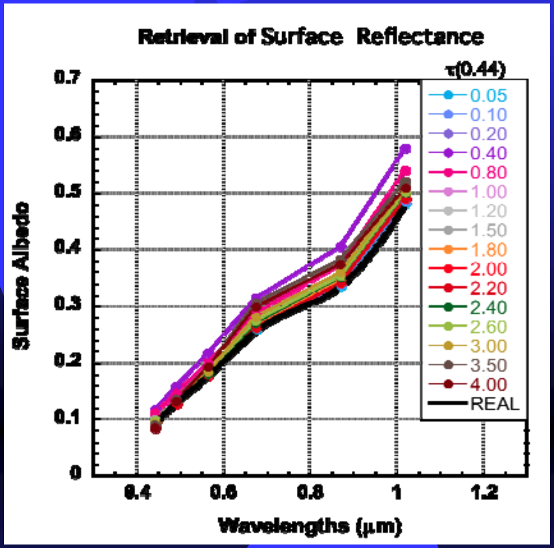
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

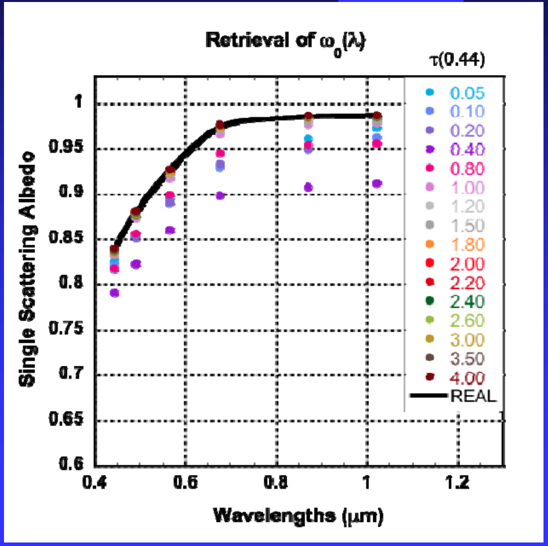
NO NOISE ADDED !!! (minor noise is always present)

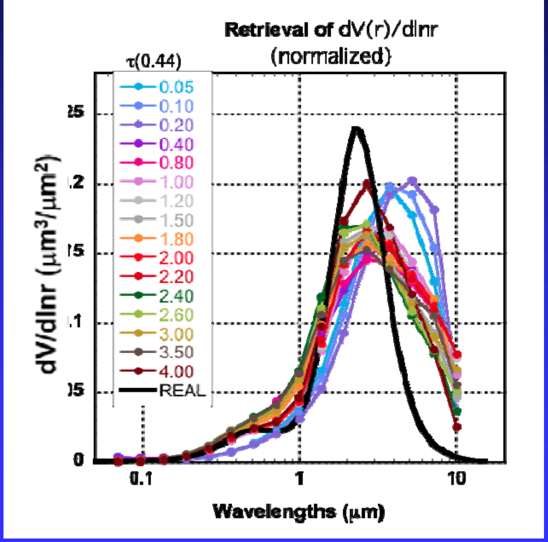
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

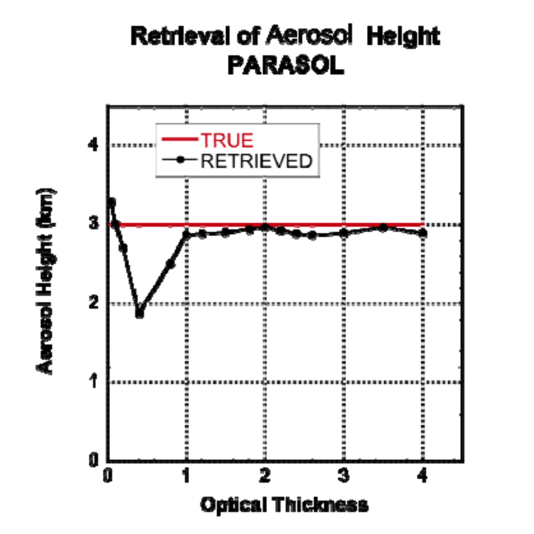








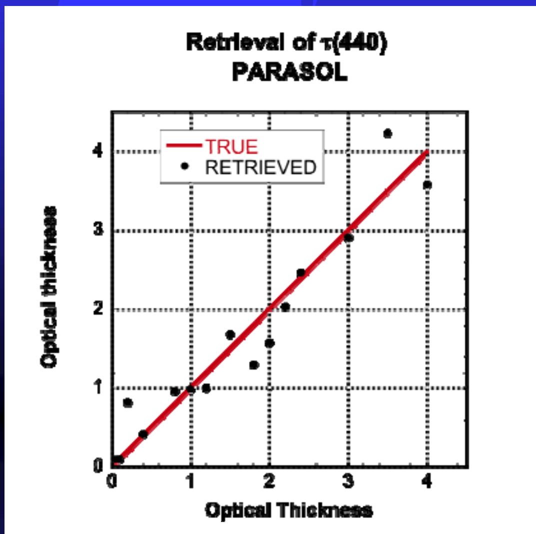


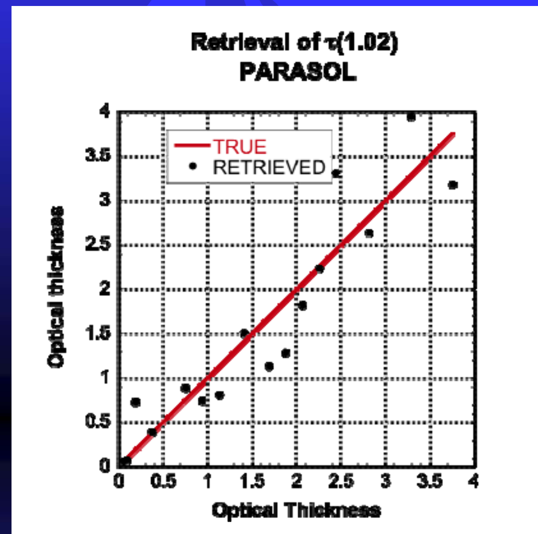


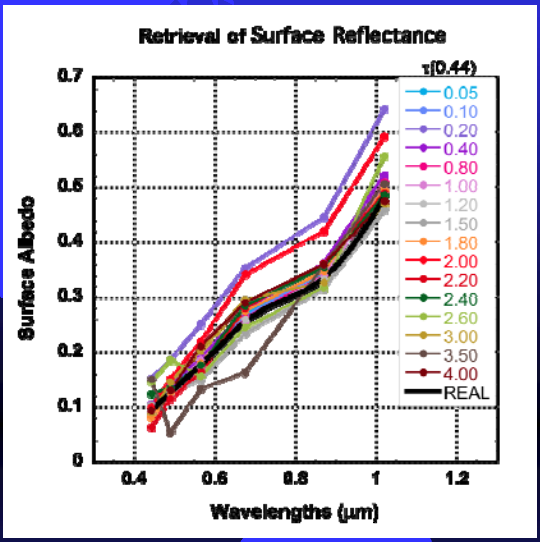
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

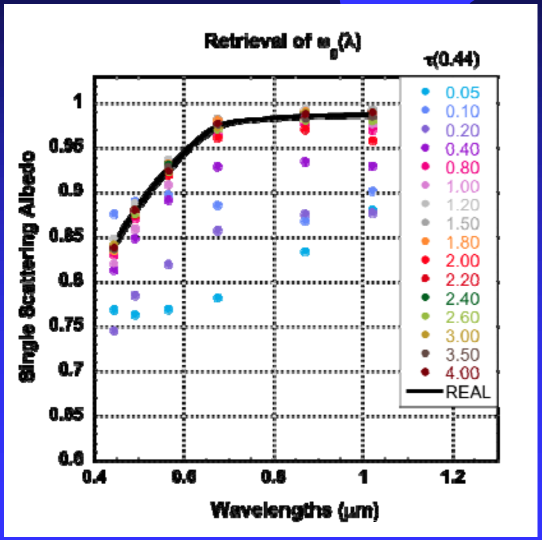
NOISE ADDED: 1% for I(λ), 0.005 for Q(λ)/I(λ) and U(λ)/I(λ) !!!

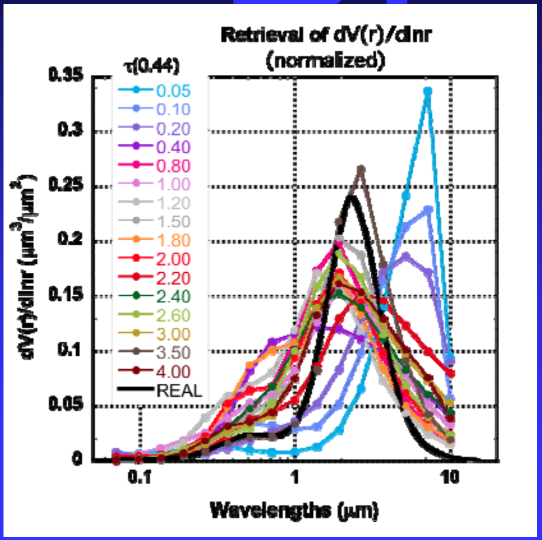
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

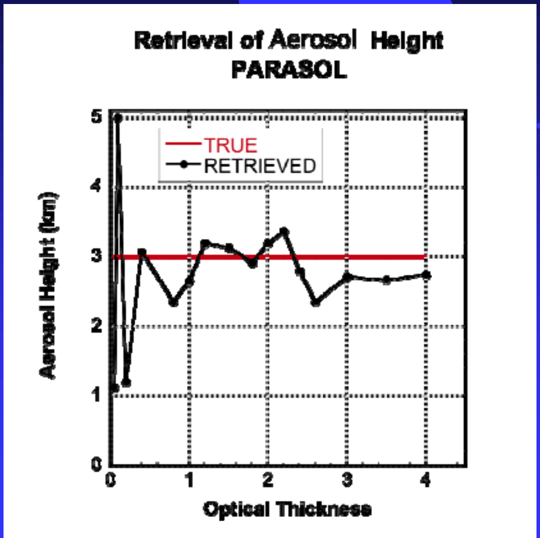






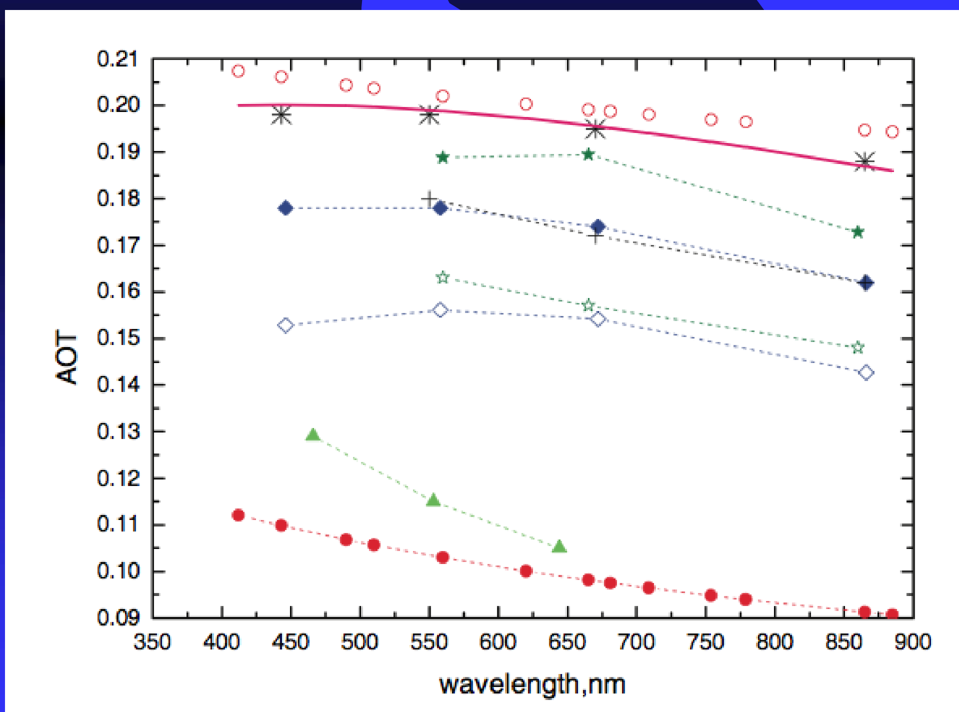


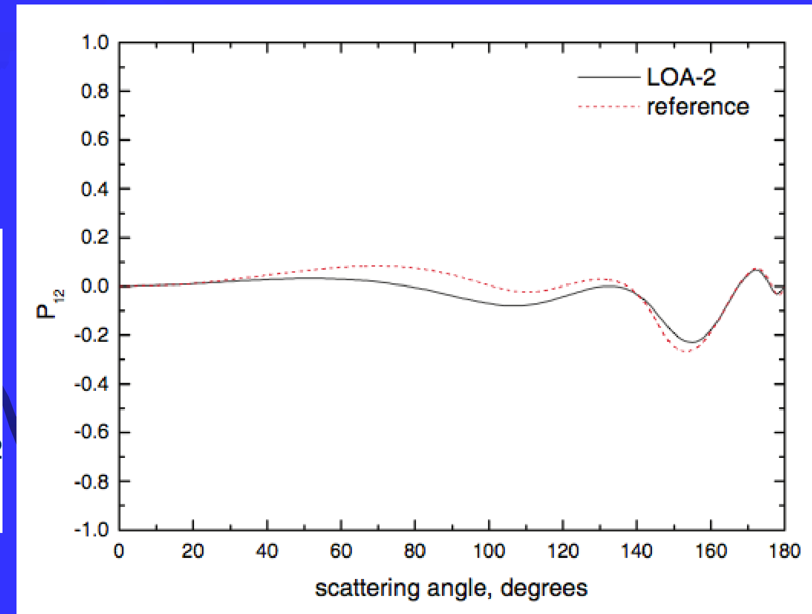


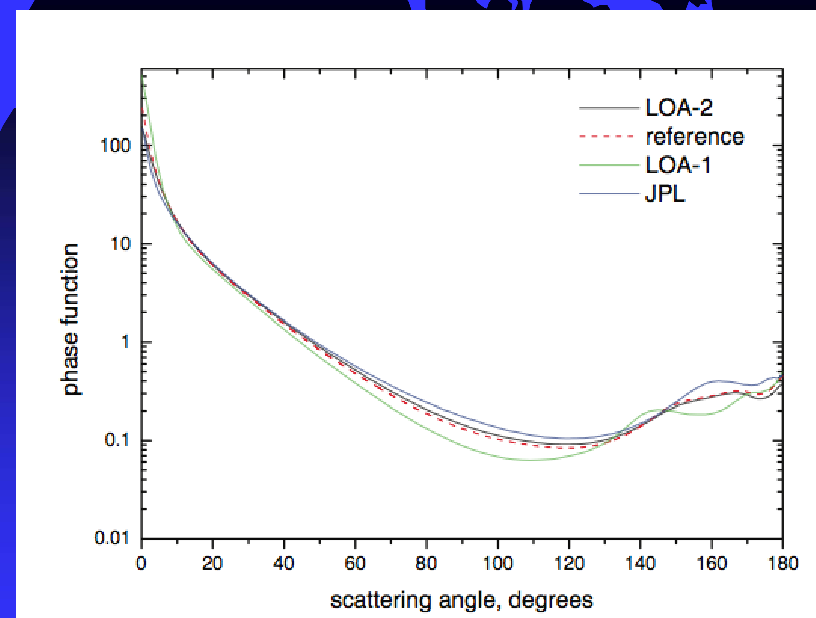


Tests over dark surface (« *Blind* » *Test*)

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

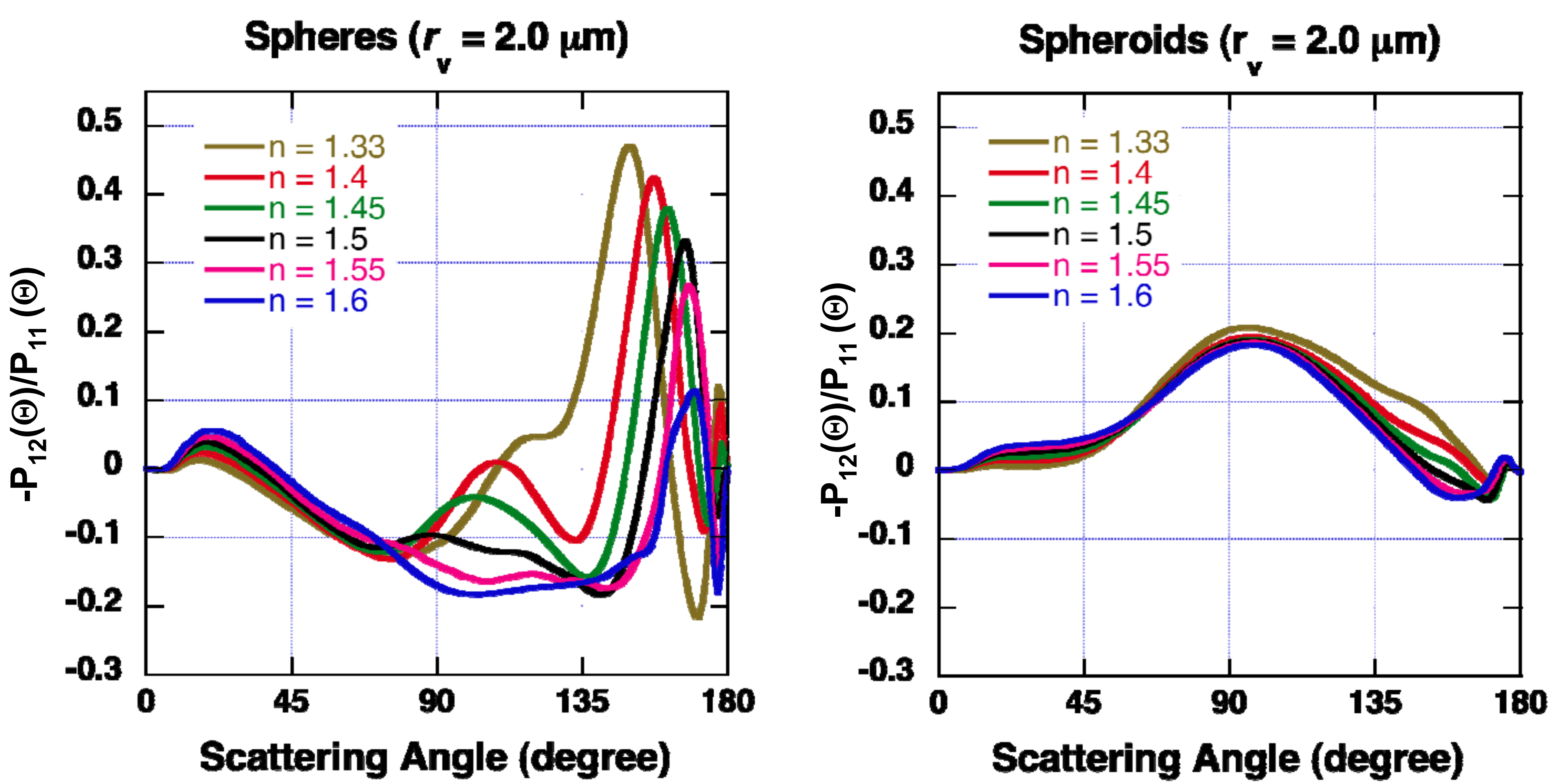






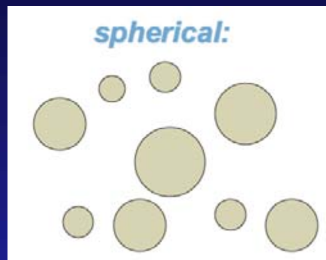
Sensitivity of polarization to particle shape

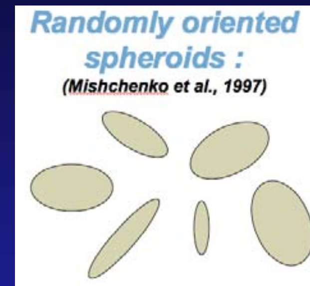
Coarse aerosol

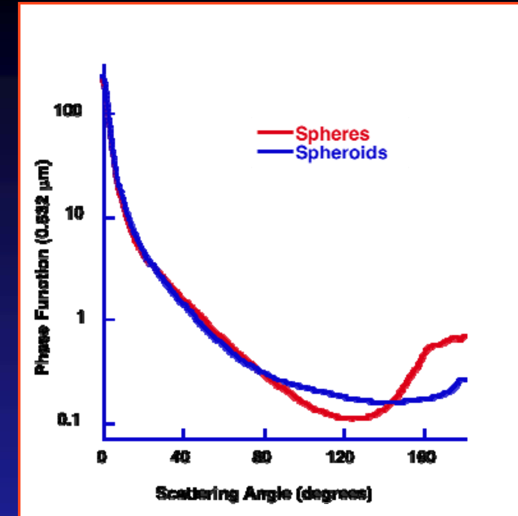


Mixing of particle shapes

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