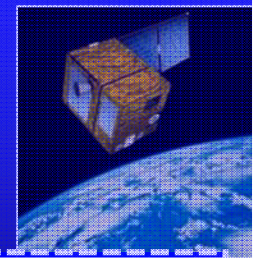
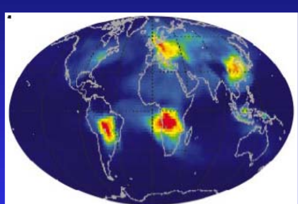
The optimized algorithm for deriving detailed properties of aerosol from satellite observations.



O. Dubovik, M. Herman, A. Holdak, T. Lapyonok, D. Tanré, F. Ducos, P. Litvinov, Y. Govaerts, A. Lopatin

Science and Technology University of Lille, CNRS, France



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

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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 (I): $N^t_\lambda=6$ (for aerosol) *(0.44, 0.49, 0.56, 0.67, 0.865, 1.02 μm)*
$N^t_\lambda=3$ (for gas absorption) *(0.763, 0.765, 0.910 μm)*

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

a lot !!! – as much as AERONET

SINGLE OBSERVATION:

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

New POLDER/PARASOL algorithm

(*Dubovik et al., AMT, 2011*)

- The new algorithm uses complete set of PARASOL angular measurements in all spectral bands including both radiance and linear polarization measurements.

- Continuous space of aerosol and surface properties is used.

- The algorithm is based on statistically optimized fitting.

The core of the new PARASOL algorithm is based on the same concept as AERONET aerosol retrieval (O. Dubovik and M. King, 2000; O. Dubovik, 2004; O. Dubovik et all, 2006).

Slide 3

1 heritage of AERONET algorithm developments

Pavel Lytvynov, 5/15/2012

New algorithm

(*Dubovik et al., AMT, 2011*)

Two main modules of the algorithm:

- forward module (VRT in coupled atmosphere-surface system)

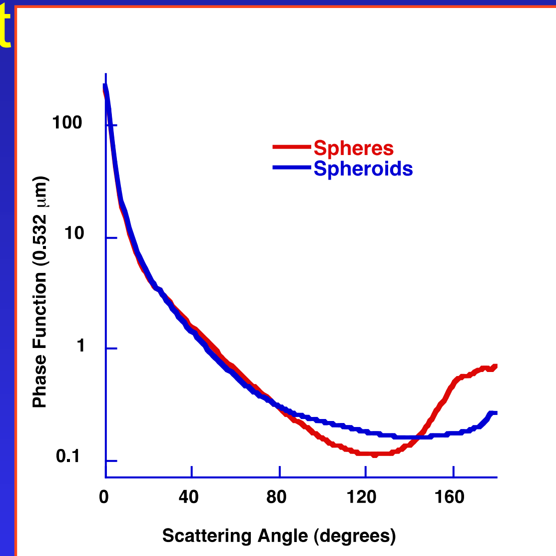
  - modeling of single scattering aerosol properties

  - modeling of surface reflection properties

- numerical inversion module

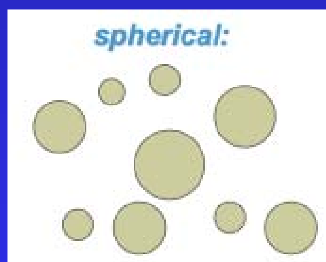
Forward module. Aerosol model

Aerosol model is the same as in AERONET retrieval (Mixing of particle shapes (Dubovik et al., 2006))



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.

Forward module. Aerosol model

The kernels were simulated in the wide range of size parameter $x = 2\pi r / \lambda$ and complex refractive index $m = n + ik$

$$0.012 \le x \le 625$$

$$1.3 \le n \le 1.7$$

$$0.0005 \le k \le 0.5$$

T-matrix (when $x < 50$) and geometric-optic (when $x > 50$) approximations were used for kernels calculations (Dubovik et al., 2006).

Retrieved aerosol parameters:

C_V	– total volume concentration of aerosol ($\mu m^3/\mu m^2$)
$dV(r_i)/d\ln$	– ($i = 1, ..., N_r$) values of volume size distribution in N_i size bins r_i, normalized by C_V
C	– faction of spherical particles
$n(\lambda_i)$	– ($i = 1, ..., N_\lambda = 6$) the real part of the refractive index at every λ_i of the POLDER/PARASOL sensor
$k(\lambda_i)$	– ($i = 1, ..., N_\lambda = 6$) the imaginary part of the refractive index at every λ_i of the POLDER/PARASOL sensor
h_0	– mean height of aerosol layer.

Forward module. Surface reflection model

Semi-empirical BRDF models (for surface total reflectance description):

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

-Ross-Li sparse model, Ross-Li dense model (*Ross, (1981), Li, X., Strahler (1992)*)

-Ross-Roujean model (*Roujean* ***et al., (1992)***)

Semi-empirical BPDF models (for surface polarized reflectance description):

-Nadal-Breon model (*Nadal and Bréon, (1999))*

-Maignan model (*Maignan et al., (2009))*

Physically based models for the reflection matrix for surfaces.

-Cox-Munk model, Koepke model for whitecaps (for aerosol retrieval over ocean)

-Physical models for land surface reflection matrix (under development) (Litvinov et al., 2011)

The concept of the algorithm.
Numerical inversion module

The concept of statistical optimization is similar to AERONET retrieval (O. Dubovik and M. King, 2000; O. Dubovik 2004)

Two scenarios of retrieval (***Dubovik et al., AMT, 2011***):

- Conventional: single-pixel retrieval (each single pixel are inverted independently)
- New concept: multiple-pixel retrieval (group of pixels are inverted simultaneously)

Numerical inversion module. 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)

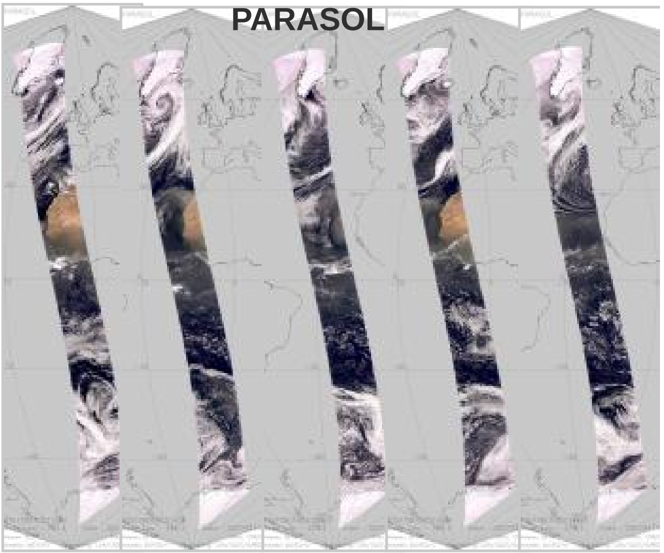
a_j - Parameters to be retrieved:

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

-***Surface*** properties (***over land***):
- BRDF parameters; - BPDF parameters

!!!

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



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;

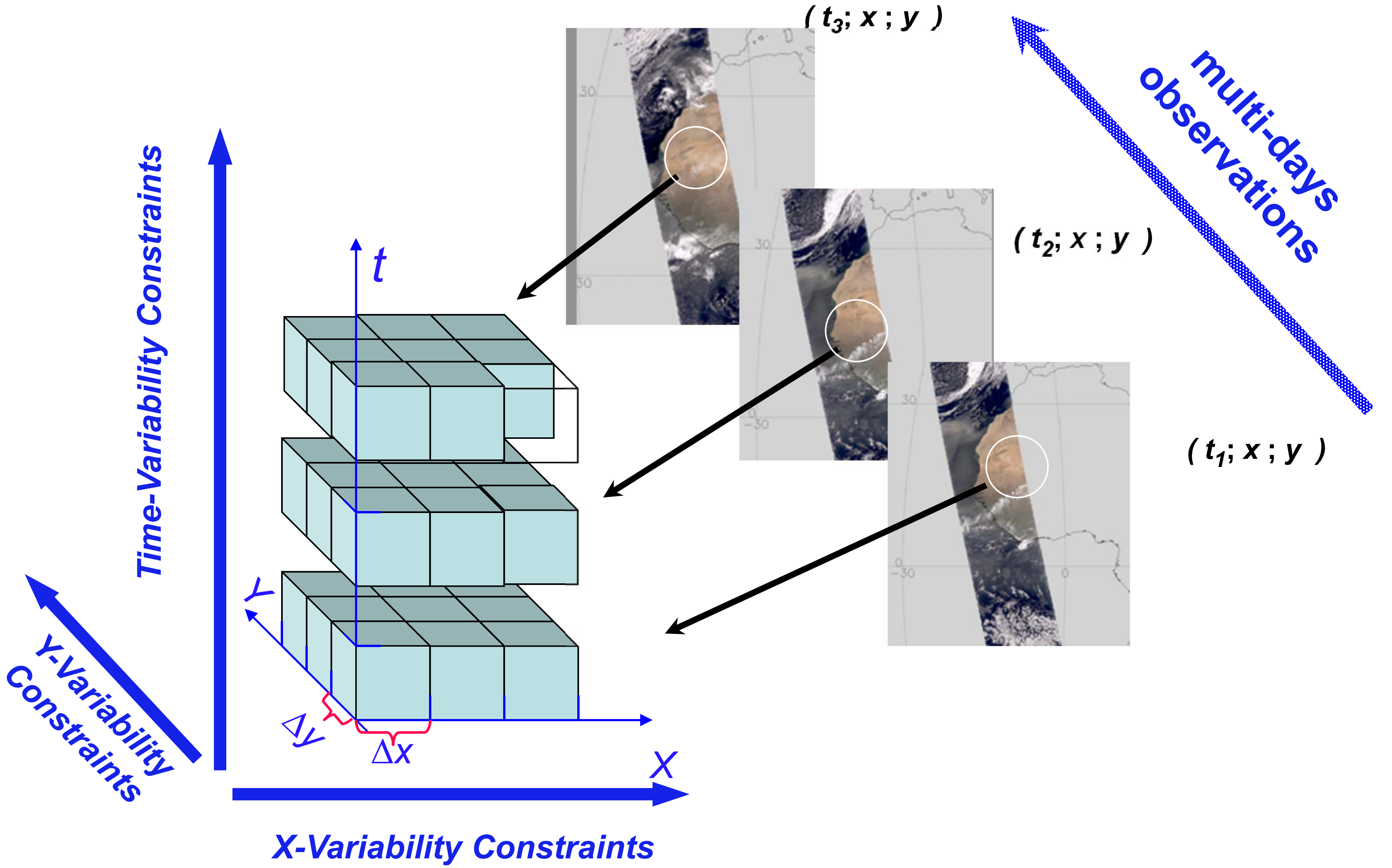
- for surface (e.g. in AERONET/satellite retrievals, *Sinuyk et al. 2007)* **:**
- spectral variability of BRDF/ PBDF parameters.

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

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

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

Numerical inversion module. The concept of multi-pixel retrieval



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Numerical inversion module. Multi - Pixel Retrieval:

$$\begin{cases} \begin{pmatrix} \mathbf{f}_1^* \\ O_1^* \end{pmatrix} \\ \begin{pmatrix} \mathbf{f}_2^* \\ O_2^* \end{pmatrix} \\ \begin{pmatrix} \mathbf{f}_3^* \\ O_3^* \end{pmatrix} \\ \dots \\ O_t^* \\ O_x^* \\ O_y^* \end{cases} = \begin{pmatrix} \begin{pmatrix} \mathbf{F}_1 \\ \mathbf{D}_1 \end{pmatrix} & \begin{matrix} 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} \\ \begin{matrix} 0 \\ 0 \end{matrix} & \begin{pmatrix} \mathbf{F}_2 \\ \mathbf{D}_2 \end{pmatrix} & \begin{matrix} 0 \\ 0 \end{matrix} \\ \begin{matrix} 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \end{matrix} & \begin{pmatrix} \mathbf{F}_3 \\ \mathbf{D}_3 \end{pmatrix} \\ \dots & \dots & \dots \\ \mathbf{D}_{t,1} & \mathbf{D}_{t,2} & \mathbf{D}_{t,2} \\ \mathbf{D}_{x,1} & \mathbf{D}_{x,2} & \mathbf{D}_{x,3} \\ \mathbf{D}_{y,1} & \mathbf{D}_{y,2} & \mathbf{D}_{y,3} \end{pmatrix} \begin{pmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} + \begin{pmatrix} \begin{pmatrix} \Delta_1^m \\ \Delta_1^a \end{pmatrix} \\ \begin{pmatrix} \Delta_2^m \\ \Delta_2^a \end{pmatrix} \\ \begin{pmatrix} \Delta_3^m \\ \Delta_3^a \end{pmatrix} \\ \dots \\ \Delta_t^a \\ \Delta_x^a \\ \Delta_y^a \end{pmatrix}$$

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:***

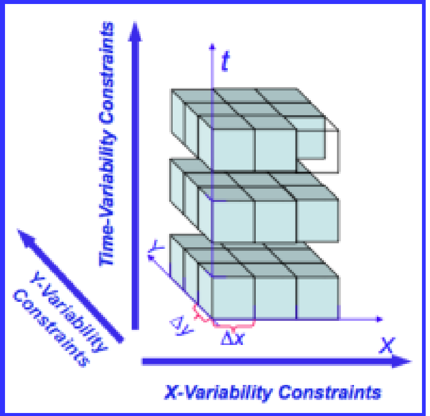
$$\begin{pmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} = \left[\begin{pmatrix} \mathbf{F}_1^T \mathbf{W}_1^{-1} \mathbf{F}_1 & 0 & 0 \\ 0 & \mathbf{F}_2^T \mathbf{W}_2^{-1} \mathbf{F}_2 & 0 \\ 0 & 0 & \mathbf{F}_3^T \mathbf{W}_3^{-1} \mathbf{F}_3 \end{pmatrix} + \begin{pmatrix}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

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

Algorithm testing. LOA synthetic data

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:

- *RPV BRDF (3 parameters for each λ);*
- *BPDF (1 parameter for each λ)*

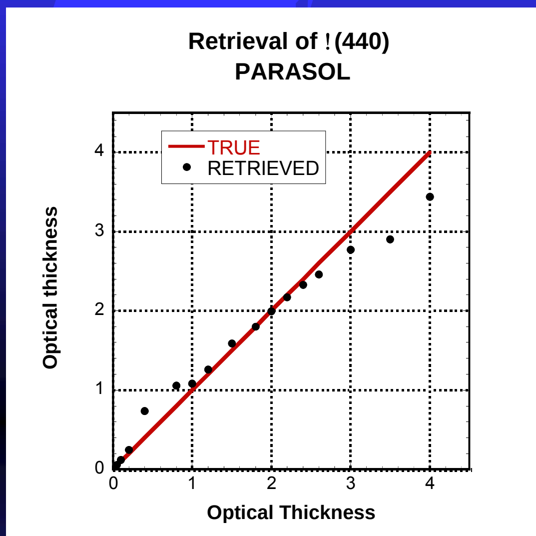
SPATIAL – TEMPORAL:

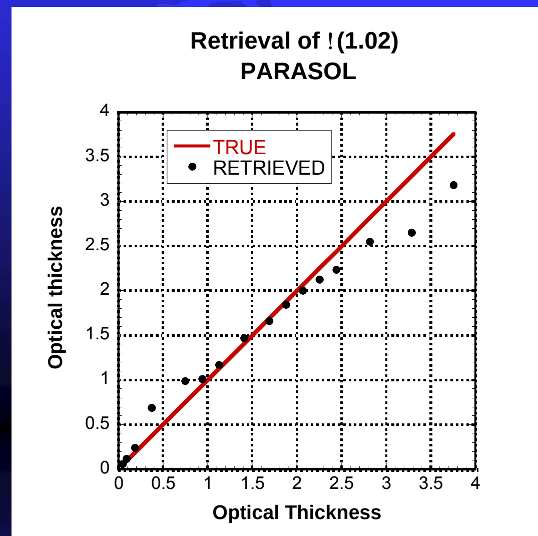
- *4 pixels for each of 4 days*

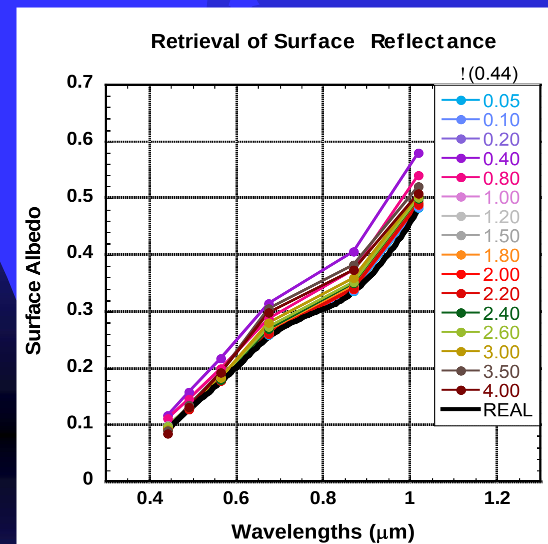
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

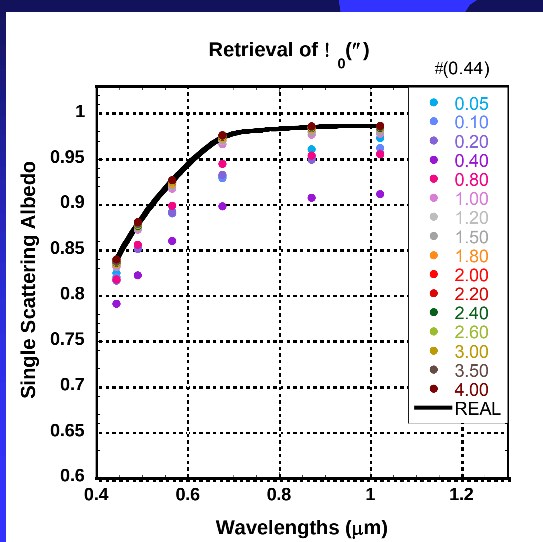
NO NOISE ADDED !!! (minor noise is always present)

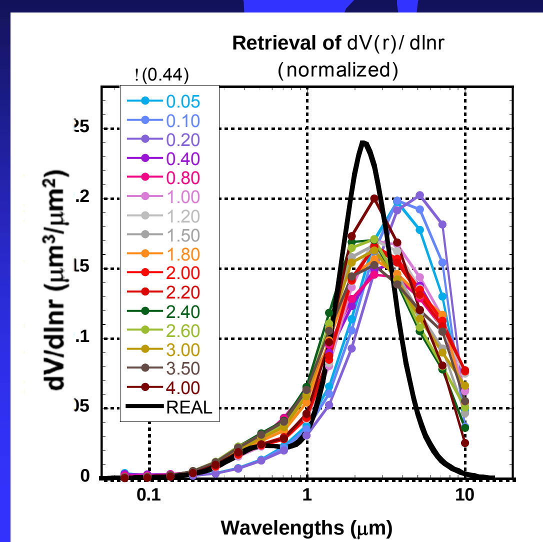
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

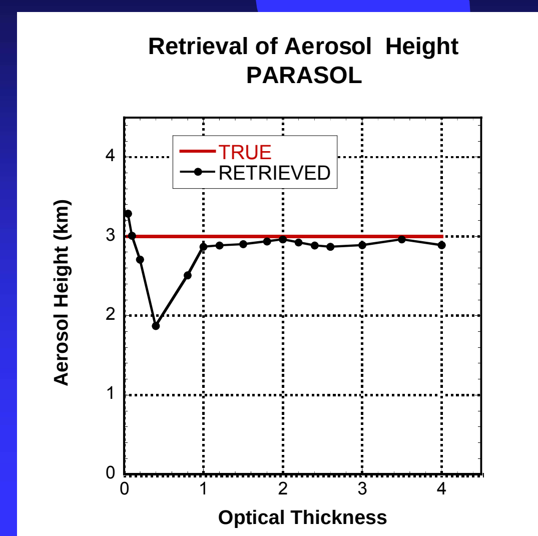








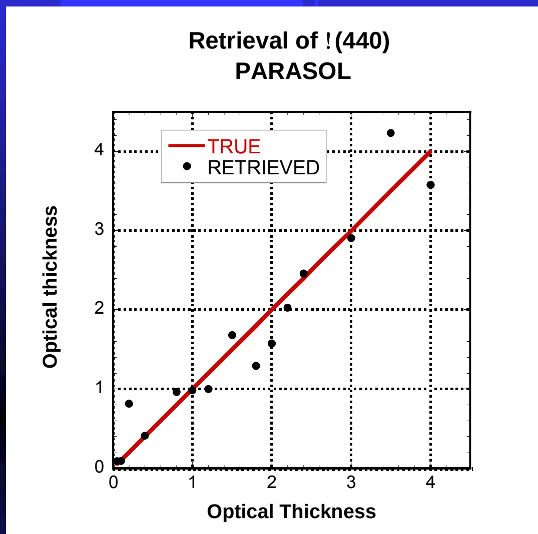


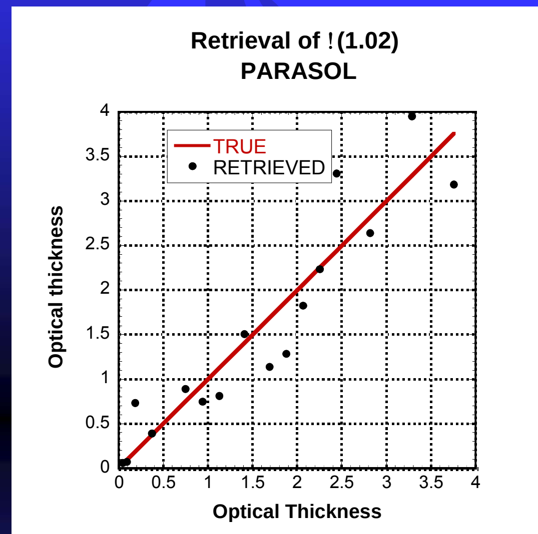


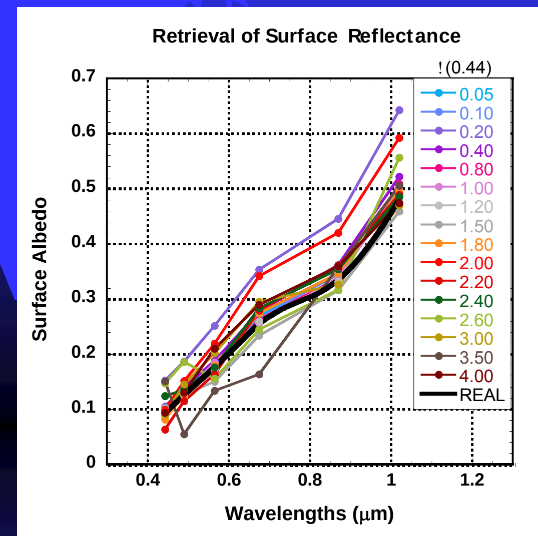
***PARASOL:** 0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

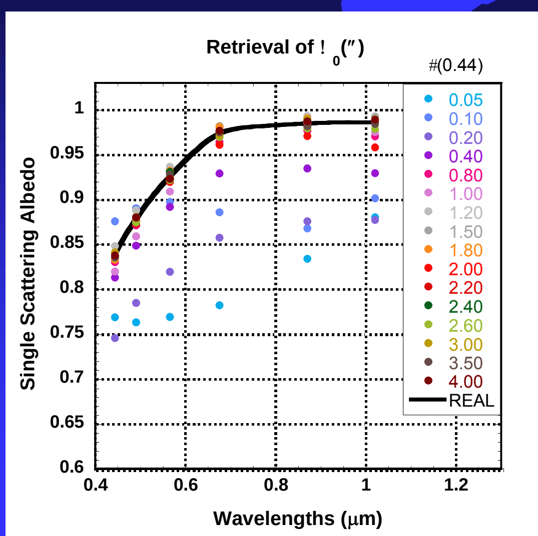
NOISE ADDED: 1% for $I(\lambda)$, 0.005 for $Q(\lambda)/I(\lambda)$ and $U(\lambda)/I(\lambda)$!!!

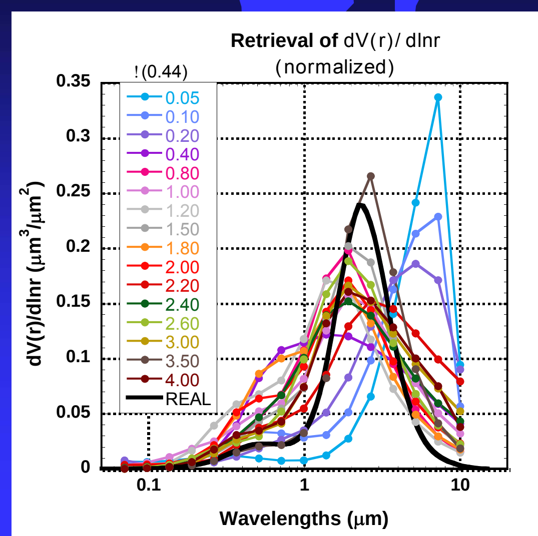
Single-Pixel Retrieval, Desert Dust aerosol (non-spherical!!!)

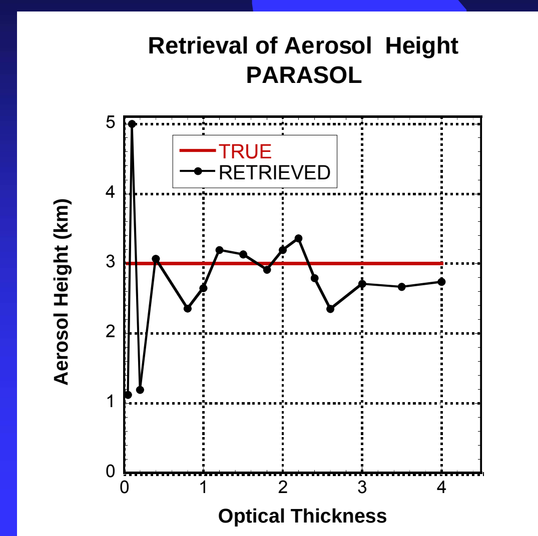












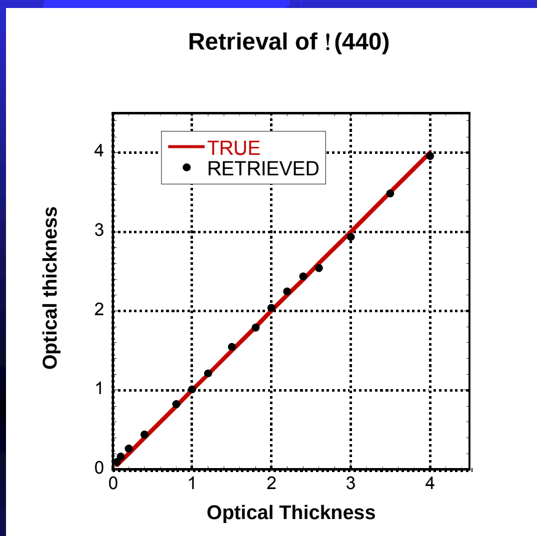
PARASOL: *0.44, 0.49 (p+), 0.565, 0.675 (p+), 0.87(p+), 1.02 μm*

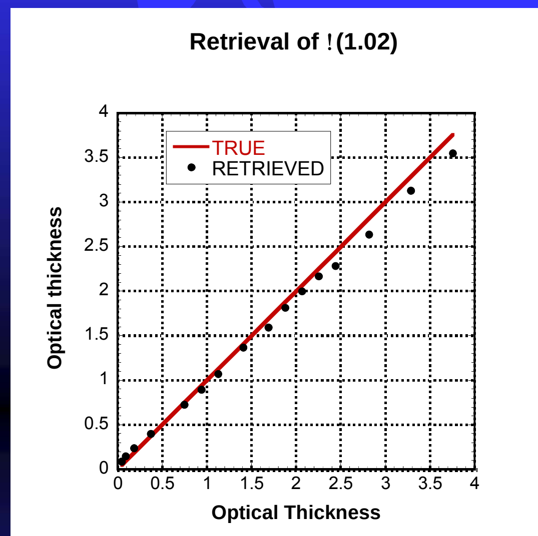
NOISE ADDED: 1% for I(λ), 0.5% for Q(λ)/I(λ) and U(λ)/I(λ) !!!

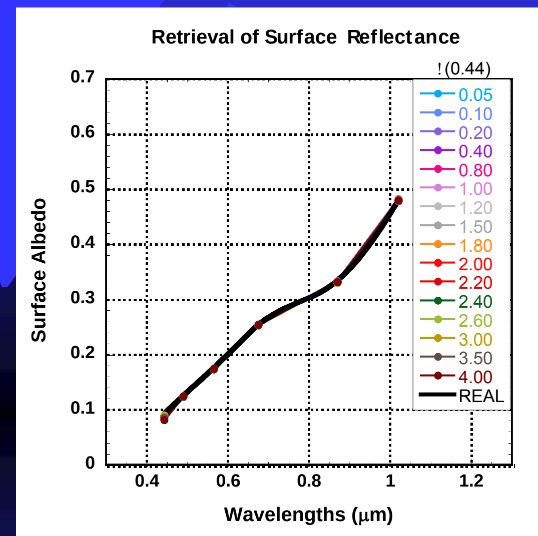
Multi-Pixel Retrieval (i.e. temporal and spatial variability of surface and aerosol is limited)

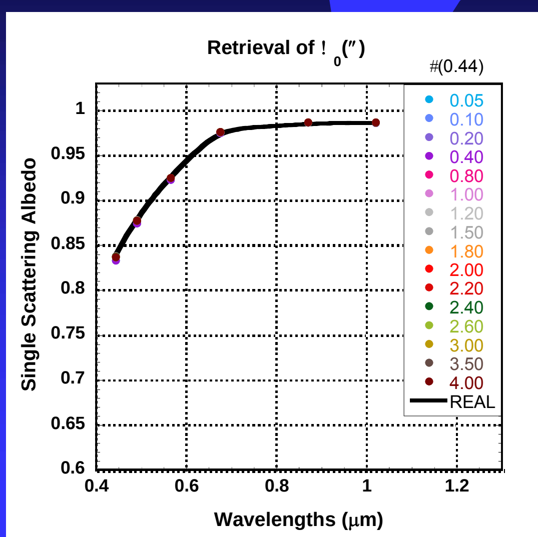
Desert Dust aerosol (non-spherical!!!)

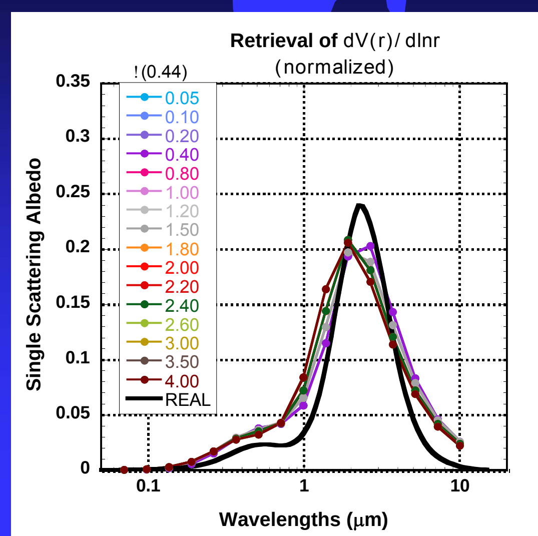
Dubovik et al.
AMT, 2011

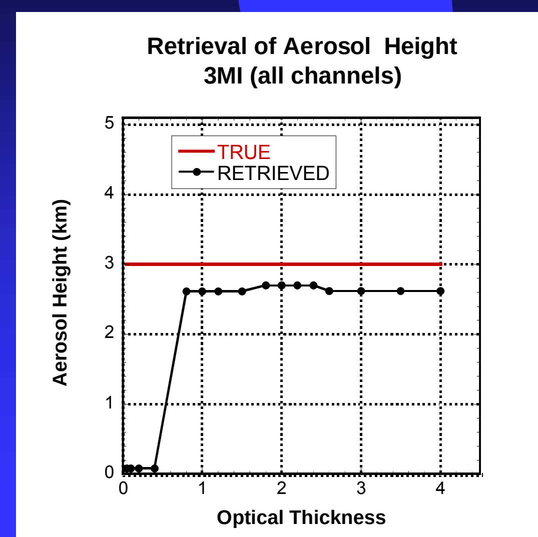




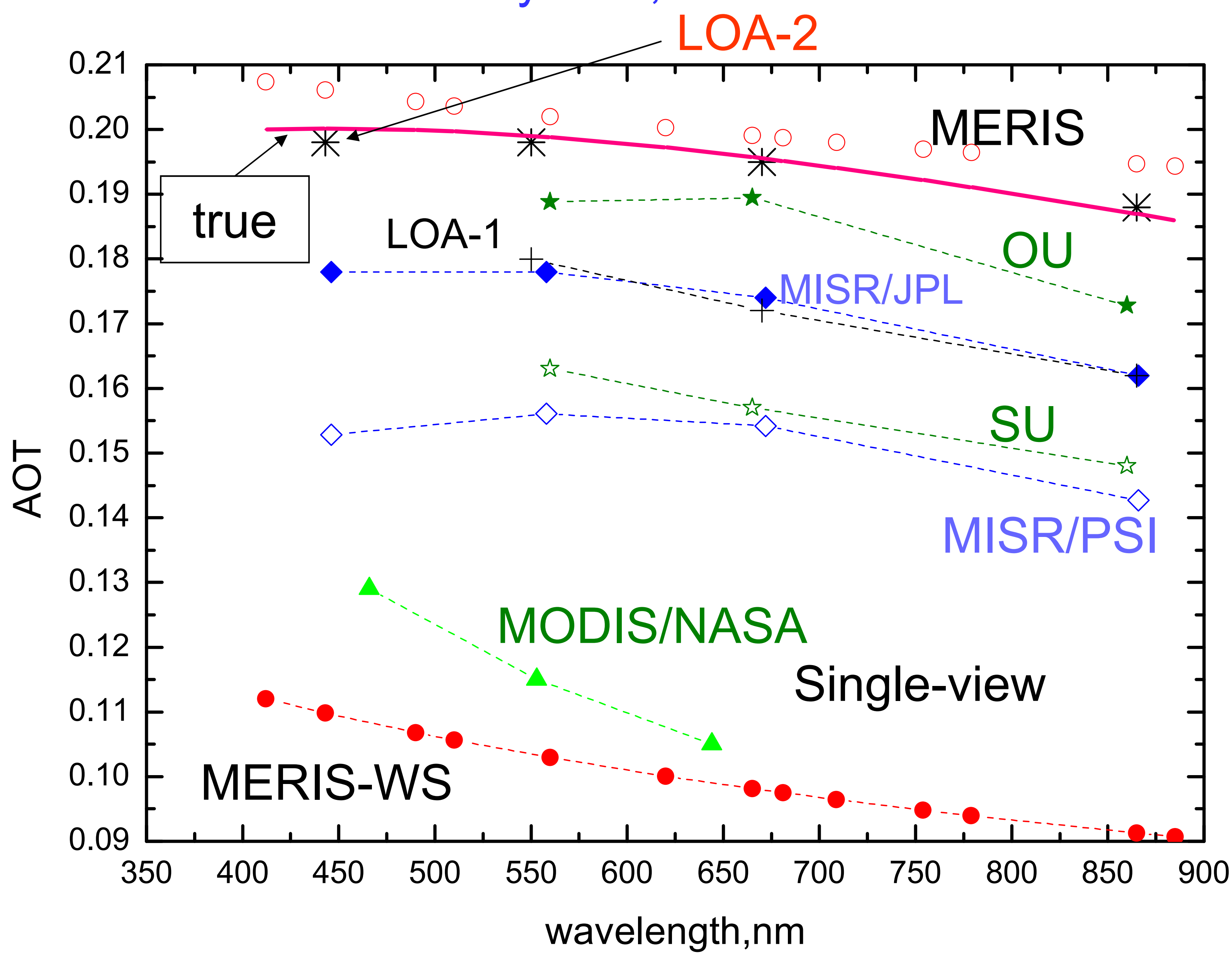








A.Kokhanovsky et al, 2010. "Blind tests"

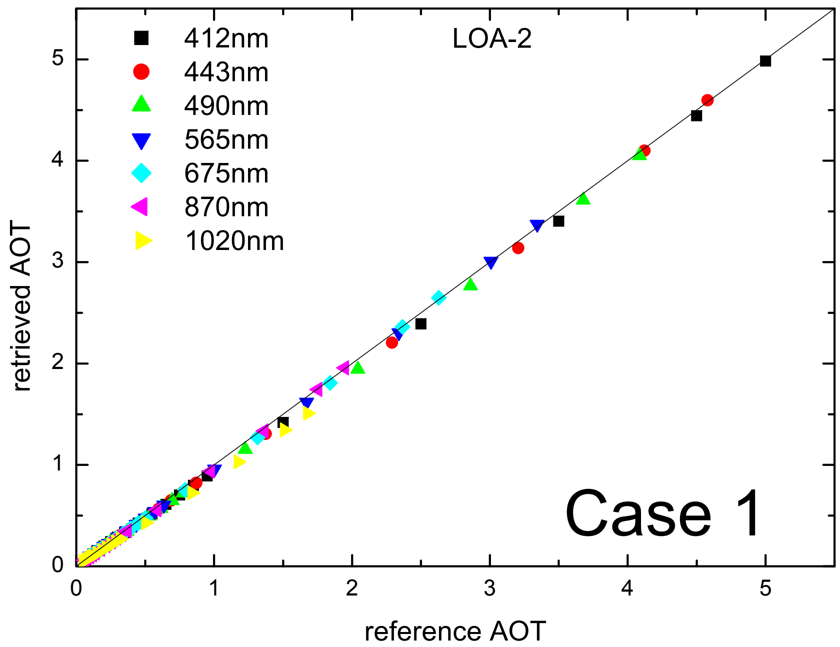


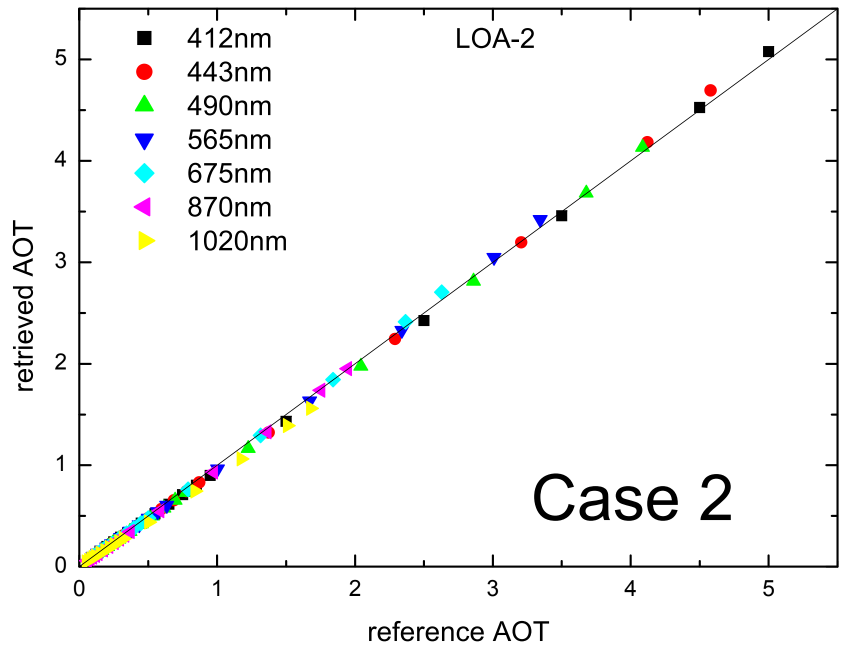
Black underlying surface

AOT(412)=0.2

Algorithm testing. Synthetic case studies, A.Kokhanovsky, 2012 CCI project “Climate ESA Retrieval of Aerosols”

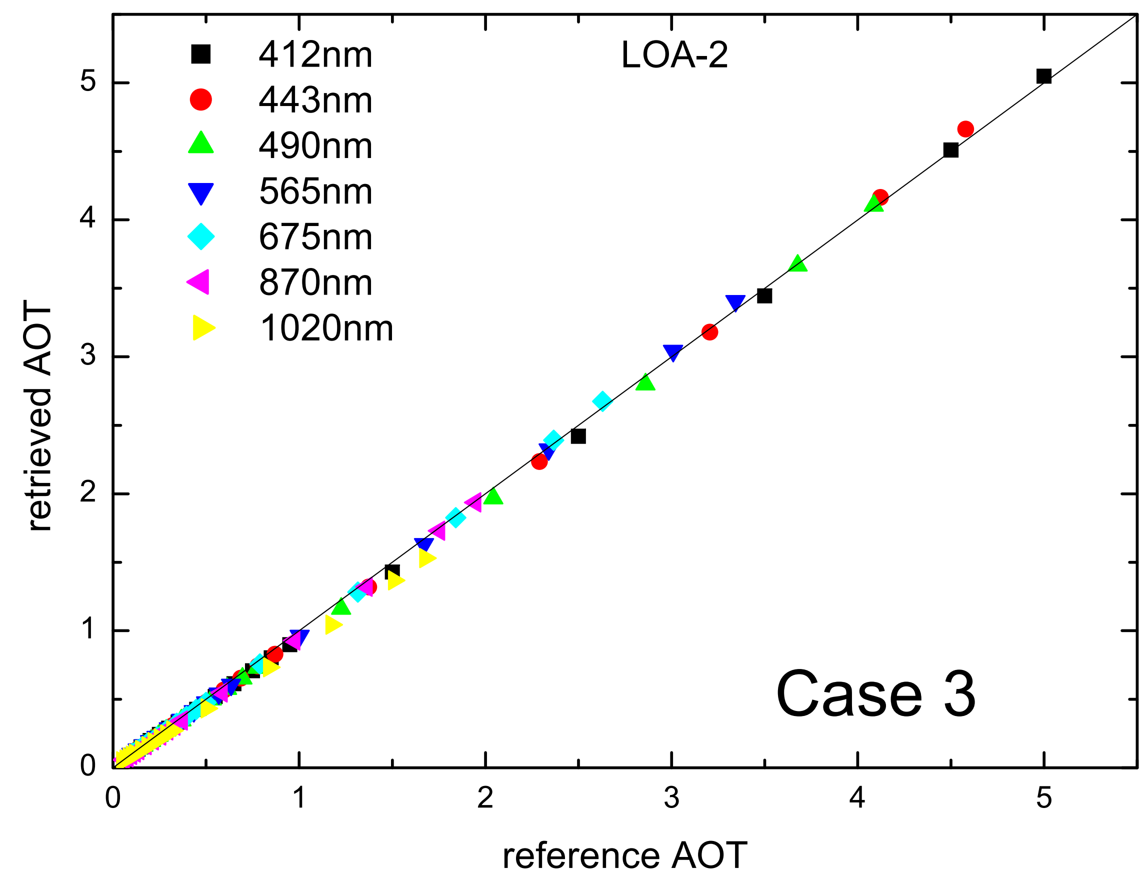
POLDER: LOA-2(Dubovik) algorithm (BRDF)





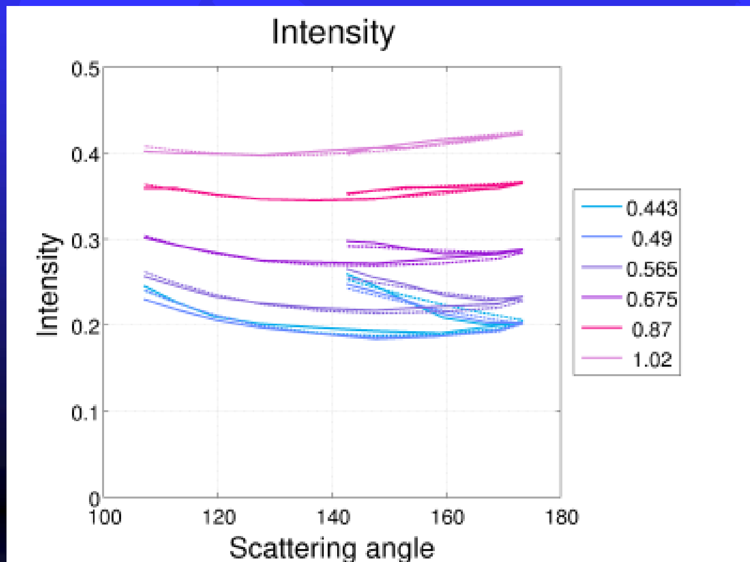
Algorithm testing. Synthetic case studies, A.Kokhanovsky, 2012 CCI project "Climate ESA Retrieval of Aerosols"

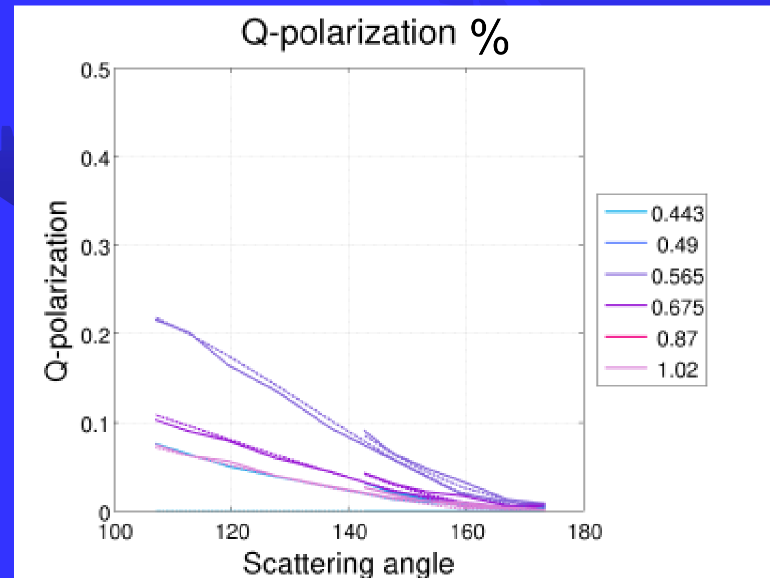
POLDER: LOA-2(Dubovik) algorithm (BRDF)

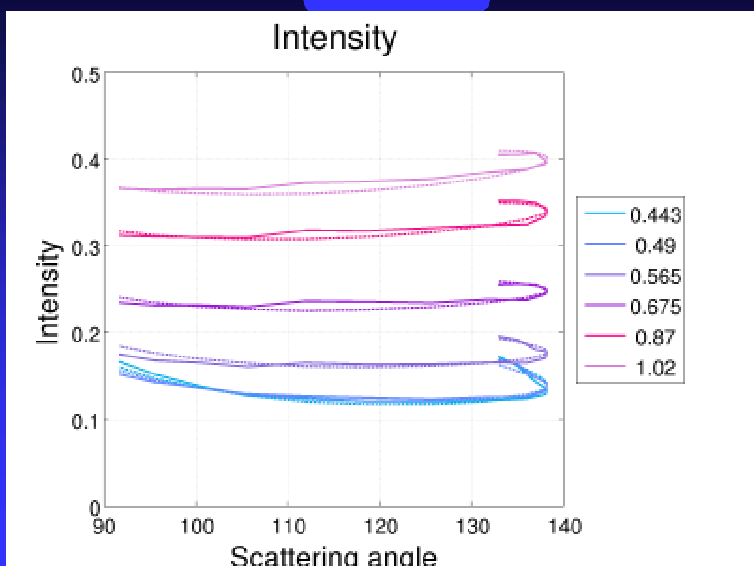


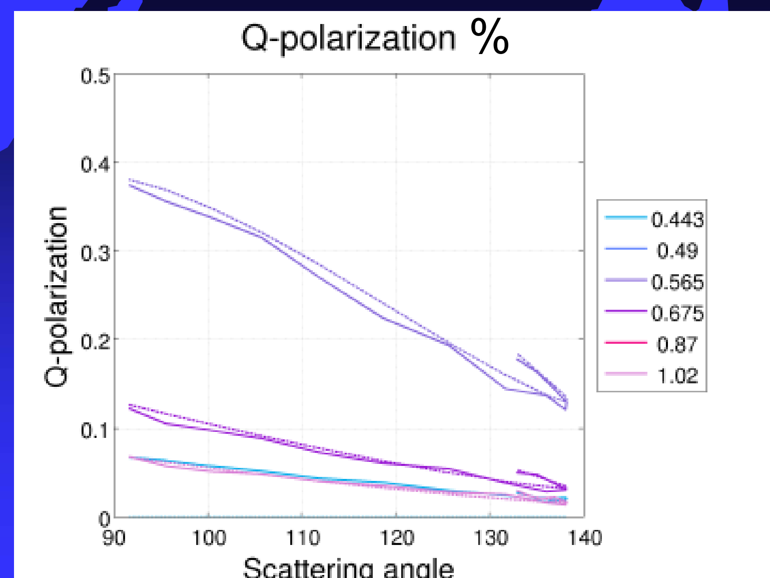
Application to the POLDER/PARASOL data

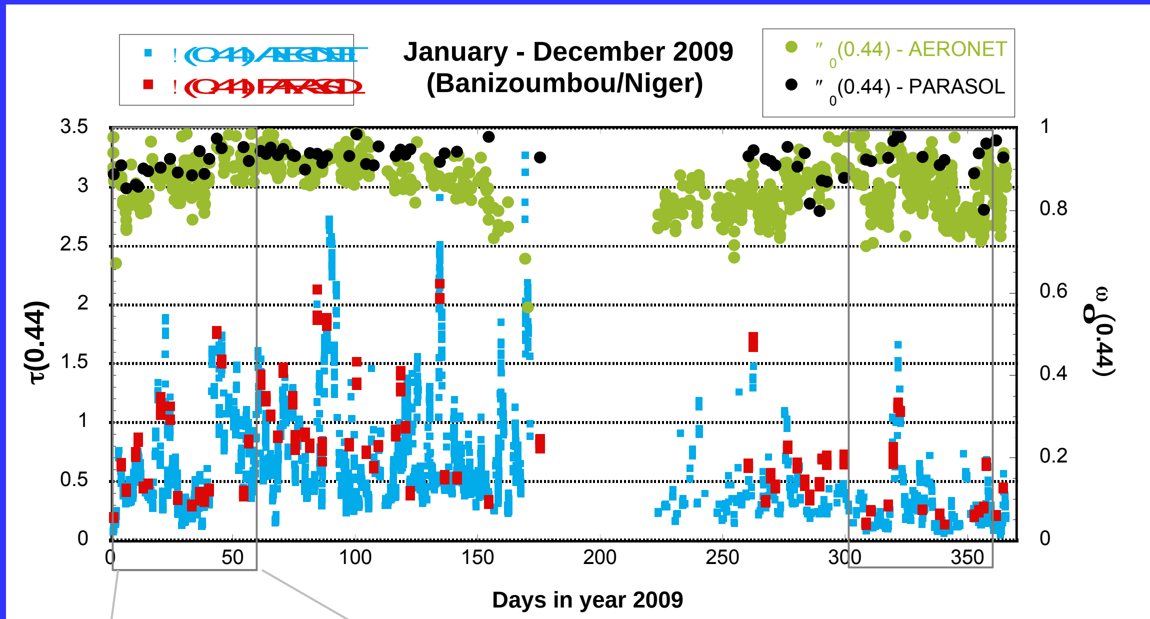
Dust and biomass
Banizoumbu/Niger

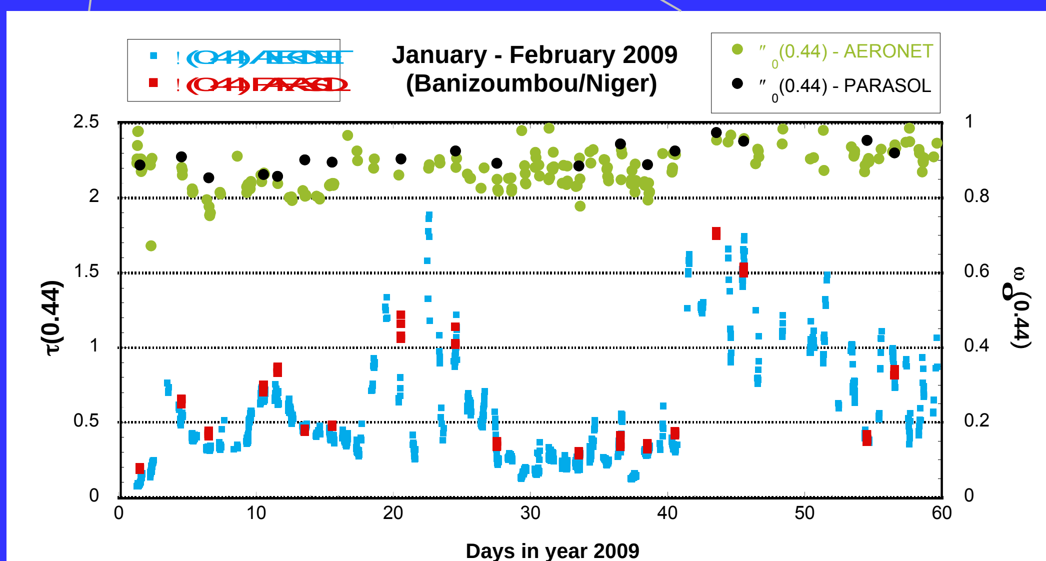












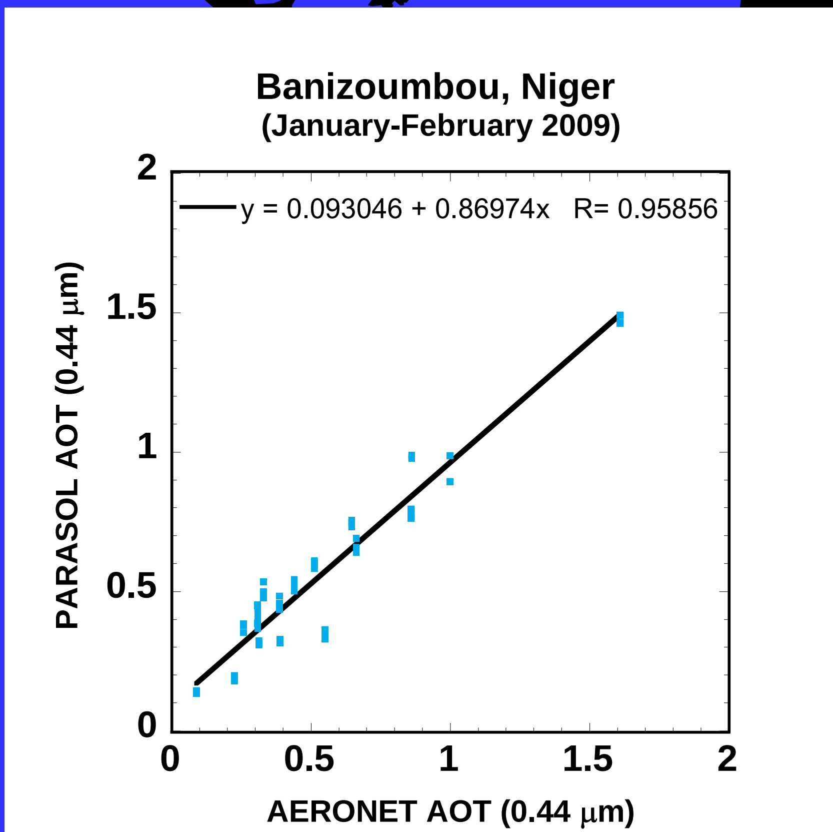
Banizoumbou
NIGER

Application to the POLDER/PARASOL data

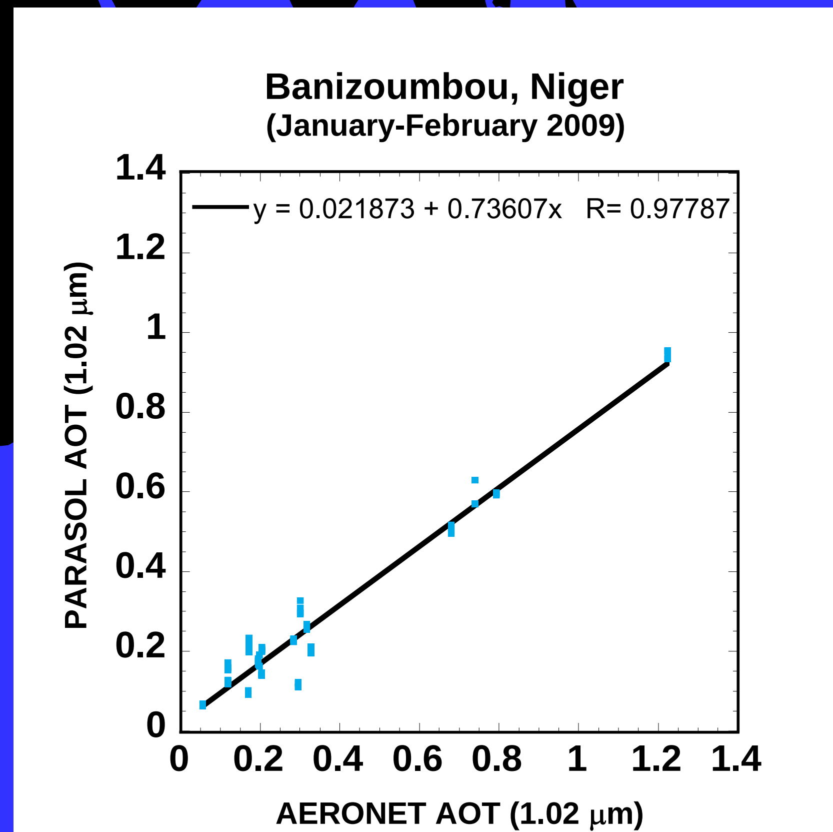
Optical Thickness

PARASOL versus AERONET

0.44 µm



1.02 µm

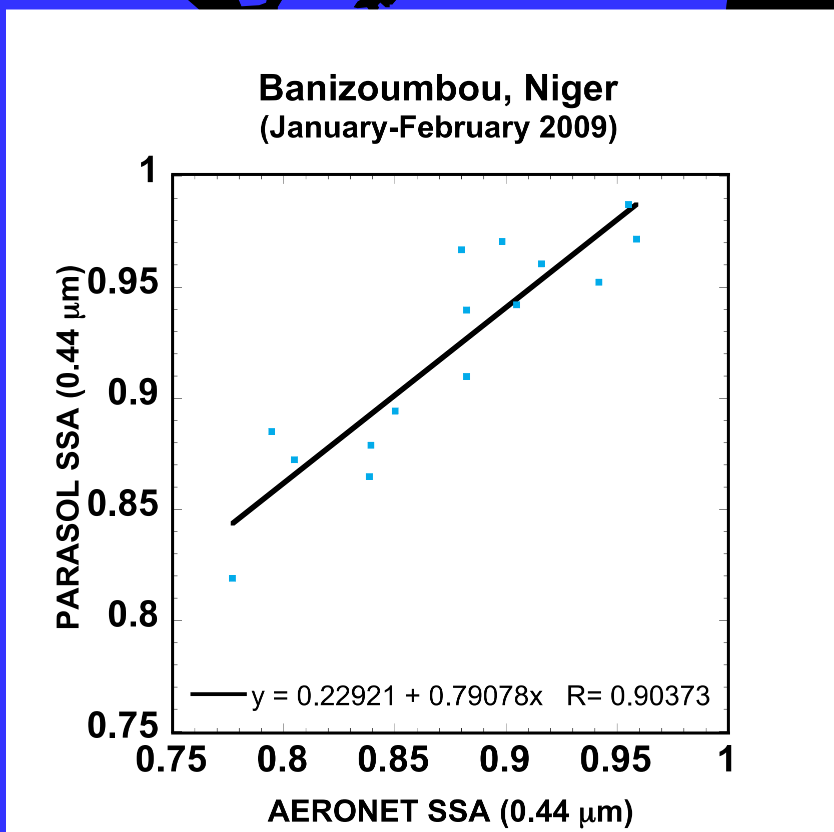


Application to the POLDER/PARASOL data

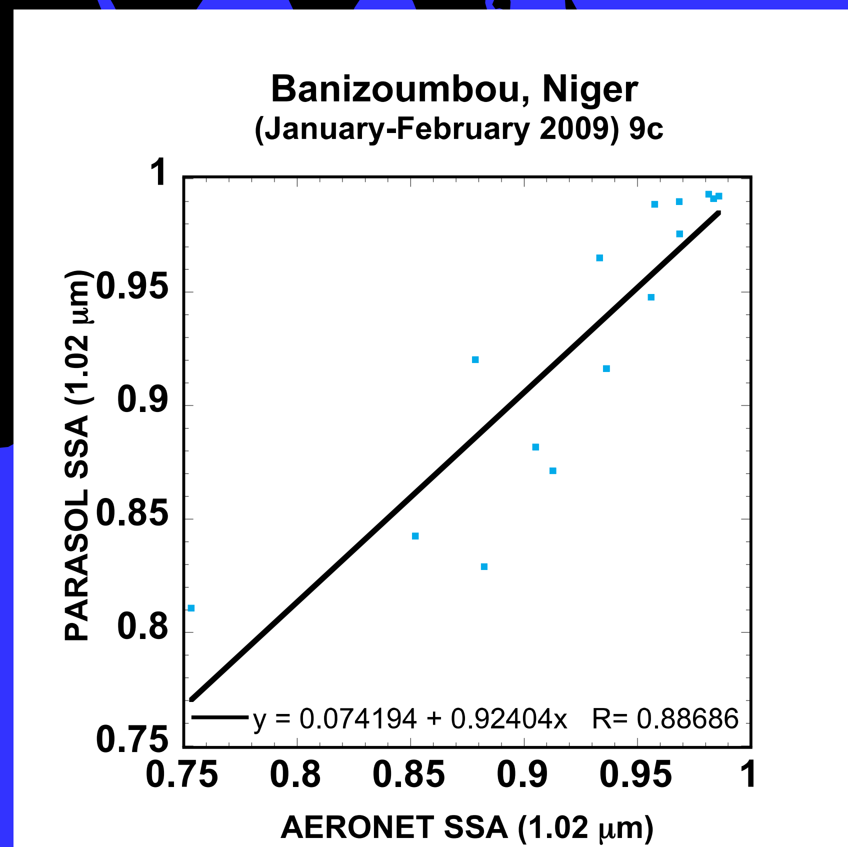
Single Scattering Albedo

PARASOL versus AERONET

0.44 µm

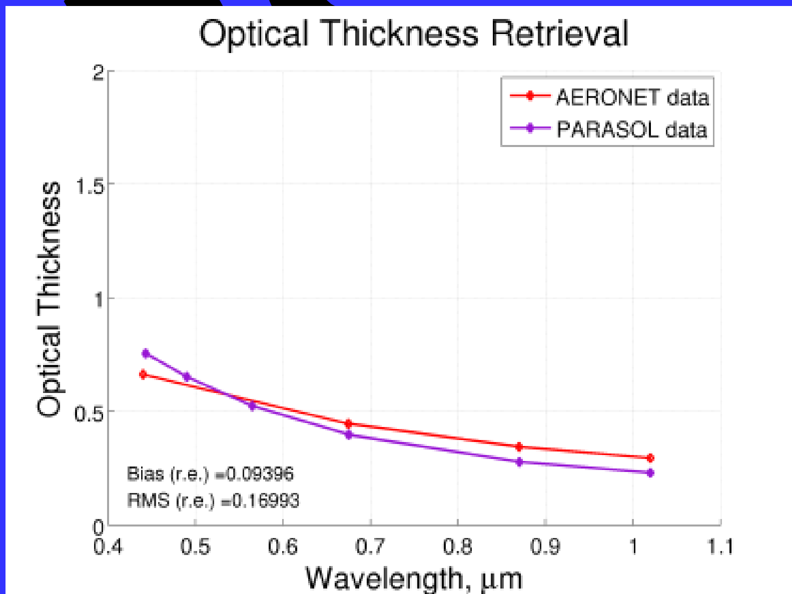


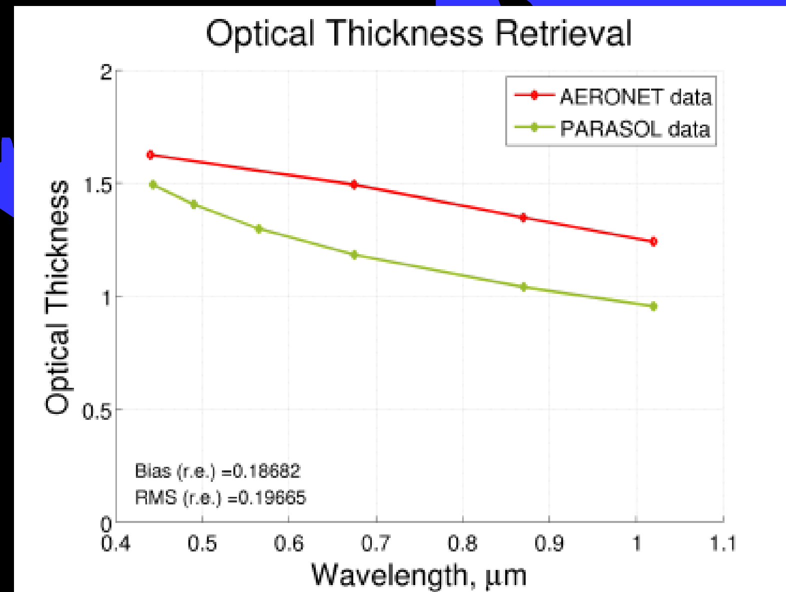
1.02 µm

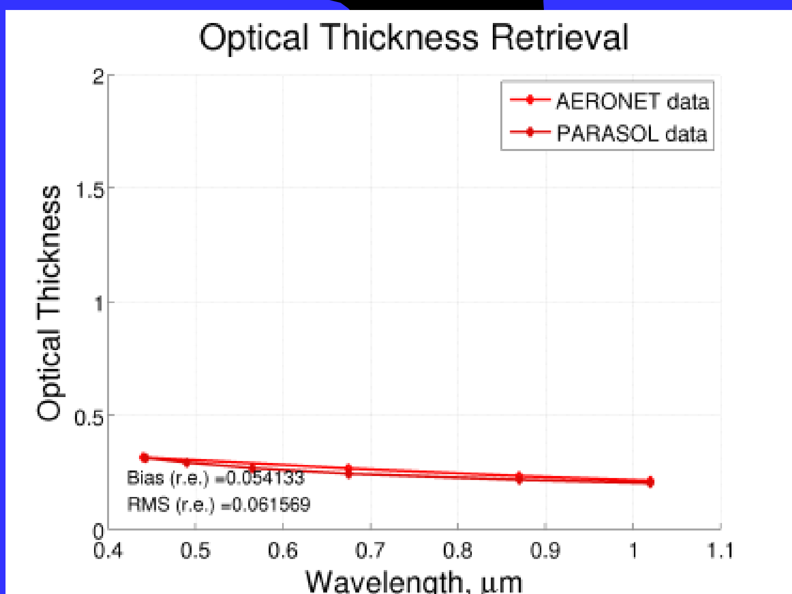


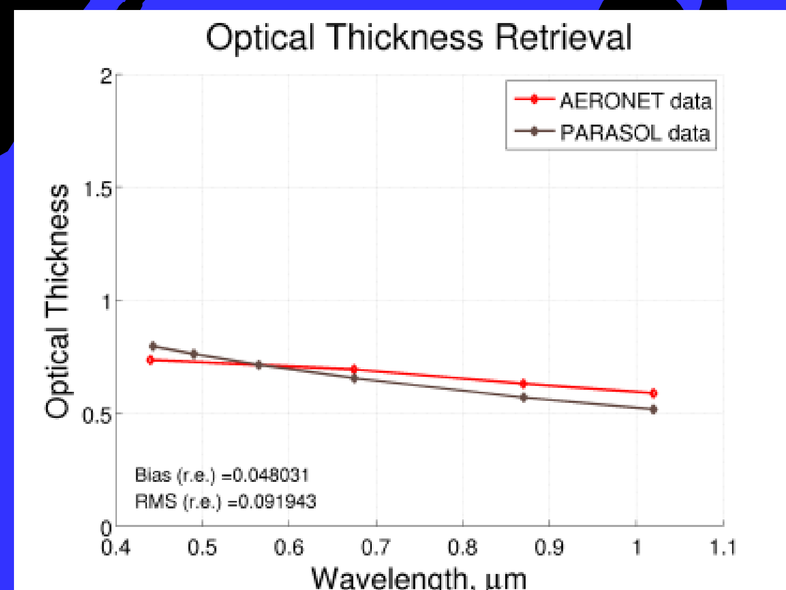
PARASOL versus AERONET

Dust and biomass
Banizoumbu/Niger



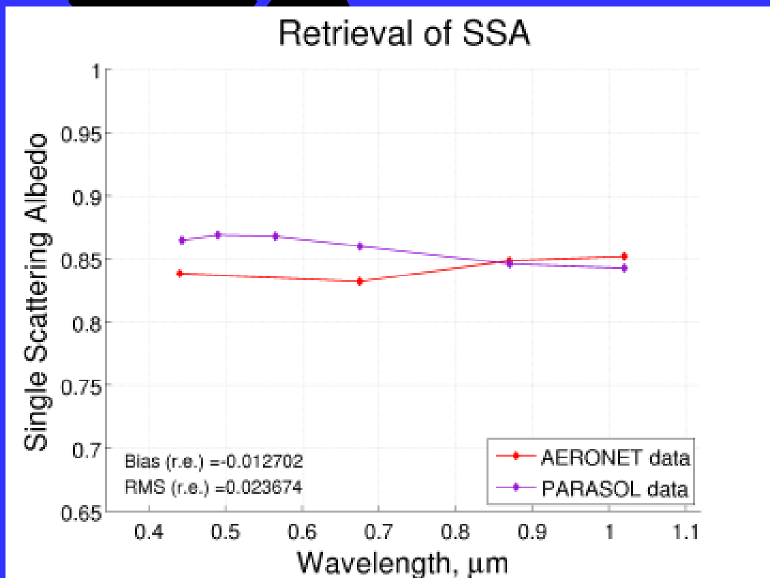


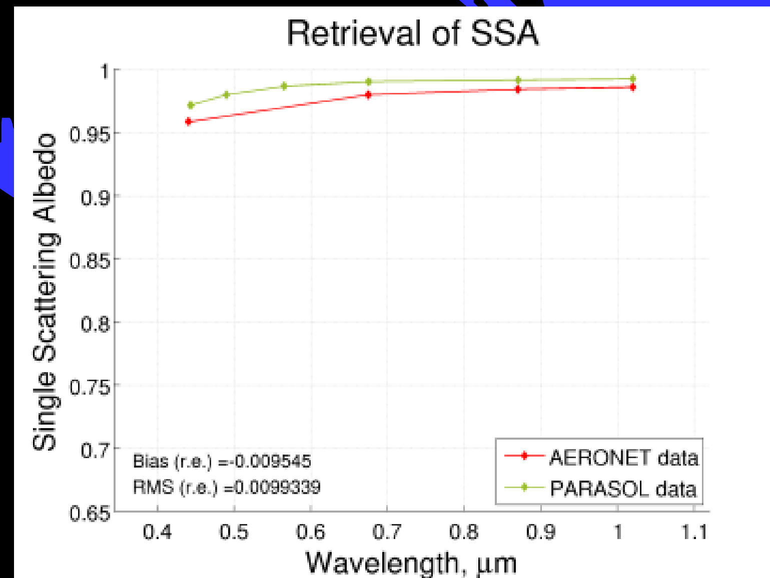


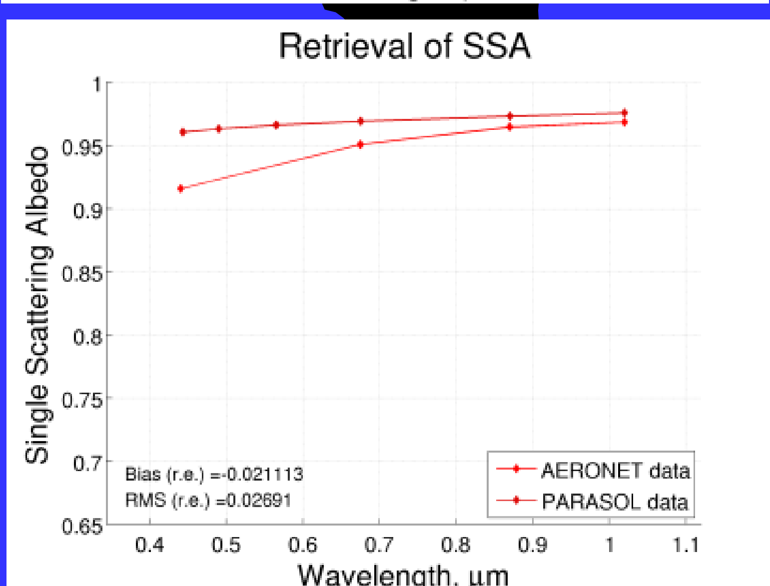


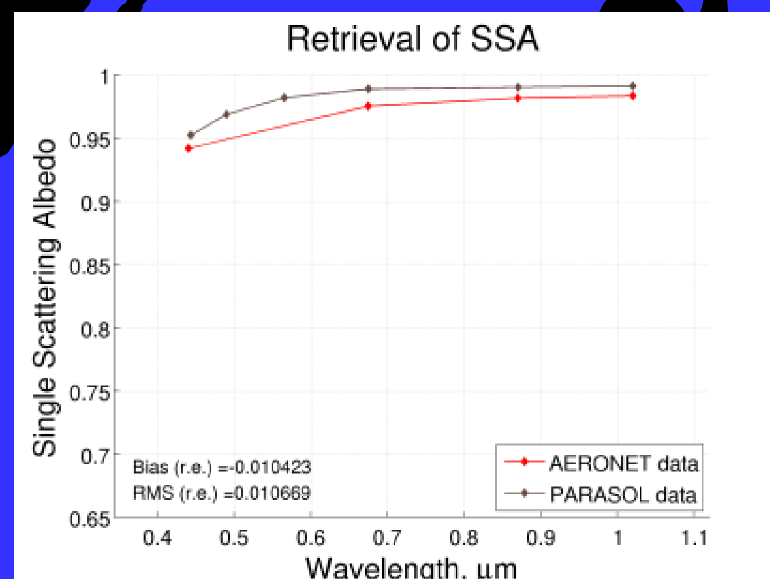
PARASOL versus AERONET

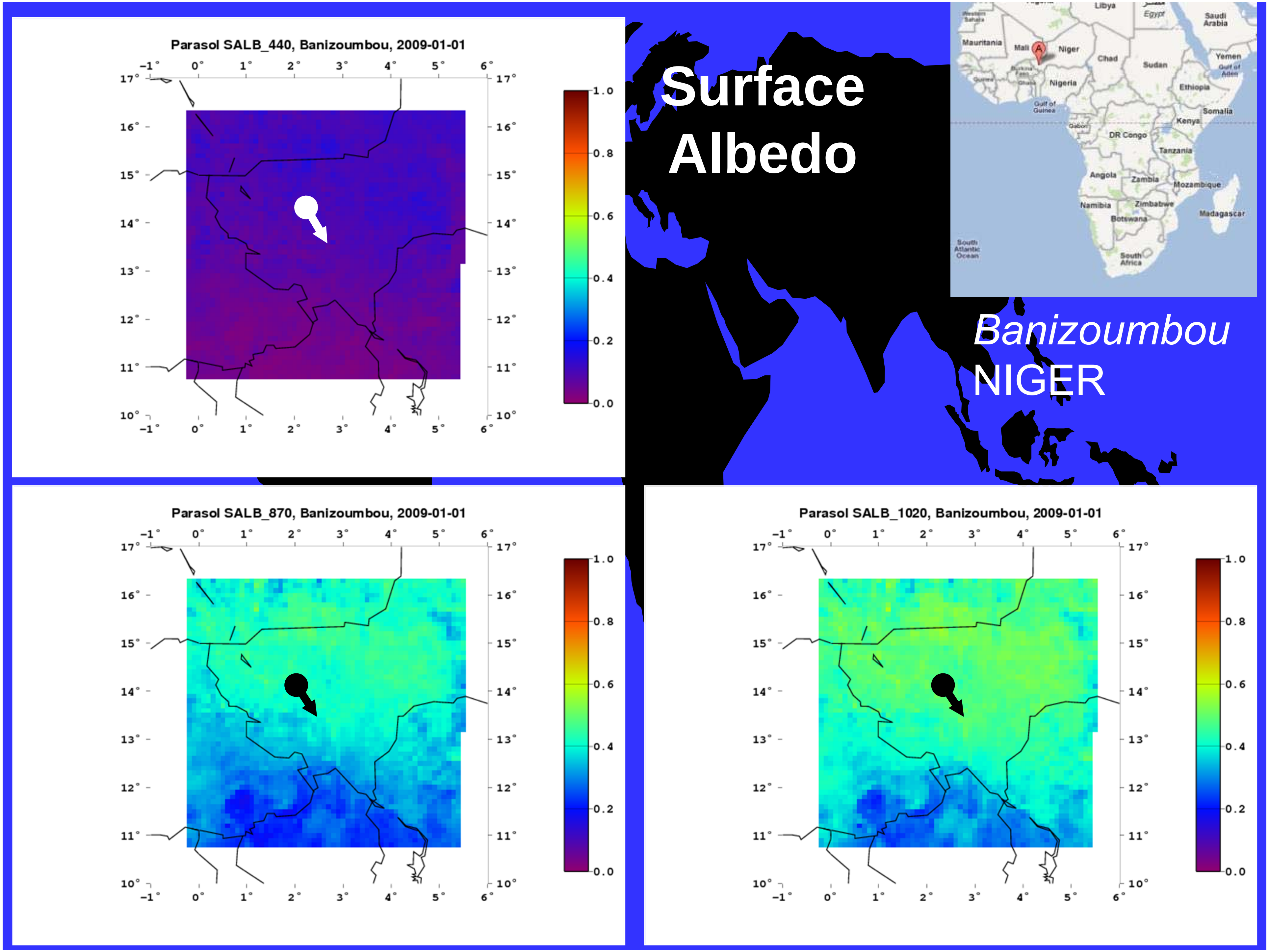
Dust and biomass
Banizoumbu/Niger





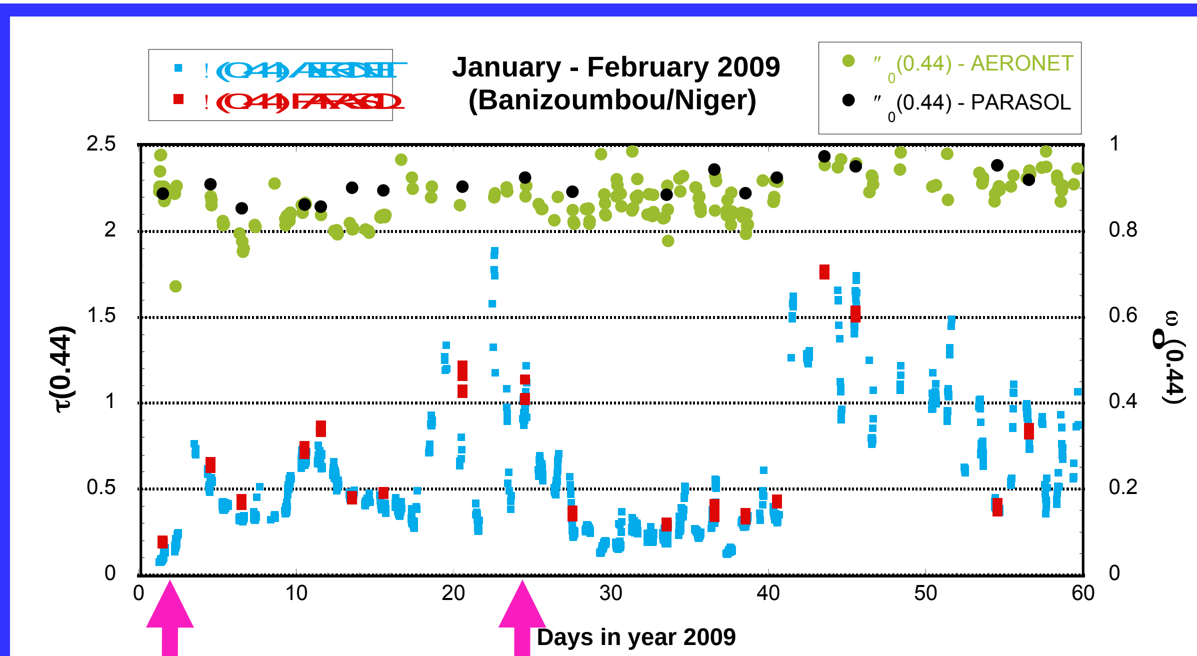


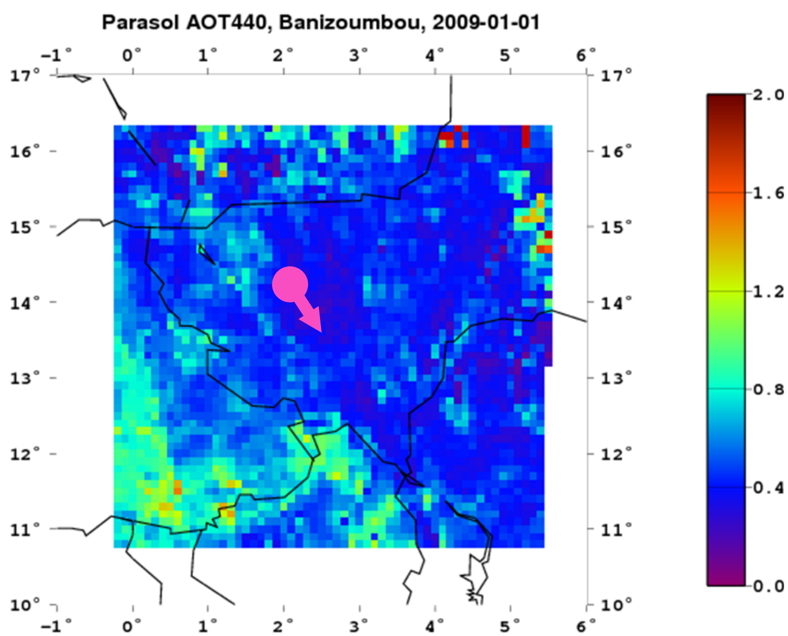


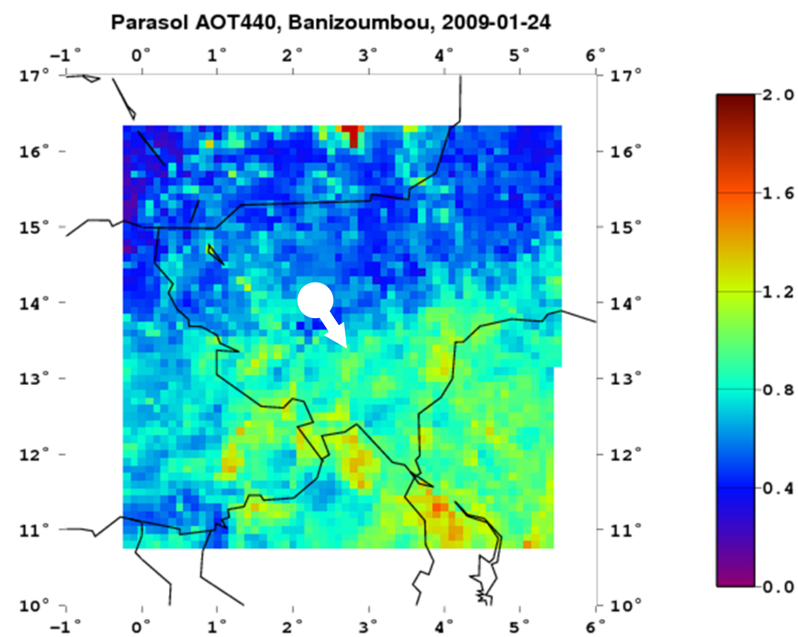

Surface Albedo
Parasol SALB_440, Banizoumbou, 2009-01-01
Parasol SALB_870, Banizoumbou, 2009-01-01
Parasol SALB_1020, Banizoumbou, 2009-01-01
−1° 0° 1° 2° 3° 4° 5° 6°
10° 11° 12° 13° 14° 15° 16° 17°
0.0 0.2 0.4 0.6 0.8 1.0
Libya
Egypt
Saudi Arabia
Mauritania
Mali
Niger
Chad
Sudan
Yemen
Nigeria
Ethiopia
Somalia
Kenya
DR Congo
Tanzania
Angola
Zambia
Mozambique
Namibia
Zimbabwe
Botswana
Madagascar
South Africa
Banizoumbou
NIGER

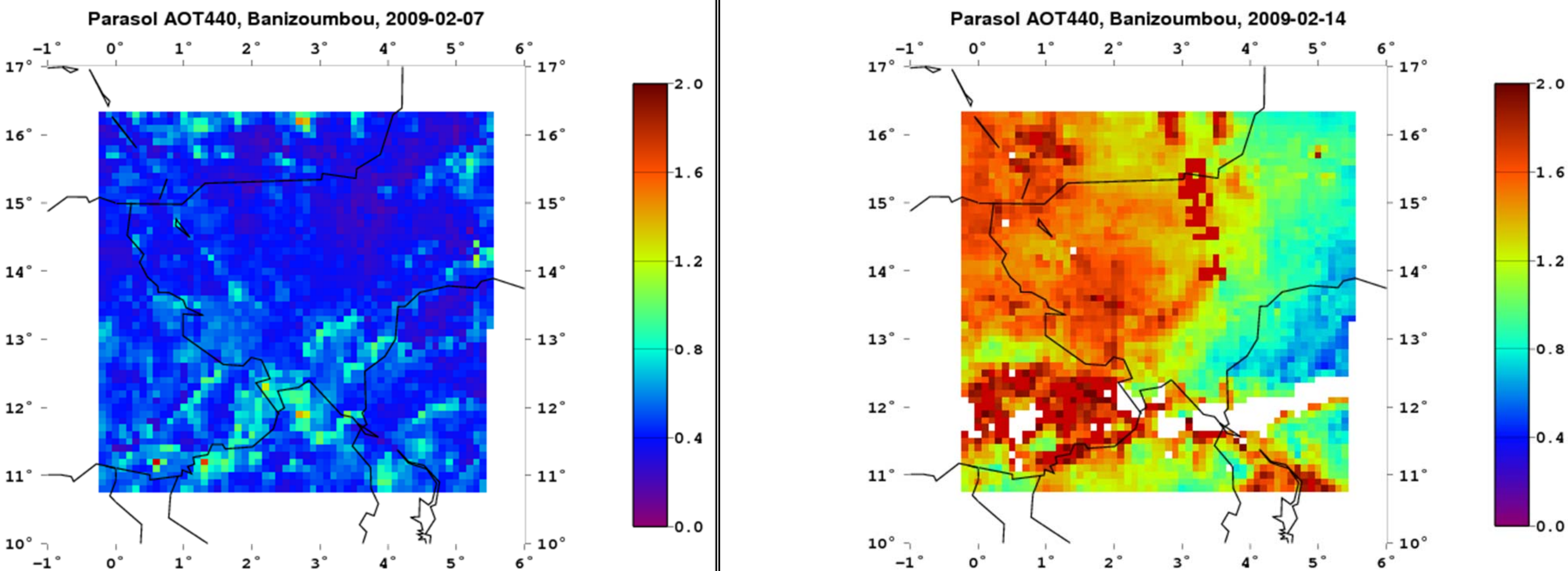
Banizoumbou

NIGER

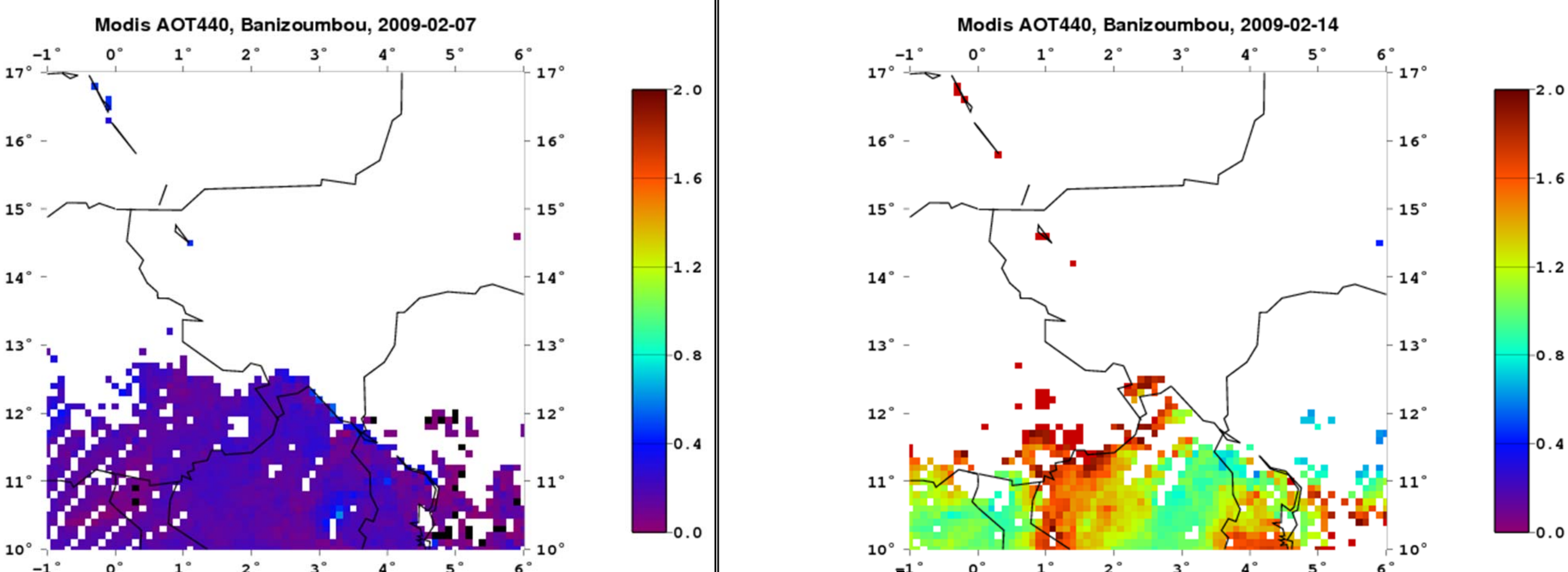






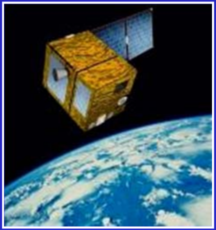


New PARASOL algorithm



MODIS (dark target)

Described in Dubovik et al., AMT, 2011



Algorithm Status:

1. Core Algorithm is developed and performs well:

- **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)**
- **can be applied for other satellites/instruments**
- **can use data from other satellite/inmessagestruments (CALIPSO, MODIS, AERONET etc)**

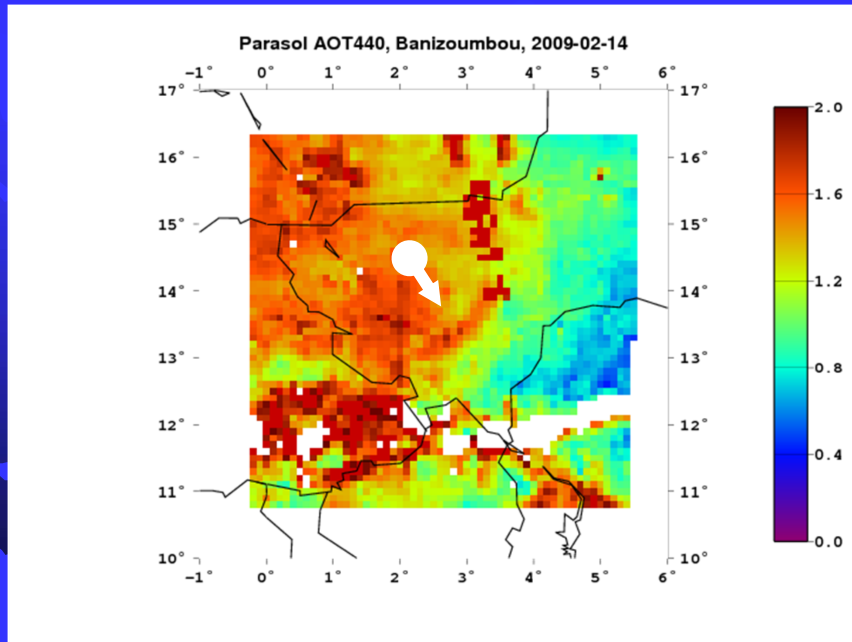
2. Issues:

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

Main Objective:

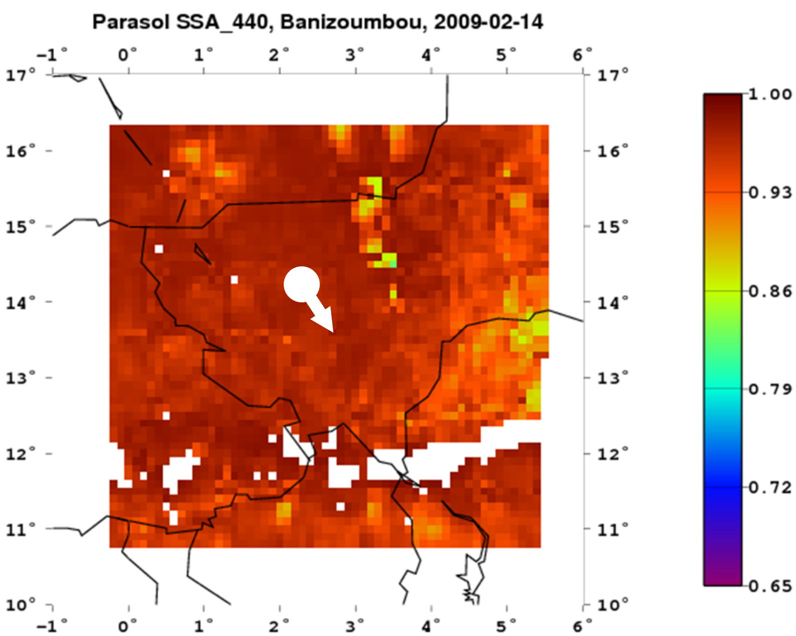
to make algorithm practical

$\tau(0.44)$

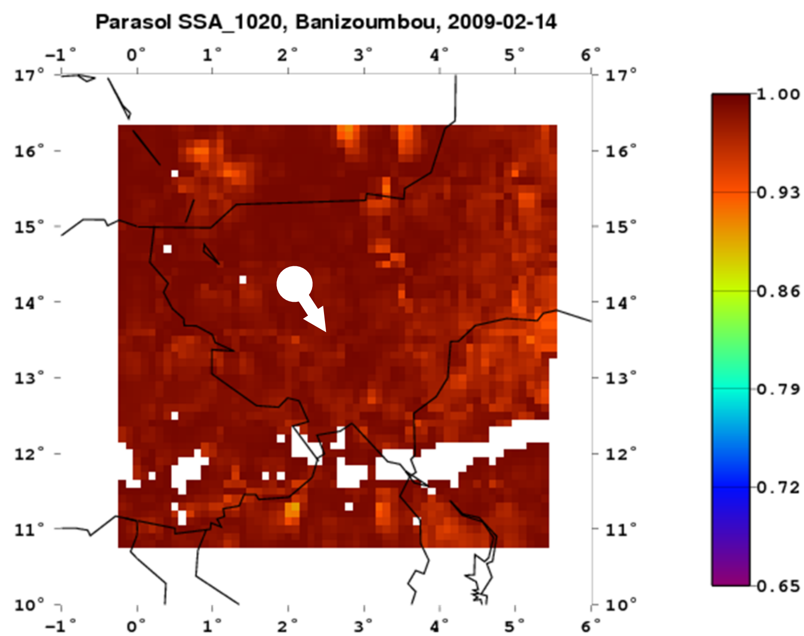


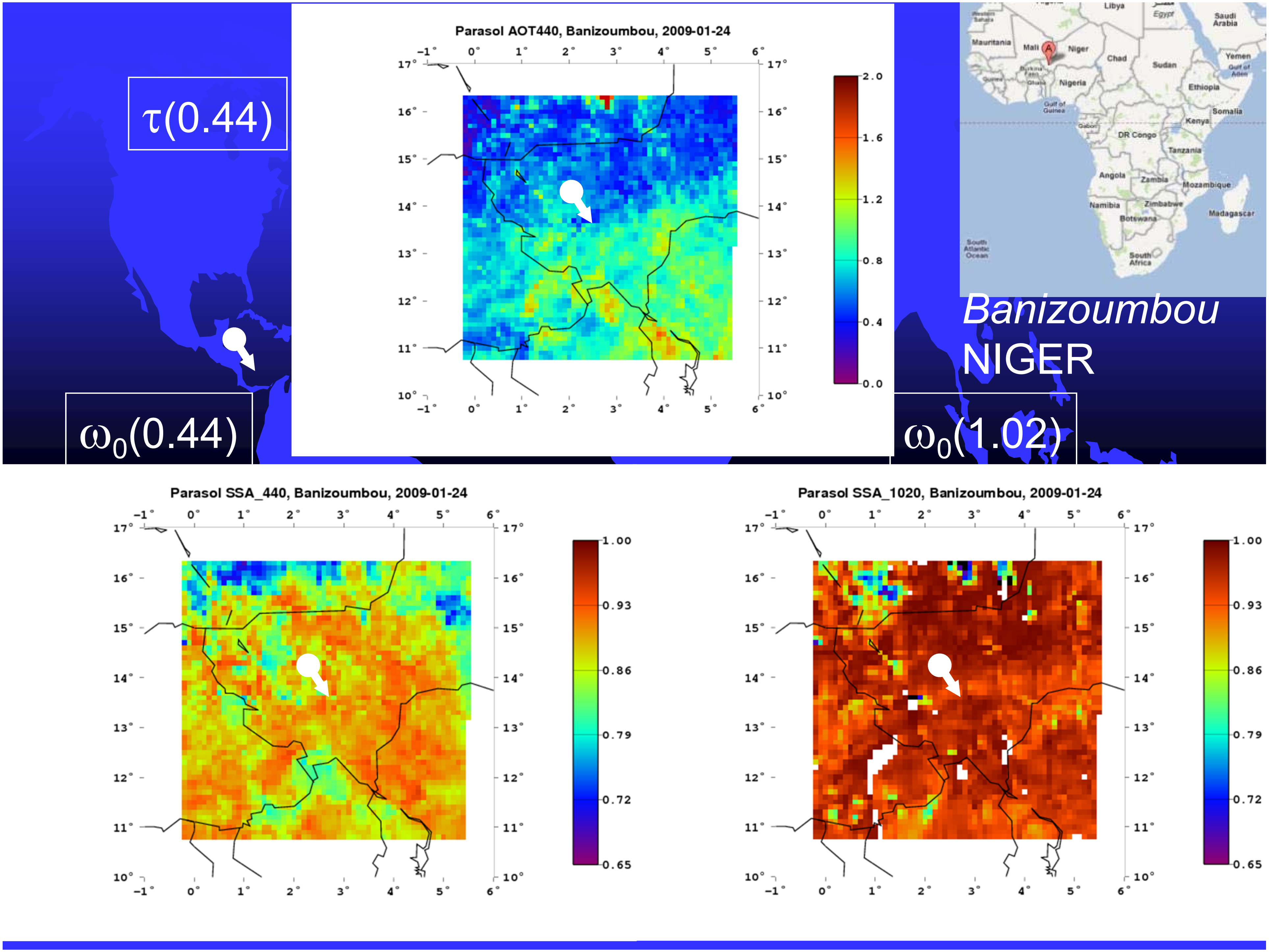
Banizoumbou
NIGER

$\omega_0(0.44)$



$\omega_0(1.02)$

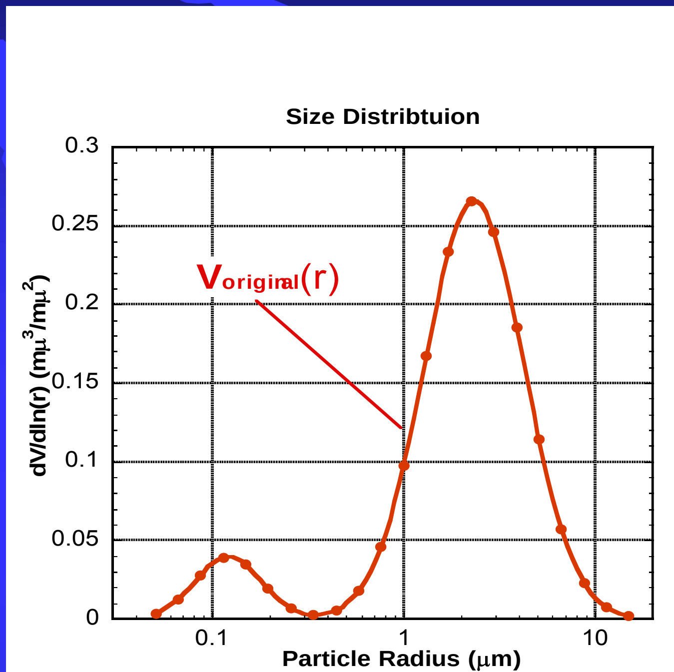


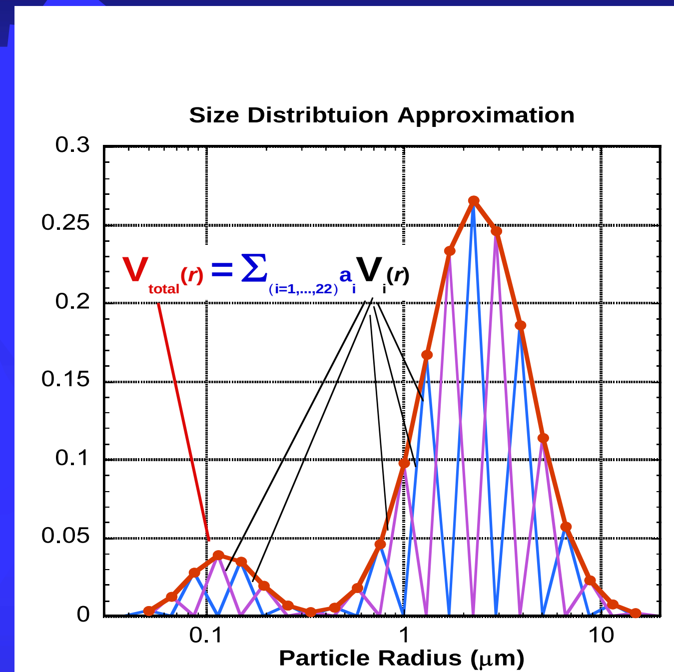


τ(0.44)
Parasol AOT440, Banizoumbou, 2009-01-24
ω0(0.44)
Banizoumbou
NIGER
ω0(1.02)
Parasol SSA_440, Banizoumbou, 2009-01-24
Parasol SSA_1020, Banizoumbou, 2009-01-24

Aerosol particle size distribution

Trapezoidal approximation





(Twomey 1977)

ASSUMPTIONS used by AERONET:

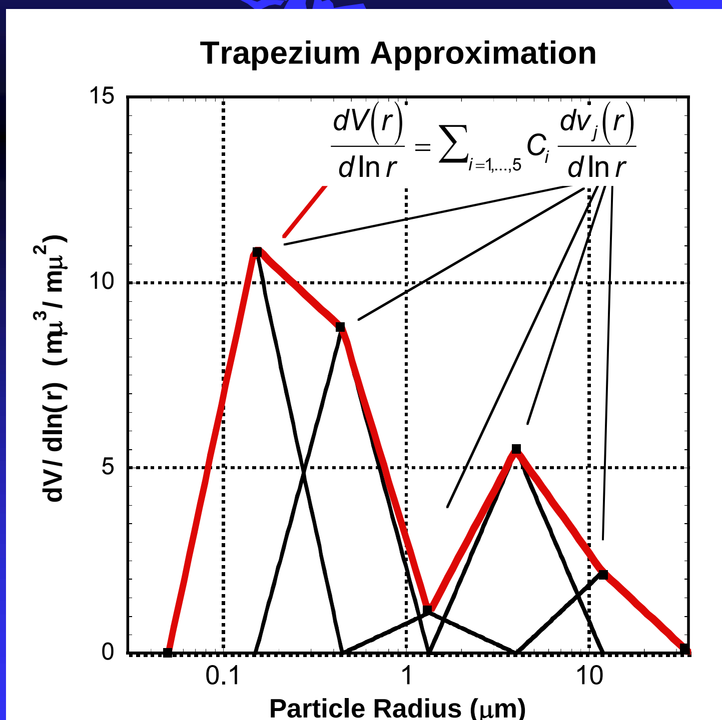
- dV/dlnr - volume size distribution of aerosol in total atmospheric column;
- size distribution is modeled using 22 triangle size bins (0.05 ≤ R ≤ 15 μm);
- size distribution is smooth

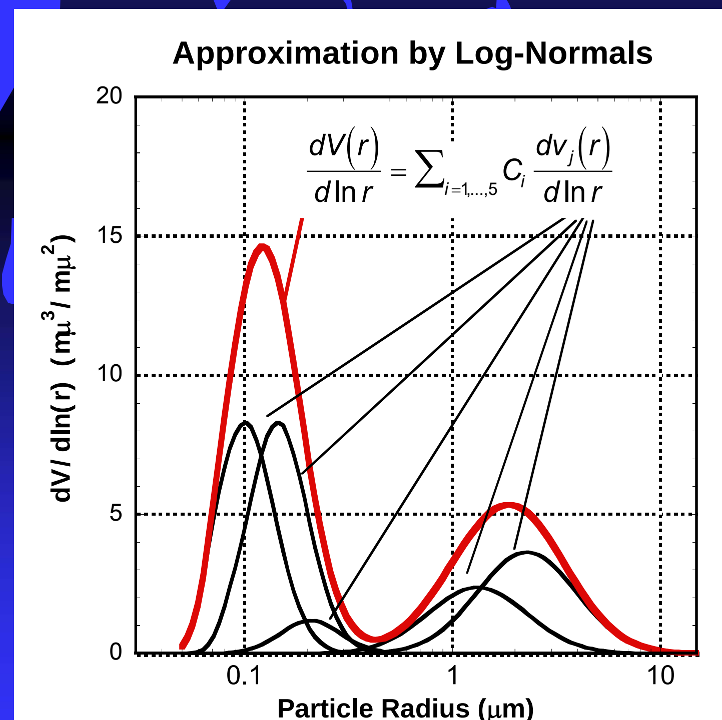
Optimized representation of aerosol size distribution with limited number of size bins

Approximation by Small number of « bins »

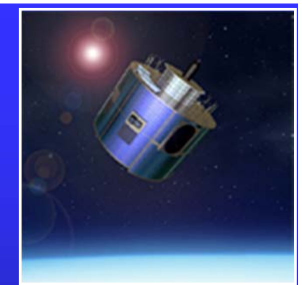
Modeling Polydispersions:

$$\frac{dV(r)}{d\ln r} = \sum_{i=1,\dots,N} C_i \frac{dv_j(r)}{d\ln r}$$



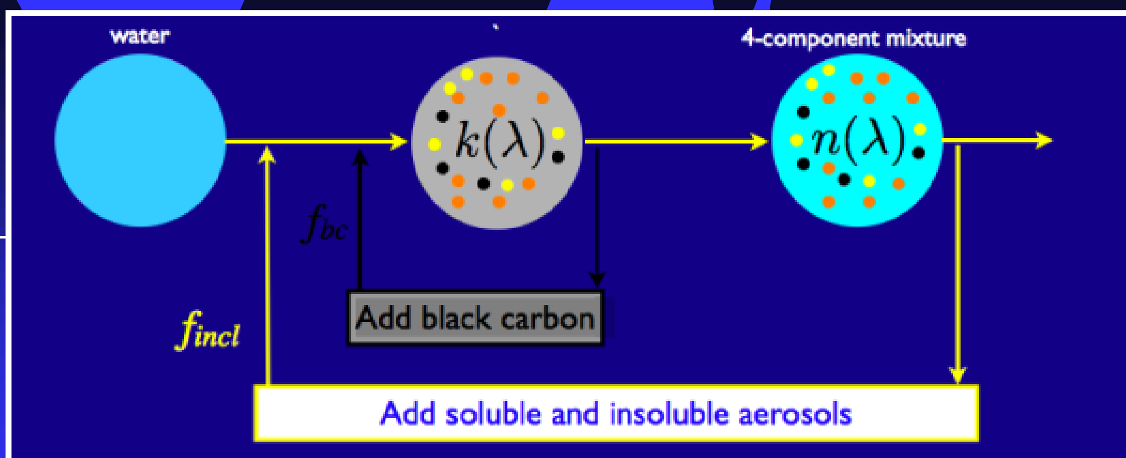


WP-1.2 Aerosol composition representation :



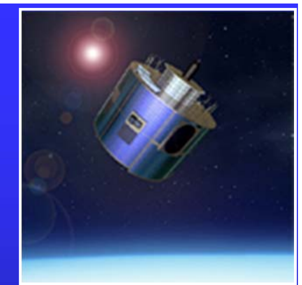
The software has been prepared for calculating spectral complex refractive index based on Shuster et al. 2009 approach:

Water+
Soluble+
Insoluble+
+BC+IRON



$n(\lambda)$
$k(\lambda)$

Concept of internal mixing of the aerosol components:

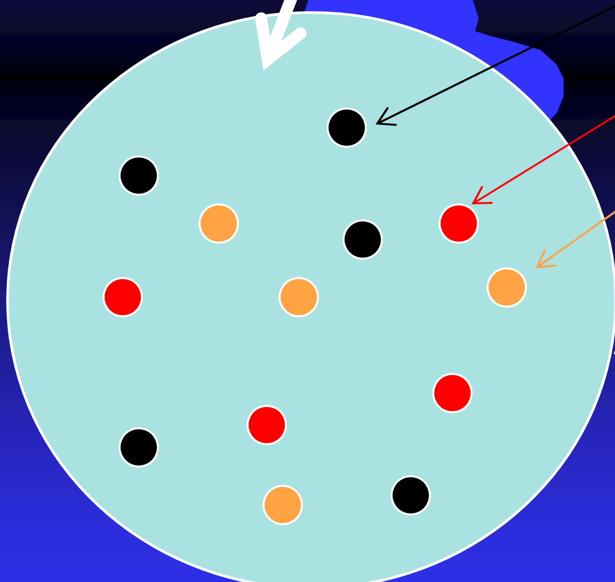


Host media: Water + Soluble

<u>Soluble - Ammonium Nitrate</u> with the properties depending on Relative Humidity (RH)

Insoluble Inclusions:

- Black Carbon
- Iron
- other insoluble components ("quartz")



Schuster et al. 2005, 2009

Maxwell Garnett's Effective Medium Approximation:

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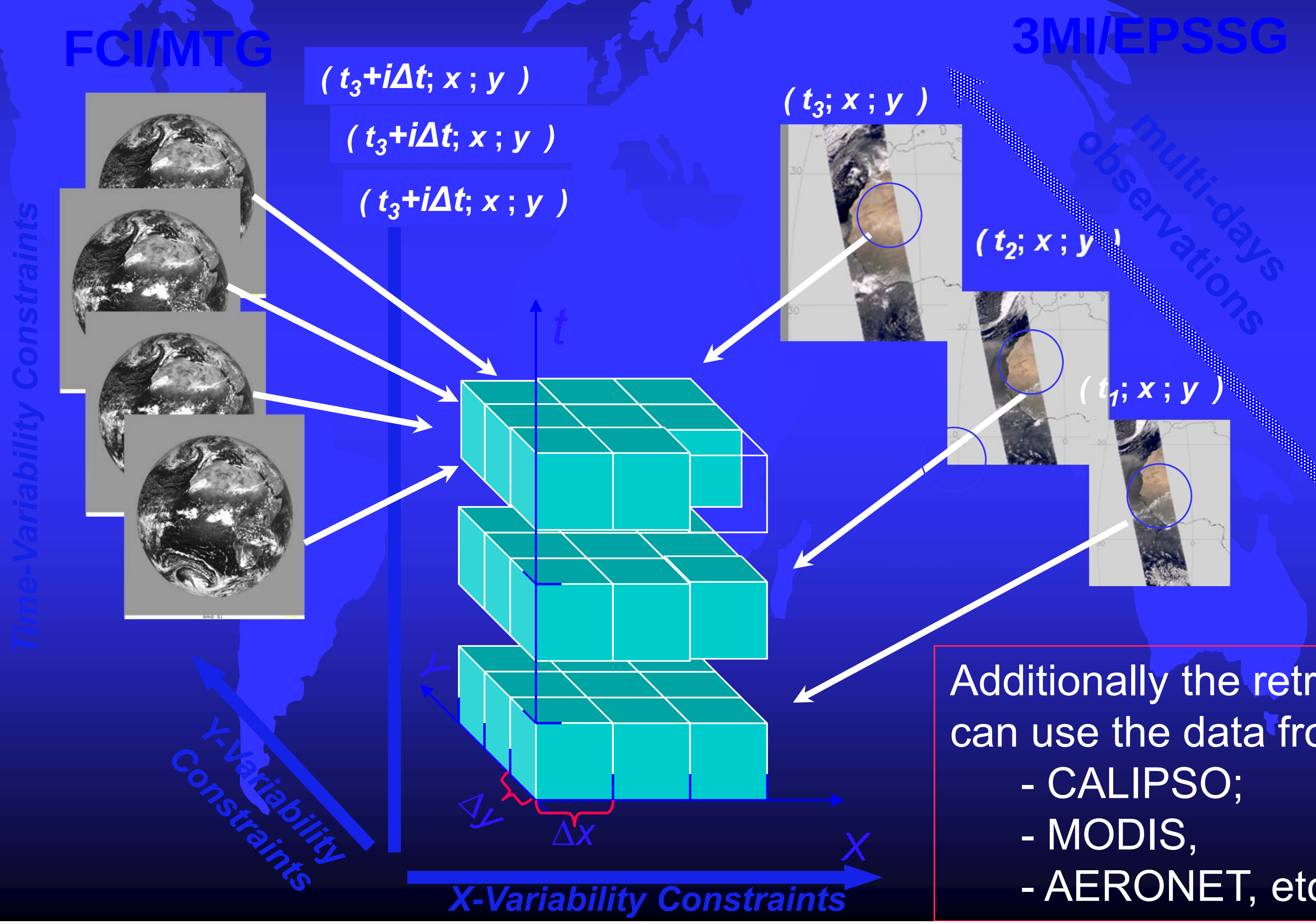
describes the macroscopic properties of a medium based on the properties and the relative fractions of its components

→ $n(\lambda)$

$k(\lambda)$

Synergy GEOSTATIONARY and POLAR (multi-pixel approach)



Additionally the retrieval can use the data from:

- CALIPSO;
- MODIS,
- AERONET, etc.