



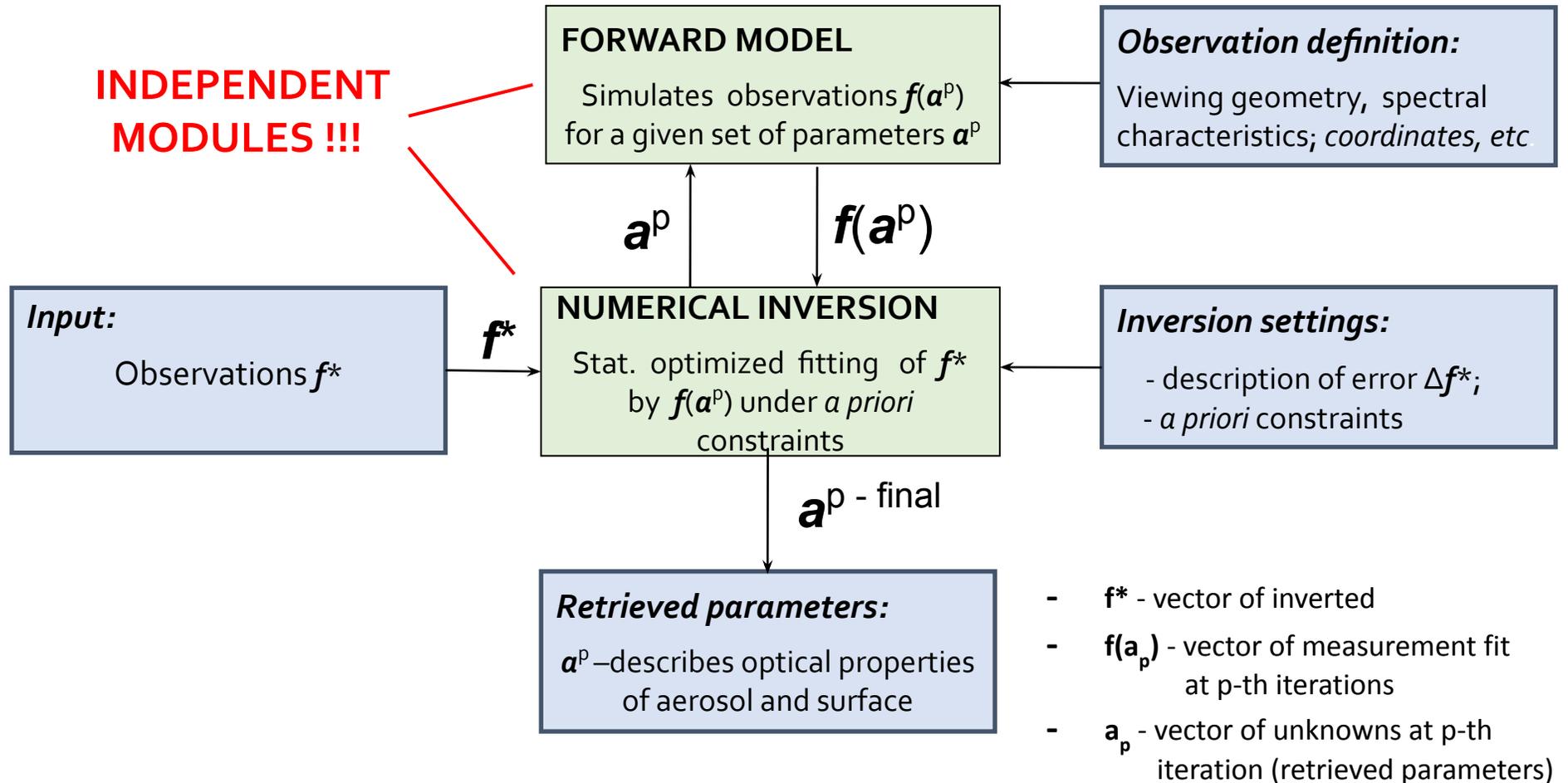
# Modelling of aerosol scattering in GRASP & addressing particle non-sphericity

Anton Lopatin, Oleg Dubovik, Lei Bi, Wushao Lin, Masanori Saito, Tatsiana Lapionak, Gregory Schuster, Syiao Zhai, Moritz Haarig, Albert Ansmann, Pavel Lytvinov, Chong Li, Cheng Chen, Christian Matar and David Fuertes



Funded by  
the European Union

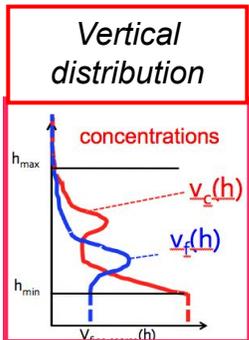
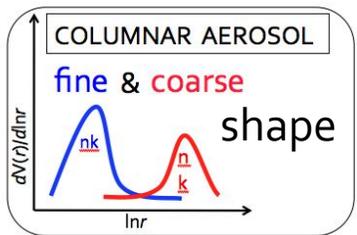
# General structure of the GRASP algorithm



# Modular Forward Model



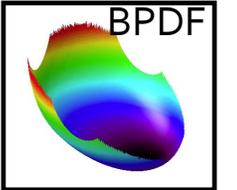
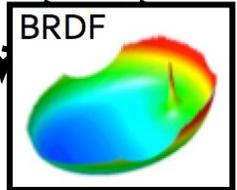
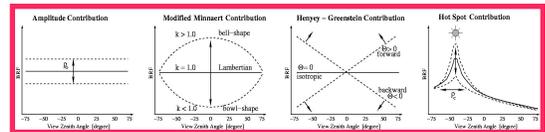
Vector of retrieved parameters :  
 $a^{aer}$  - aerosol properties  
 $a^{surf}$  - surface properties  
 $a^{gas}$  - gas absorption



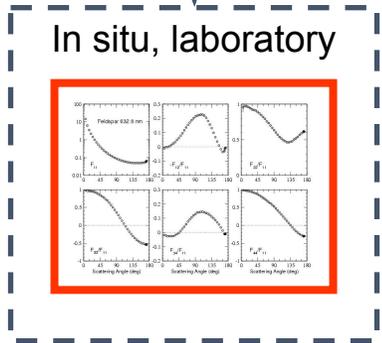
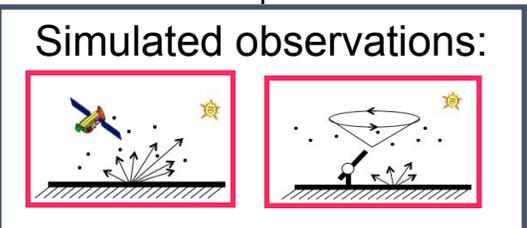
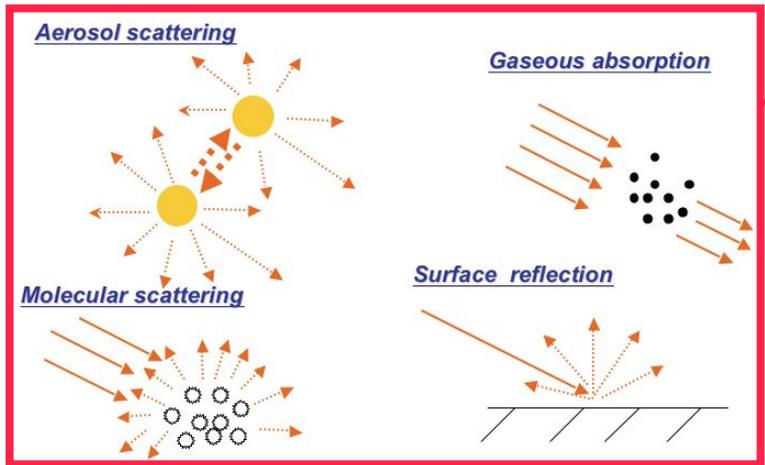
**Aerosol single scattering**  
 $\tau(\lambda, h), \omega_0(\lambda, h), P(\lambda, \Theta, h)$

**Gaseous absorption**  
 $\tau(\lambda, h), \omega_0(\lambda, h), P(\lambda, \Theta, h)$

**Surface reflectance**  
 BRDF | BPDF



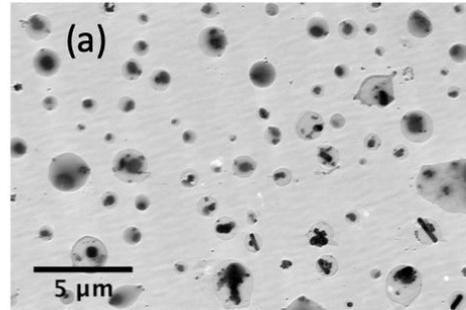
**Multiple scattering effects**  
Radiative Transfer:  
 $F(\lambda, \Theta, \dots)$



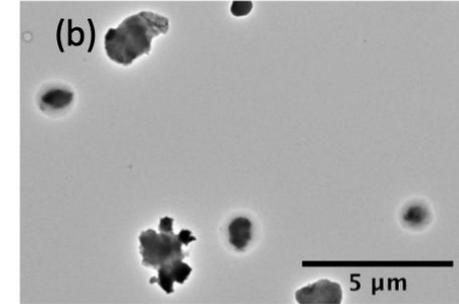
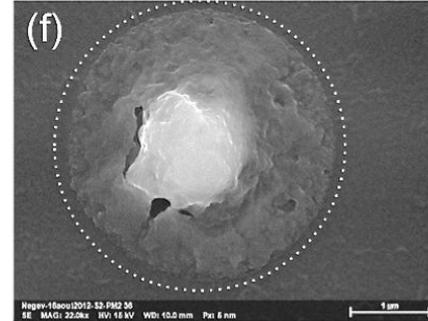
More from Masahiro Momoi @ 12:00

# Complex properties of atmospheric aerosols

Urban aerosol (Lille, France)



Desert aerosol (Senegal and Israel)

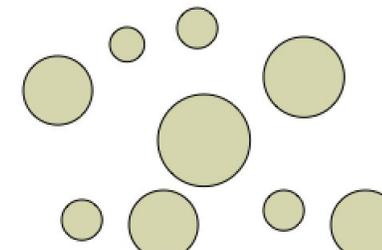
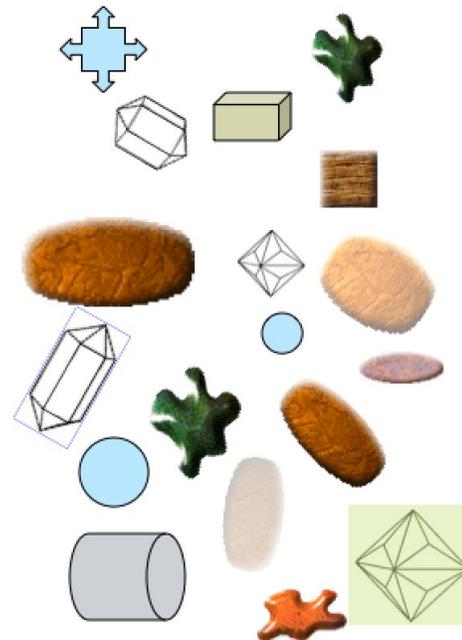


Real

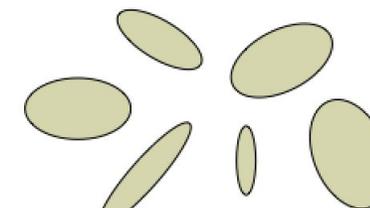
aerosol

Modeled

spherical:



Randomly oriented spheroids :



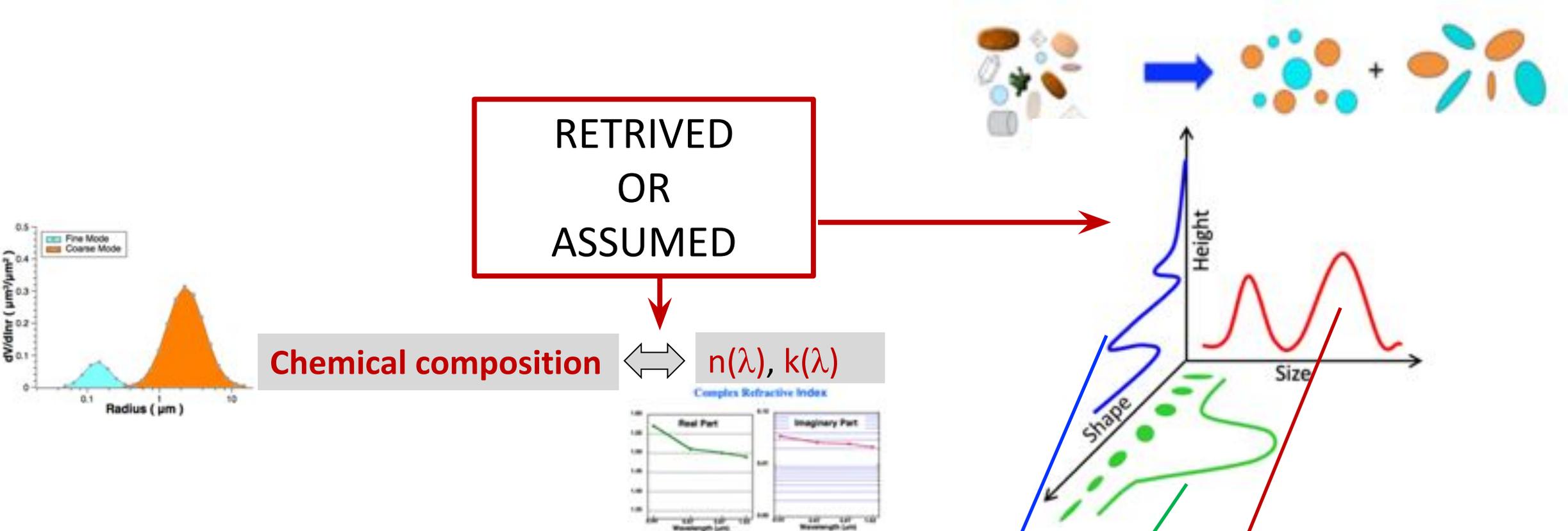
AERONET model

!!! Aerosol is complex

!!! Models are limited

# Aerosol model in GRASP

Multi-component mixture of spheres and randomly oriented spheroids



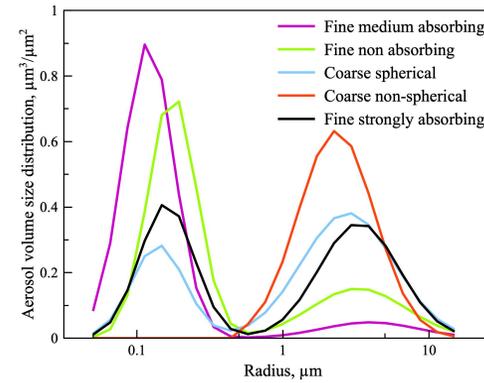
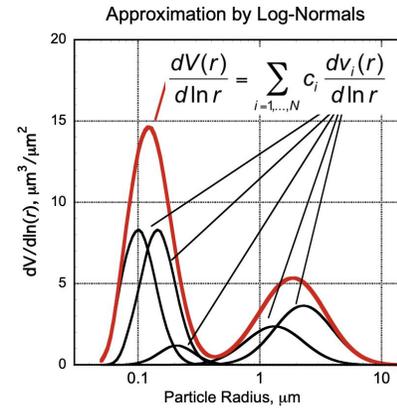
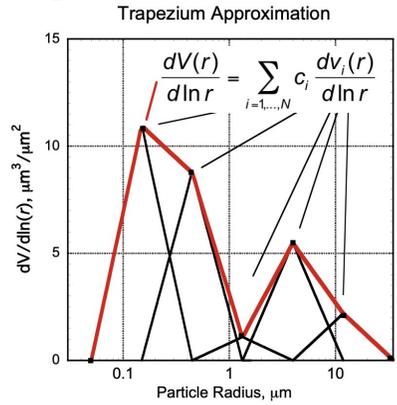
Measurements:

$$\tau_{scat/ext} = \sum_{k=1}^K \left( \int_{h_{min}}^{h_{max}} \int_{\epsilon_{min}}^{\epsilon_{max}} \int_{r_{min}}^{r_{max}} \frac{C_{scat/ext} \left( n_k(\lambda), k_k(\lambda); h; \epsilon; r \right)}{V(r)} \frac{dV_k(h)}{dh} \frac{dn_k(r)}{d\epsilon} \frac{dV_k(r)}{dr} dh d\epsilon dr \right)$$

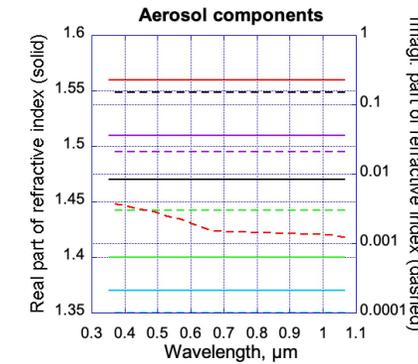
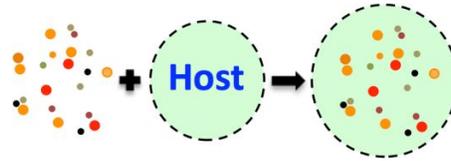
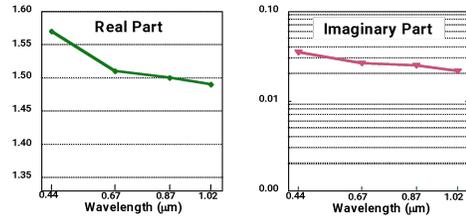
# Flexibility of aerosol modelling

Dubovik et al, 2002  
Lopatin et al, 2021

Size distribution



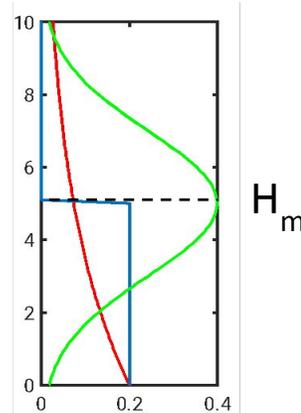
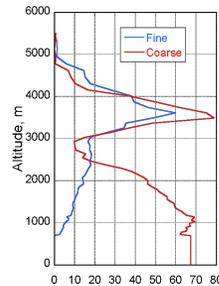
Complex refractive index



simple

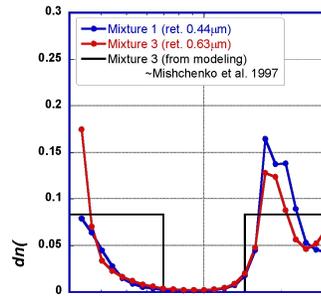
5-dimensional

Vertical distribution



Fixed  $H_m$

Shape distribution

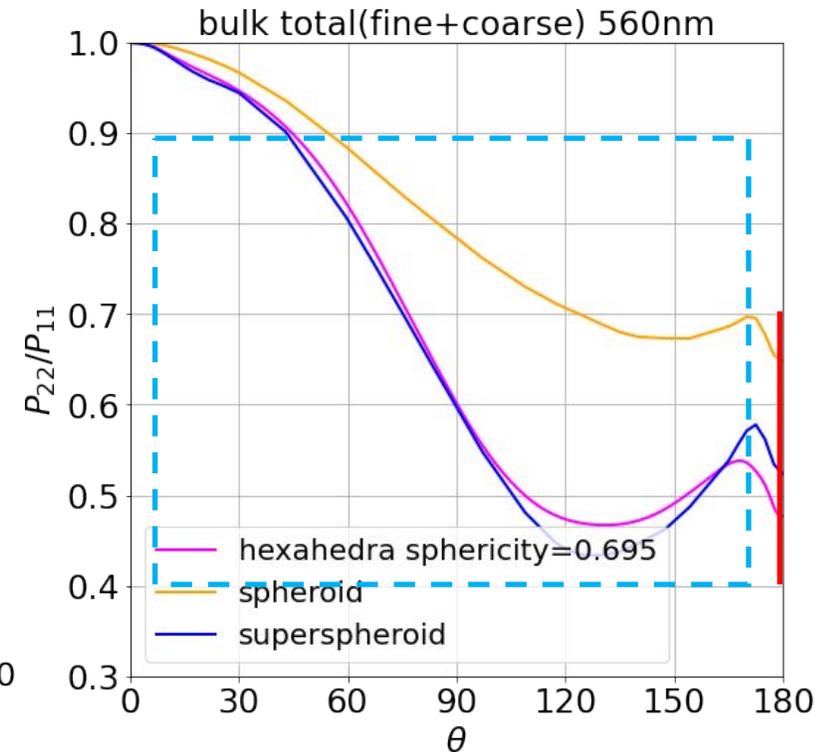
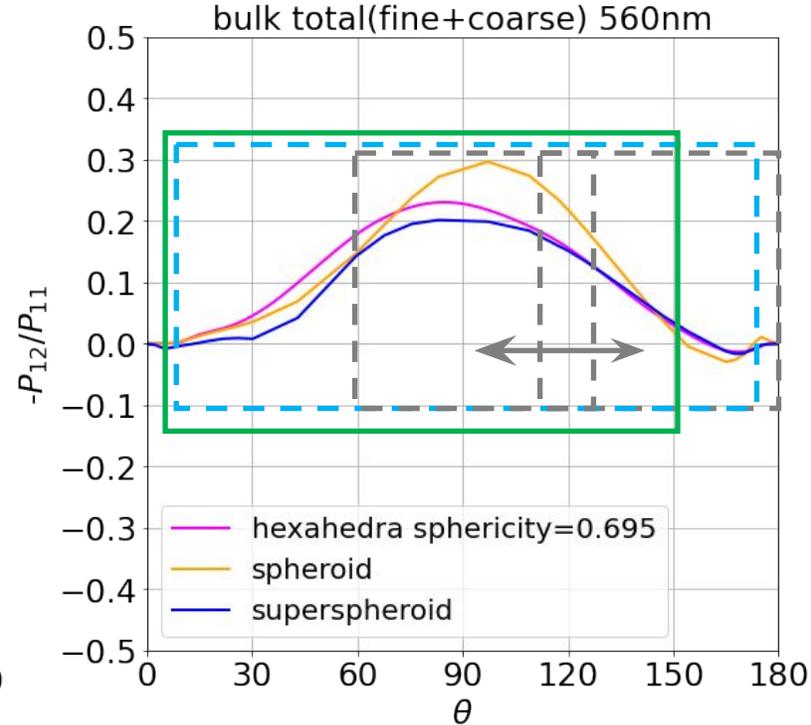
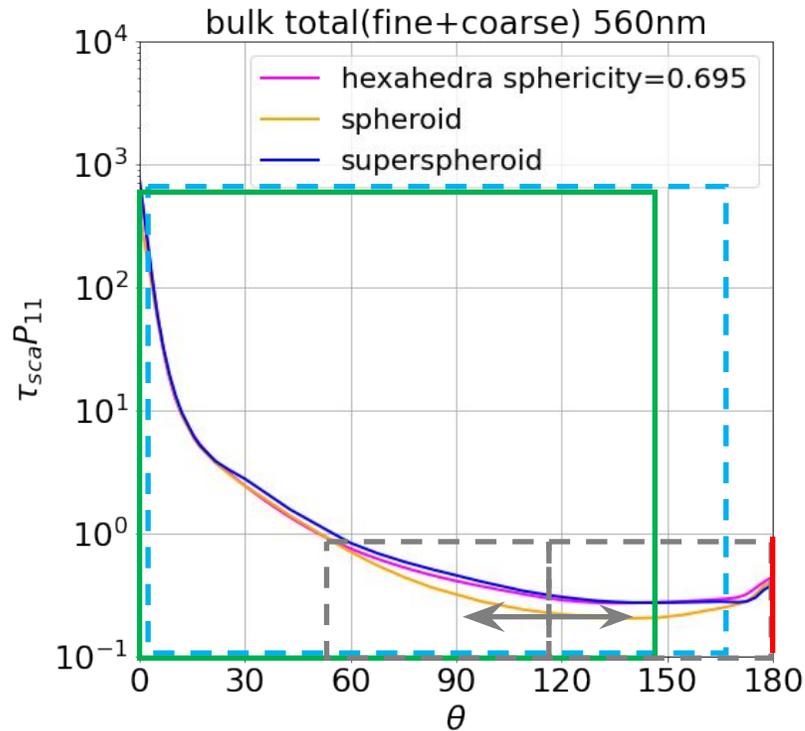


Fixed shape distribution  
 $\%C_{sph}$  retrieved

Fixed  $\%C_{sph}$

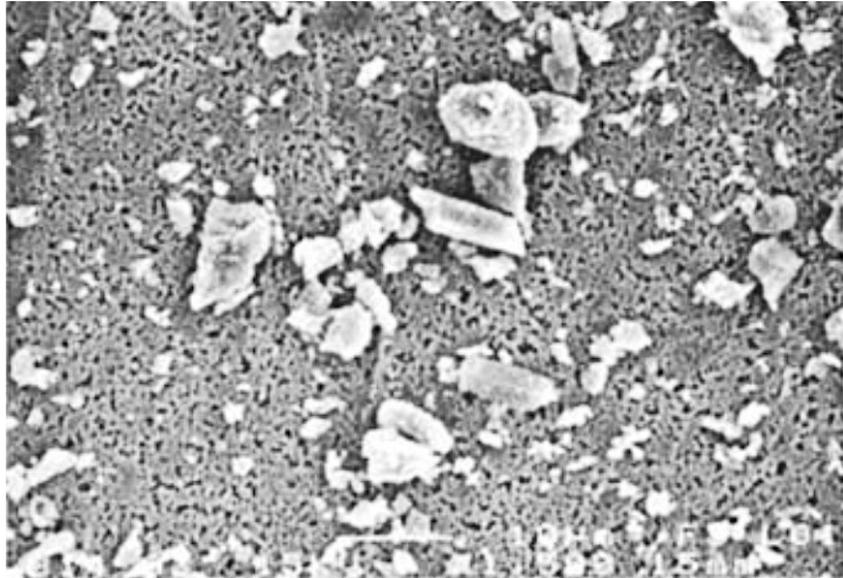
1-dimensional

# Aerosol (dust) as seen by remote sensing

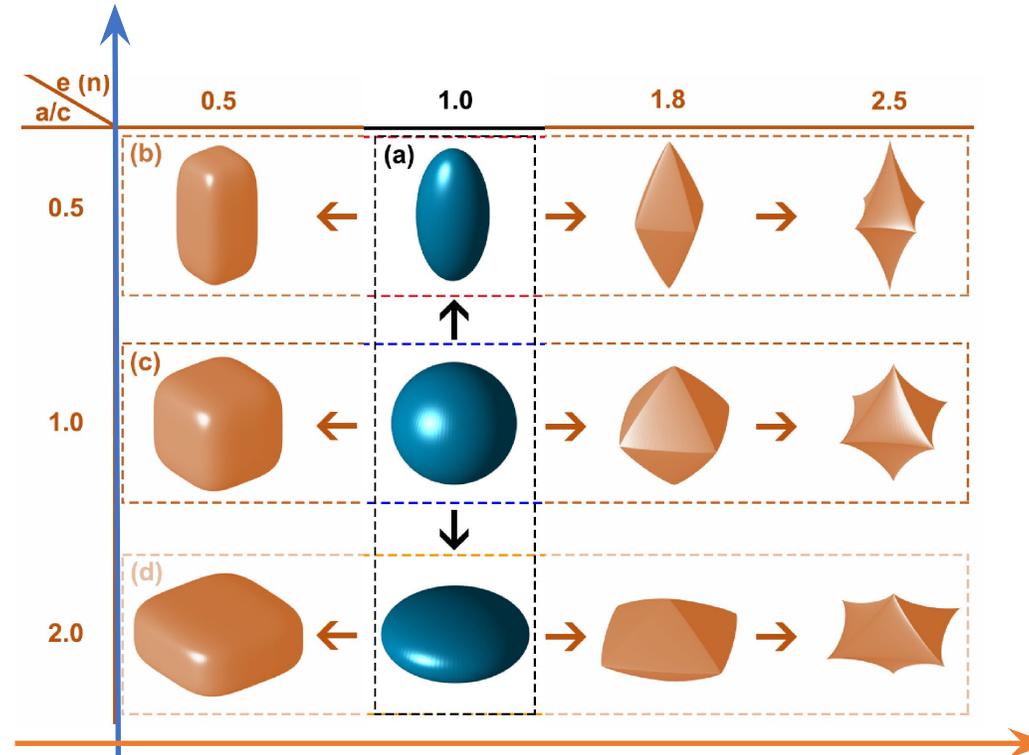


- Spaceborne polarimeters ( $\sim \text{km}^3$ )
  - Multi-wavelength lidar\* ( $\sim \text{m}^3$ )
  - Ground-based sun-photometers ( $\sim \text{km}^3$ )
- \*single scattering

# Dust: reality vs models



SEM image by Volten et al. 2001  
(feldspar sample)



Spheroids  
Dubovik et al., 2006

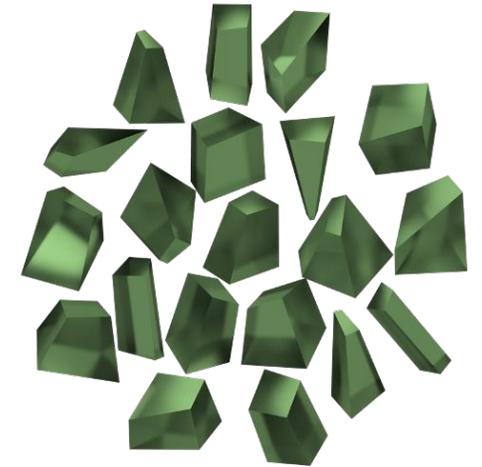
$n = [1.3, \dots, 1.7]$   
 $k = [0, \dots, 0.5]$

Super Spheroids  
Bi et al., 2018

$n = [1.1, \dots, 2.0]$   
 $k = [0, \dots, 0.5]$

Hexahedrons  
Saito et al., 2021 a,b

$n = [1.37, \dots, 1.7]$   
 $k = [0.0001, \dots, 0.1]$



# Accounting for particle non-sphericity in aerosol remote sensing using spheroid approximation

The development of non-spherical dust model and integrating the approach in remote sensing retrievals and in AERONET algorithm

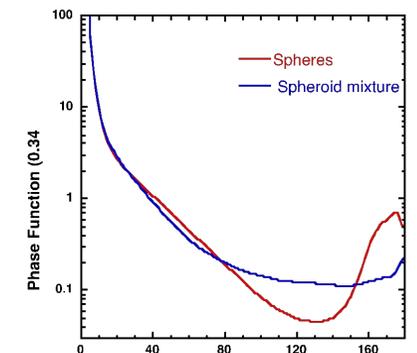
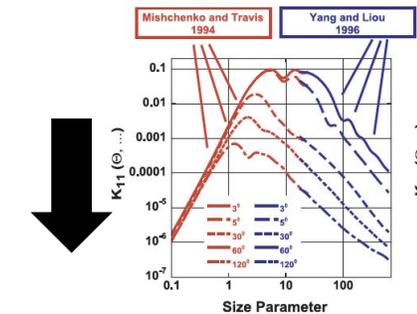
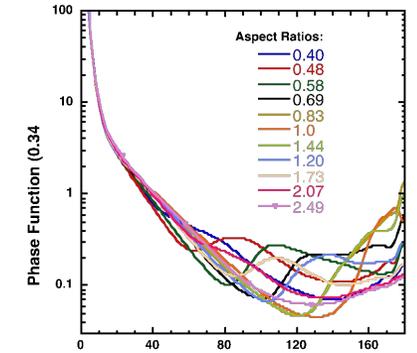
Dubovik, O., B. N. Holben, T. Lapyonok, A. Sinyuk, **M. I. Mishchenko**, **P. Yang** and I. Slutsker, Non-spherical aerosol retrieval method employing light scattering by spheroids, *Geophys. Res. Lett.*, 29, 1415, 10.1029/2001GL014506, 2002.

Google Scholar 485 citations

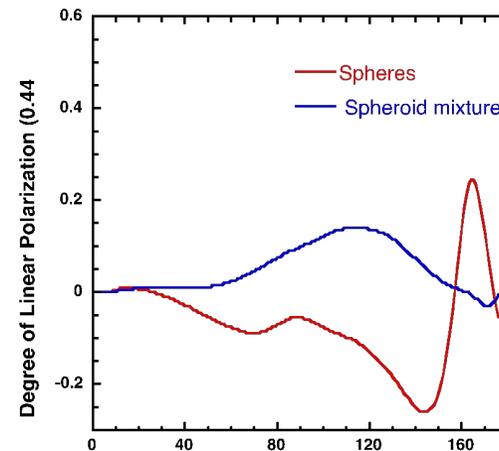
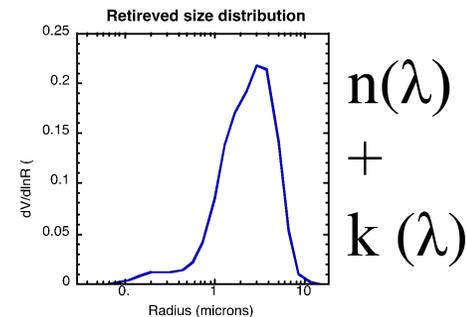
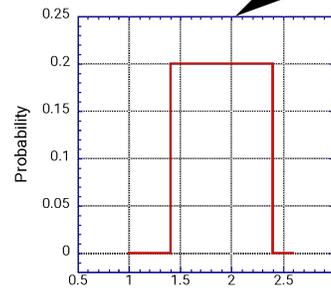
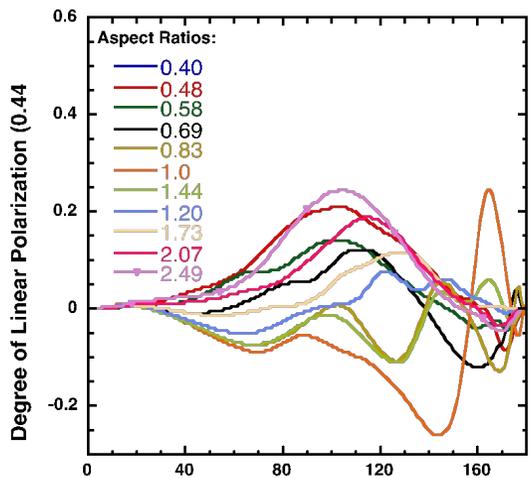
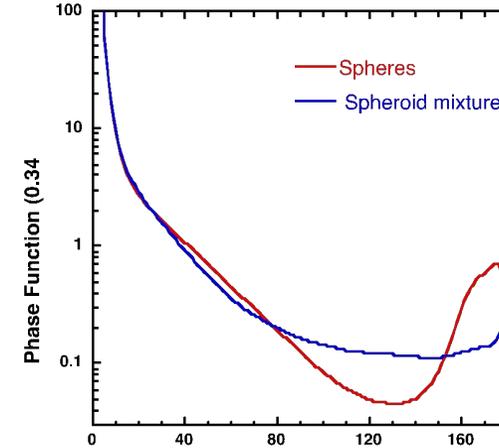
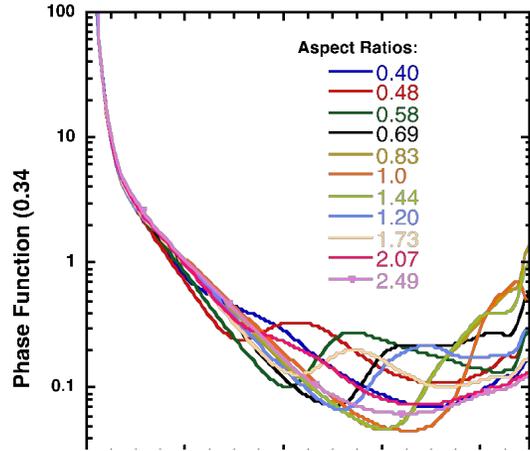
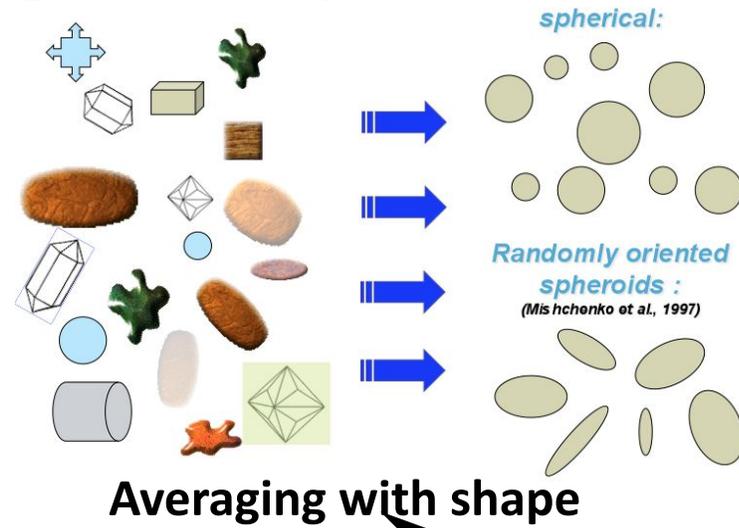
Dubovik, O., A. Sinyuk, T. Lapyonok, B. N. Holben, **M. Mishchenko**, **P. Yang**, T. F. Eck, H. Volten, O. Munoz, B. Veihelmann, W. J. van der Zander, M. Sorokin, and I. Slutsker, Application of spheroid models to account for aerosol particle nonsphericity in remote sensing of desert dust., *J. Geophys. Res.*, 111, D11208, doi:10.1029/2005JD006619d, 2006.

Google Scholar 1430 citations

One of the most widely used approaches and software in aerosol remote sensing



# Modelling dust particle non-sphericity



# Phase matrix inversion

## Example of water suspension inversion

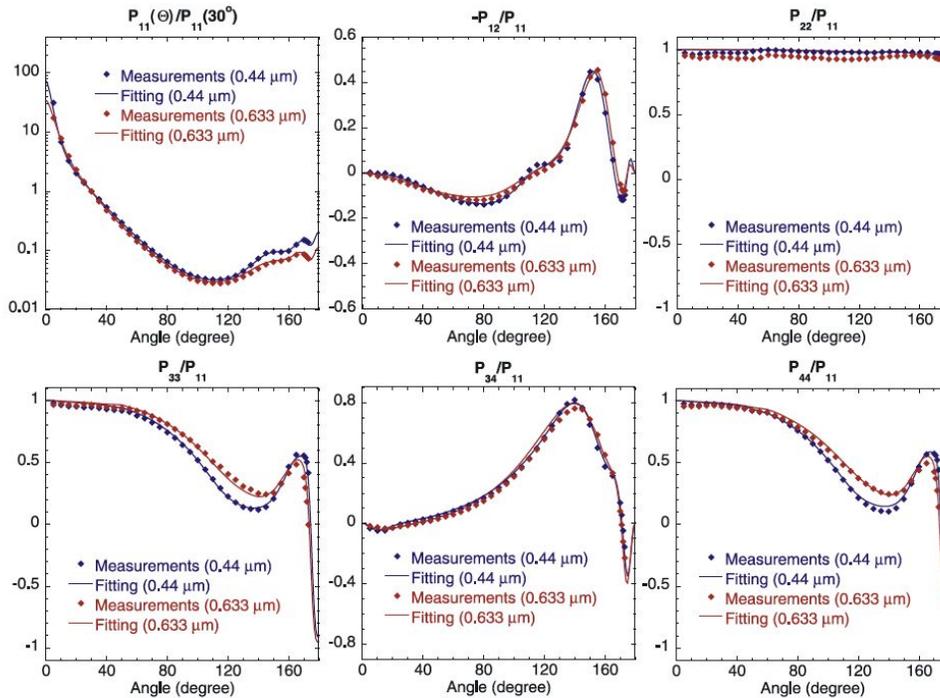


Figure 6. Results of fitting a water droplet scattering matrix by a mixture of spheroids.

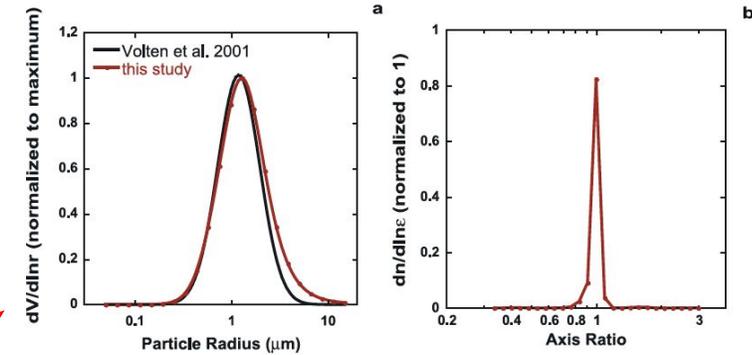


Figure 7. (a) Size distribution (used by Volten et al. [2001], black line; retrieved in this study, red line). (b) Axis ratio distribution retrieved from an inversion of water droplet scattering matrix (measured at two wavelengths 0.441 and 0.633  $\mu\text{m}$ ).

*Dubovik et al. 1995, 2006*

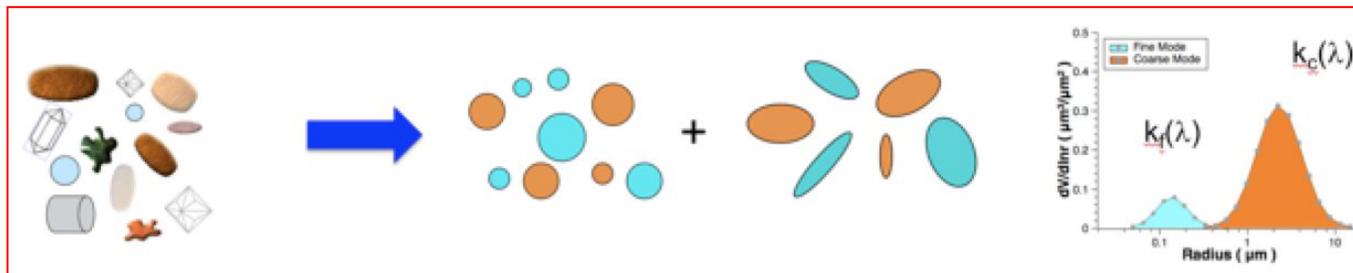
### Refractive index:

- Real part =  $\sim 1.34$ ;
- Imaginary part =  $\sim 0.0006$

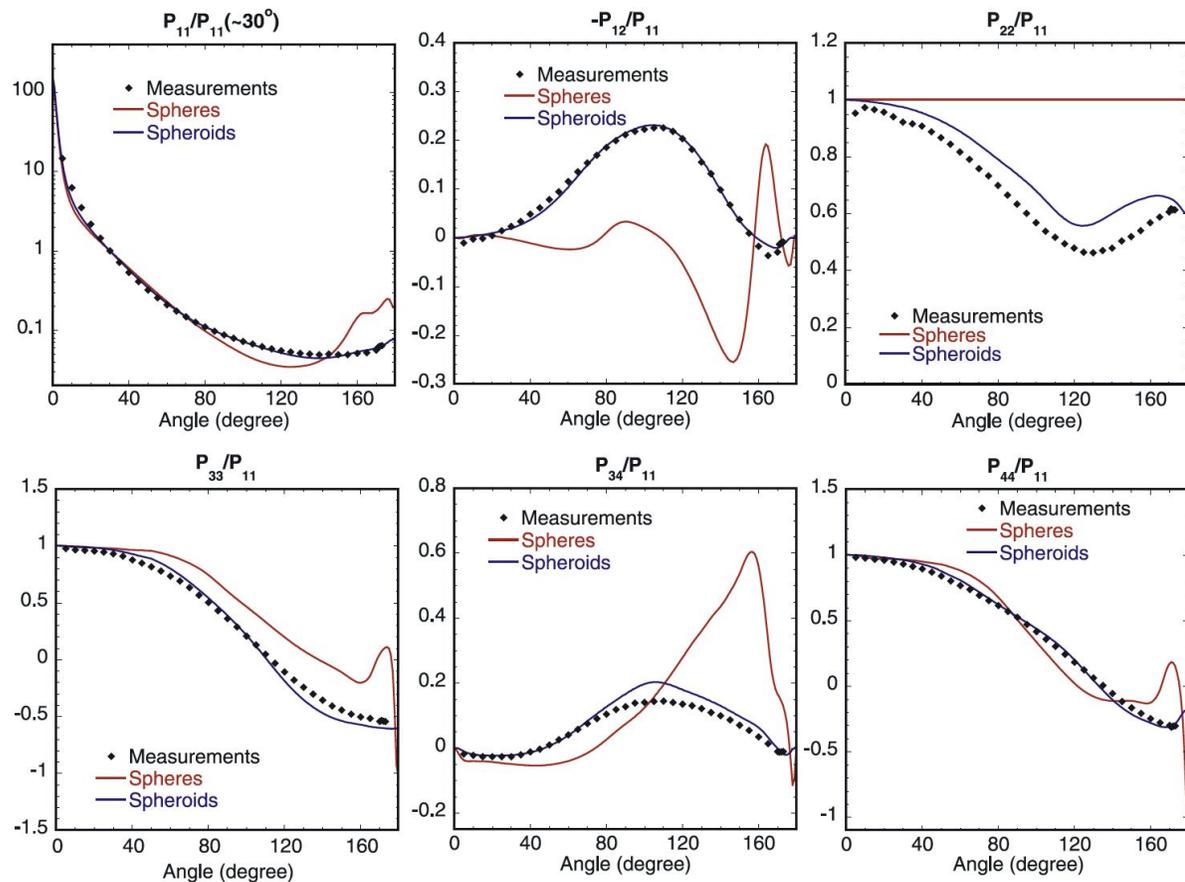
### More recent papers:

Gayet et al. 2012, Schuster et al. 2019

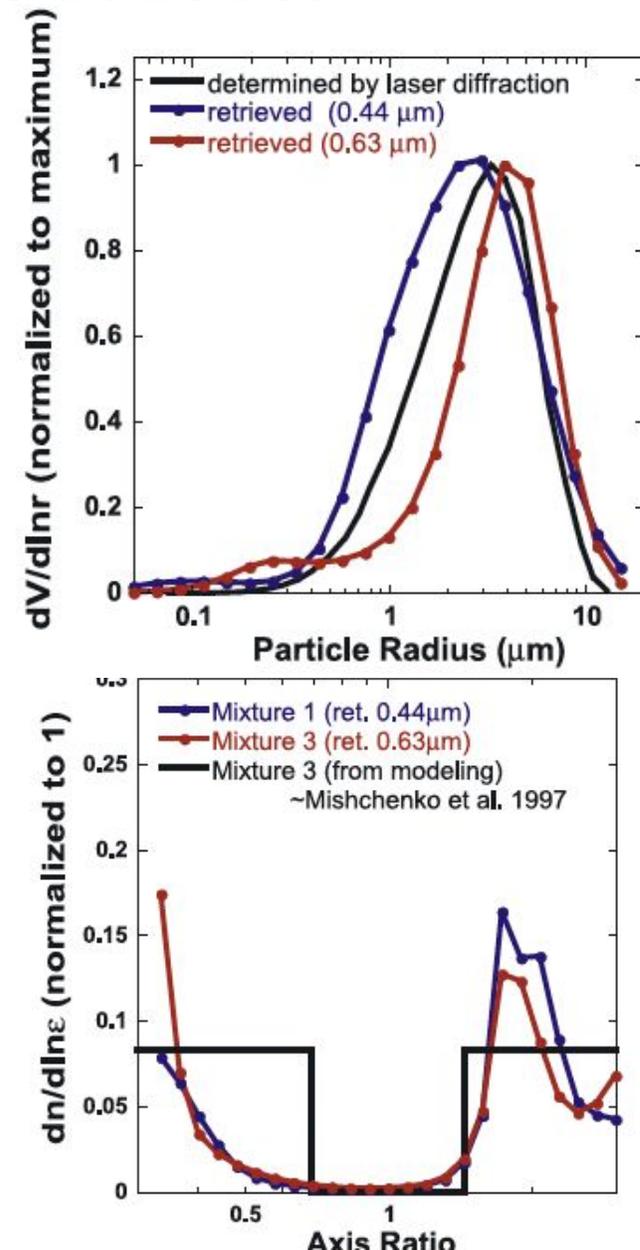
Espinosa et al. 2017, 2019;



# Feldspar sample phase matrix inversion



fitting



# Elastic backscattering: effect of non-sphericity

## Depolarization ratio

$$\delta(\lambda) = \frac{1 - P_{22}(\lambda, 180^\circ)/P_{11}(\lambda, 180^\circ)}{1 + P_{22}(\lambda, 180^\circ)/P_{11}(\lambda, 180^\circ)} 100\%.$$

$$L(\lambda, h) \sim \left( \frac{\sigma_{ext}^{aer}(h)}{S_{aer}} + \frac{\sigma_{ext}^{mol}(h)}{S_{mol}} \right) \exp\left(-2 \int_0^h (\sigma_{ext}^{aer}(h) + \sigma_{ext}^{mol}(h)) dh\right)$$

Extinction

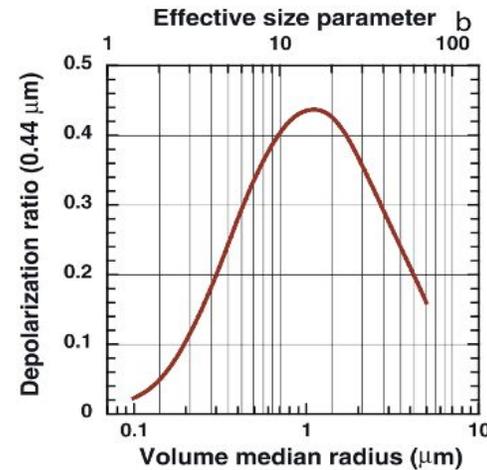
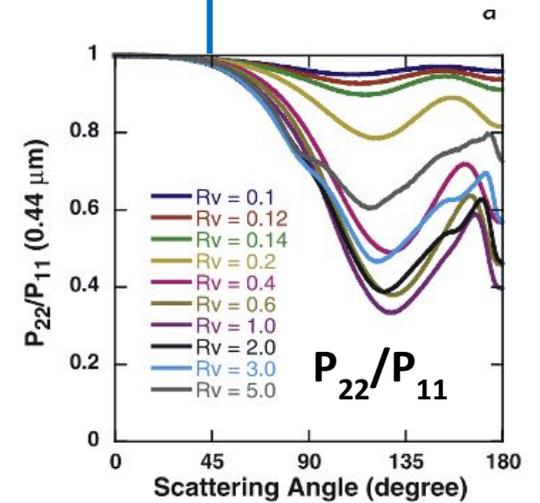
$$\int_0^h (\sigma_{ext}^{aer}(h) + \sigma_{ext}^{mol}(h)) dh = \tau(\lambda)$$

$$S(\lambda) = \frac{4\pi}{\omega_0(\lambda) P_{11}(\lambda, 180^\circ)}$$

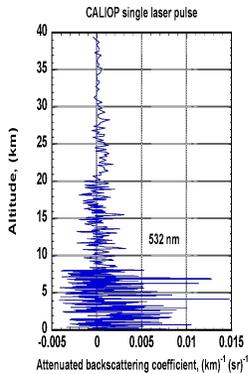
Lidar Ratio

Catrrall et al., 2005

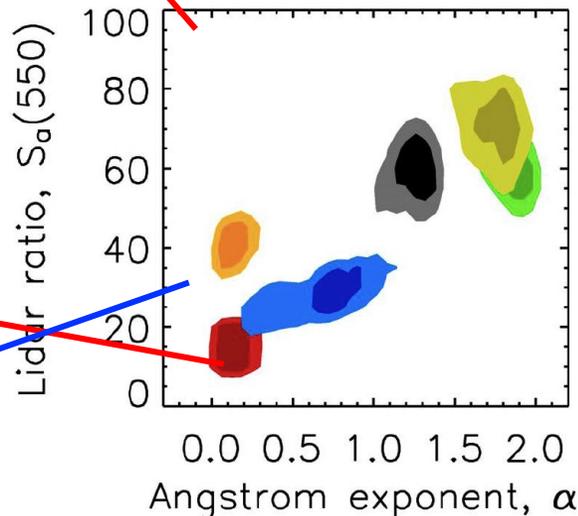
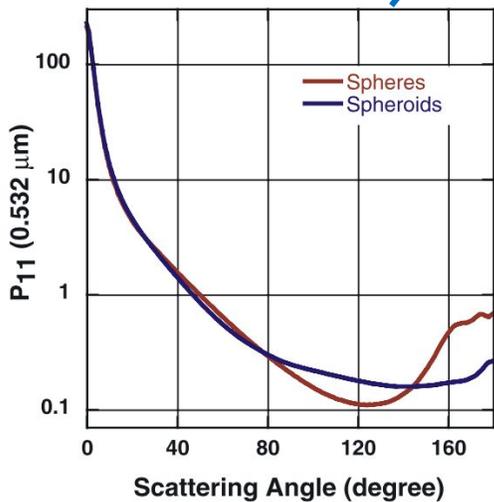
$\delta(0.44)$



Effect of non-sphericity  
Dubovik et al., 2006

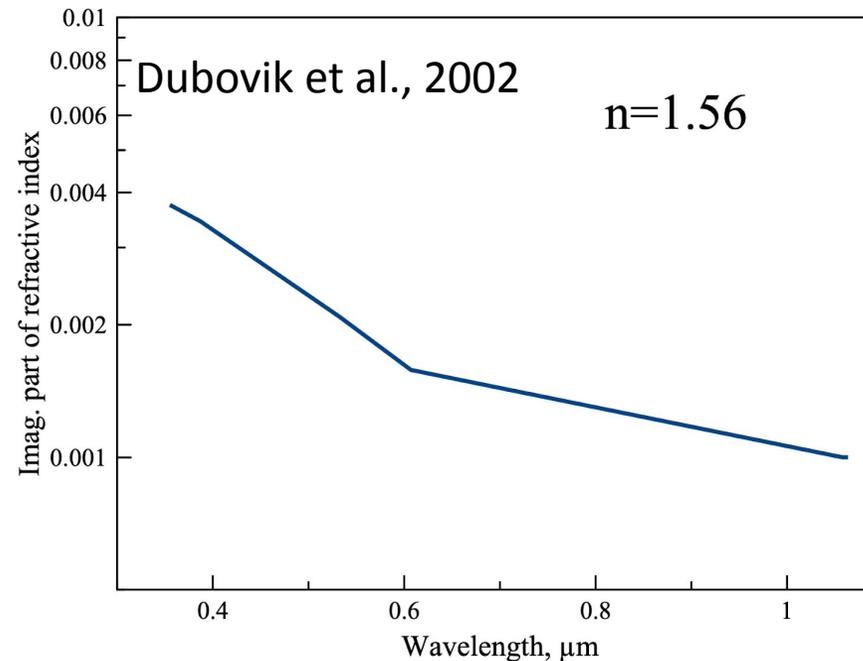
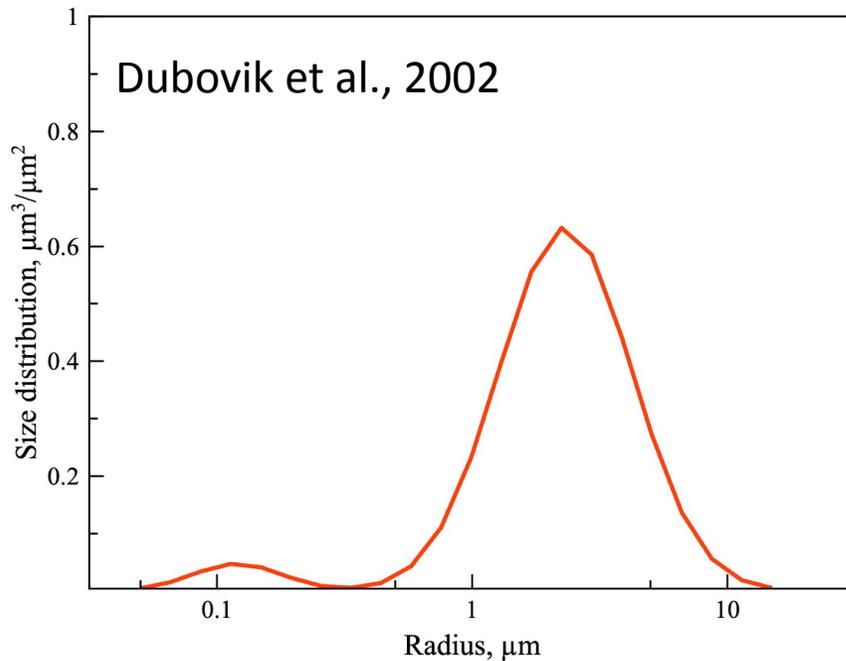
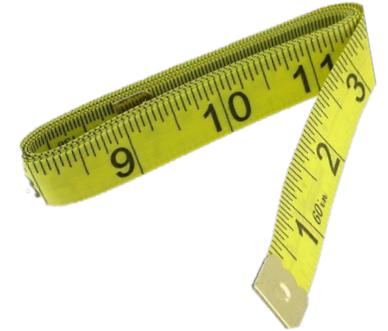


$P_{11}$



# Comparison procedure

- Spheroids (SPHD) shape distribution by Dubovik et., al. 2006
- Super-Spheroids (SS) with  $e=3$ , and equal  $a/c$
- Hexahedrons (HEX) with sphericity 6



# Comparison procedure: the “biathlon”

Round 1



Round 2



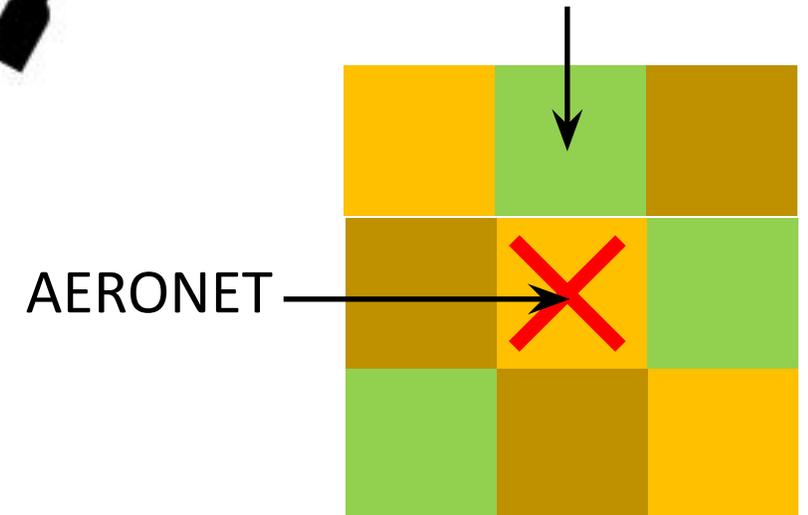
## Challenging obstacles:

- LIDAR (3 delta + 3 alpha + 3 beta) (Haarig et al., 2022)
- POLDER+AERONET (Banizombou & Kanpur sites)

## Equipment:

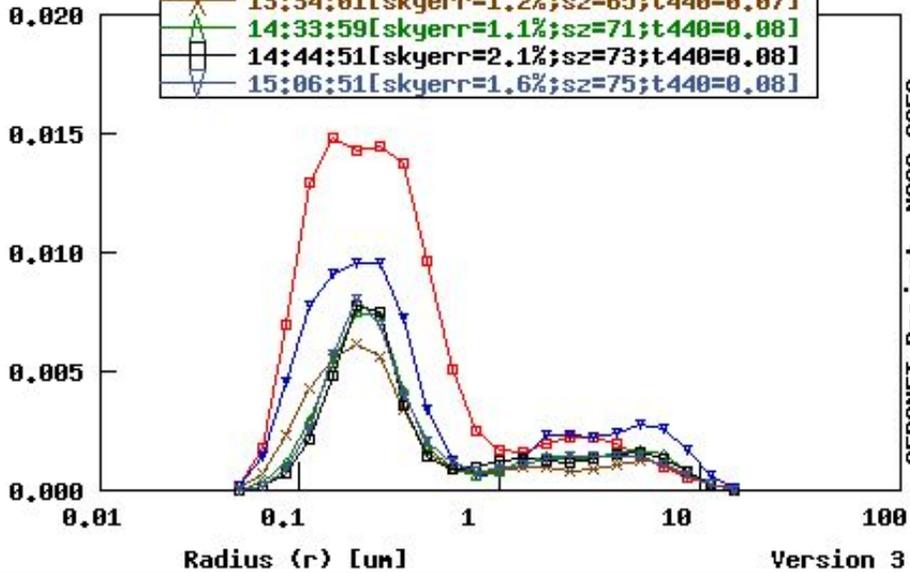
- “models” GRASP retrievals  
(Dubovik et al, 2011, Lopatin et al., 2021,2024)

POLDER 6x6 km pixel

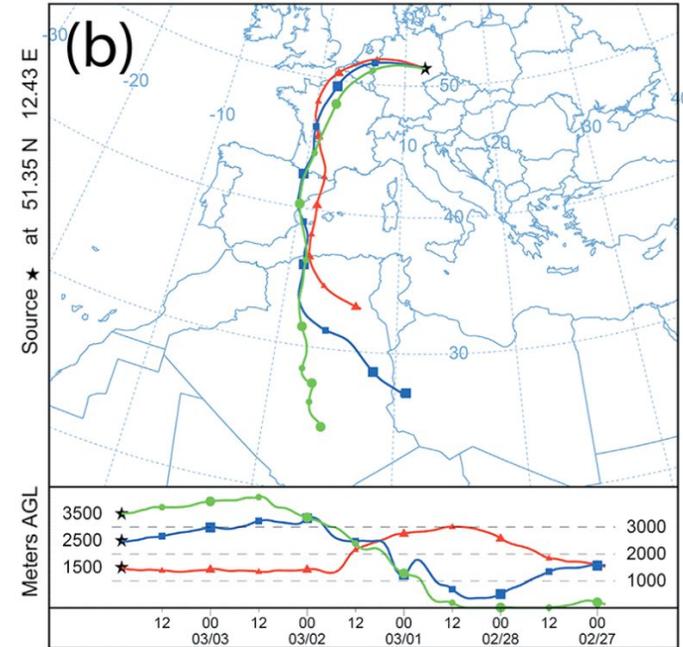
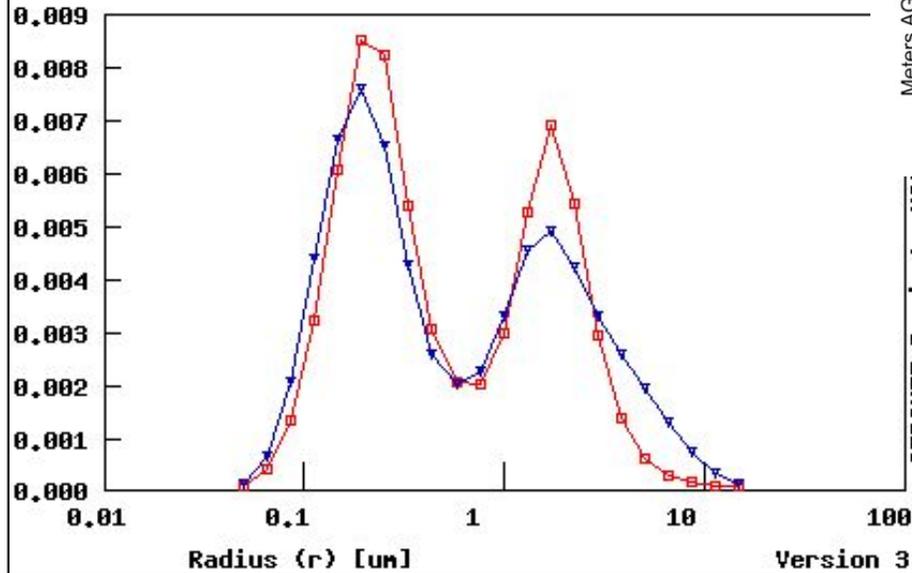


# Aerosol situation on on 2–3 March 2021

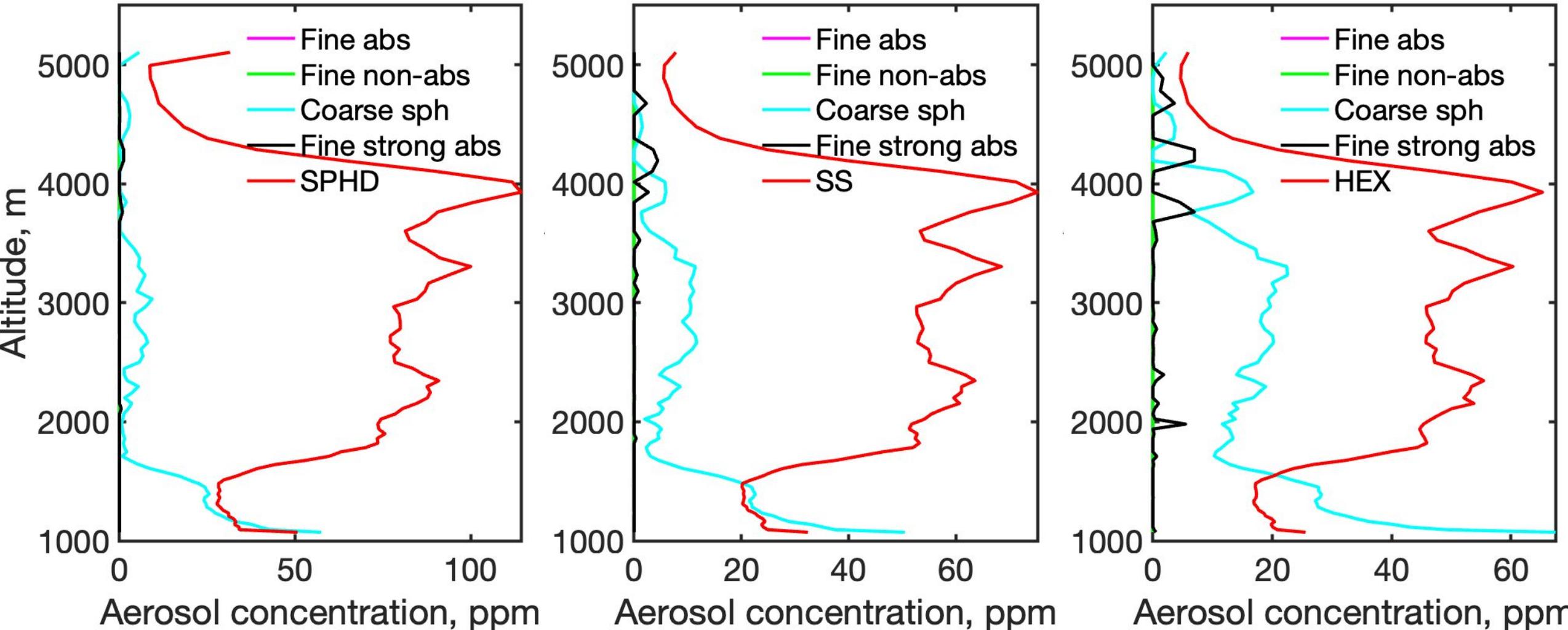
Leipzig , N 51.352, E 12.435, Alt 125 m,  
 PI : Albert\_Ansmann, albert@tropos.de  
 Size Distribution Almucentar Level 2.0; 2 MAR 2021



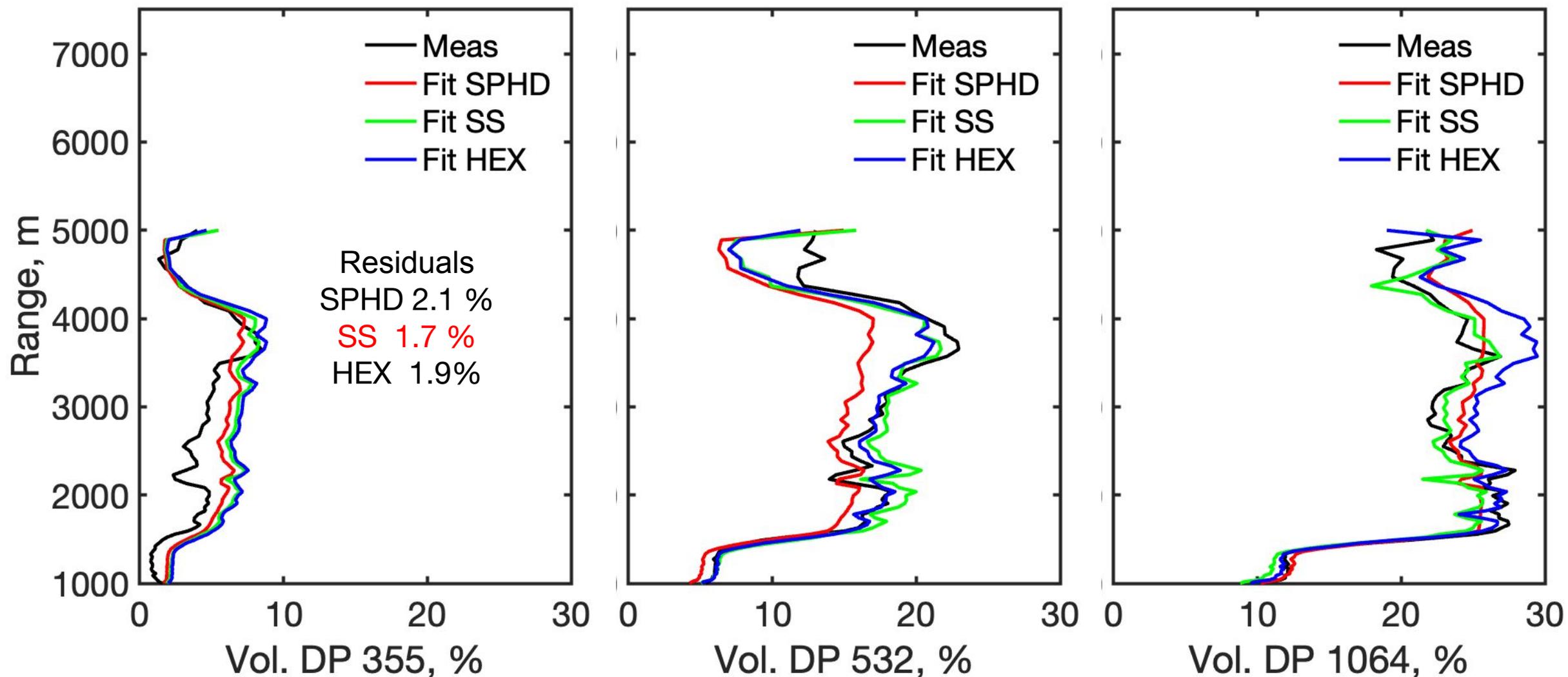
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 Size Distribution Almucentar Level 1.5; 3 MAR 2021



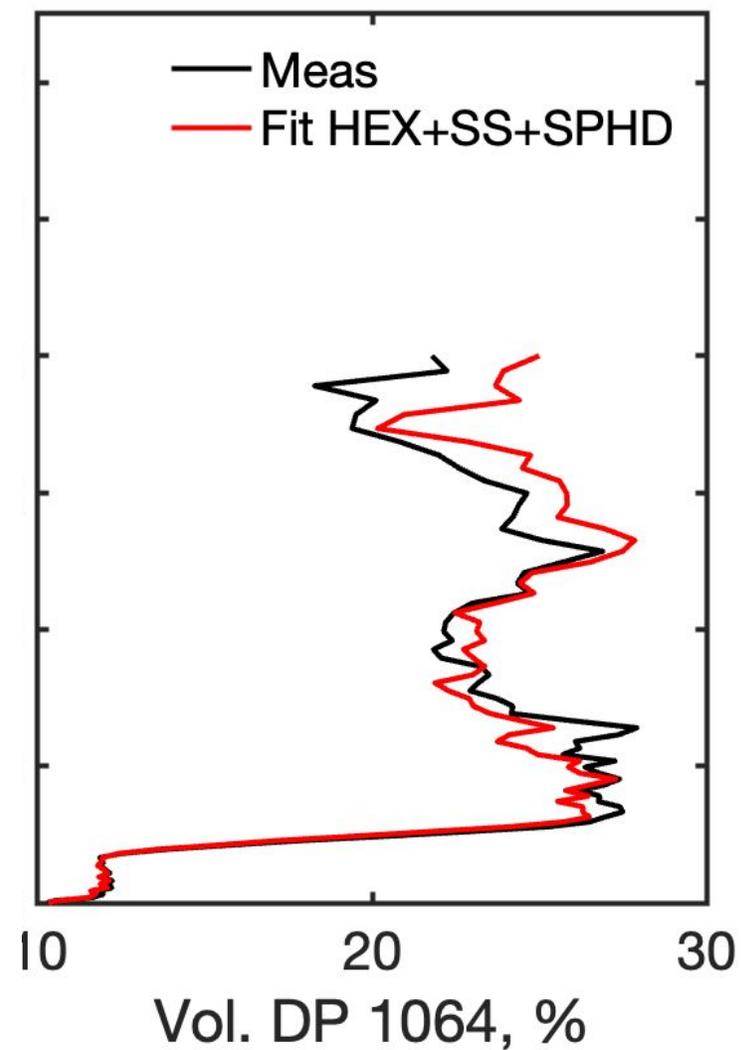
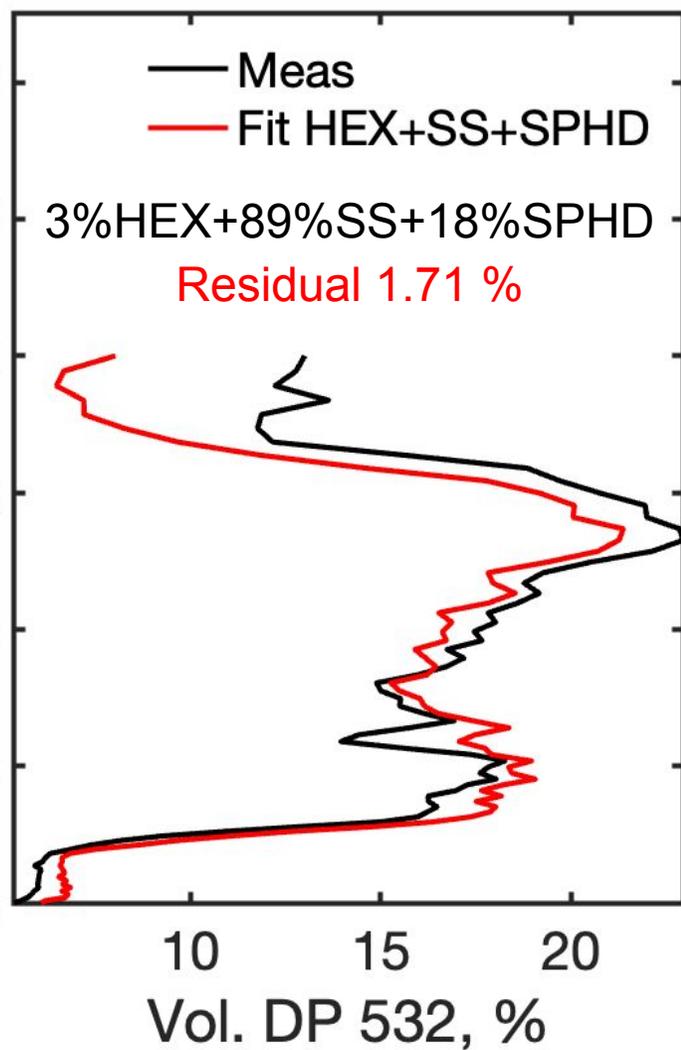
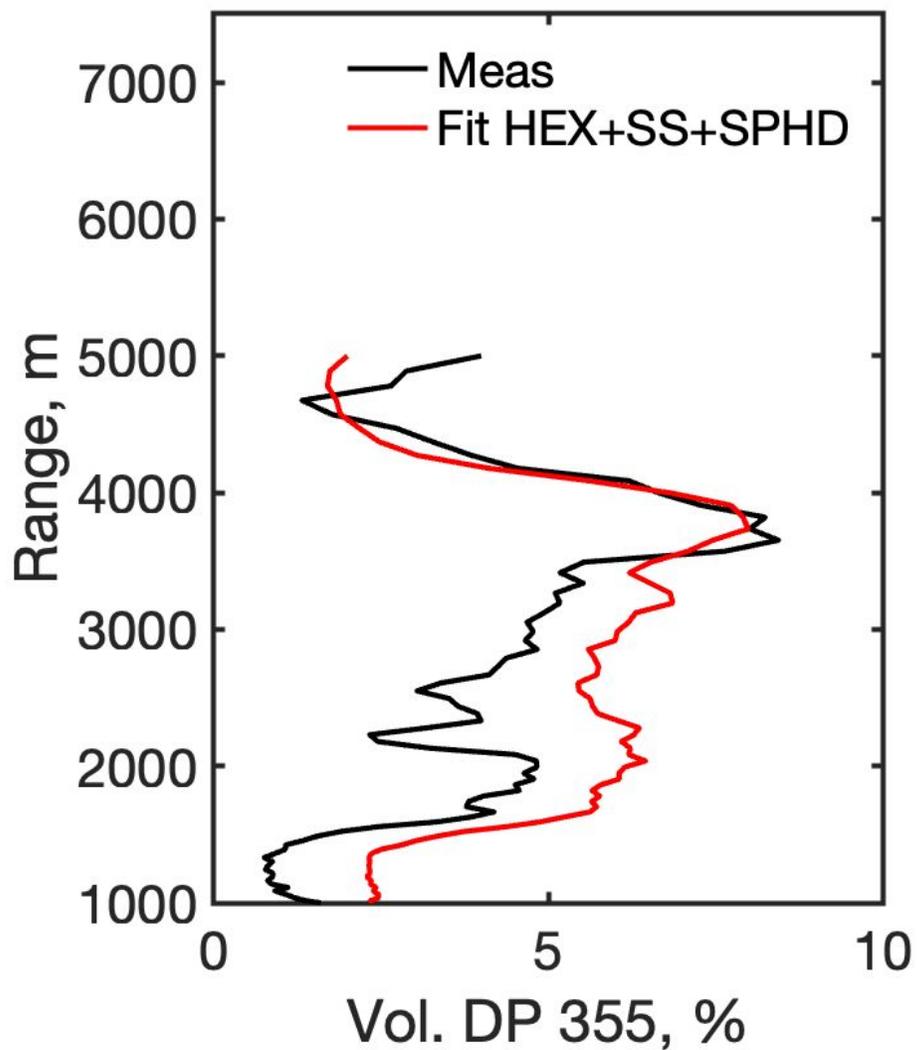
# Round 1: 5 model inversion, different non-spherical model



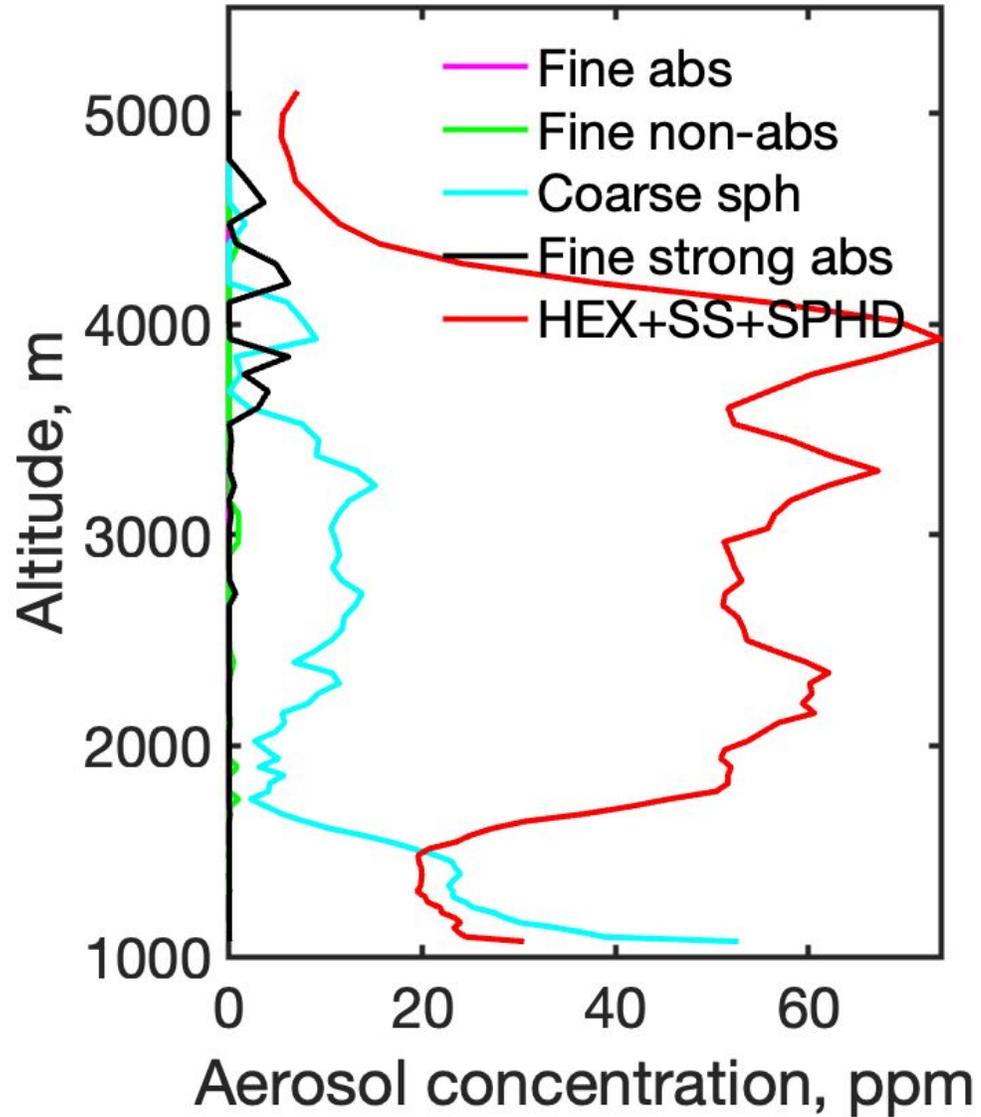
# Lidar: Round 1, Depolarisation



# Lidar: Round 2

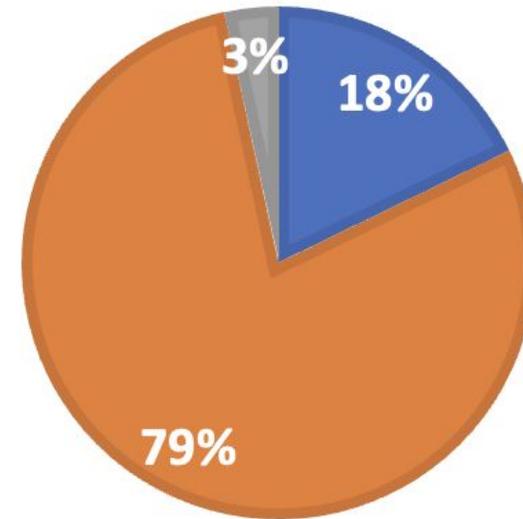


# Lidar: Round 2



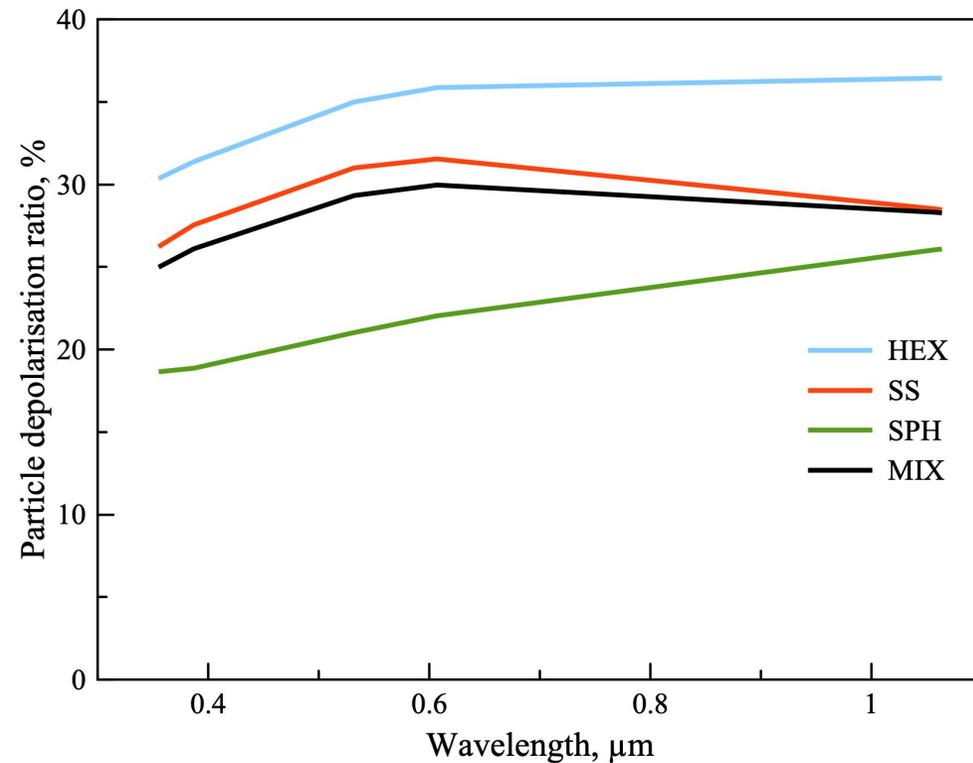
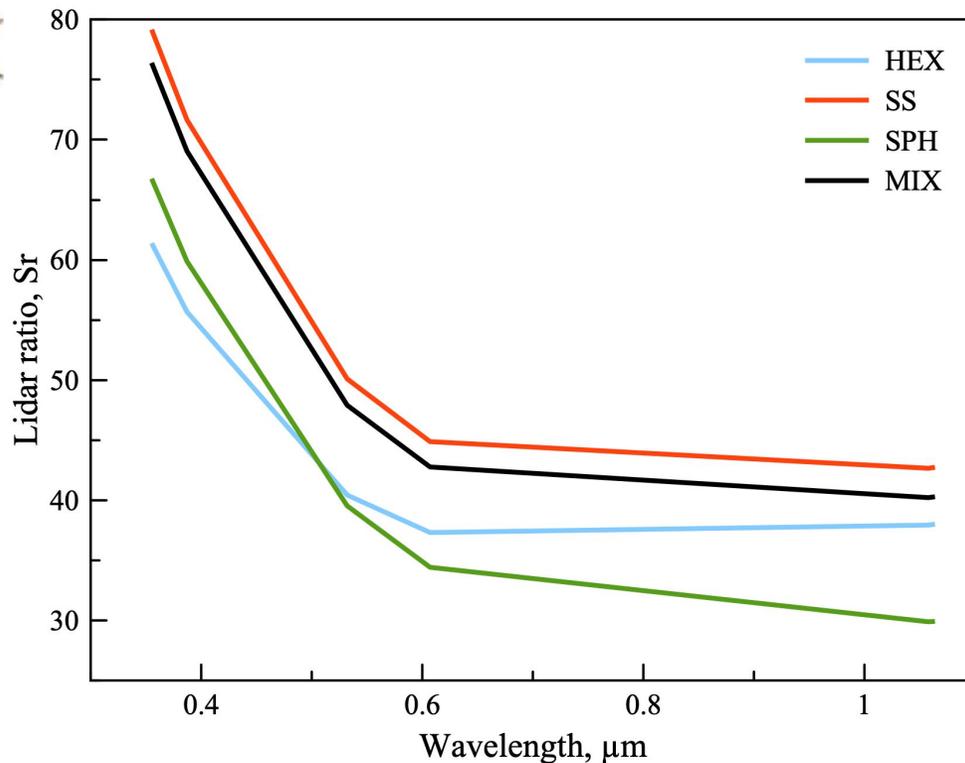
## COMBINED NON-SPHERICAL MODEL COMPOSITION

■ SPHD ■ SS ■ HEX



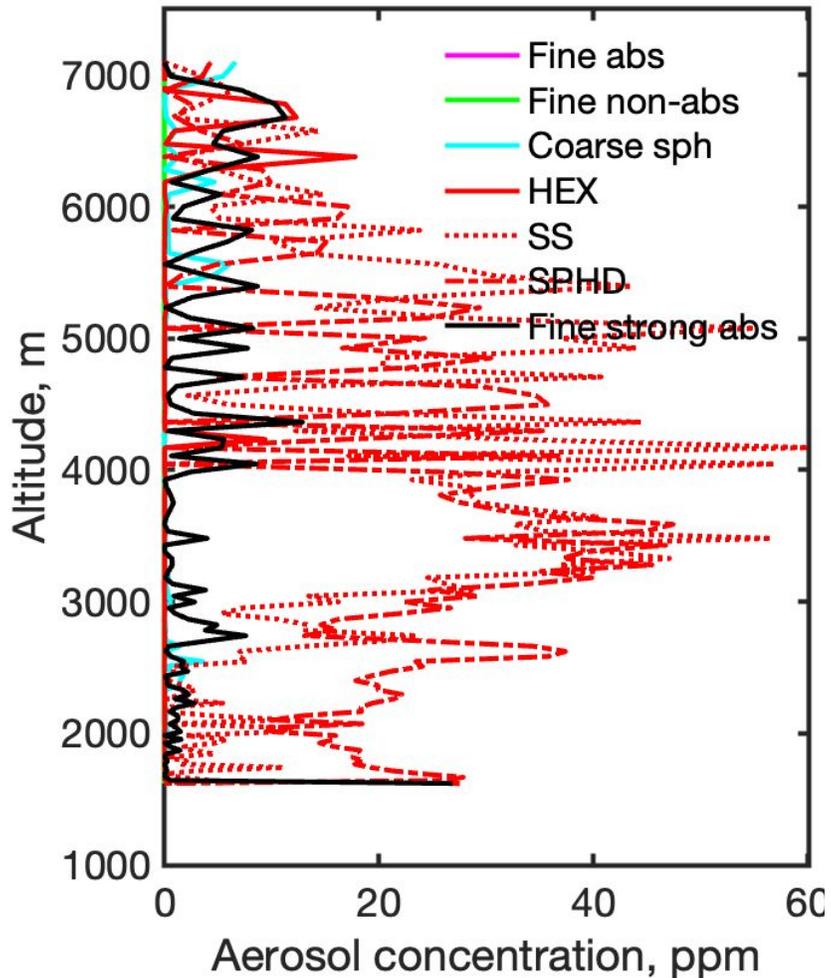
# Lidar round 1 & 2

	SPHD	SS	HEX	SPHD+SS+HEX
Volume depolarization	2.1	1.7	1.9	1.71
Elastic backscatter	16.27	11.50	11.84	11.20
Inelastic backsatter	2.67	1.073	1.069	1.01

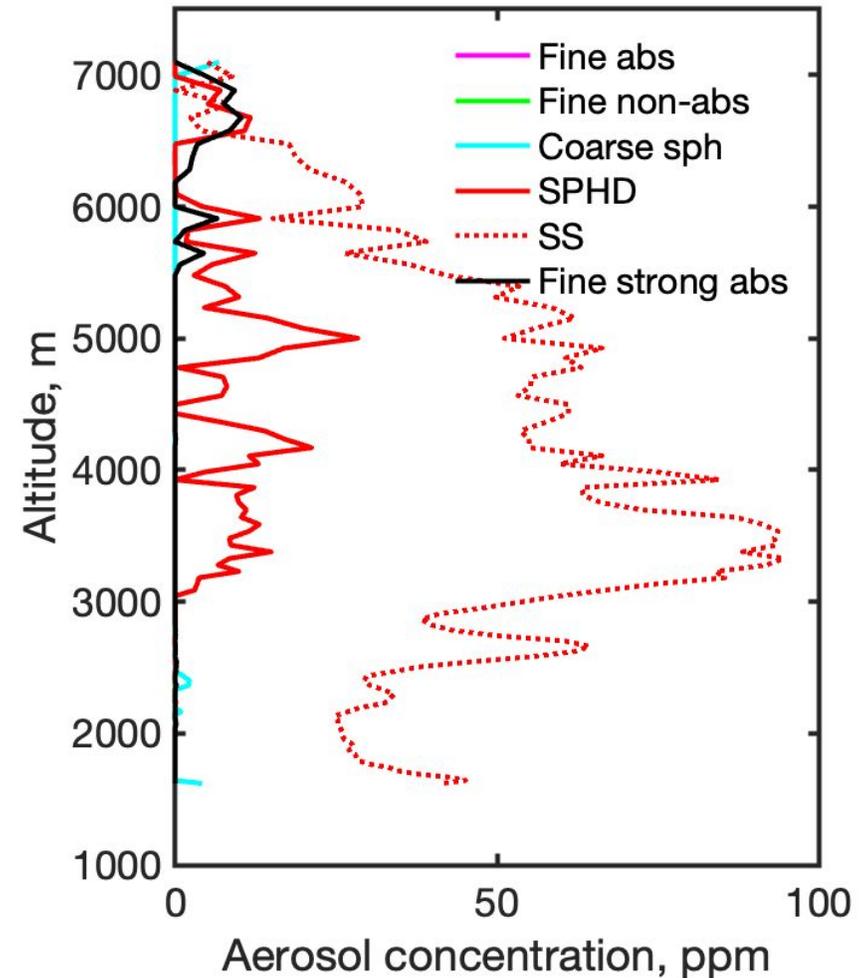


# Overtime! Round 1.5 “Battle royale”

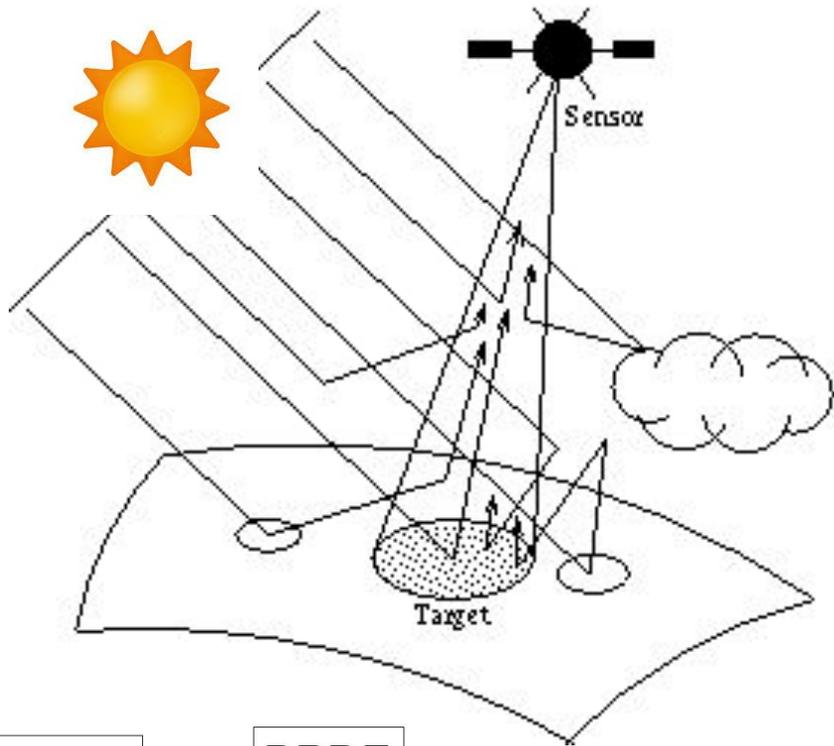
7 vertical profiles



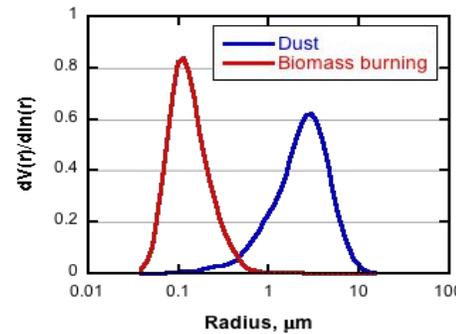
6 vertical profiles



# Orbital MAP: difficult to distinguish aerosol contribution in satellite observations

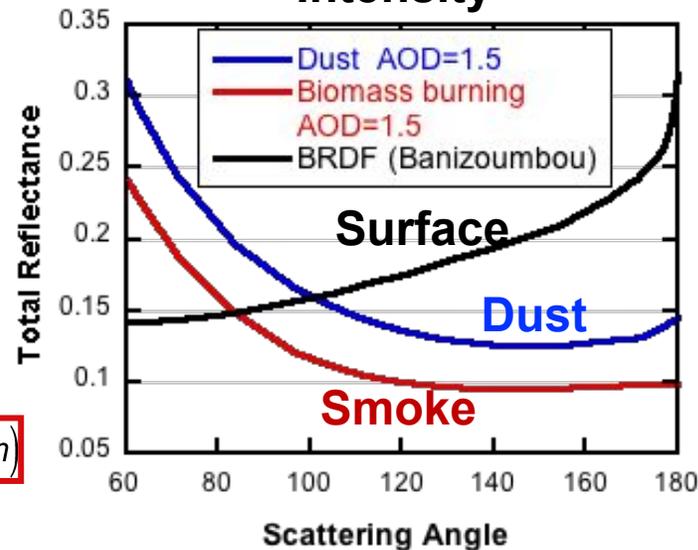


Sensitivity to aerosol vs surface

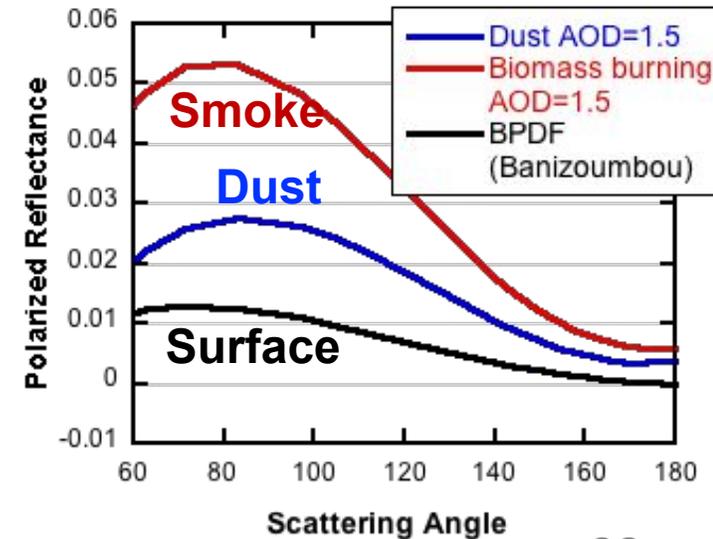


- Polarization helps with fine particles
- Less advantages for coarse particles

Intensity

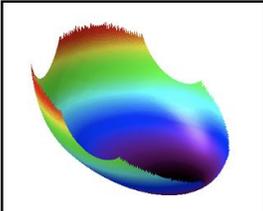
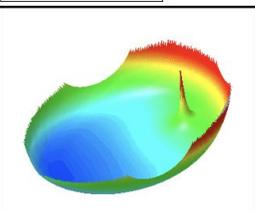


Polarization



BRDF

BPDF



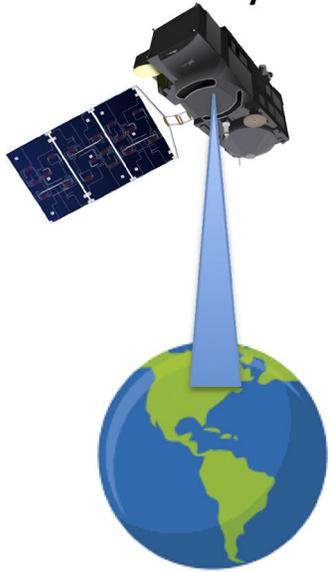
Surface Reflectance

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

# GRASP Synergetic Satellite + AERONET retrieval with GRASP

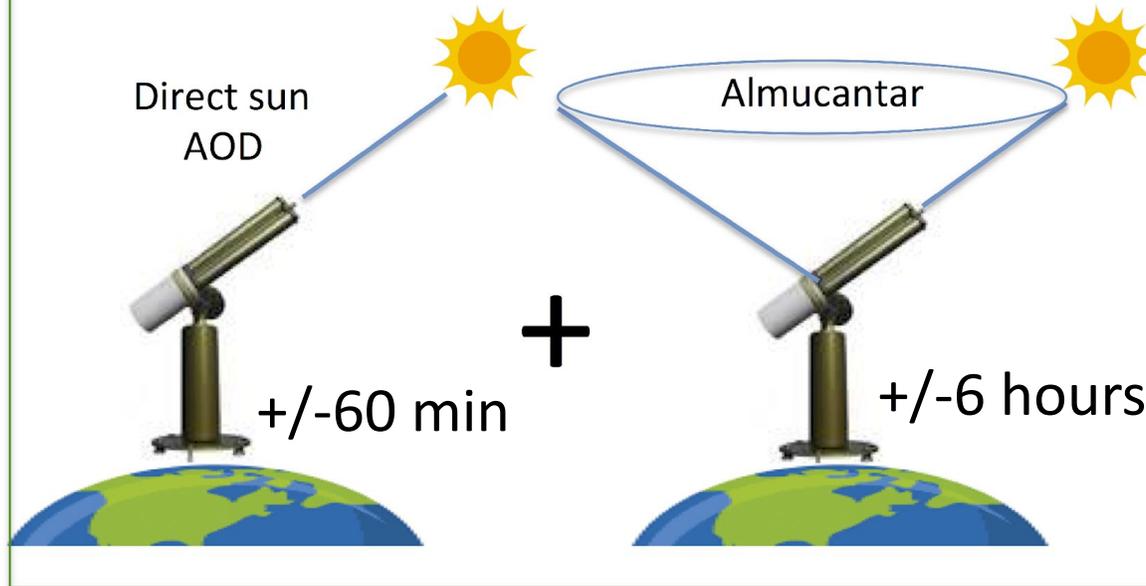
Satellite + Nearest AERONET TOD + Almuquantar (or Combined Almuquantar and Principal plane) measurements

Surface properties mainly



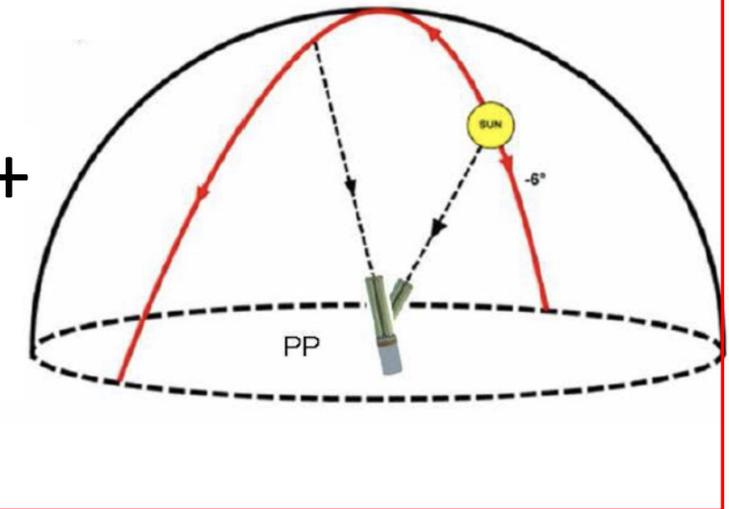
+

Aerosol properties mainly



+

Principal Plane



## Conditions:

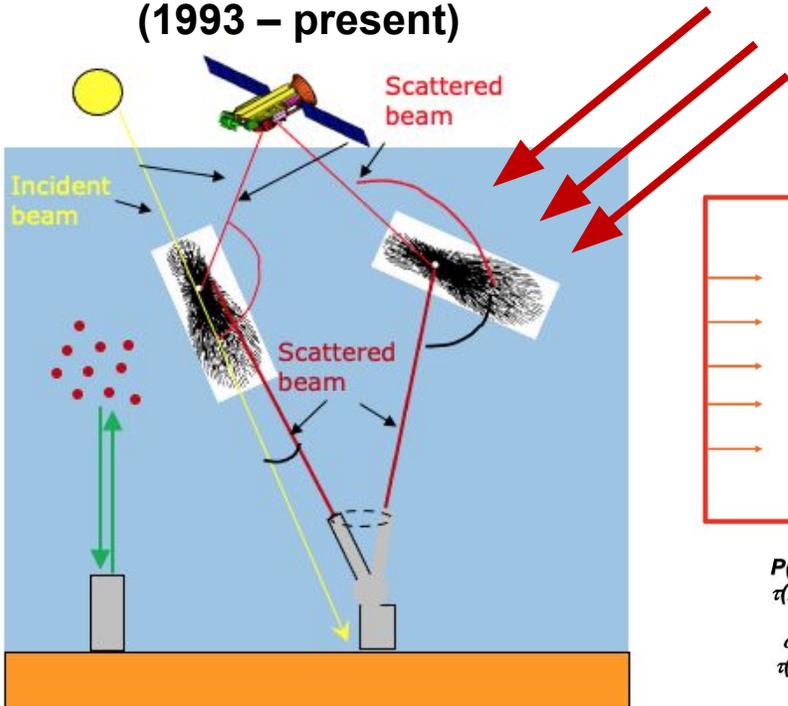
1. Reasonable fit of measurements (less than radiometric error).
2. Good correspondence of the retrieved aerosol properties with AERONET.
3. Instrument is well calibrated.

## New Possibilities:

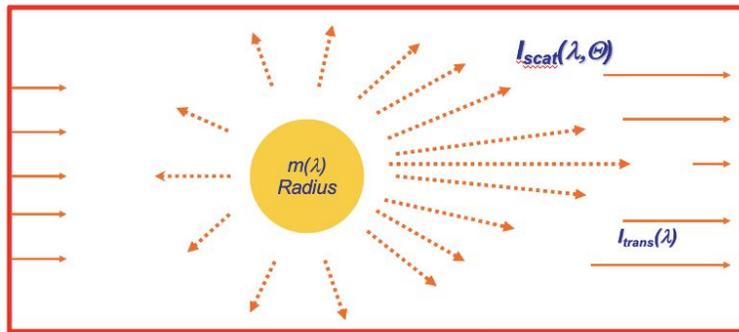
1. Validation tool for forward models of aerosol and surface
2. Surface Reference Database for surface validation
3. Instrument inter-calibration.

# Diffuse radiation observations

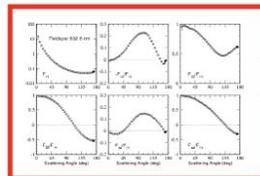
AERONET and NASA/GSFC  
(1993 – present)



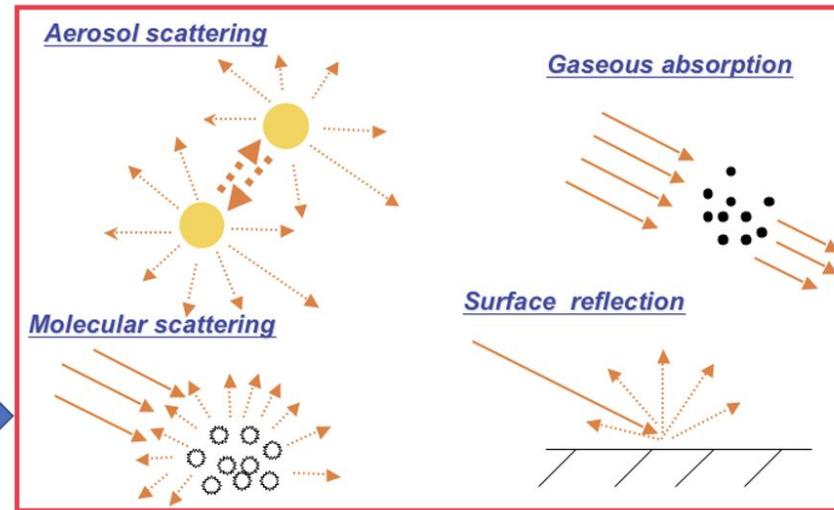
**Aerosol single scattering**



$\mathbf{P}(\Theta)$  - Phase Matrix;  
 $\tau(\lambda)$  - extinction optical thickness;  
 $\omega_0(\lambda)$  - single scattering albedo  
 $\tau(\lambda)\omega_0(\lambda)$  - scattering optical thickness



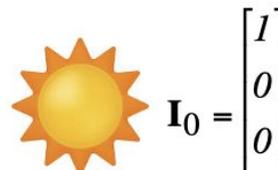
**Multiple scattering**



$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{\mu_0 (\exp(-\mu_0 \tau) - \exp(-\mu_1 \tau))}{\mu_0 + \mu_1} (\omega_0 \tau \mathbf{L}_2 \mathbf{P}(\Theta; \lambda) \mathbf{L}_1 \mathbf{I}_0 + \text{mult. scat.})$$

$$I(\Theta; \lambda) \sim (\omega_0 \tau \mathbf{F}_{11}(\Theta; \lambda) + \text{mult. scat.}) \quad \text{- Intensity}$$

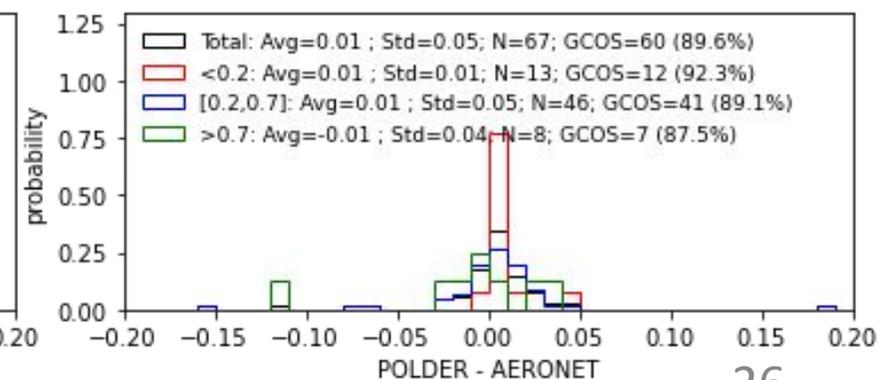
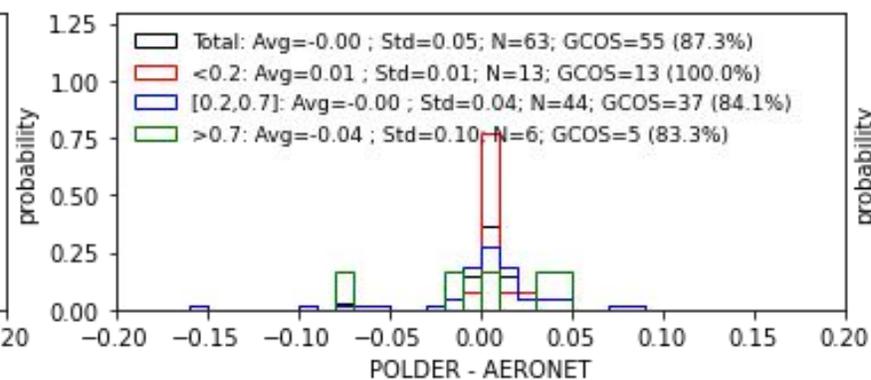
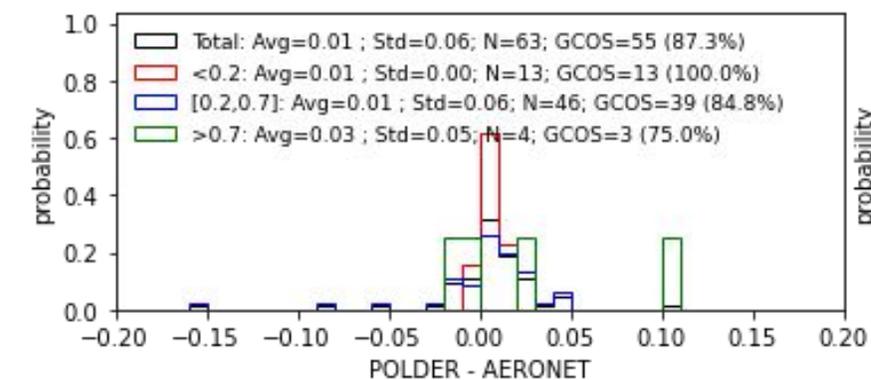
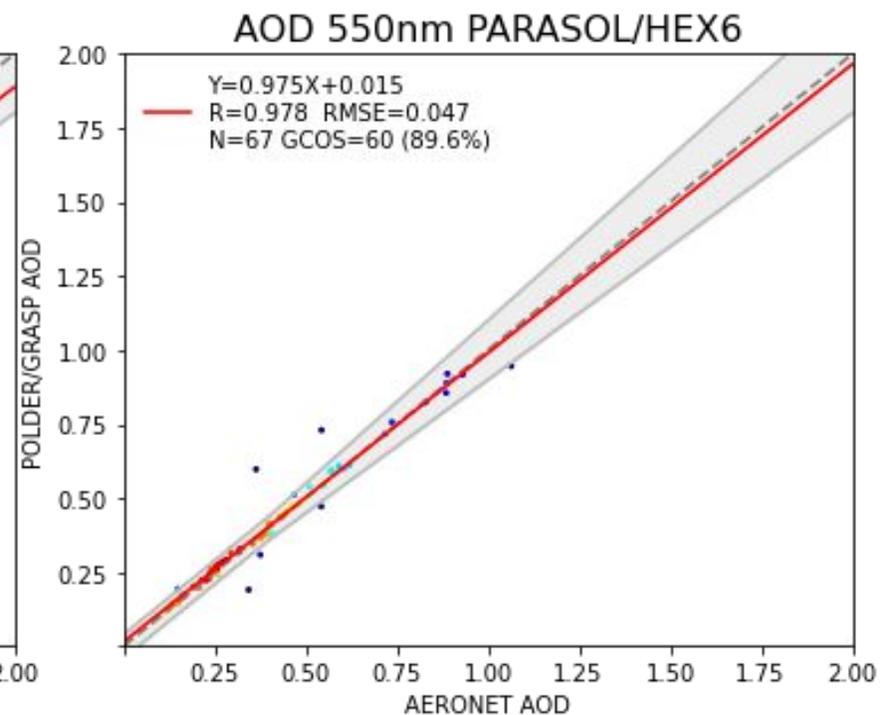
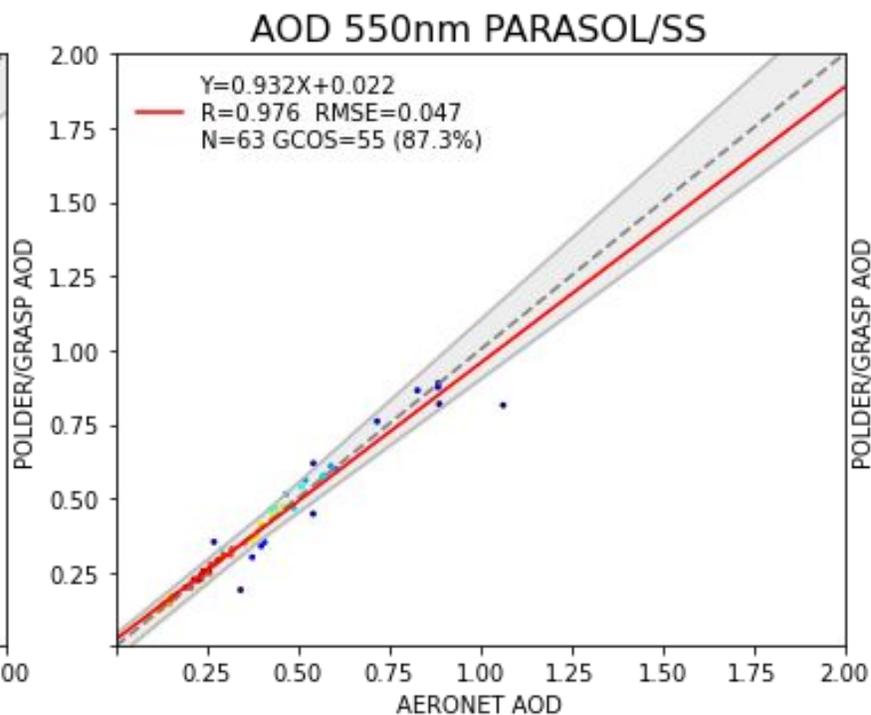
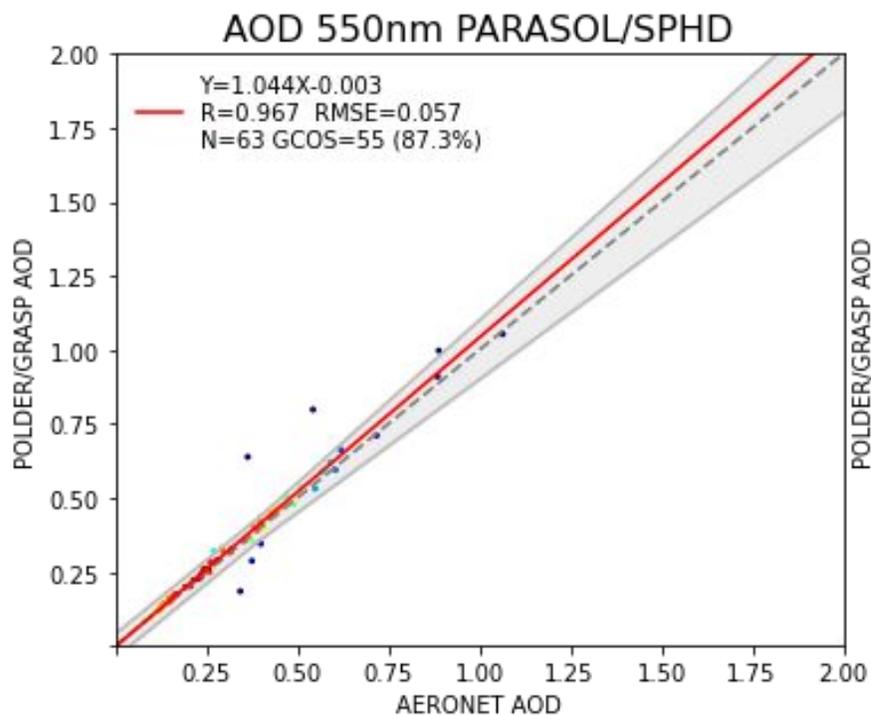
$$P(\Theta; \lambda) \sim (-\mathbf{F}_{12}(\Theta; \lambda) / \mathbf{F}_{11}(\Theta; \lambda) + \text{mult. scat.}) \quad \text{- Linear Polarization}$$



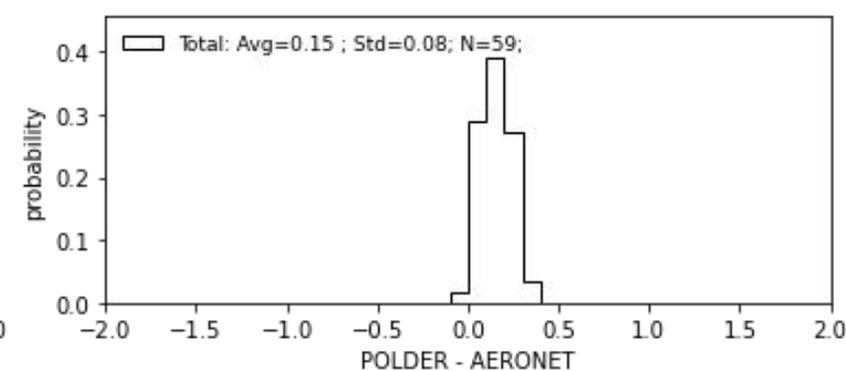
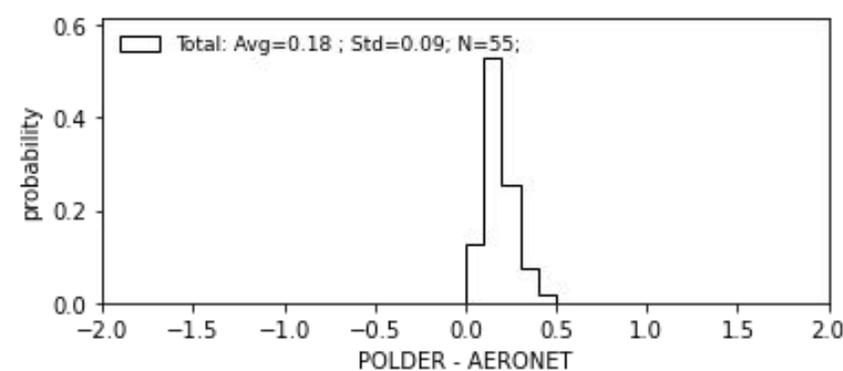
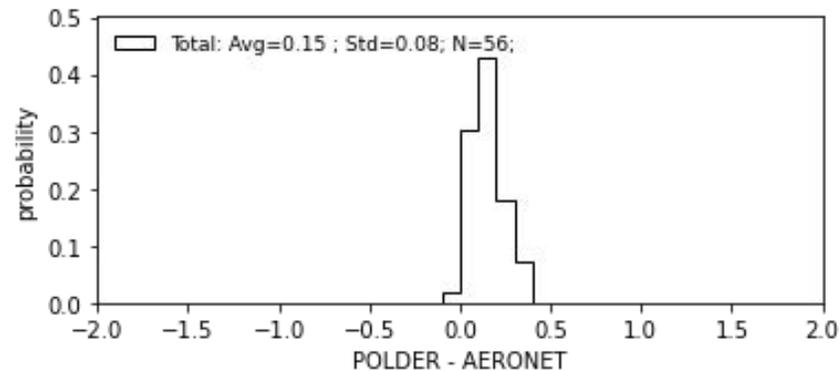
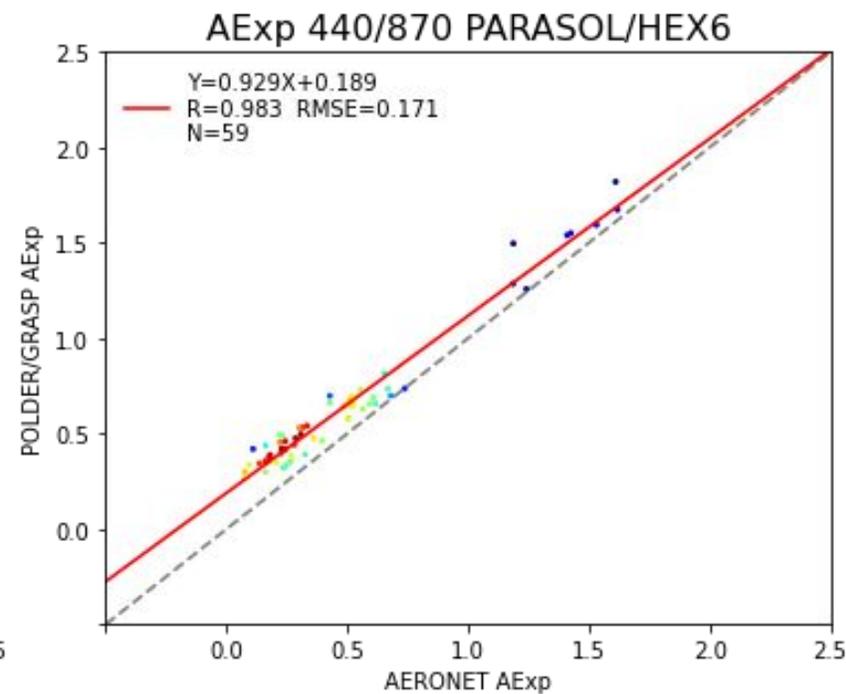
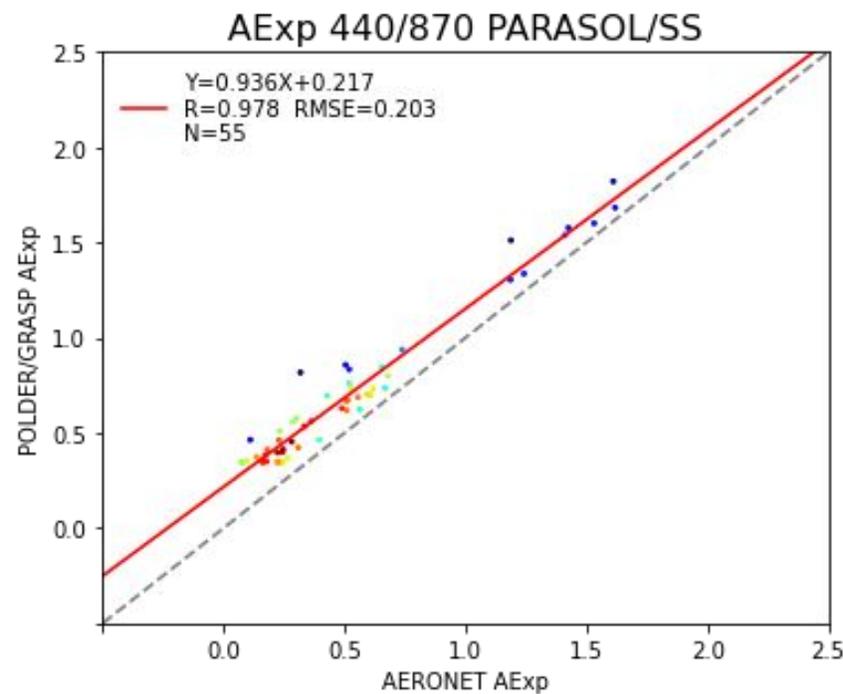
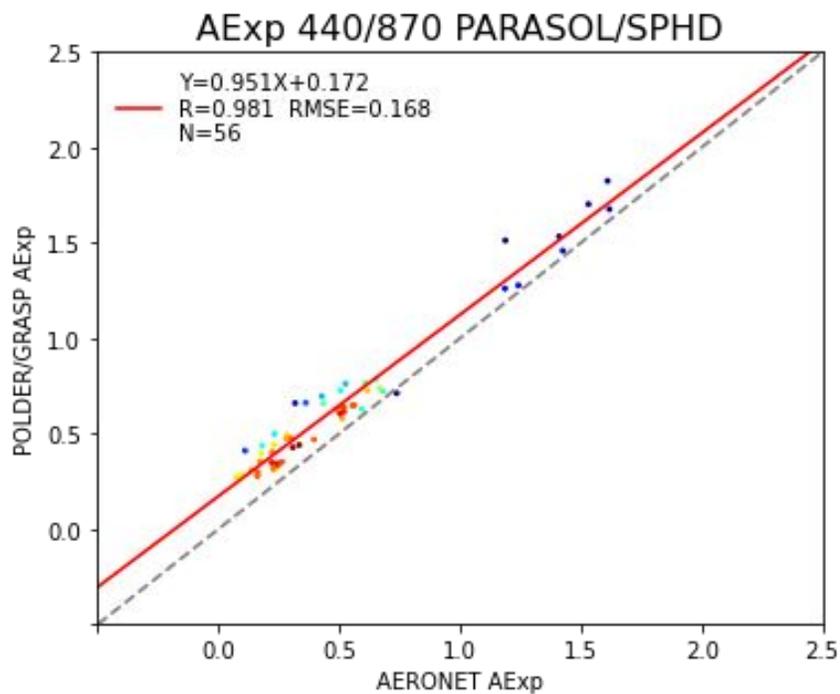
$$\mathbf{I}_0 = \begin{bmatrix} I \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



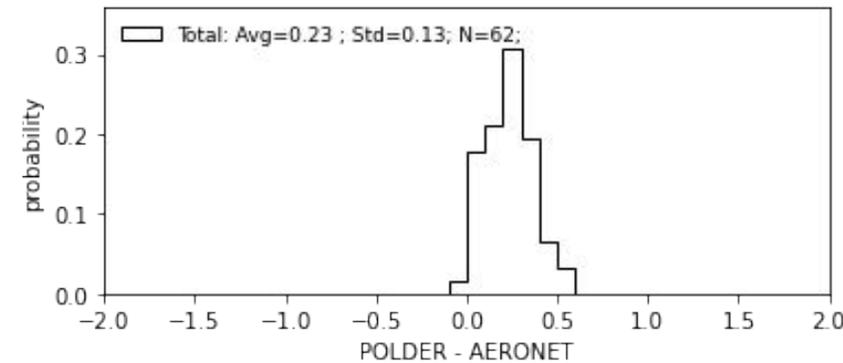
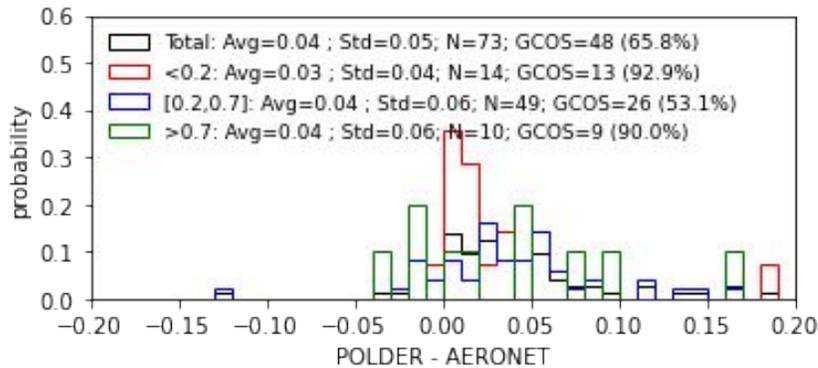
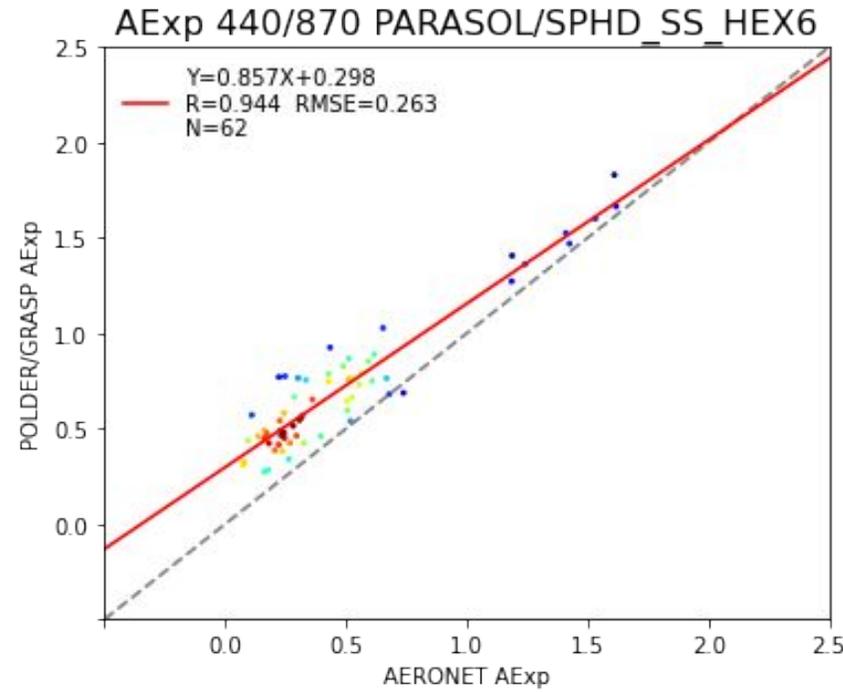
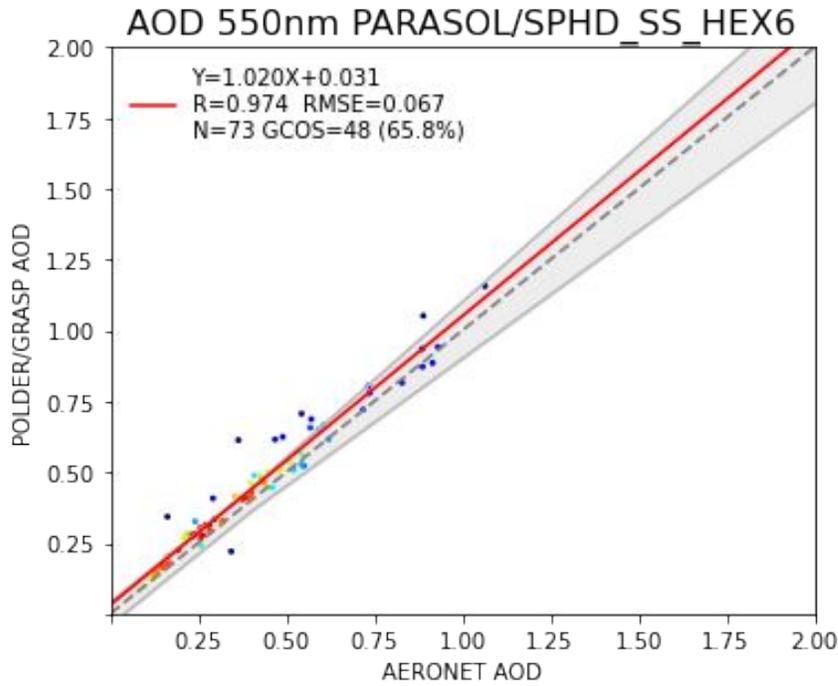
# POLDER+AERONET: Round 1



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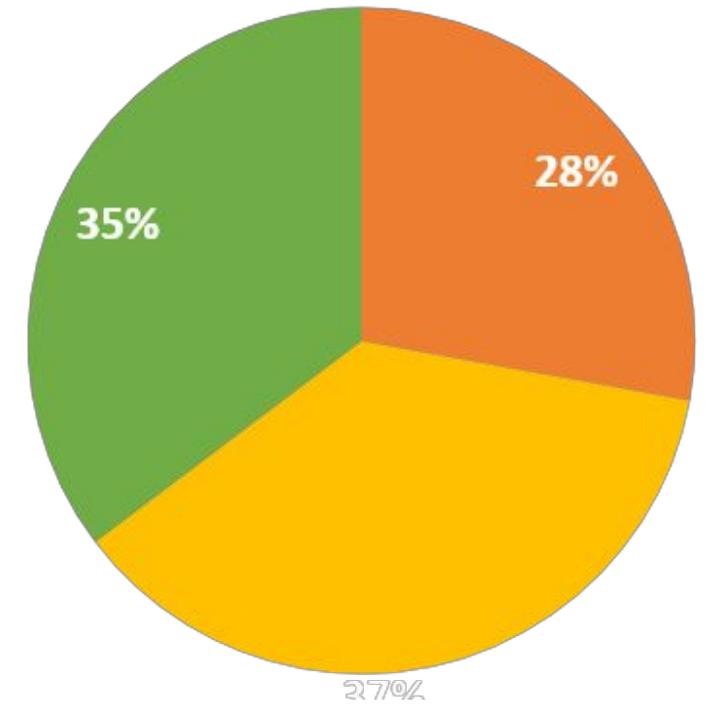


# POLDER+AERONET: Round 2



## Averaged dust composition

SPHD SS HEX



# POLDER+AERONET: Measurement Fits

Measurement	Spheroids (SPHD)	Super Spheroids (SS)	Hexaedrons (HEX6)	Mixture (SPHD+SS+HEX)
POLDER radiance	3.56 %	3.64 %	2.81%	3.47%
POLDER DOLP	0.0080	0.0075	0.0073	0.0078
AERONET AOD	0.0243	0.0290	0.0197	0.0382
AERONET radiance	11.82 %	14.67%	13.1%	13.05%

# Thank you!

Questions?