The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

2256-7

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

8 - 12 August 2011

Development of aerosol retrieval: Applications in ground-based remote sensing

O. Dubovik

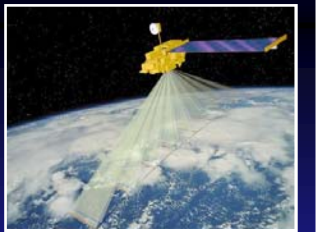
Lab. d'Optique Atmospherique, Lille, France

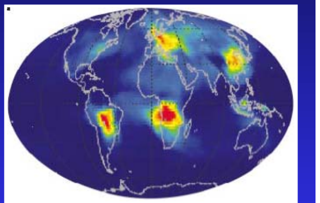
Remote sensing of atmospheric aerosols:

Oleg Dubovik

University of Lille 1, CNRS, France

NASA/GSFC, Greenbelt, USA





Part 1:

✧ ***aerosol remote sensing and climate - overview***

✧***remote sensing from ground: AERONET***

- *concept of retrieval;*
- *aerosol model;*
- *AERONET primary and secondary retrieval products*
- *error estimations, sensitivity studies*

Part 1:

✧ ***potential of remote sensing from space:***

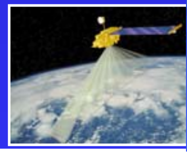
- *aerosol monitoring using satellite imagers:* **PARASOL**
- *synergy of remote sensing and modeling:* **inverse modeling**

Microphysical properties:
Concentration, sizes, composition, shapes, mixing, orientation, etc.

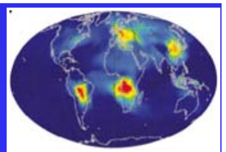
Theory of electromagnetic interactions of light with small particles, etc.

Remote sensing:

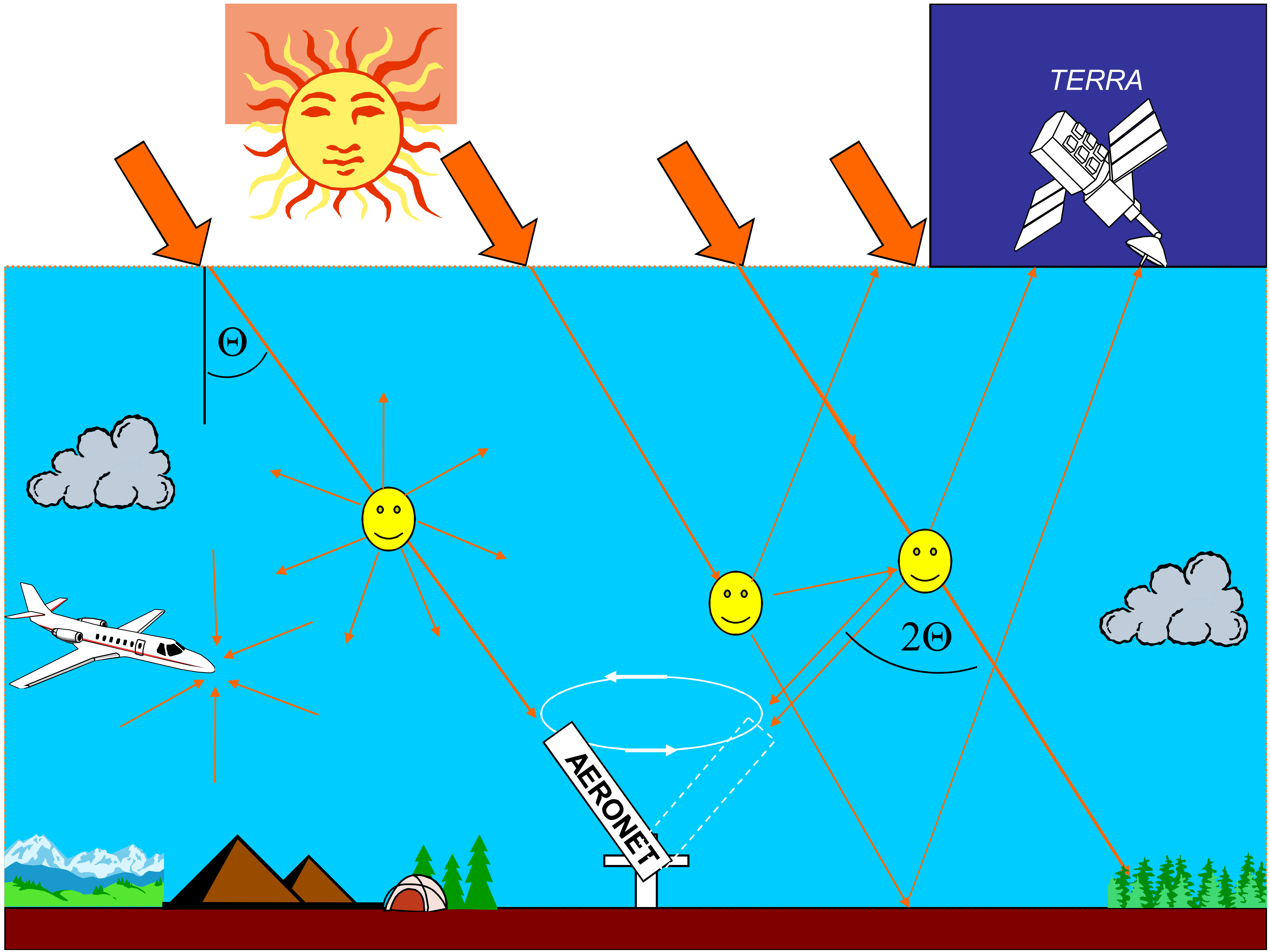
- passive,
- active,
- satellite,
- ground-based,
- airborne,
- etc.



Geophysical:
Spatial and temporal distributions of microphysical properties



Climate, Environment, etc. :
Heating, Cooling, Air Quality, etc



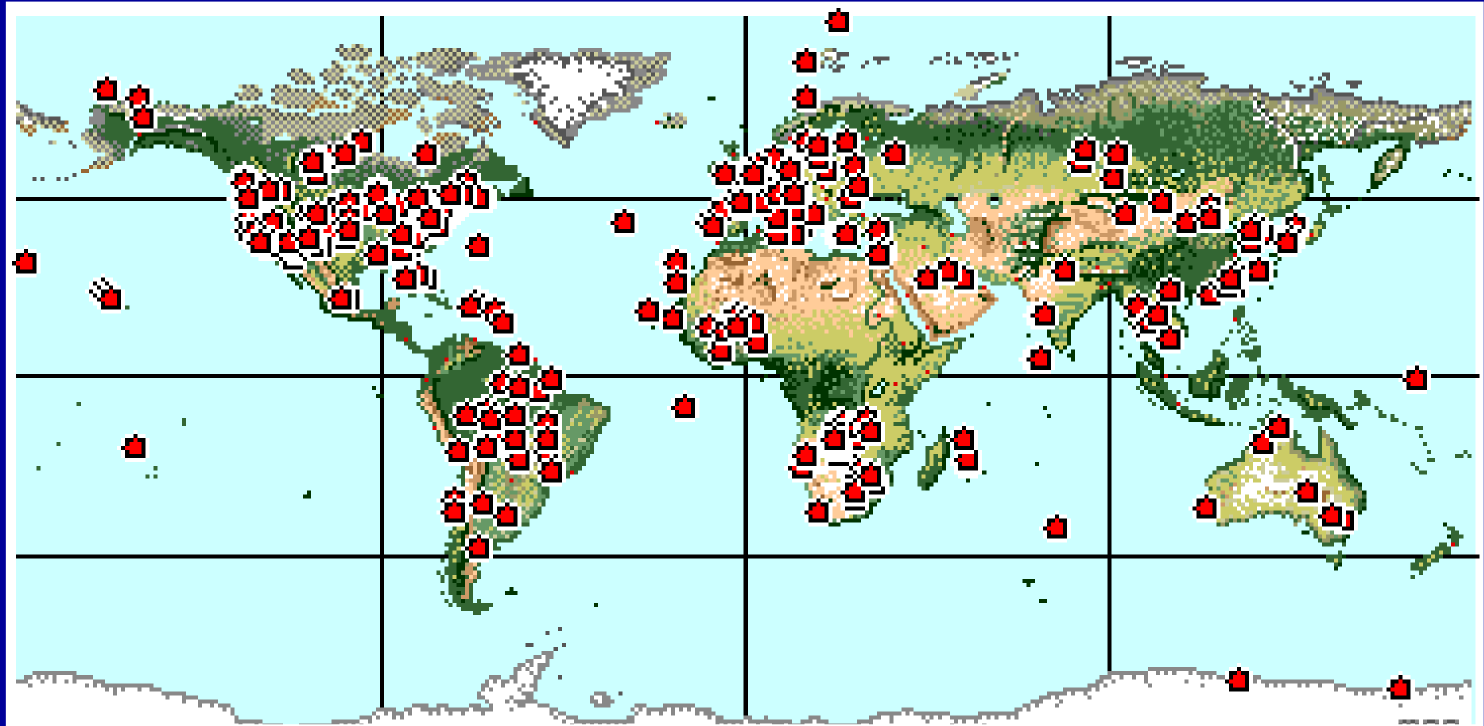
TERRA
Θ
2Θ
AERONET

AERONET (*AErosol RObotic NETwork*)-

An internationally Federated Network

1993-2003

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE



- *Characterization of aerosol optical properties*
- *Validation of satellite aerosol retrieval*
- *Near real-time acquisition; long term measurements*
- *Homepage access: http://aeronet.gsfc.nasa.gov*

Home | DATA | Operations | Installation/ Shipping | Site Photos | Field Campaigns | Aeronet Papers | Aerosol/Flux Networks | NASA Links | Site Outline | System Descripti

Data Display Controls

AERONET Data Type: ◉ AOT ○ Water Vapor
AOT Level: ◉ Level 1.0 ○ Level 1.5 ○ Level 2.0
Data Format: ○ Daily averages ◉ All points
Apply

Related Product Availability (select each day below):

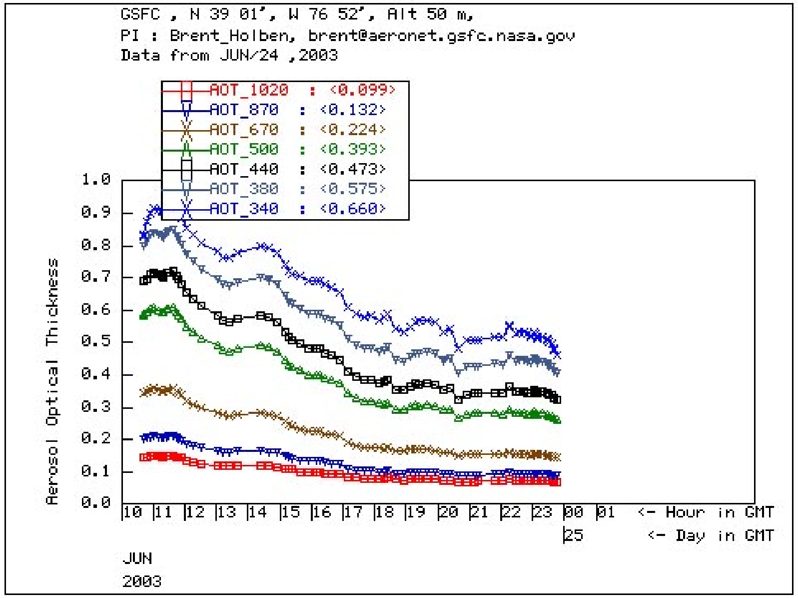
- Show Spherical OR Spheroid Almucantars
- Show Back Trajectories - Disclaimer
- Show MPLNET Images - Disclaimer
- MODIS Images (Not available)
- Visible Satellite Images (Not available)

Choose year :	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Choose month of 2003 :	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP		

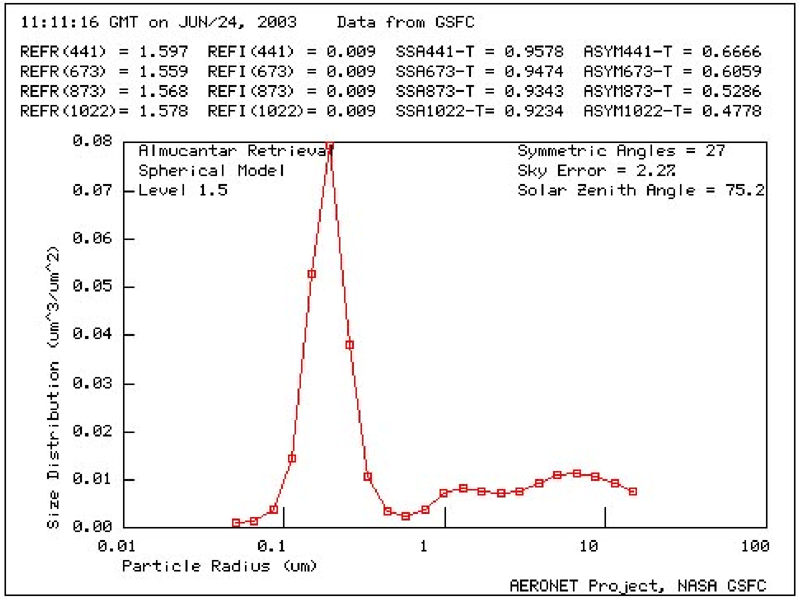
Choose day of JUN 2003

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30						

AOT Level 1.0 Data from JUN 24 of 2003



Level 1.5 Spherical Model Almucantar Retrieval No 1 on JUN 24 of 2003



Download Data for Capo_Verde

Select the start and end time of the data download period:

START:	1 JAN 1994	END:	1 JAN 2003

Data Descriptions Data Units Development Status Update Log

Note: Data are not available if the data type is *italicized*

Select the data type(s) with checkbox:

Aerosol Optical Thickness*:
1. ☐ Level 1.0 (Raw)
2. ☐ Level 1.5 (Cloud Screened)
3. ☐ Level 2.0 (Quality Assured)
*also WV and Angstrom Parameters
☐ Select All AOT

Raw Data (Calibration Applied):
4. ☐ Almucantars
5. ☐ Polar Principal Planes
6. *BRDF*
7. ☐ Principal Planes
☐ Select All Raw Data

Nakajima Almucantar Retrievals
8. ☐ SKYRAD.PAK

Almucantar Retrievals

Total Only
9. ☐ Size Distribution
10. ☐ Refractive Index
11. ☐ AOT Coincident
☐ Select All Retrievals

Total/Fine/Coarse Modes
12. ☐ Volume
13. ☐ AOT Absorption
14. ☐ AOT Extinction
15. ☐ SSA
16. ☐ Asymmetry Factor
17. ☐ Phase Functions
18. ☐ Combined Retrievals (9-16)

AERONET Data Flows

http://aeronet.gsfc.nasa.gov

Holben et al.
***RSE*, 1998**
Holben et al.
***JGR*, 2001**

Flux measurements

Direct - λ=340, 380, 440, 500, 670, 870, 940, 1020 nm
Diffuse - λ=440, 670, 870, 1020 nm (alm, pp, pol)

Calibration and processing information

Eck et al.
***JGR*, 1999**

Aerosol optical depth and precipitable water computations

Smirnov et al.
***RSE*, 2000**

Cloud screening and quality control

Dubovik and King
***JGR*, 2000**
Dubovik et al.
***JGR*, 2000**
***GRL*, 2002, 2006**

Inversion products

Volume size distribution (0.05<R<15 μm), refractive index, single scattering albedo (λ=440, 670, 870, 1020 nm), fraction of spherical particles

AERONET Inversion

Forward Model:

Single Scat: *ensemble of polydisperse randomly oriented spheroids*
(mixture of spherical and non-spherical aerosol components)

Multiple Scat: *(scalar) Nakajima and Tanaka, 1988, or*
(polarized) Lenouble et al., JQSRT, 2007

$\tau(\lambda)$, $I(\lambda,\Theta)$, $P(\lambda,\Theta)$

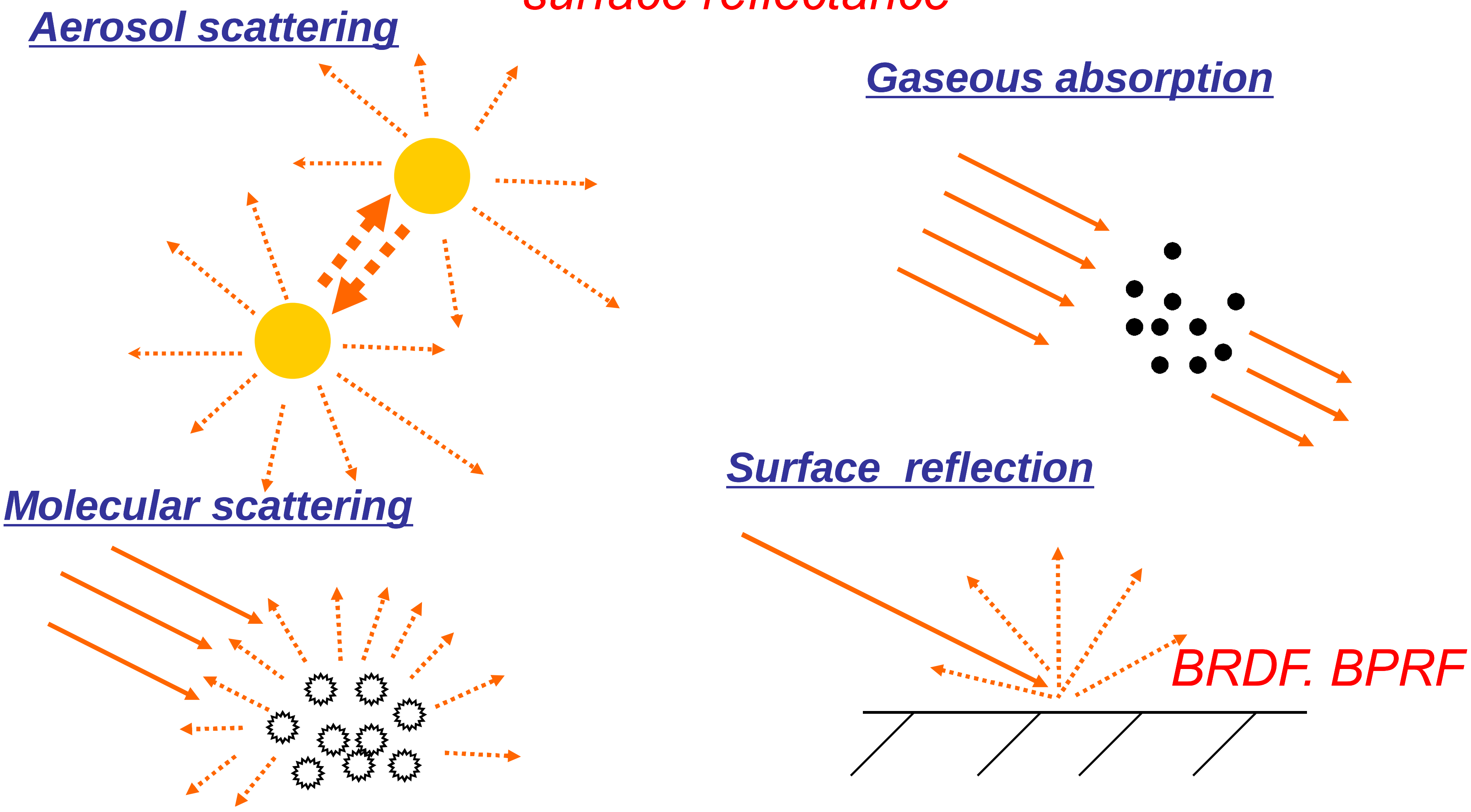
Optimized Numerical inversion:

- *Accounting for uncertainty* (F_{11}; $-F_{12}/F_{11}$!!!)
- *Setting a priori constraints*

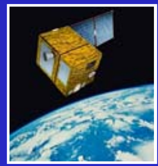
aerosol particle sizes,
complex refractive index (SSA),
Non-spherical fraction

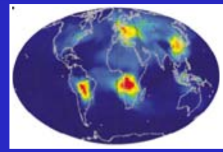
Multiple Scattering

Multiple scattering effects *are accounted by solving* *scalar* *or* *vector*
radiative transfer equation accounting for *BRDF* *or* *BPRF* *of* *surface reflectance*



Forward Model





Vector of retrieved parameters :

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

Fixed a priori:

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

$\mathbf{a}^{aer}$

$\mathbf{a}^{surf}$

Aerosol single scattering :

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

Surface reflectance :

Bi-directional Reflection Distribution Function (BRDF)

Bi-directional Polarization Distribution Function (BPDF)

τ, ω_0, $P_{ii}(\ldots)$

BRDF, BPDF

Full radiative transfer model :

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

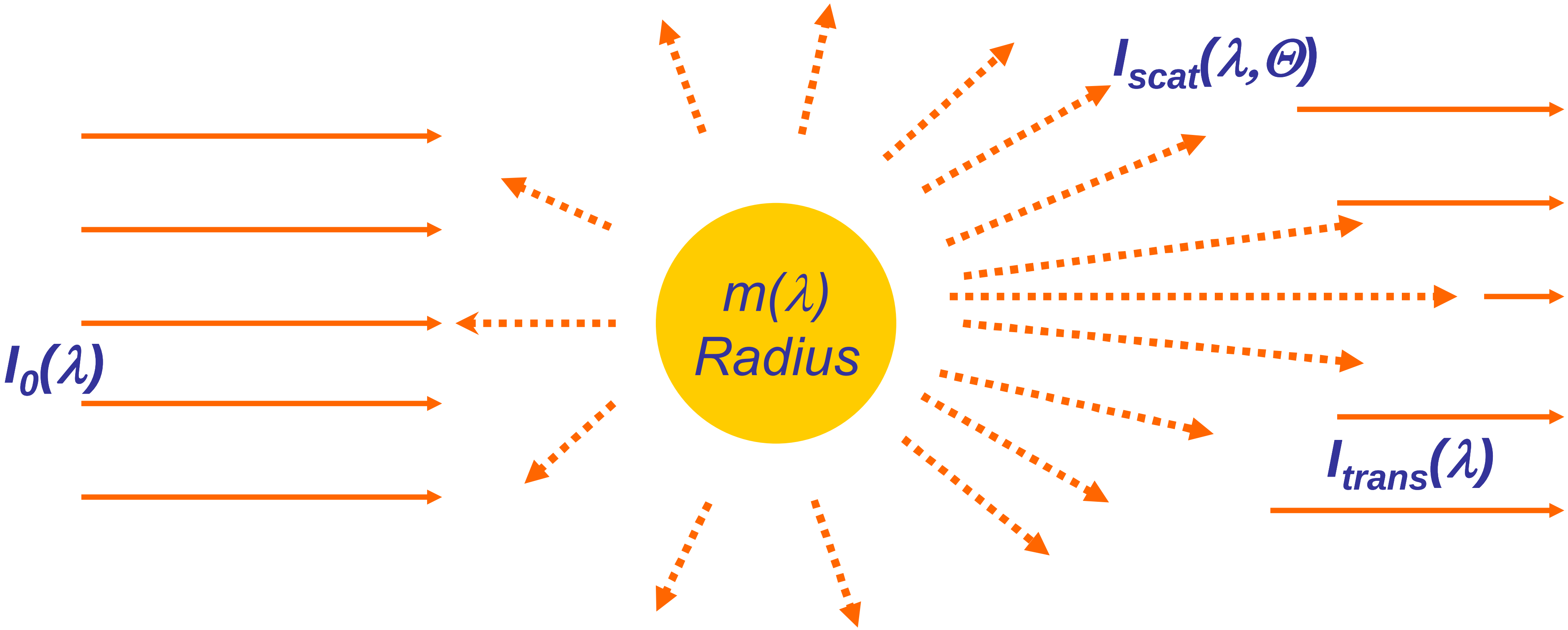
fixed a priori :

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

Simulated **AERONET** *observations:* $\boldsymbol{f}(\mathbf{a}^p)$

Single Scattering by Single Particle

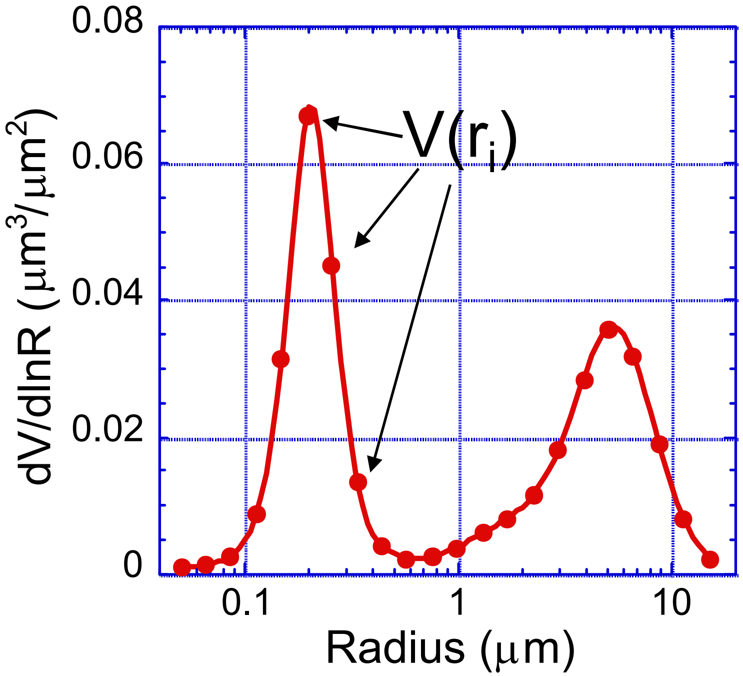
Scattering and Absorption *is modeled assuming aerosol particle as homogeneous sphere with spectrally dependent complex refractive index ($m(\lambda)= n(\lambda) - i\,k(\lambda)$) - "Mie particles"*

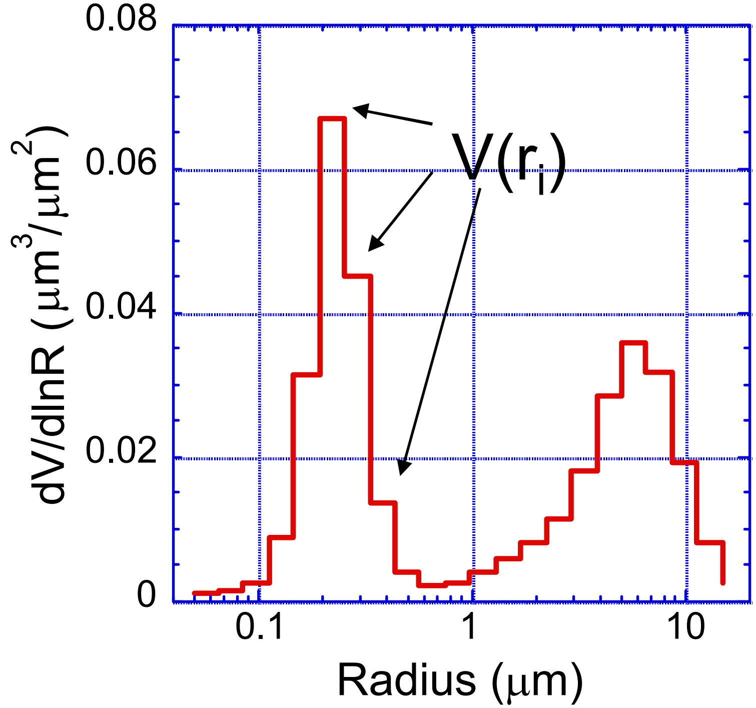


$P_{ii}(\Theta)$- Phase Matrix; ***$\omega_0(\lambda)$ -single scattering albedo***

$\tau(\lambda)$ - extinction optical thickness; ***$\tau(\lambda)\omega_0(\lambda)$ absorption optical thickness***

Modeling Polydispersions





$$\tau(\lambda) = \int_{r_{min}}^{r_{max}} K_\tau(\lambda;k;n;r)V(r)dr \approx \sum V(r_i) \int_{r_i-\Delta/2}^{r_i+\Delta/2} K_\tau(\lambda;k;n;r)dr$$

$\boxed{\mathbf{K}(\lambda;k;n;r_i)}$ - Kernel look-up table for fixed r_i (22 points) ($1.33 \le n \le 1.7$; $0.0 \le k \le 0.5$)

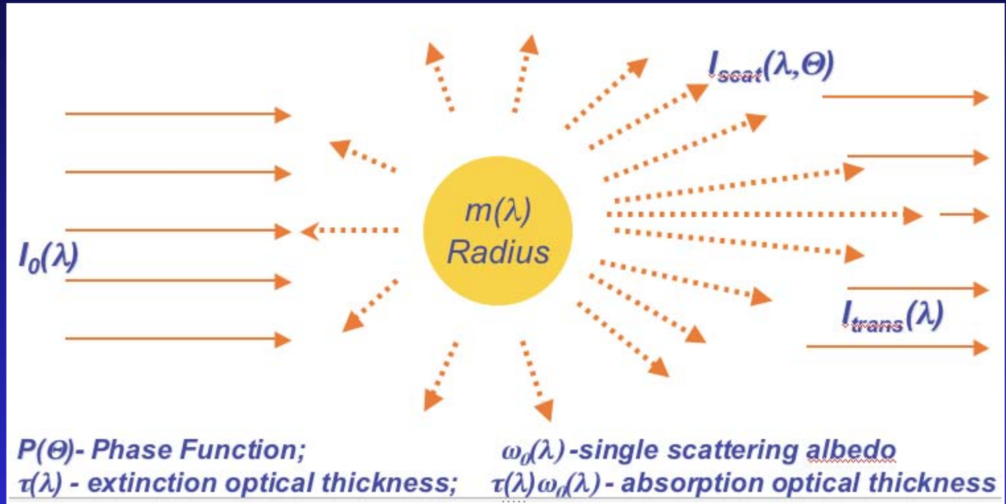
Aerosol single particle scattering:

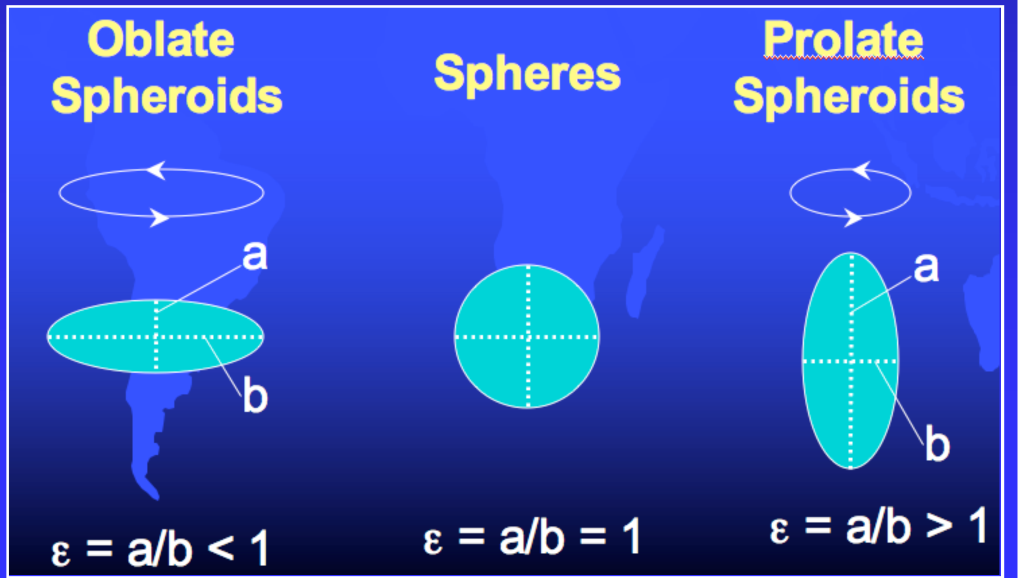
ASSUMPTIONS in the retrievals:

EACH AEROSOL PARTICLE

- <u>sphere or spheroid (!!!);</u>
- homogeneous;
- $1.33 \leq n \leq 1.7$
- $0.0 \leq k \leq 0.5$

-n and k spectrally dependent *<u>(but smooth)</u>*

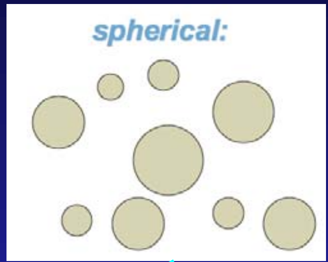




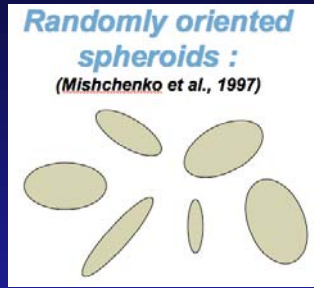
Mixing of particle shapes

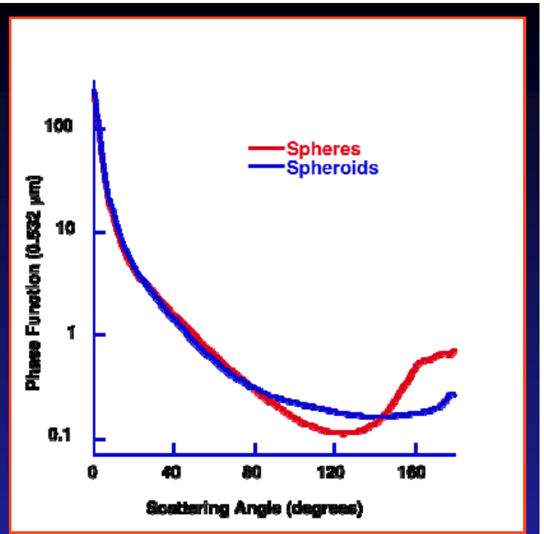
retrieved

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:

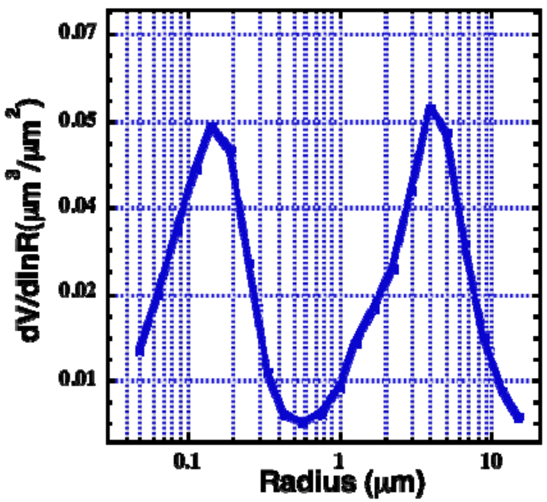
- dV/dlnr - volume size distribution is the same for both components;
- non-spherical - mixture of randomly oriented polydisperse spheroids;
- aspect ratio distribution $N(\varepsilon)$ is fixed to the retrieved by Dubovik et al. 2006

Aerosol is driven by 31 variables in AERONET retrieval :

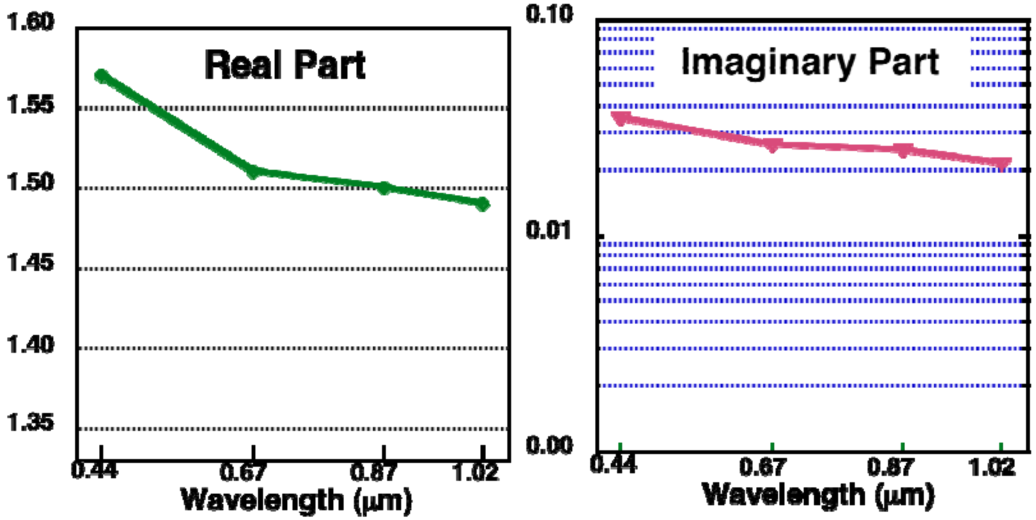
dV/lnr - size distribution (~22 values);
n(λ) and k(λ) - ref. index (4 +4 values)
C_{spher} (%) - spherical fraction (1 value)

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



Inversion strategy

More details are given in paper:
Dubovik and King [2000],
" A flexible algorithm …"

Principles of statistical optimization:

- all data (measured and a priori) are considered as multi-source data with known accuracy;

- the inversion is a search for the best fit of all data by forward model that accounts for the accuracy levels of the fitted data;

Multi-source data include:

1. Measurements:

- spectral optical thickness;
- angular distribution of sky-radiance;

2. *A priori* smoothness constraints on

- particle size distribution;
- spectral dependence of the real part of the index of refraction;
- spectral dependence of the imaginary part of the index of refraction;

Multi-Term LSM

(e.g. see Dubovik and King 2000, Dubovik 2004)

Multi-sensor data

sensor 1

sensor 2

Independent !!!

$$\begin{cases} \boldsymbol{f}_1^* = \mathbf{F}_1\, \boldsymbol{a} + \Delta_1 \\ \boldsymbol{f}_2^* = \mathbf{F}_2\, \boldsymbol{a} + \Delta_2 \\ \ldots \end{cases}$$

$$\boxed{\hat{\boldsymbol{a}} = \left(\mathbf{F}_1^T\mathbf{C}_1^{-1}\mathbf{F}_1 + \mathbf{F}_2^T\mathbf{C}_2^{-1}\mathbf{F}_2 + \ldots\right)^{-1}\left(\mathbf{F}_1^T\mathbf{C}_1^{-1}\boldsymbol{f}_1^* + \mathbf{F}_2^T\mathbf{C}_2^{-1}\boldsymbol{f}_2^* + \ldots\right)}$$

Single-sensor data

sensor

a priori

$$\begin{cases} \boldsymbol{f}^* = \mathbf{F}\, \boldsymbol{a} + \Delta_f \\ \boldsymbol{a}^* = \boldsymbol{a} + \Delta_a \end{cases}$$

$$\boxed{\hat{\boldsymbol{a}} = \left(\mathbf{F}^T\mathbf{C}_f^{-1}\mathbf{F} + \mathbf{C}_a^{-1}\right)^{-1}\left(\mathbf{F}^T\mathbf{C}_f^{-1}\boldsymbol{f}^* + \mathbf{C}_a^{-1}\, a^*\right)}$$

"Optimum Estimations" by Rodgers
Levenberg-Marquardt
Maximum Entropy Method
Kalman Filter …,
4D Variational Assimilation (4DVR)
…
Phillips – Tikhonov - Twomey

Multi-sensor data

Multi-Term LSM

(e.g. see Dubovik 2004)

sensor 1

sensor 2

Independent !!!

$$\begin{cases} \boldsymbol{f}_1^* = \mathbf{F}_1\, \boldsymbol{a} + \Delta_1 \\ \boldsymbol{f}_2^* = \mathbf{F}_2\, \boldsymbol{a} + \Delta_2 \\ \dots \end{cases}$$

$$\boxed{\hat{\boldsymbol{a}} = \left(\mathbf{F}_1^T \mathbf{C}_1^{-1} \mathbf{F}_1 + \mathbf{F}_2^T \mathbf{C}_2^{-1} \mathbf{F}_2 + \dots\right)^{-1} \left(\mathbf{F}_1^T \mathbf{C}_1^{-1} \boldsymbol{f}_1^* + \mathbf{F}_2^T \mathbf{C}_2^{-1} \boldsymbol{f}_2^* + \dots\right)}$$

Single-sensor data

sensor

a priori

$$\begin{cases} \boldsymbol{f}_1^\bullet = \boldsymbol{f}^* = \mathbf{F}\, \boldsymbol{a} + \Delta_f \\ \boldsymbol{f}_2^\bullet = \boldsymbol{0}^* = \mathbf{S}\boldsymbol{a} + \Delta(\Delta \boldsymbol{a}) \end{cases}$$

$$\boxed{\hat{\boldsymbol{a}} = \left(\mathbf{F}^T \mathbf{C}_f^{-1} \mathbf{F} + \mathbf{S}^T \mathbf{S}\right)^{-1} \left(\mathbf{F}^T \mathbf{C}_f^{-1} \boldsymbol{f}^*\right)}$$

Phillips-Tikhonov-Twomey formula

A priori restrictions on smoothness

A priori equation system

Normally distributed errors with variance ε_i^2

$$\mathbf{0}^* = (\Delta \mathbf{a})^* = \mathbf{Sa} + \Delta(\Delta \mathbf{a})$$

$$\frac{\partial V(a)}{\partial a} =$$

Coefficients of differences/derivatives:

e.g. for second dif. (k=2),

$$\Delta^2 = (\hat{a}_{i+2} - \hat{a}_{i+1}) - (\hat{a}_{i+1} - \hat{a}_{I}) = \hat{a}_{i+2} - 2\,\hat{a}_{i+1} + \hat{a}_{I}:$$

$$\mathbf{S}_2 = \begin{pmatrix} 1 & -2 & 1 & 0 & \ldots & & & \\ 0 & 1 & -2 & 1 & 0 & \ldots & & \\ 0 & 0 & 1 & -2 & 1 & 0 & \ldots & \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & 0 & 1 & -2 & 1 \end{pmatrix}$$

Statistically Optimized Minimization - Fitting

POLDER/PARASOL

$$\hat{a} = \left(F_1^T C_1^{-1} F_1 + F_2^T C_2^{-1} F_2 + \ldots\right)^{-1} \left(F_1^T C_1^{-1} f_1^* + F_2^T C_2^{-1} f_2^* + \ldots\right)$$

Measurements:

-their covariances

(should depend on λ and Θ)

-lognormal error distributions

a priori *restrictions on*

norms of derivatives of:

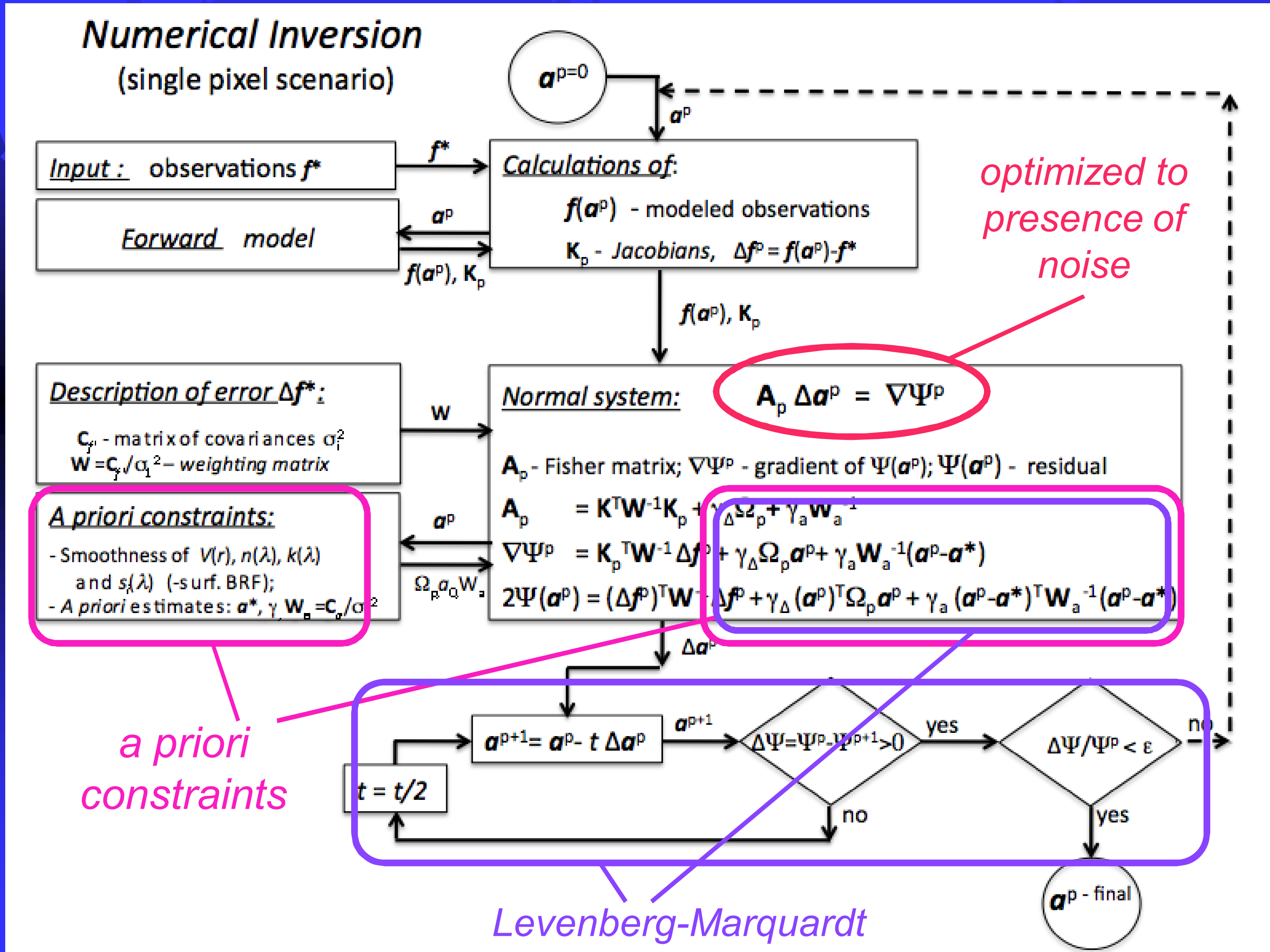
i=2 ***-size distr.*** ***variability;***

i=3 ***-n spectral variability;***

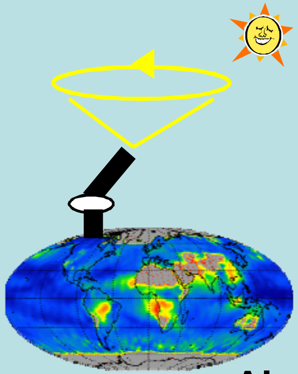
i=4 ***-k spectral variability;***

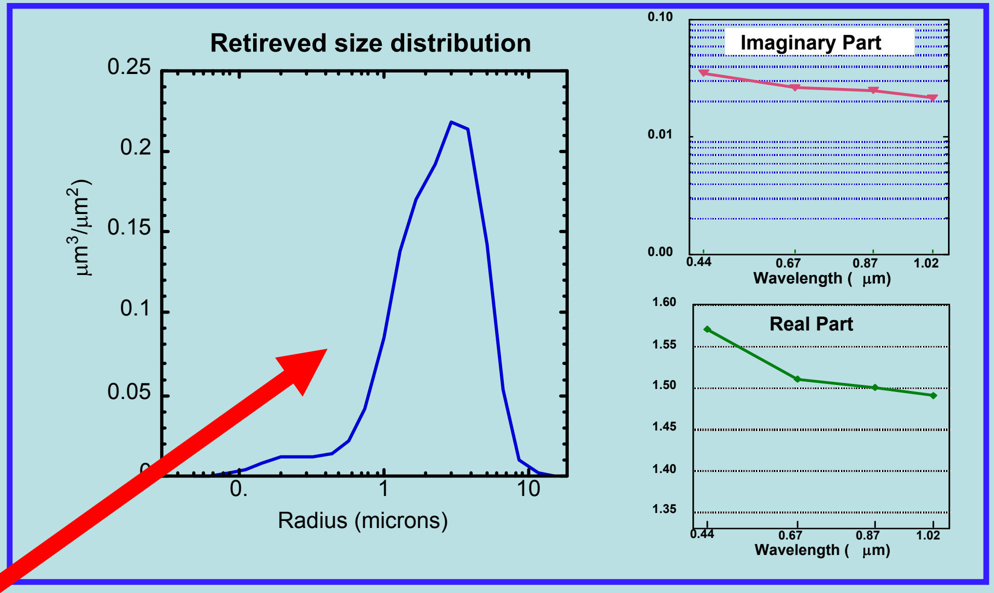
« AERONET like » statistically optimized « no look-up tables » inversion

Dubovik et al., AMT, 2011

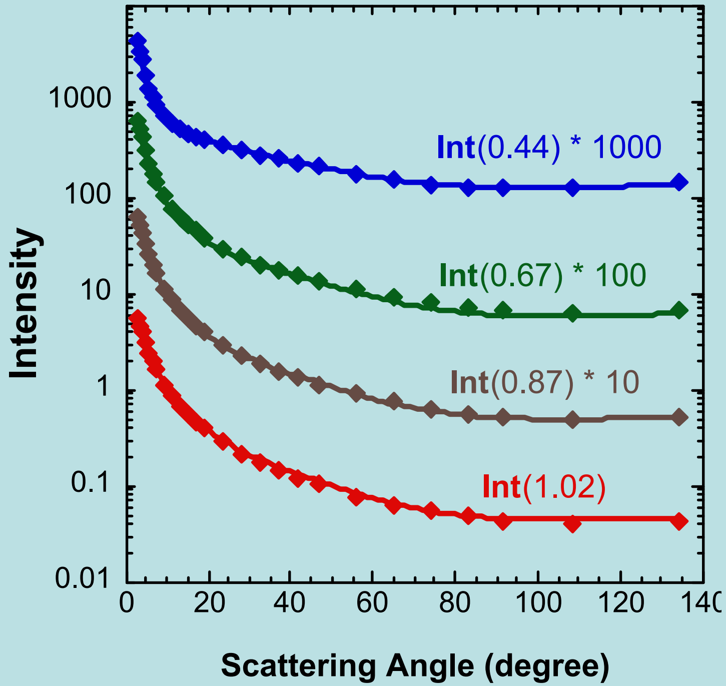


Fitting as a retrieval strategy

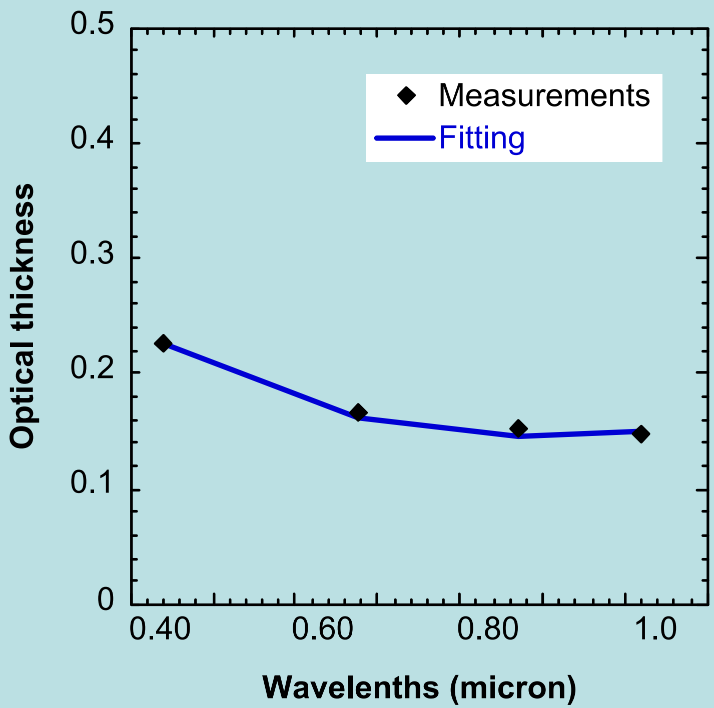




Almucantar Fitting

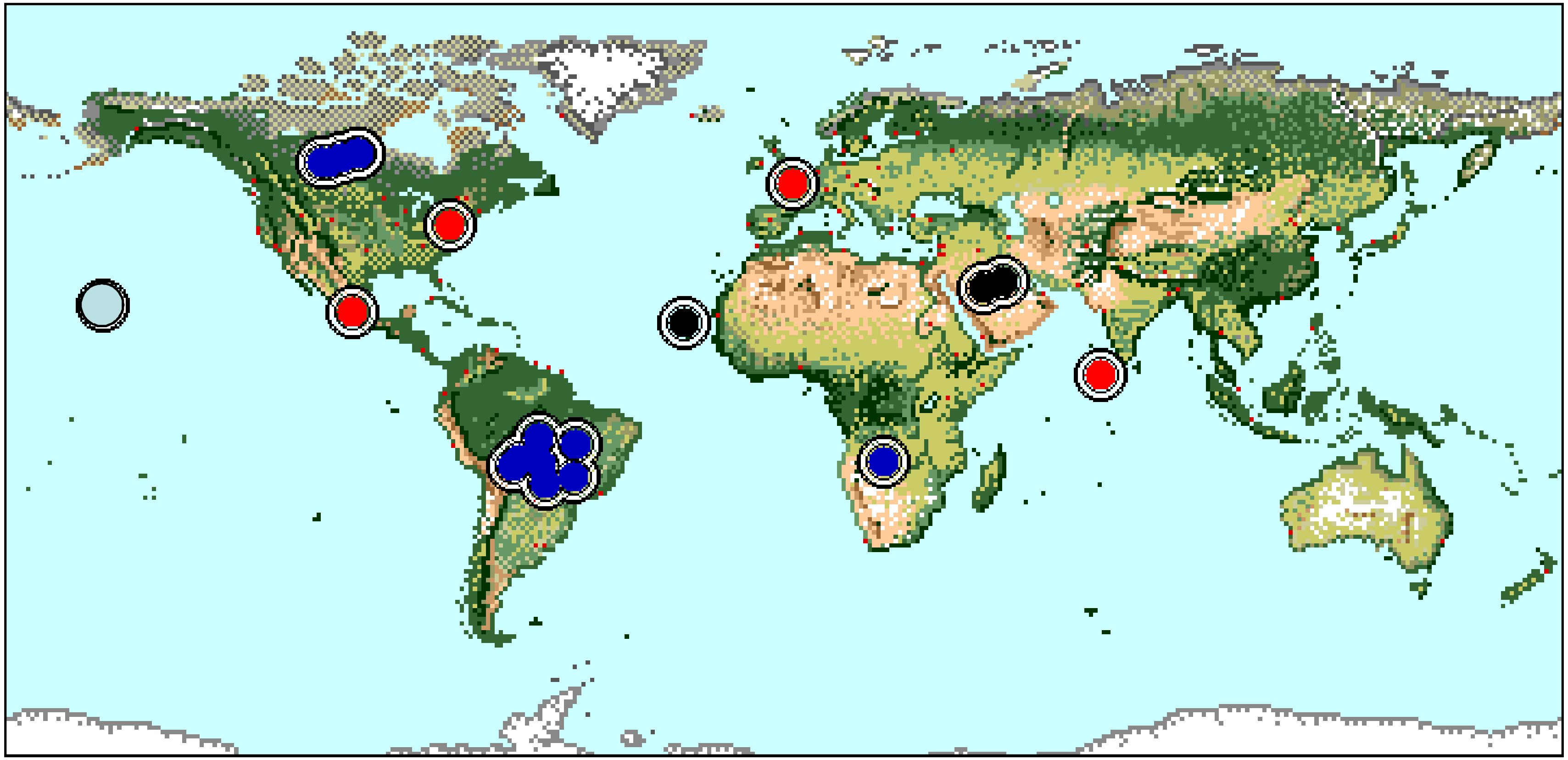


Fitting of optical thickness in retrievals



Observation Sites for Climatology

- **- Urban/Industrial** (*GSFC, Paris, Mexico-City, INDOEX*)
- **- Biomass Burning** (*Savanna, Cerrado, Forest*)
- **- Desert Dust** (*Cape Verde, Saudi Arabia, Persian Gulf*)
- **- Oceanic Aerosol** (*Hawaii*)



The averaged optical properties of various aerosol types (Dubovik et al., 2002, JAS)

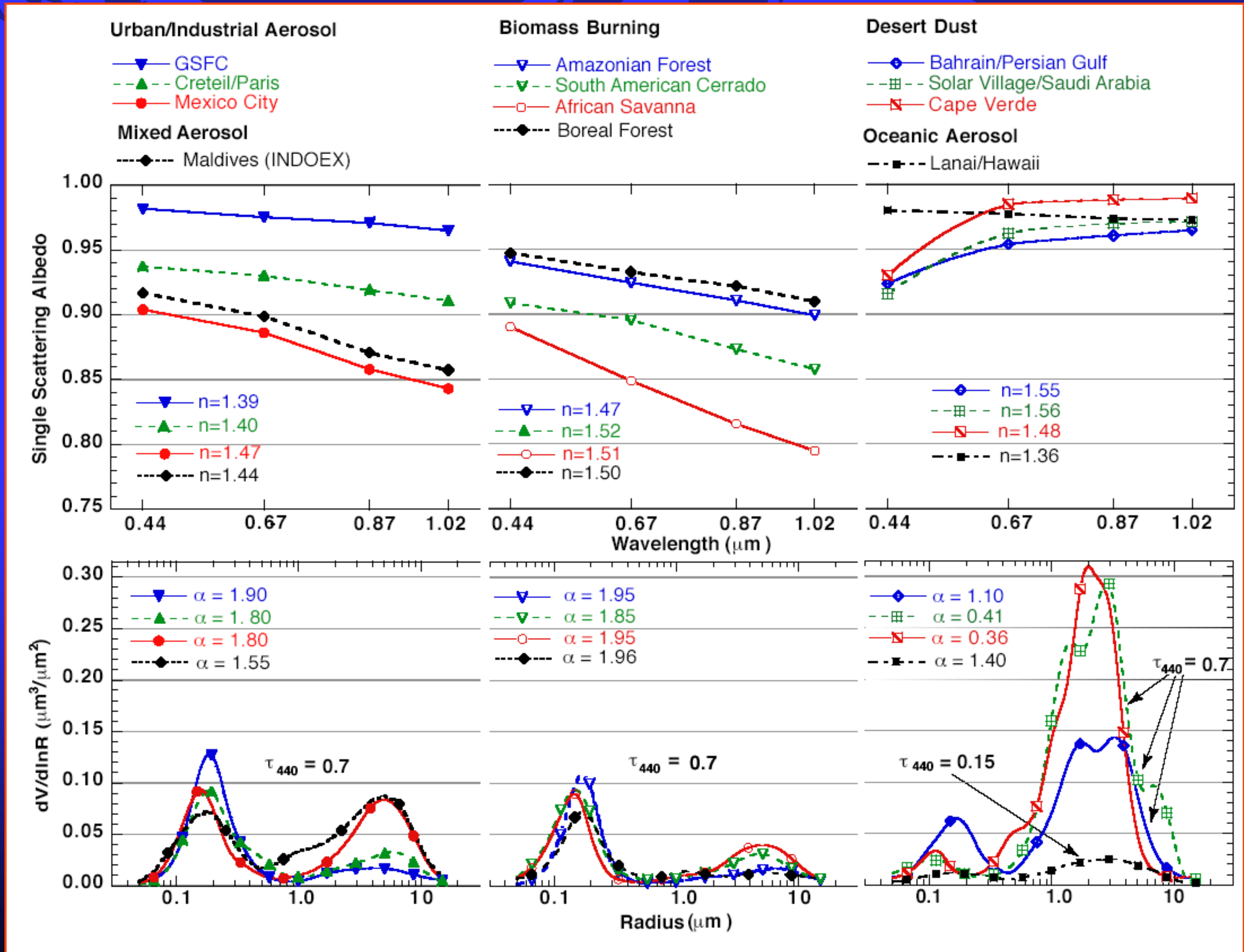


Table 1. Summary of aerosol optical properties retrieved from worldwide AERONET network of ground-based radiometers.

Urban/Industrial & Mixed:	**GSFC/ Greenbelt /USA** (1993-2000)	**Creteil/ Paris France** (1999)	**Mexico City** (1999 - 2000)	**Maldives (INDOEX)** (1999-2000)
Number of meas. (total)	2400	300	1500	700
Number of meas. (for ω_0, *n*, *k*)	200 (June ĞSeptember)	40 (June ĞSeptember)	300	150 (January Ğ April)
Range of optical thickness;$<\tau>$	$0.1 \le \tau(440) \le 1.0$; $<\tau(440)>= 0.24$	$0.1 \le \tau(440) \le 0.9$; $<\tau(440)>= 0.26$	$0.1 \le \tau(440) \le 1.8$; $<\tau(440)>= 0.43$	$0.1 \le \tau(440) \le 0.7$; $<\tau(440)>= 0.27$
Range of €ngstrom parameter	$1.2 \le \alpha \le 2.5$	$1.2 \le \alpha \le 2.3$	$1.0 \le \alpha \le 2.3$	$0.4 \le \alpha \le 2.0$
$<g>$ (440/ 670/ 870/ 1020)	0.68/ 0.59/ 0.54/ 0.53 $\pm$ 0.08			
n; *k*	$1.41 - 0.03\tau(440) \pm 0.01$; 0.003 ± 0.003	1.40 ± 0.03; 0.009 ± 0.004	1.47 ± 0.03; 0.014 ± 0.006	1.44 ± 0.02; 0.011 ± 0.007
ω_0(440/ 670/ 870/ 1020)	0.98/ 0.97/ 0.96/ 0.95 $\pm$0.02	0.94/ 0.93 / 0.92 / 0.91 $\pm$ 0.03	0.90 / 0.88 / 0.85/ 0.83 $\pm$ 0.02	0.91/ 0.89 / 0.86 / 0.84 $\pm$ 0.03
r_{vf} (μm); σ_f	$0.12+0.11\ \tau(440) \pm 0.03$; 0.38 ± 0.01	$0.11+ 0.13\ \tau(440) \pm 0.03$; 0.43 ± 0.05	$0.12 + 0.04\ \tau(440) \pm 0.02$; 0.43 ± 0.03	0.18 ± 0.03; 0.46 ± 0.04
r_{vc} (μm); σ_c	$3.03+0.49\ \tau(440) \pm 0.21$; 0.75 ± 0.03	$2.76 + 0.48\ \tau(440) \pm 0.30$; 0.79 ± 0.05	$2.72 + 0.60\ \tau(440) \pm 0.23$; 0.63 ± 0.05	$2.62 + 0.61\tau(440) \pm 0.31$; 0.76 ± 0.05
C_{vf} ($\mu m^3/\mu m^2$)	$0.15\ \tau(440) \pm 0.03$	$0.01 + 0.12\ \tau(440) \pm 0.04$	$0.12\ \tau(440) \pm 0.03$	$0.12\ \tau(440) \pm 0.03$
C_{vc} ($\mu m^3/\mu m^2$)	$0.01 + 0.04\ \tau(440) \pm 0.01$	$0.01 + 0.05\ \tau(440) \pm 0.02$	$0.11\ \tau(440) \pm 0.03$	$0.15\ \tau(440) \pm 0.04$

Biomass burning:	**Amazonian Forest: Brazil** (1 993-1994); **Bolivia** (1998-1999)**;**	**South American Cerrado: Brazil** (1993-1995)	**African Savanna: Zambia** (1995 - 2000)	**Boreal Forest: USA, Canada** (1994 - 1998)
Number of meas. (total)	700	550	2000	1000
Number of meas. (for ω_0, *n*, *k*)	250 (August Ğ October)	350 (August ĞOctober)	700 (August ĞNovember)	250 (June ĞSeptember)
Range of optical thickness;$<\tau>$	$0.1 \le \tau(440) \le 3.0$; $<\tau(440)>= 0.74$	$0.1 \le \tau(440) \le 2.1$; $<\tau(440)>= 0.80$	$0.1 \le \tau(440) \le 1.5$; $<\tau(440)>= 0.38$	$0.1 \le \tau(440) \le 2.0$; $<\tau(440)>= 0.40$
Range of €ngstrom parameter	$1.2 \le \alpha \le 2.1$	$1.2 \le \alpha \le 2.1$	$1.4 \le \alpha \le 2.2$	$1.0 \le \alpha \le 2.3$
$<g>$ (440/ 670/ 870/ 1020)	0.69/ 0.58/ 0.51/ 0.48 $\pm$ 0.06	0.67/ 0.59/ 0.55/ 0.53 $\pm$ 0.03	0.64/ 0.53/ 0.48/ 0.47 $\pm$ 0.06	0.69/ 0.61/ 0.55/ 0.53 $\pm$ 0.06
n; *k*	1.47 ± 0.03; 0.0093 ± 0.003	1.52 ± 0.01; 0.015 ± 0.004	1.51 ± 0.01; 0.021 ± 0.004	1.50 ± 0.04; 0.0094 ± 0.003
ω_0(440/ 670/ 870/ 1020)	0.94/ 0.93 /0.91/0.90 $\pm$0.02	0.91/ 0.89/ 0.87/ 0.85 $\pm$0.03	0.88 / 0.84 / 0.80 / 0.78 $\pm$0.015	0.94 / 0.935 / 0.92 / 0.91 $\pm$ 0.02
r_{vf} (μm); σ_f	$0.14+0.013\tau(440) \pm 0.01$; 0.40 ± 0.04	$0.14+0.01\tau(440) \pm 0.01$; 0.47 ± 0.03	$0.12 + 0.025\tau(440) \pm 0.01$; 0.40 ± 0.01	$0.15 + 0.015\tau(440) \pm 0.01$; 0.43 ± 0.01
r_{vc} (μm); σ_c	$3.27+0.58\tau\ (440) \pm 0.45$; 0.79 ± 0.06	$3.27+0.51\tau(440) \pm 0.39$; 0.79 ± 0.04	$3.22 + 0.71\tau(440) \pm 0.43$; 0.73 ± 0.03	$3.21+ 0.2\tau(440) \pm 0.23$; 0.81 ± 0.2
C_{vf} ($\mu m^3/\mu m^2$)	$0.12\ \tau(440) \pm 0.05$	$0.1\ \tau(440) \pm 0.06$	$0.12\ \tau(440) \pm 0.04$	$0.01 + 0.1\ \tau(440) \pm 0.04$
C_{vc} ($\mu m^3/\mu m^2$)	$0.05\ \tau(440) \pm 0.02$	$0.04 + 0.03\ \tau(440) \pm 0.03$	$0.09\ \tau(440) \pm 0.02$	$0.01 + 0.03\ \tau(440) \pm 0.03$

Desert Dust & Oceanic:	**Bahrain/ Persian Gulf** (1998 Ğ2000)	**Solar-Vil./ Saudi Arabia**(1998-2000)	**Cape Verde** (1993 Ğ2000)	**Lanai/Hawaii** (1995-2000)
Number of meas. (total)	1800	1500	1500	800
Number of meas. (for ω_0, *n*, *k*)	100	250	300	150
Range of optical thickness;$<\tau>$	$0.1 \le \tau(1020) \le 1.2$, $<\tau(1020)>= 0.22$	$0.1 \le \tau(1020) \le 1.5$; $<\tau(1020)>= 0.17$	$0.1 \le \tau(1020) \le 2.0$; $<\tau(1020)>= 0.39$	$0.01 \le \tau(1020) \le 0.2$; $<\tau(1020)>= 0.04$
Range of €ngstrom parameter	$0 \le \alpha \le 1.6$	$0.1 \le \alpha \le 0.9$	$-0.1 \le \alpha \le 0.7$	$0 \le \alpha \le 1.55$
$<g>$ (440/ 670/ 870/ 1020)	0.68/ 0.66/ 0.66/ 0.66 $\pm$ 0.04	0.69/ 0.66/ 0.65/ 0.65 $\pm$ 0.04	0.73/ 0.71/ 0.71/ 0.71 $\pm$ 0.04	0.75/ 0.71/ 0.69/ 0.68 $\pm$ 0.04
n	1.55 ± 0.03	1.56 ± 0.03	1.48 ± 0.05	1.36 ± 0.01
k(440/ 670/ 870/ 1020)	0.0025/ 0.0014 / 0.001/ 0.001 $\pm$ 0.001	0.0029 /0.0013 /0.001/ 0.001 $\pm$ 0.001	0.0025/ 0.0007/ 0.0006/ 0.0006 $\pm$0.001	0.0015 ± 0.001
ω_0(440/ 670/ 870/ 1020)	0.92 / 0.95/ 0.96 / 0.97 $\pm$ 0.03	0.92/ 0.96/ 0.97/ 0.97 $\pm$ 0.02	0.93/ 0.98 /0.99 /0.99 $\pm$ 0.01	0.98/ 0.97 /0.97 /0.97 $\pm$ 0.03
r_{vf} (μm); σ_f	0.15 ± 0.04; 0.42 ± 0.04	0.12 ± 0.05; 0.40 ± 0.05	0.12 ± 0.03; $0.49 + 0.10\ \tau \pm 0.04$	0.16 ± 0.02; 0.48 ± 0.04
r_{vc} (μm); σ_c	2.54 ± 0.04; 0.61 ± 0.02	2.32 ± 0.03; 0.60 ± 0.03	1.90 ± 0.03; $0.63 - 0.10\ \tau \pm 0.03$	2.70 ± 0.04; 0.68 ± 0.04
C_{vf} ($\mu m^3/\mu m^2$)	$0.02 + 0.1\ \tau(1020) \pm 0.05$	$0.02 + 0.02\ \tau(1020) \pm 0.03$	$0.02 + 0.02\ \tau(1020) \pm 0.03$	$0.40\ \tau(1020) \pm 0.01$
C_{vc} ($\mu m^3/\mu m^2$)	$-0.02 + 0.92\ \tau(1020) \pm 0.04$	$-0.02 + 0.98\ \tau(1020) \pm 0.04$	$0.9\ \tau(1020) \pm 0.09$	$0.80\ \tau(1020) \pm 0.02$

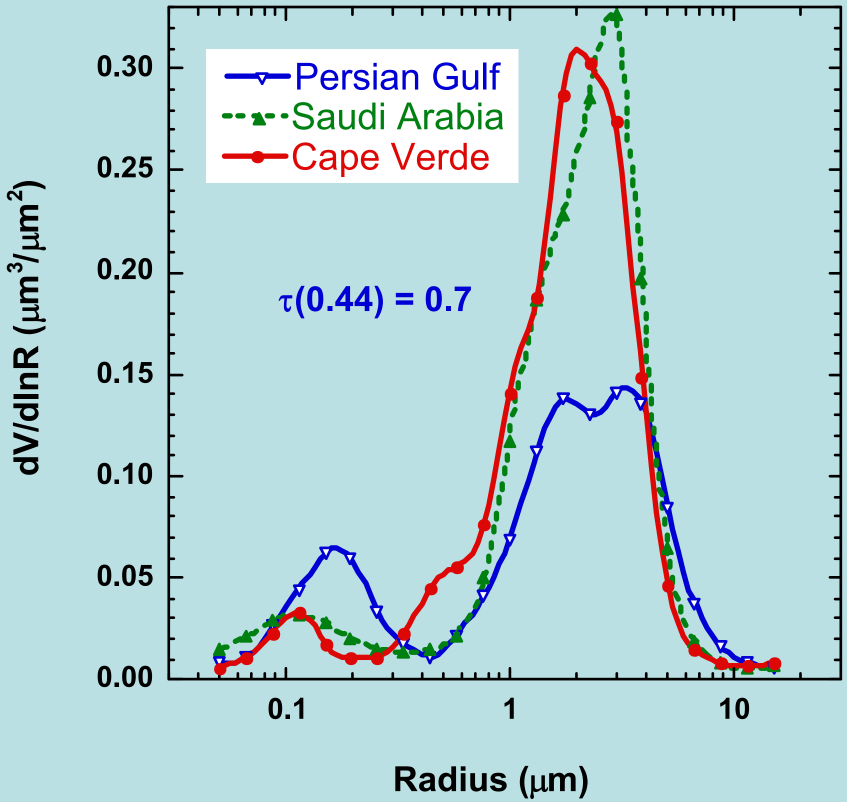
Dubovik et al. 2002

Retrieved Properties of Saharan Dust

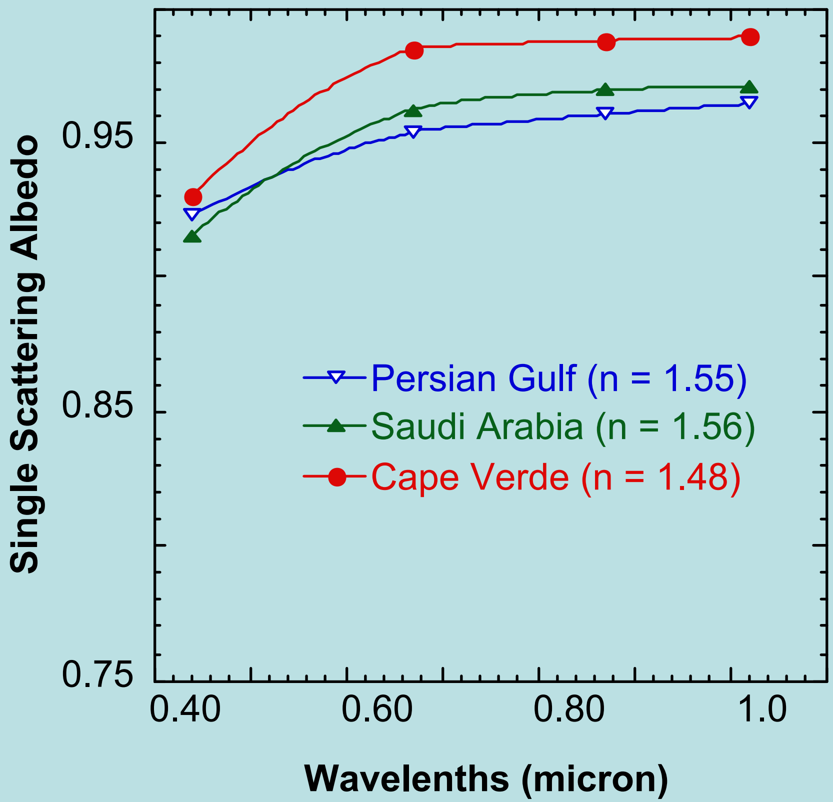
Angstrom < 0.75

***Dubovik* et al., 2002**

Average Size Distributions

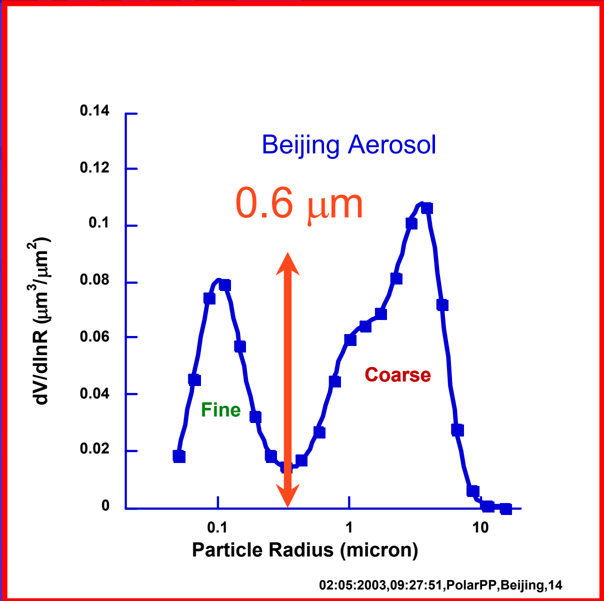


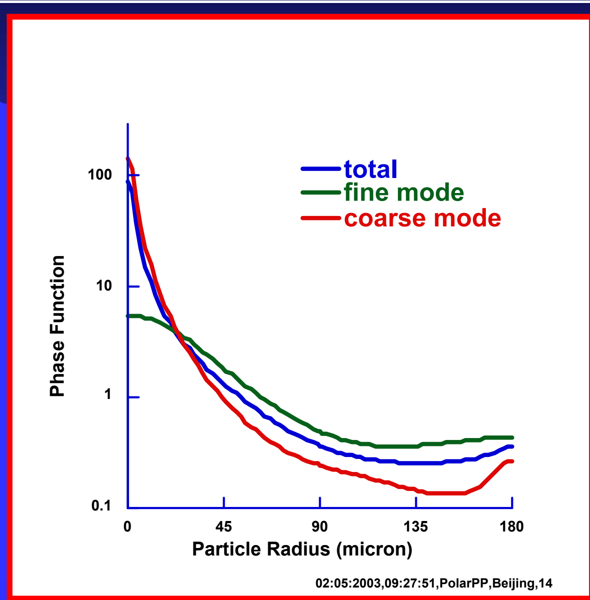
Average Single Scattering Albedo

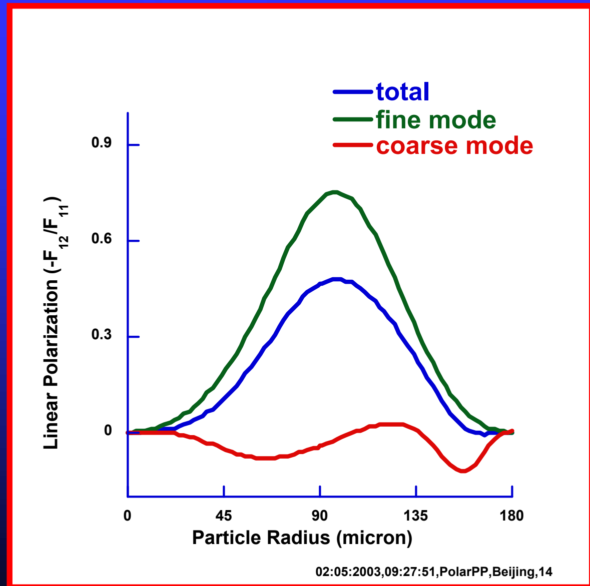


Fine / Coarse modes parameters:

Flexible separation:
minimum between: 0.194 and 0.576 μm







Integral parameters of dV/dlnR:

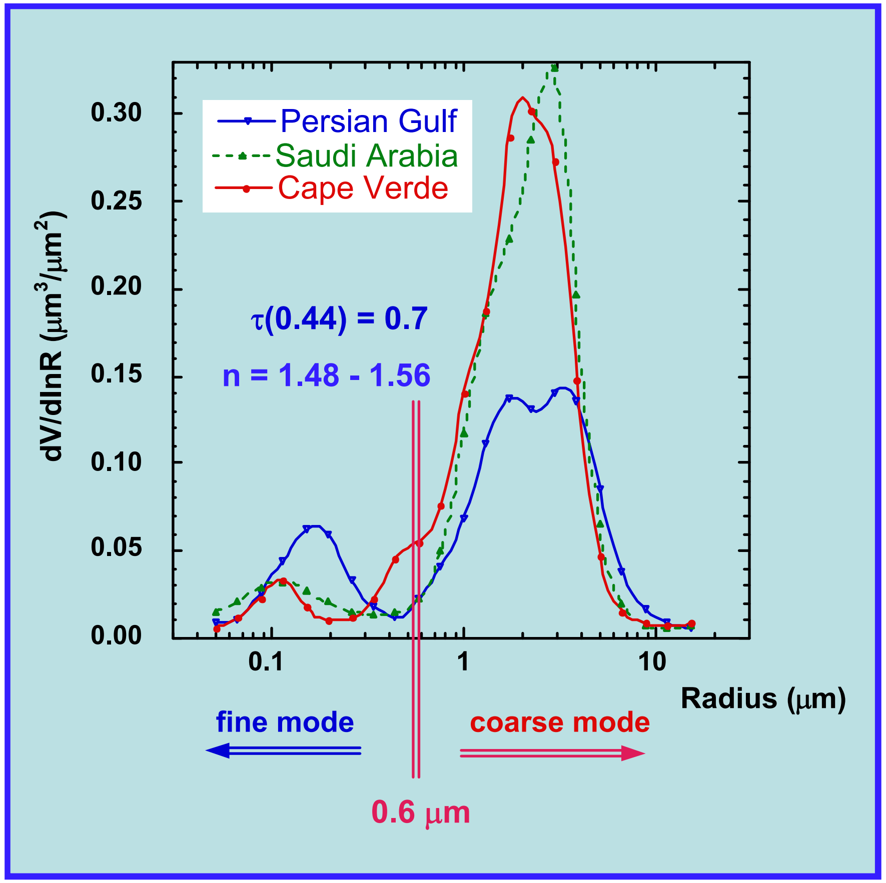
t - total; f - fine ; c - coarse

C(t,f,c) - Volume Concentration

R_v(t,f,c) - Mean Radius

σ(t,f,c) - Standard Deviation

R_{eff} (t,f,c) - Effective Radius



Parameters of Bi-Modal Size Distributions:

V_{coarse}/V_{fine} ~ 10 (15 - 5)

R_{coarse} ~ 2.6 -1.9 µm

R_{fine} ~ 0.12 -0.16 µm

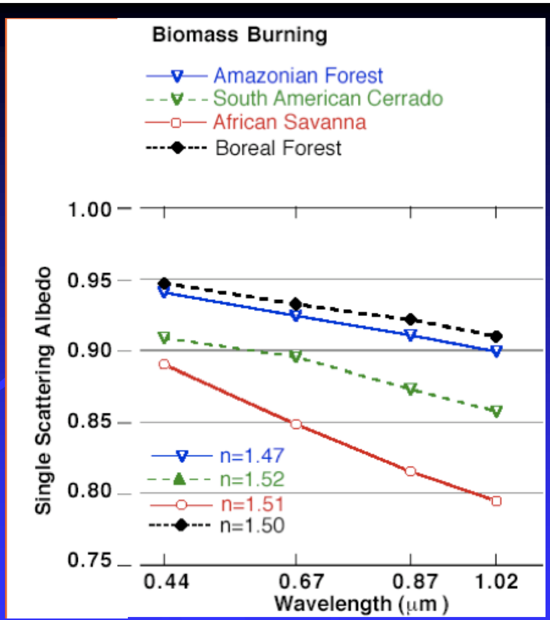
σ_{coarse} ~ 0.60

σ_{fine} ~ 0.40

Table from *Dubovik* et al., 2002

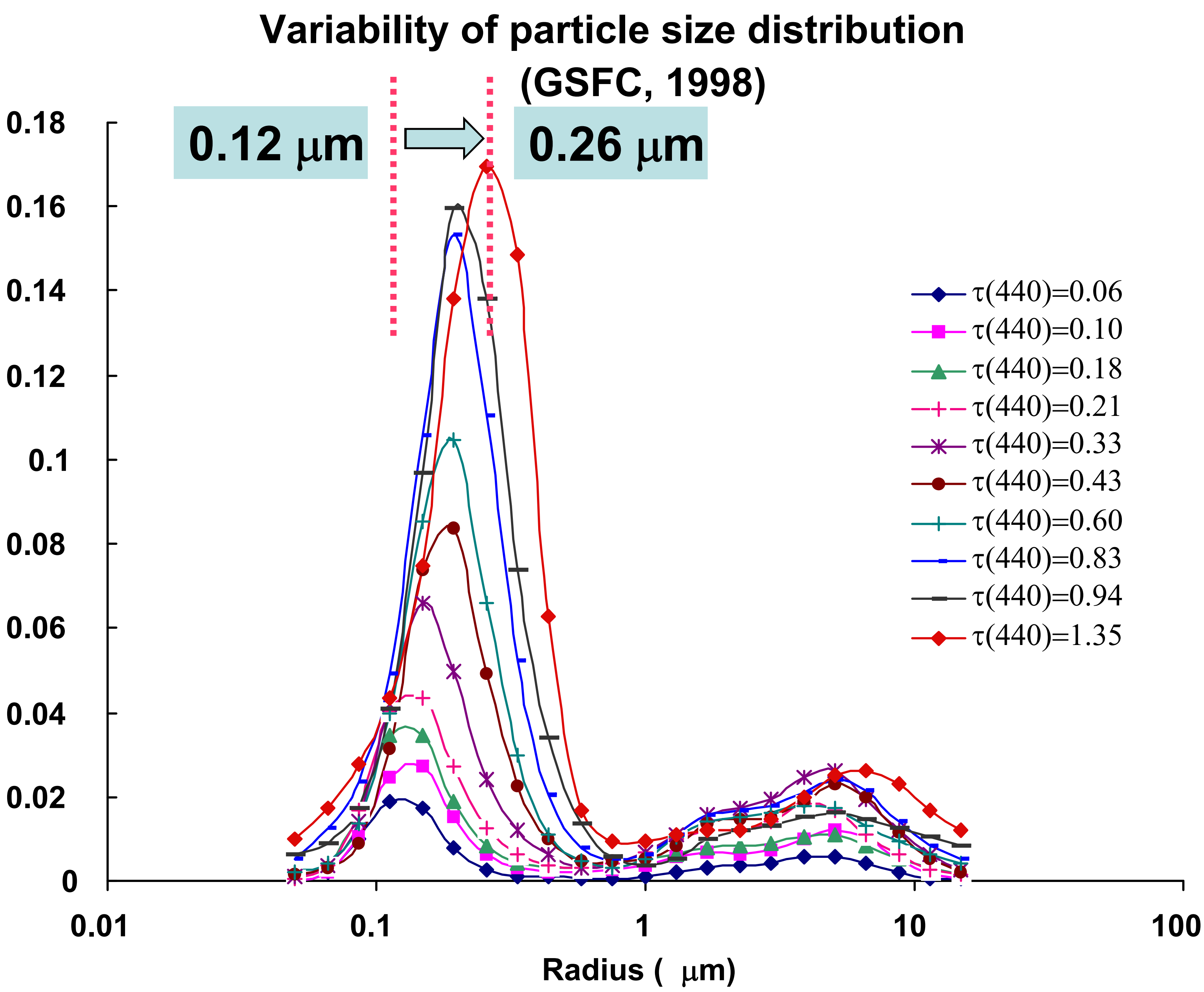
Desert Dust	**Bahrain/ Persian Gulf** (1998 Ğ2000)	**Solar-Vil./ Saudi Arabia**(1998-2000)	**Cape Verde** (1993 Ğ2000)
Number of meas. (total)	1800	1500	1500
Number of meas. (for ω_0, *n*, *k*)	100	250	300
Range of optical thickness;$<\tau>$	$0.1 \le \tau(1020) \le 1.2$, $<\tau(1020)>= 0.22$	$0.1 \le \tau(1020) \le 1.5$; $<\tau(1020)>= 0.17$	$0.1 \le \tau(1020) \le 2.0$; $<\tau(1020)>= 0.39$
Range of € ngstrom parameter	$0 \le \alpha \le 1.6$	$0.1 \le \alpha \le 0.9$	$-0.1 \le \alpha \le 0.7$
$<g>$ (440/ 670/ 870/ 1020)	0.68/ 0.66/ 0.66/ 0.66 ± 0.04	0.69/ 0.66/ 0.65/ 0.65 ± 0.04	0.73/ 0.71/ 0.71/ 0.71 ± 0.04
n	1.55 ± 0.03	1.56 ± 0.03	1.48 ± 0.05
k(440/ 670/ 870/ 1020)	0.0025/ 0.0014 / 0.001/ 0.001 ± 0.001	0.0029 /0.0013 /0.001/ 0.001 ± 0.001	0.0025/ 0.0007/ 0.0006/ 0.0006 ±0.001
ω_0(440/ 670/ 870/ 1020)	0.92 / 0.95/ 0.96 / 0.97 ± 0.03	0.92/ 0.96/ 0.97/ 0.97 ± 0.02	0.93/ 0.98 /0.99 /0.99 ± 0.01
r_{vf} (µm); σ_f	0.15 ± 0.04; 0.42 ± 0.04	0.12 ± 0.05; 0.40 ± 0.05	0.12 ± 0.03; 0.49 + 0.10 τ ± 0.04
r_{vc} (µm); σ_c	2.54 ± 0.04; 0.61 ± 0.02	2.32 ± 0.03; 0.60 ± 0.03	1.90 ± 0.03; 0.63 - 0.10 τ ± 0.03
C_{vf} ($\mu m^3/\mu m^2$)	0.02 + 0.1 τ(1020) ± 0.05	0.02 + 0.02 τ(1020) ± 0.03	0.02 + 0.02 τ(1020) ± 0.03
C_{vc} ($\mu m^3/\mu m^2$)	-0.02 + 0.92 τ(1020) ± 0.04	-0.02 + 0.98 τ(1020) ± 0.04	0.9 τ(1020) ± 0.09

ABSORPTION of SMOKE



flaming combustion
Rio Branco, Brazil

smoldering combustion
Quebec fires, July 2002



Variability of particle size distribution
(GSFC, 1998)
0.12 μm
0.26 μm
τ(440)=0.06
τ(440)=0.10
τ(440)=0.18
τ(440)=0.21
τ(440)=0.33
τ(440)=0.43
τ(440)=0.60
τ(440)=0.83
τ(440)=0.94
τ(440)=1.35
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.01
0.1
1
10
100
Radius (μm)

Maritime aerosol

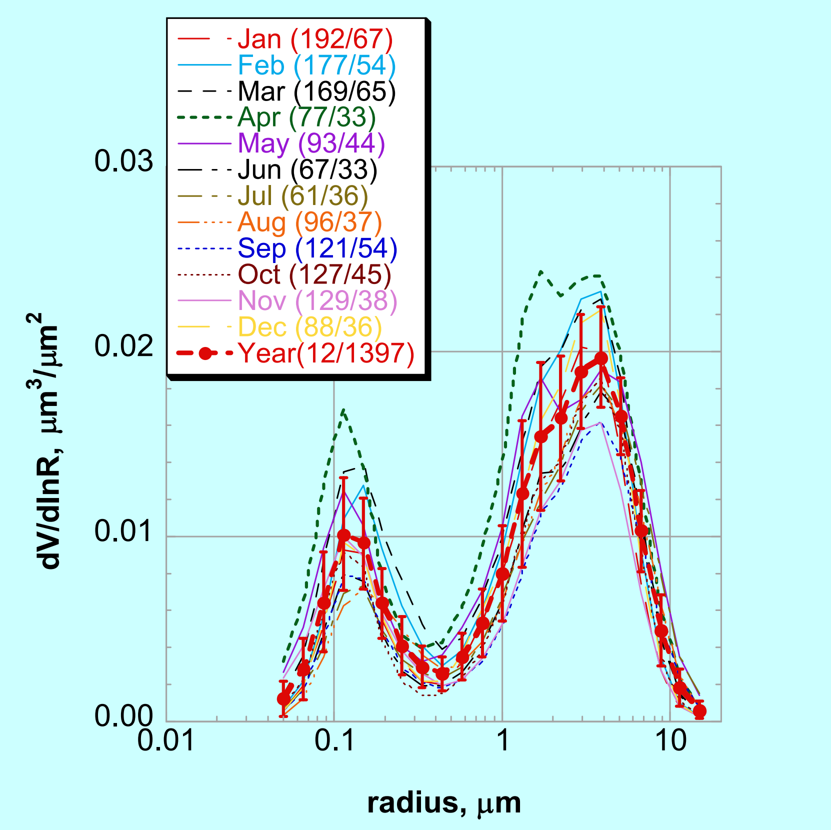
Marcello Bartinetti
“Sea storm in Camogli”

Duck, North Carolina, March 1999

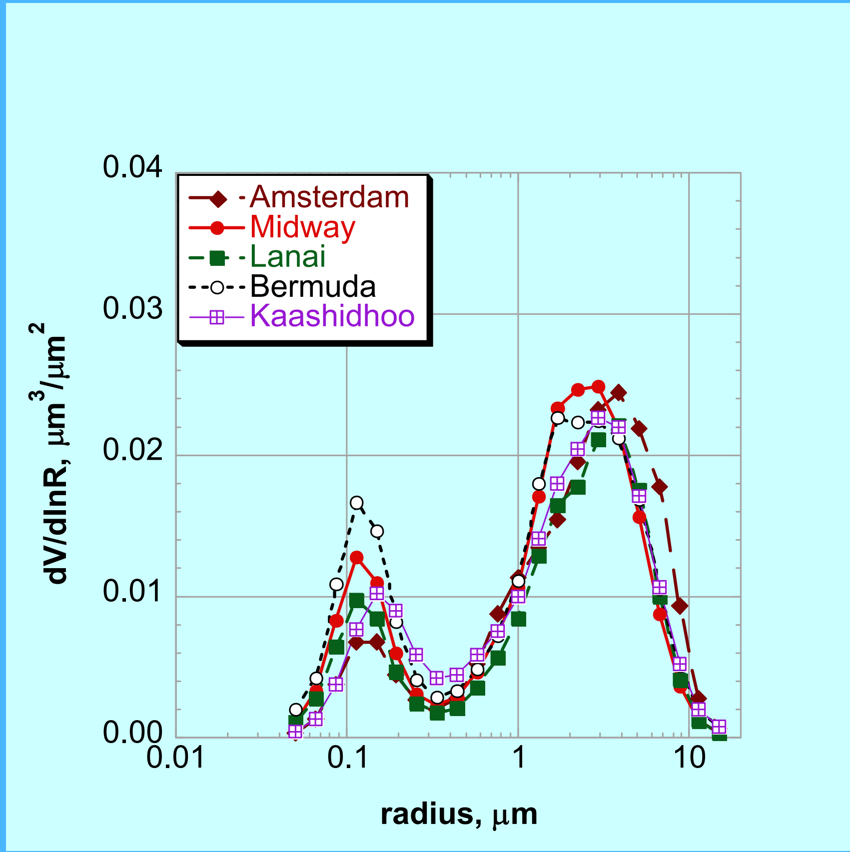
‼Smirnov et al.

Oceanic aerosol

Lanai, Hawaii

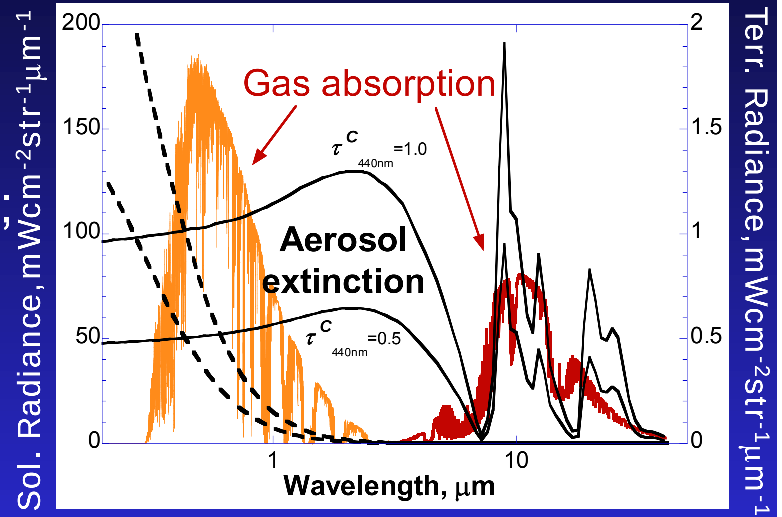


Worldwide locations



AERONET estimated broad-band fluxes in solar spectrum

$$F_{broadband} = \int_{\lambda_{min}}^{\lambda_{max}} F(\lambda)\,d\lambda$$



Integrations details:

- ✓ $\lambda_{min} = 0.2\ \mu m$, $\lambda_{max} = 4.0\ \mu m$;
- ✓ more than 200 points of integration between;

Aerosol:

- ✓ dV/dlnR - retrieved
- ✓ $n(\lambda)$ and $k(\lambda)$ are interpolated/extrapolated; from $n(\lambda_i)$ and $k(\lambda_i)$ retrieved;
- ✓ Radiative transfer code uses 12 moments for $P_{11}(\Theta)$

Surface:

- ✓ Surface reflection is Lambertian;
- ✓ Values of surface refelctance are interpolated/ extrapolated from MODIS data values

Gases:

- ✓ Gaseous absorption is calculated using correlated k-distributions implemented by P. Dubuisson

Validation studies:
Derimian et al. 2008
Garcia et al. 2008
($F^{\downarrow}_{BOA}$ ~ 10% agreement)

Rigorous ERRORS estimates: *Dubovik 2004*

General case: *large number of unknowns and redundant measurements*

$$\left\langle \left(\Delta \hat{x}_i\right)^2 \right\rangle \approx \left\langle \left(\Delta \hat{x}_i^{random}\right)^2 \right\rangle + \left(\Delta \hat{x}_i^{bias}\right)^2$$

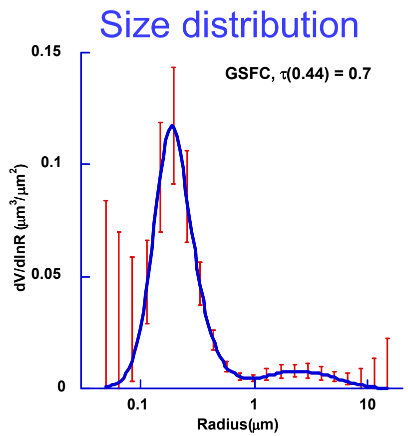
$$\mathbf{C}_{\Delta \hat{\mathbf{x}}^{random}} = \left(\mathbf{U}^T \mathbf{C}^{-1} \mathbf{U} + \mathbf{U}_a^T \mathbf{C}_a^{-1} \mathbf{U}_a\right)^{-1}$$

$$\Delta \hat{\mathbf{x}}^{bias} = \left(\mathbf{U}^T \mathbf{C}^{-1} \mathbf{U} + \mathbf{U}_a^T \mathbf{C}_a^{-1} \mathbf{U}_a\right)^{-1} \left(\mathbf{U}^T \mathbf{C}^{-1} \Delta \mathbf{I}^{bias} + \mathbf{U}_a^T \mathbf{C}_a^{-1} \Delta \mathbf{I}_a^{bias}\right)$$

U - matrix of partial derivatives in the vicinity of solution $\hat{\mathbf{x}}$

Above is valid:

- in linear approximation
- for Normal Noise
- strongly dependent on a priori constraints
- very challenging in most interesting cases



Input ERRORS and biases

Random (normally distributed with 0 means):

-optical thickness: $\sigma_\tau = 0.015 \times \mathrm{COS(SZA)}$

- sky-radiances: $\sigma_{sky} = 3\%$

- a priori: $\sigma_{sky}/\gamma_i \sim 100 - 300\ \%$ (Dubovik and King, 2000)

Biases (constant):

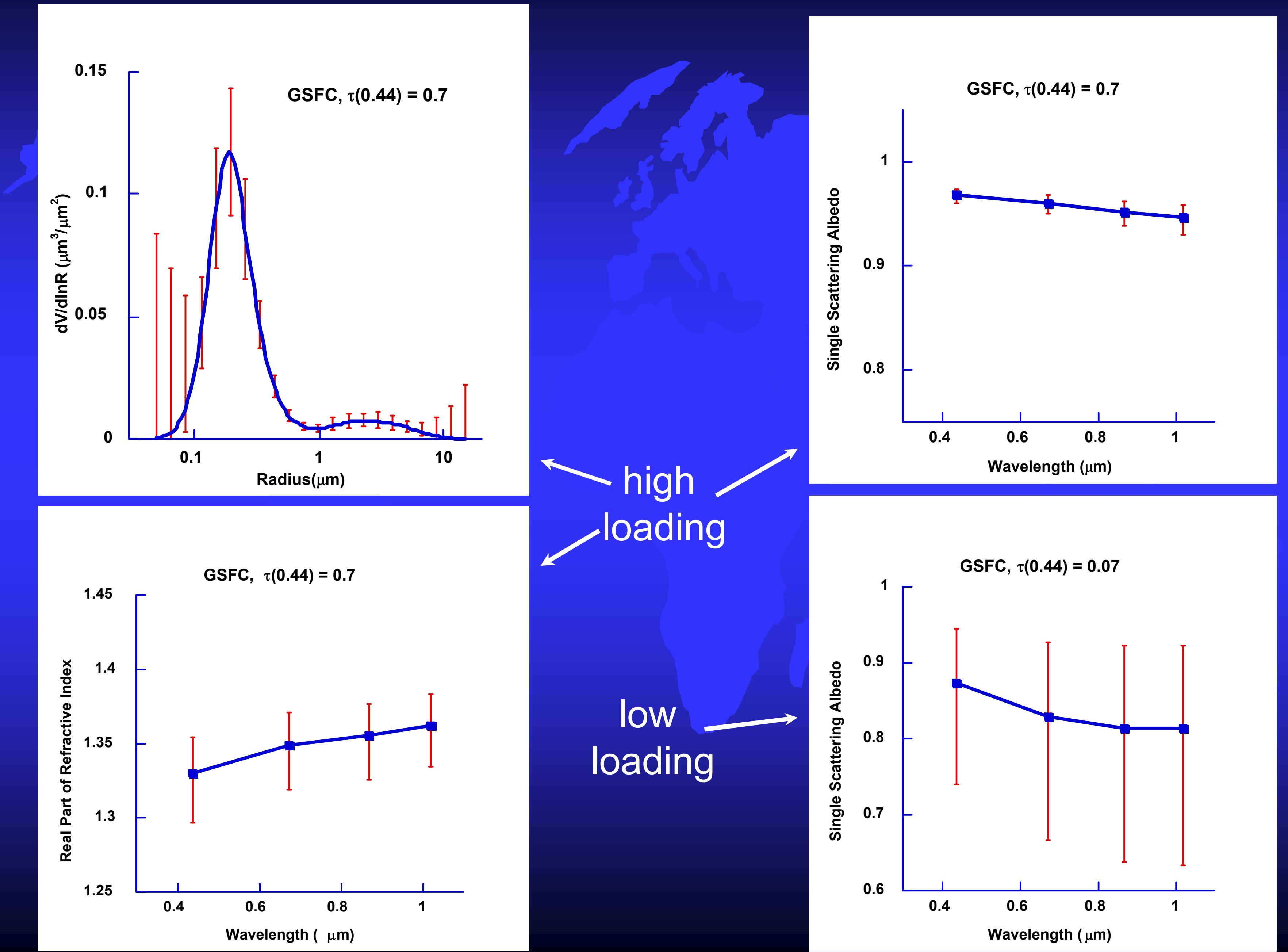
- optical thickness: $\pm 0.015 \times \mathrm{COS(SZA)}$

- sky-radiances: $\pm 3\%$ **+ obtained misfit**

- a priori: **100 - 300 %**

The error estimates are calculated twice with + and - bias.

Examples of error estimates



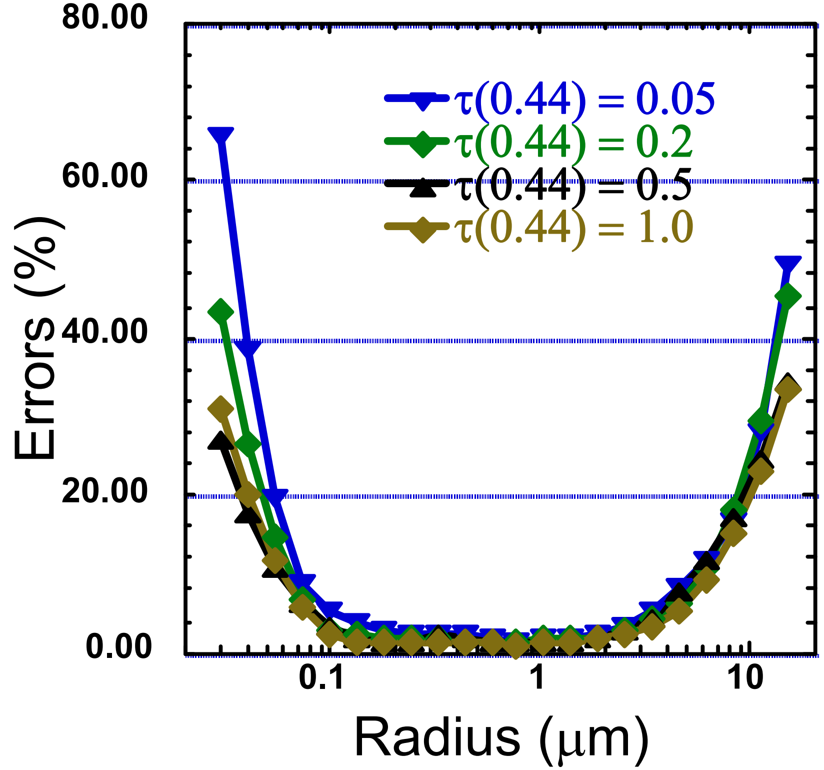
Random ERRORS in AERONET retrievals

ASSUMPTIONS:

- measurements have Normal Noise:
  - **optical thickness:** $\sigma = 0.01$
  - **sky-radiances:** $\sigma = 5\%$

CONCLUSIONS:

- the retrievals stable
- important tendencies outlined



Sensitivity to instrumental offsets

Offsets were considered in:

- **optical thickness:** $\Delta\tau(\lambda) = \pm 0.01;\ \pm 0.02;$
- **sky-channel calibration:** $\Delta_I(\lambda;\Theta)/I(\lambda;\Theta)\ 100\% = \pm 5\%;$
- **azimuth angle pointing:** $\Delta\phi = 0.5^o;\ 1^o;$
- **assumed ground reflectance:** $\Delta A(\lambda)/A(\lambda)\ 100\% = \pm 30\%;\ \pm 50\%;$

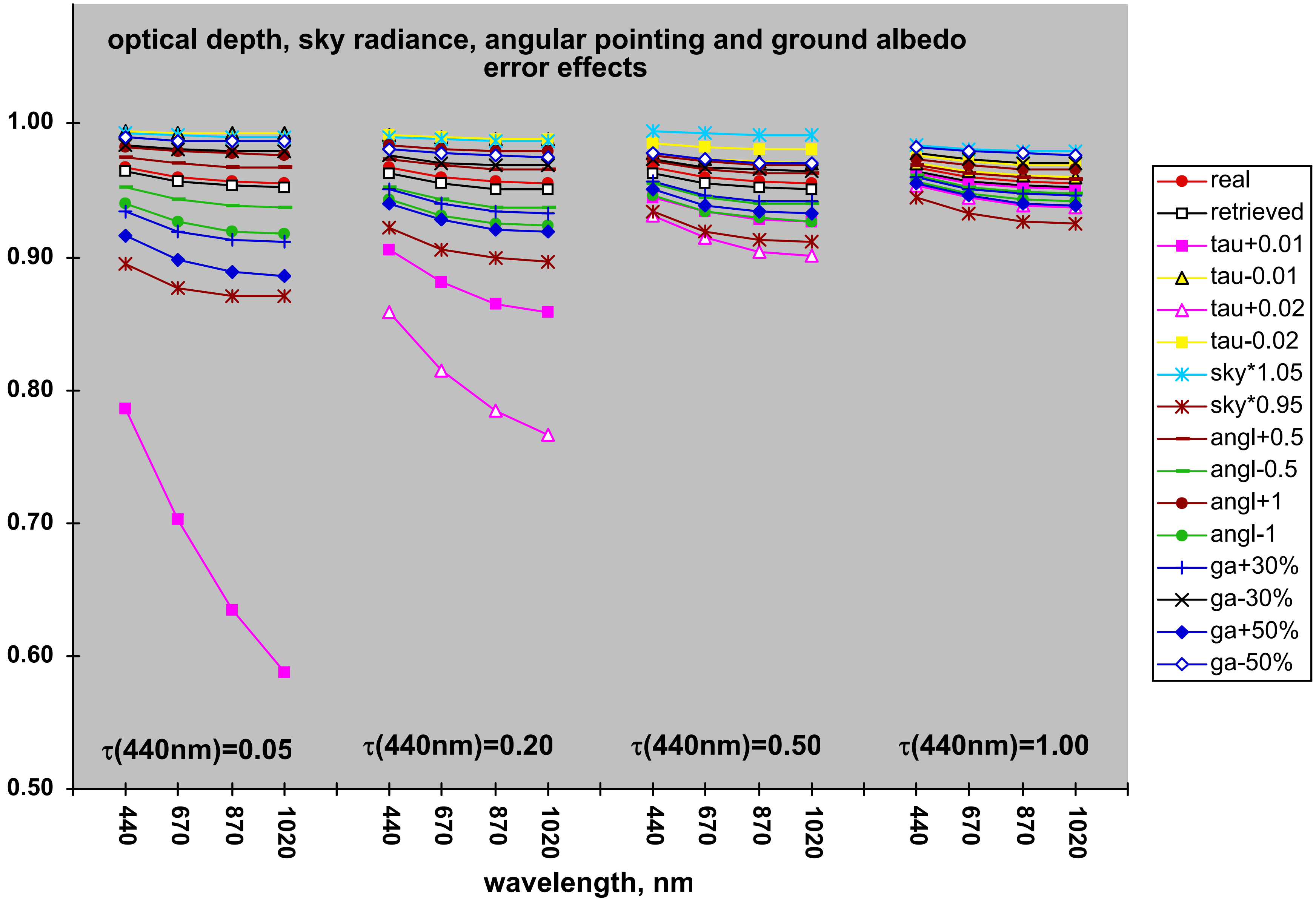
Aerosol models considered **(bi - modal log-normal):**

- **Water-soluble aerosol for 0.05 ≤ τ(440) ≤ 1;**
- **Desert dust for 0.5 ≤ τ(440) ≤ 1;**
- **Biomass burning for 0.5 ≤ τ(440) ≤ 1;**

Results summary:

- **τ(440) ≤ 0.2 - *d*V/*d*lnr (+), *n*(λ) (-), *k*(λ) (-), ω_0(λ) (-)**
- **τ(440) > 0.2 - *d*V/*d*lnr (+), *n*(λ) (+), *k*(λ) (+), ω_0(λ) (+)**
- **Angular pointing accuracy is critical for *d*V/*d*lnr of dust**

(+) CAN BE retrieved (-) CAN NOT BE retrieved



optical depth, sky radiance, angular pointing and ground albedo error effects
1.00
0.90
0.80
0.70
0.60
0.50
τ(440nm)=0.05
τ(440nm)=0.20
τ(440nm)=0.50
τ(440nm)=1.00
440
670
870
1020
wavelength, nm
real
retrieved
tau+0.01
tau-0.01
tau+0.02
tau-0.02
sky*1.05
sky*0.95
angl+0.5
angl-0.5
angl+1
angl-1
ga+30%
ga-30%
ga+50%
ga-50%

$\Delta\tau$ bias influence at $\Delta\omega_0$

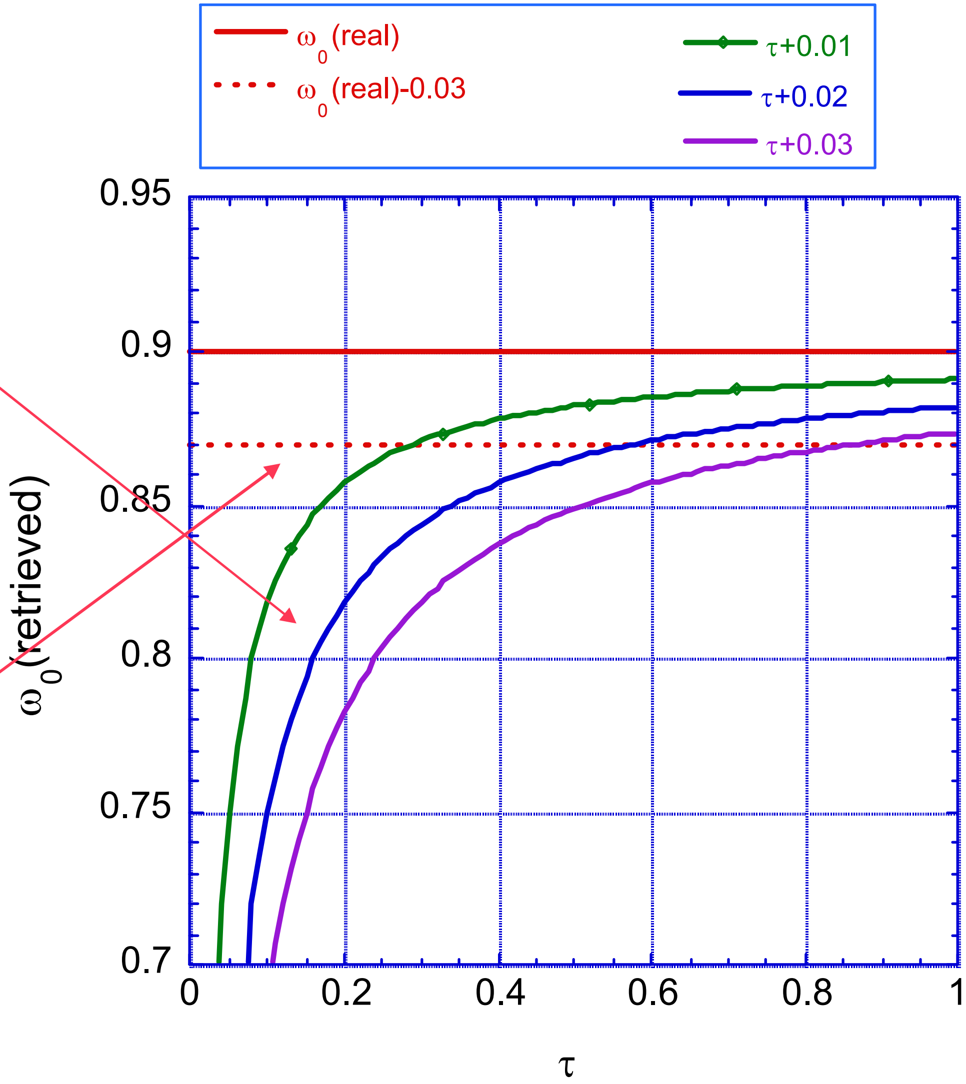
$\Delta\tau$ bias:

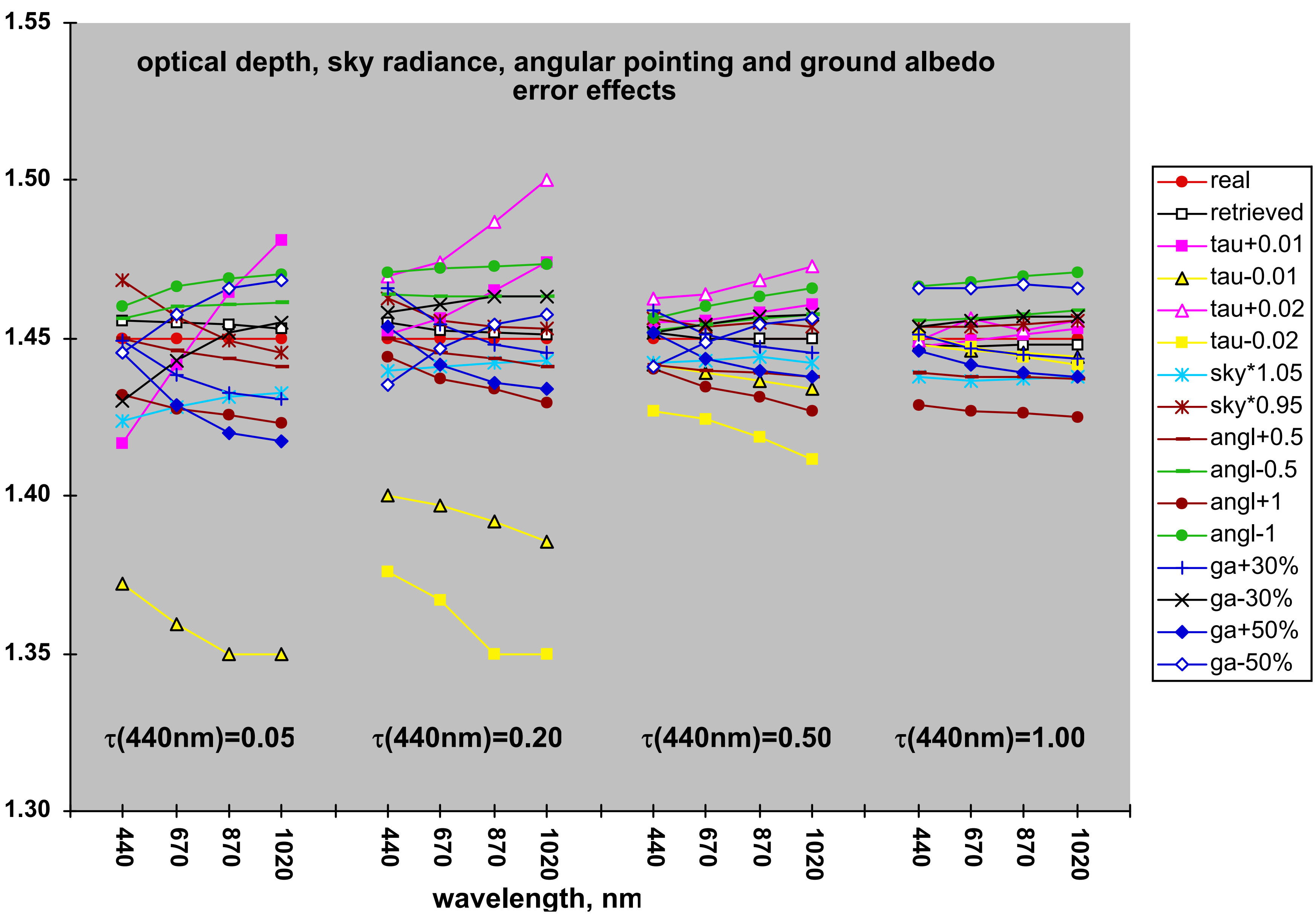
$$\tilde{\omega}_0 = \frac{\tau_{scat}}{\tau_{ext} + \Delta\tau}$$

Sky Radiance bias:

$$\tilde{\omega}_0 = \frac{\tau_{scat}\,(1-\Delta)}{\tau_{ext}}$$

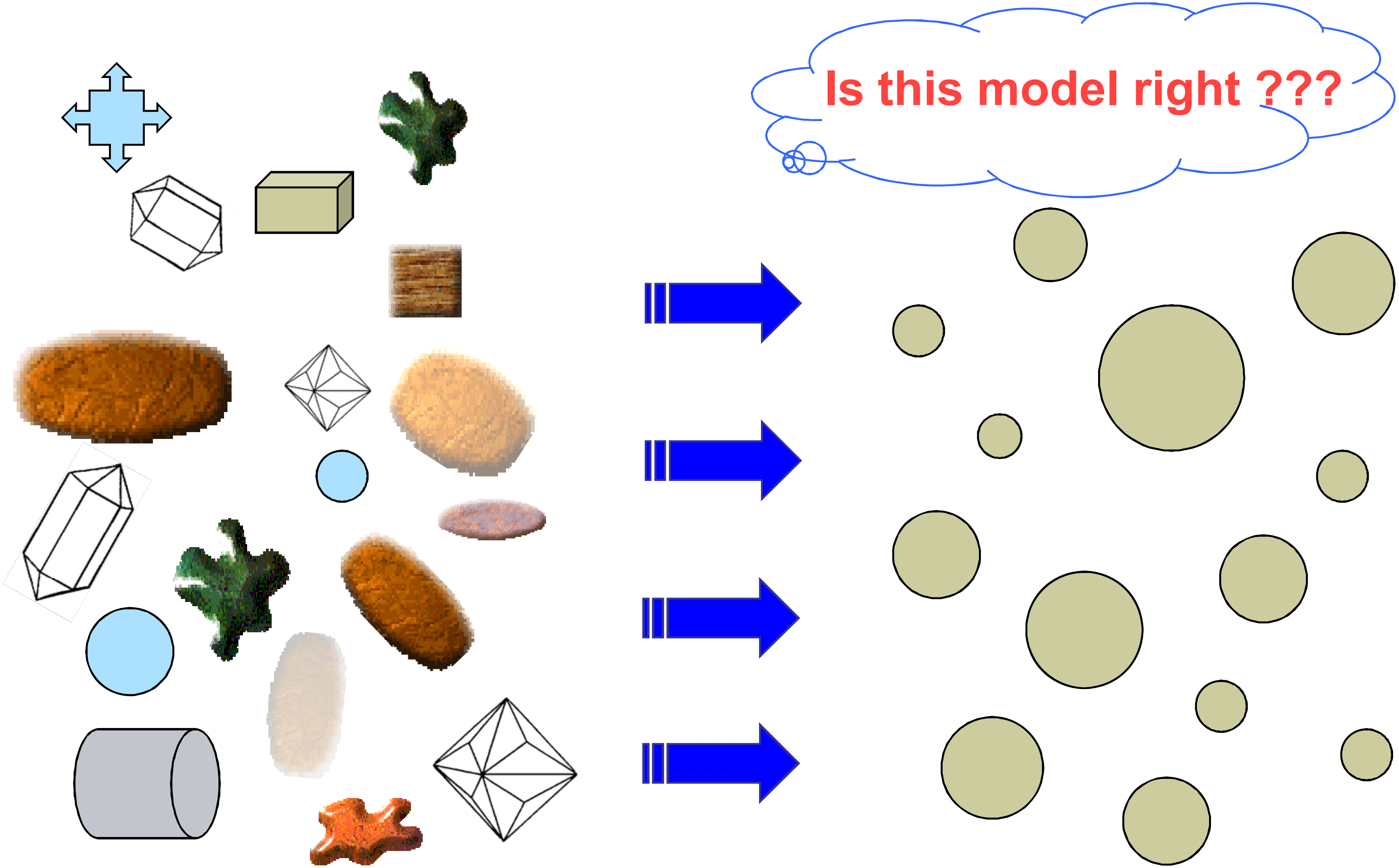
$$= \omega_0\,(1-\Delta)$$



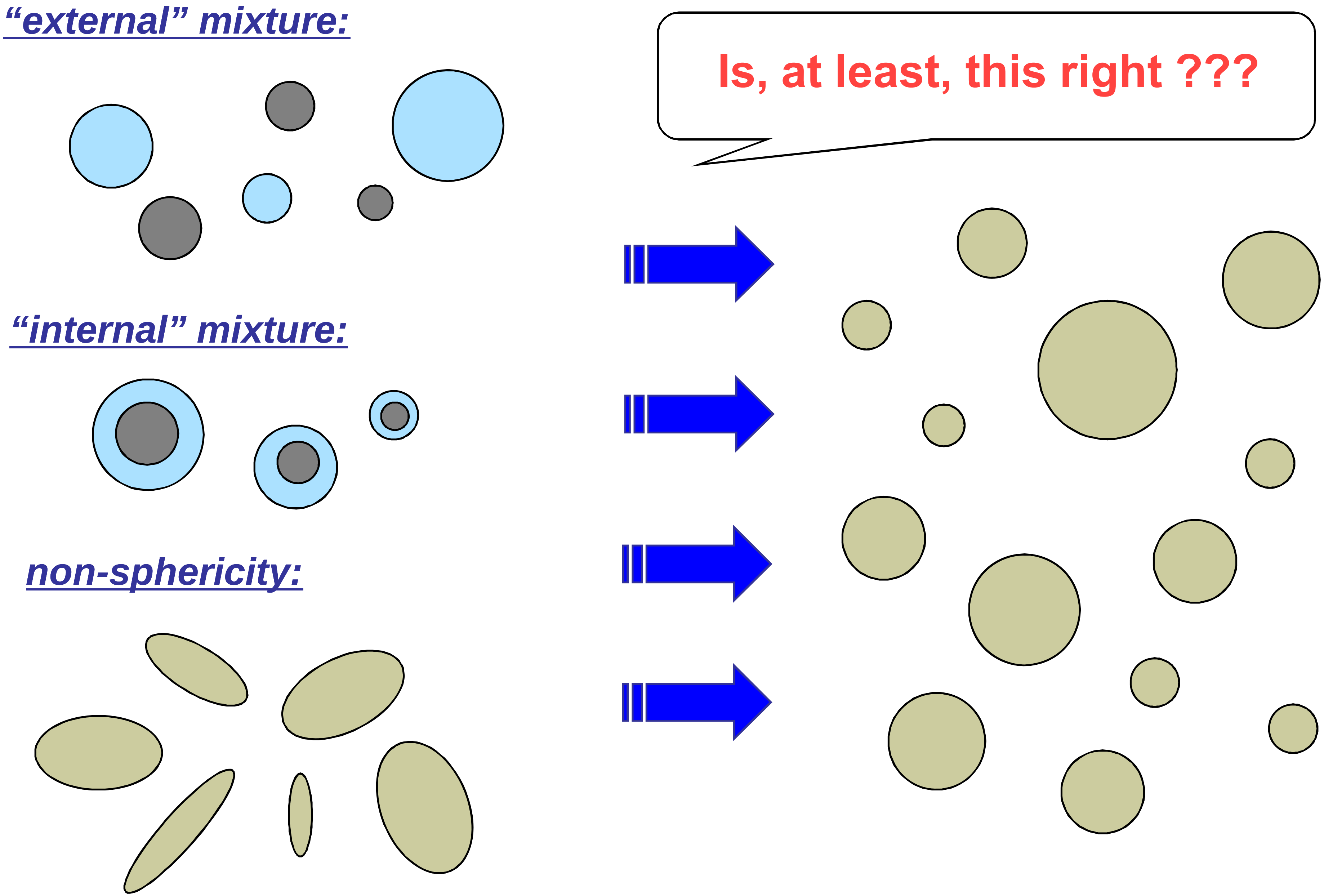


optical depth, sky radiance, angular pointing and ground albedo error effects
1.55
1.50
1.45
1.40
1.35
1.30
τ(440nm)=0.05
τ(440nm)=0.20
τ(440nm)=0.50
τ(440nm)=1.00
440
670
870
1020
wavelength, nm
real
retrieved
tau+0.01
tau-0.01
tau+0.02
tau-0.02
sky*1.05
sky*0.95
angl+0.5
angl-0.5
angl+1
angl-1
ga+30%
ga-30%
ga+50%
ga-50%

Optical model of aerosol



Questioned simplifications:



Sensitivity to forward model limitations

Mixed aerosols (inhomogeneous spherical aerosols):

- **Externally** mixed (*n*(l) and *k*(l) different for fine and coarse modes)
- **Internally** mixed (*n*(l) and *k*(l) different for core and shell) - *Biomass Burning*

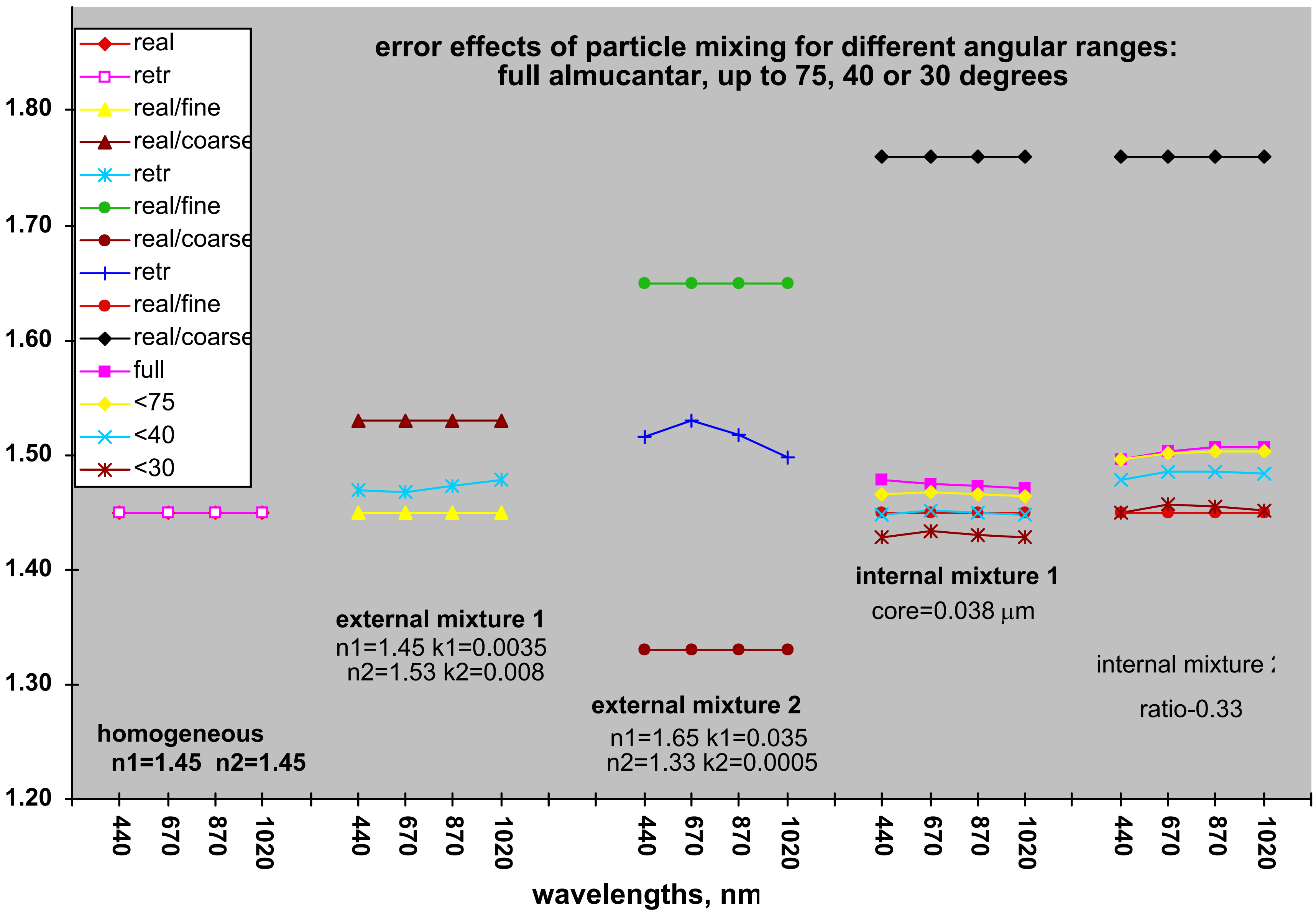
> ***Results summary***:
>
> - $dV/d\ln r$ (+), $\omega_0(\lambda)$ (+), $n(\lambda)$ (+,*effective*), $k(\lambda)$ (+, *effective*)

Non-spherical aerosols:

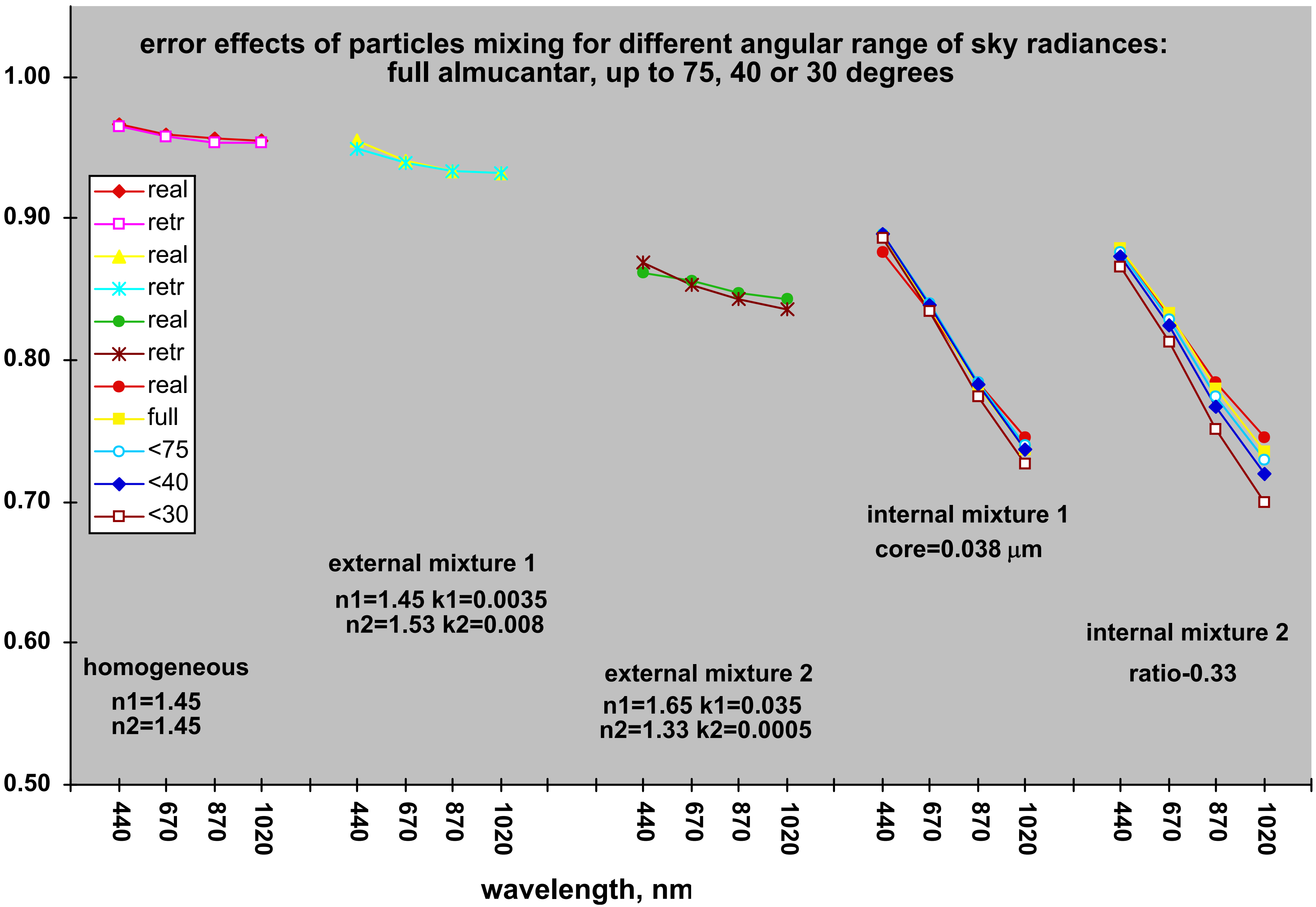
- **Spheroids** (prolate, axis ratio 2) - *Desert dust*

> ***Results summary***:
>
> - $dV/d\ln r$ - coarse mode (+), fine mode (+, zenith angle < 25^o)
> - $\omega_0(\lambda)$ (+) - full solar almucantar (zenith angle ≥ 50^o)
> - $k(\lambda)$ (+)
> - $n(440)$ (-), $n(670)$ (-), $n(870)$ (+/-), $n(1020)$ (+)

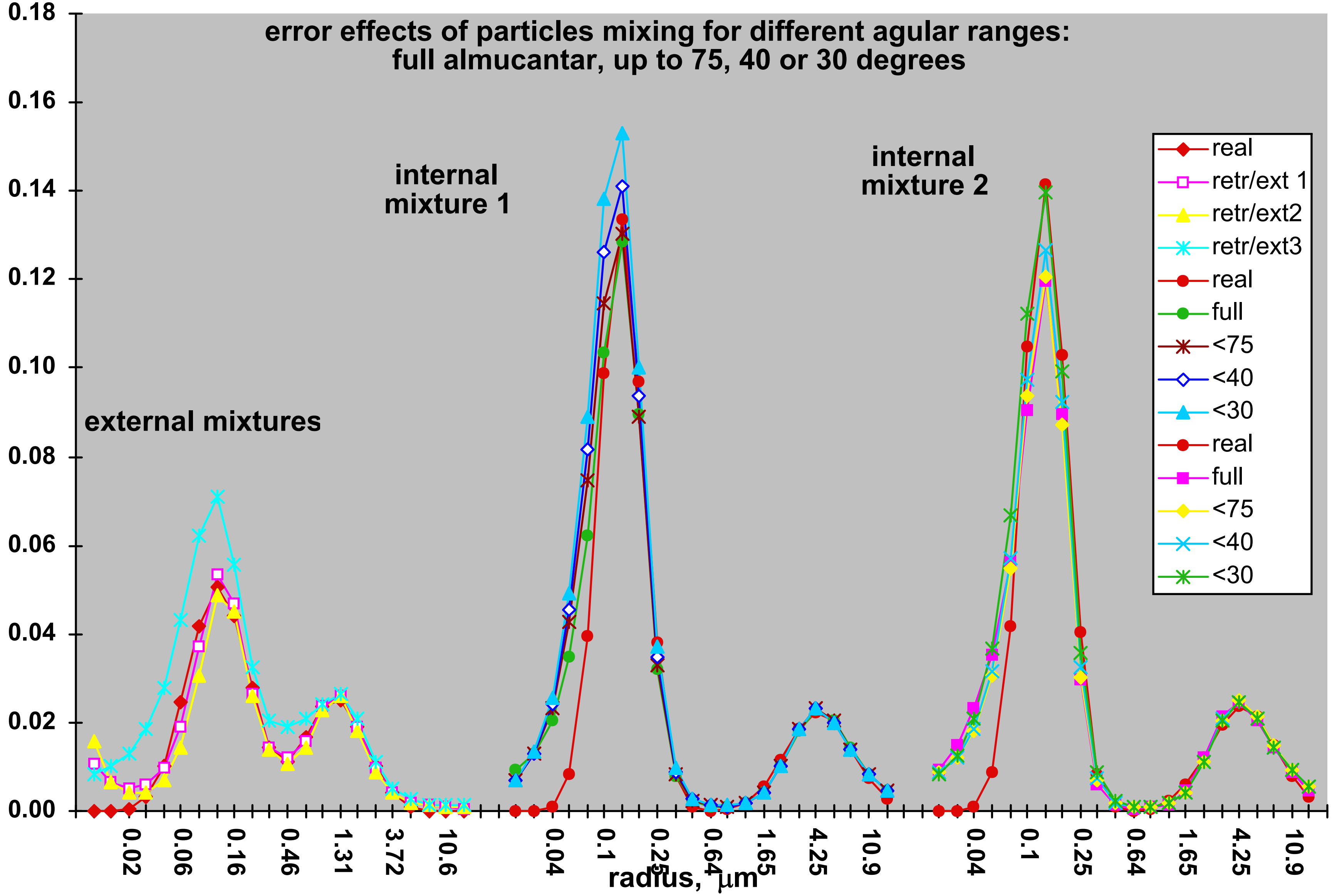
(+) CAN BE retrieved   (-) CAN NOT BE retrieved



error effects of particle mixing for different angular ranges:
full almucantar, up to 75, 40 or 30 degrees
real
retr
real/fine
real/coarse
retr
real/fine
real/coarse
retr
real/fine
real/coarse
full
<75
<40
<30
1.80
1.70
1.60
1.50
1.40
1.30
1.20
homogeneous
n1=1.45 n2=1.45
external mixture 1
n1=1.45 k1=0.0035
n2=1.53 k2=0.008
external mixture 2
n1=1.65 k1=0.035
n2=1.33 k2=0.0005
internal mixture 1
core=0.038 µm
internal mixture 2
ratio-0.33
440
670
870
1020
wavelengths, nm

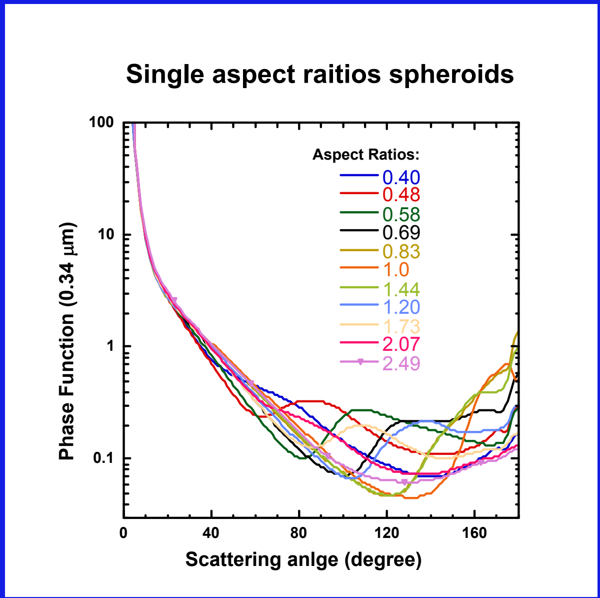


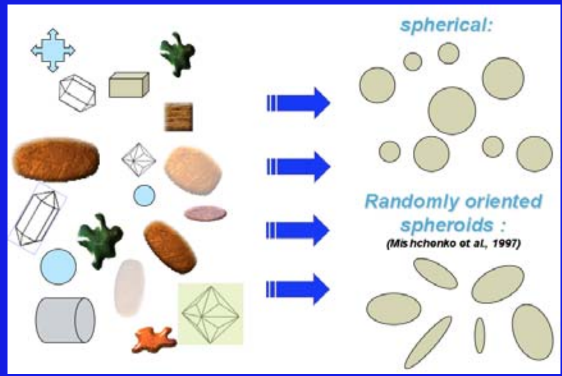
error effects of particles mixing for different angular range of sky radiances:
full almucantar, up to 75, 40 or 30 degrees
1.00
0.90
0.80
0.70
0.60
0.50
real
retr
real
retr
real
retr
real
full
<75
<40
<30
homogeneous
n1=1.45
n2=1.45
external mixture 1
n1=1.45 k1=0.0035
n2=1.53 k2=0.008
external mixture 2
n1=1.65 k1=0.035
n2=1.33 k2=0.0005
internal mixture 1
core=0.038 μm
internal mixture 2
ratio-0.33
440
670
870
1020
wavelength, nm

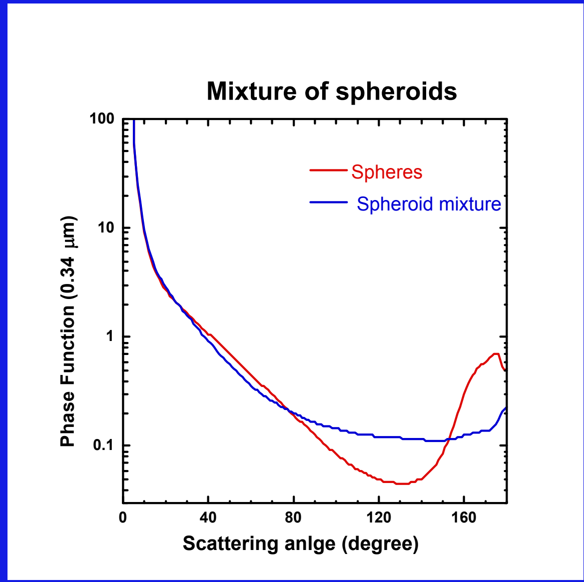


error effects of particles mixing for different agular ranges:
full almucantar, up to 75, 40 or 30 degrees
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
external mixtures
internal mixture 1
internal mixture 2
real
retr/ext 1
retr/ext2
retr/ext3
real
full
<75
<40
<30
real
full
<75
<40
<30
0.02
0.06
0.16
0.46
1.31
3.72
10.6
0.04
0.1
0.25
0.64
1.65
4.25
10.9
0.04
0.1
0.25
0.64
1.65
4.25
10.9
radius, µm

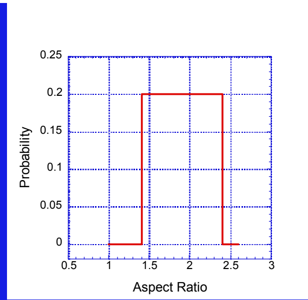
Modeling Dust particle non-sphericity

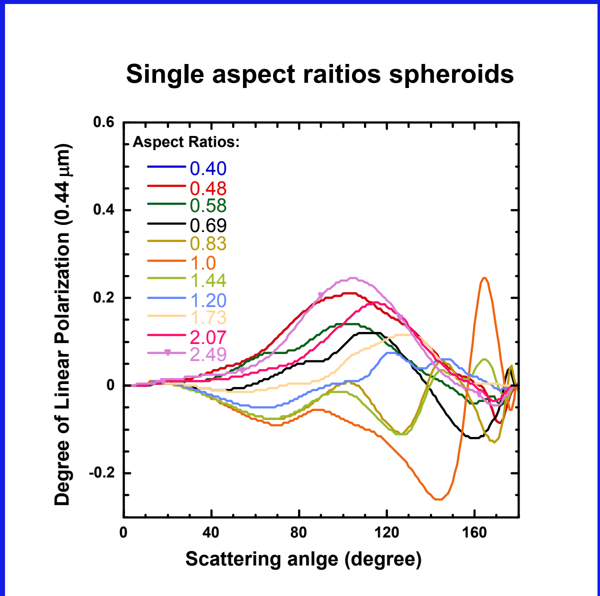


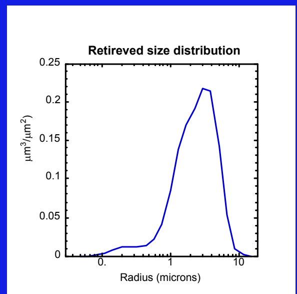




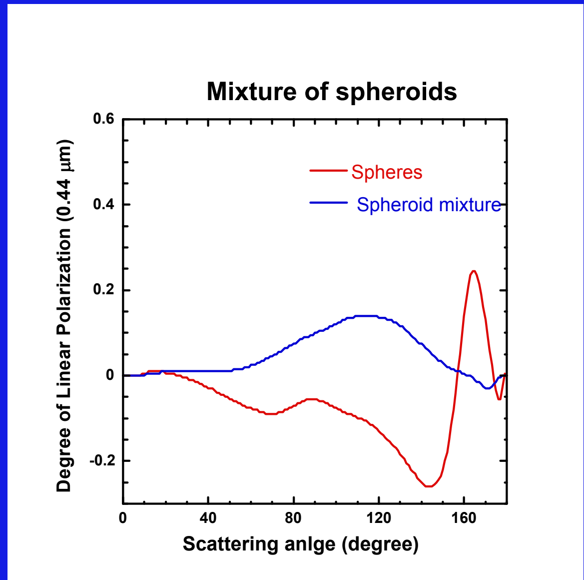
Averaging with $\omega(\varepsilon)$





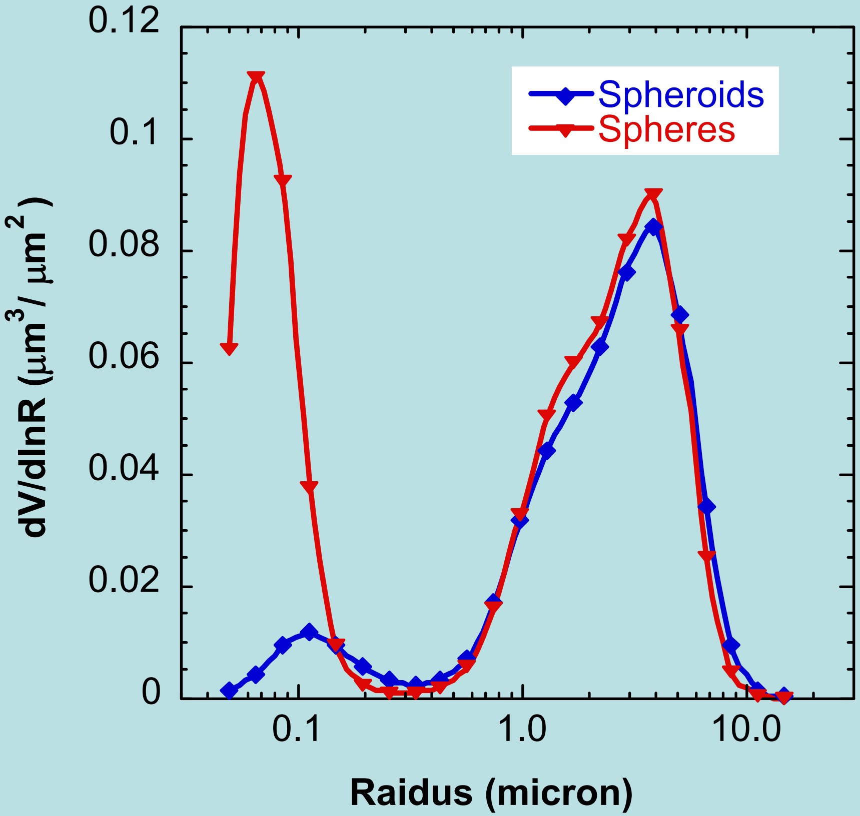


$n(\lambda)$ $k(\lambda)$

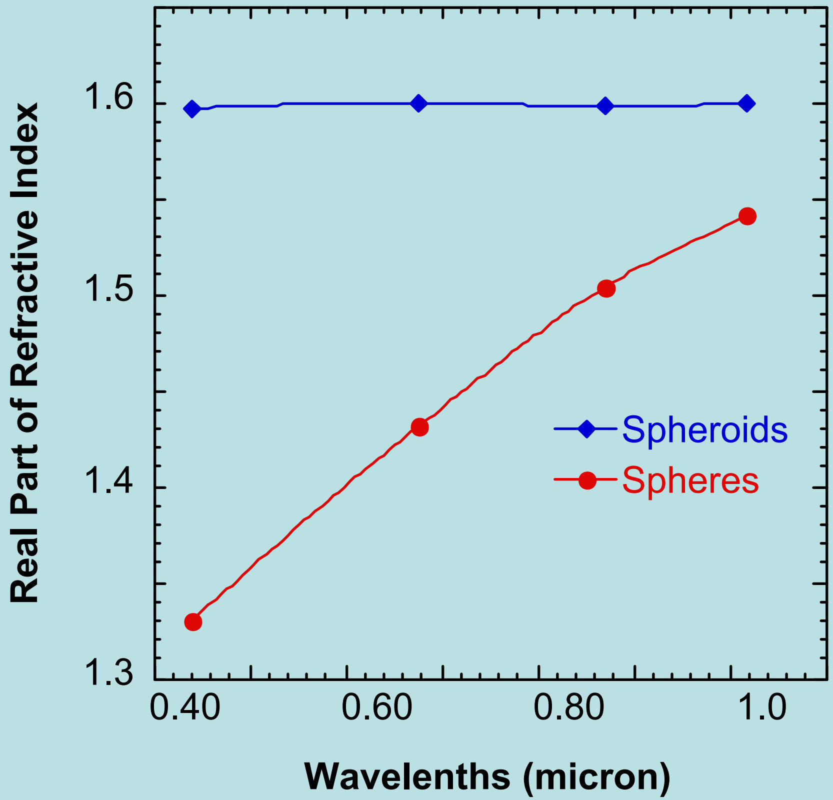


Artifacts in AERONET retrievals caused by non-sphericity of Desert Dust particles

Effect of shape assumptions on retrieved dust size distribution



Influence of shape assumtion on retireved ref. index



Retrieval accuracy and limitations

Sensitivity tests by Dubovik et al. 2000

Effective

wide angular coverage

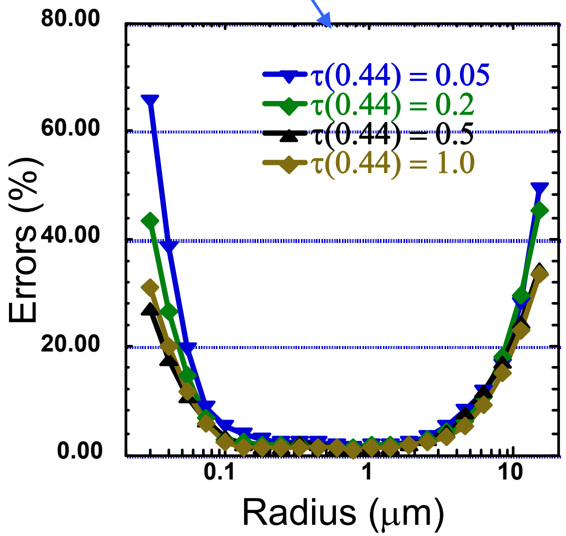
bias $\Delta\tau = \pm\ 0.01$

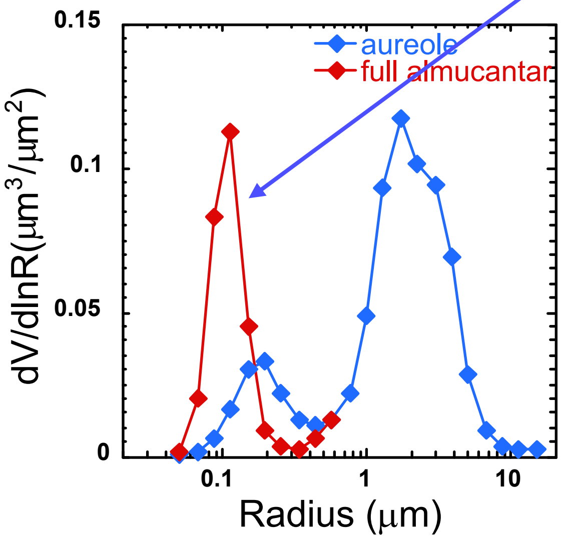
	$\tau(0.44) \leq 0.2$	$\tau(0.44) \geq 0.5$
Real Part	0.05	0.025
Imaginary Part	80-100%	50%
SSA	0.05-0.07	**0.03**

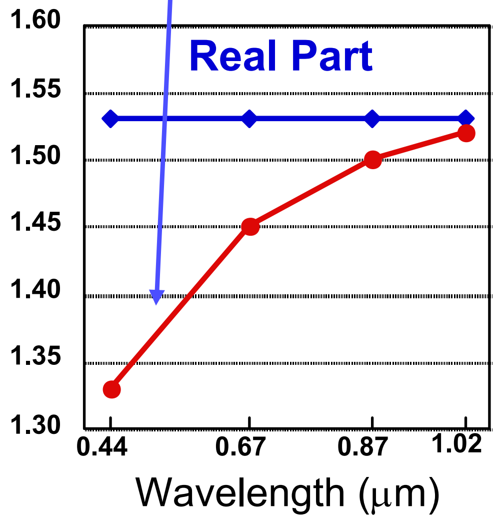
Size Distribution:

Random errors

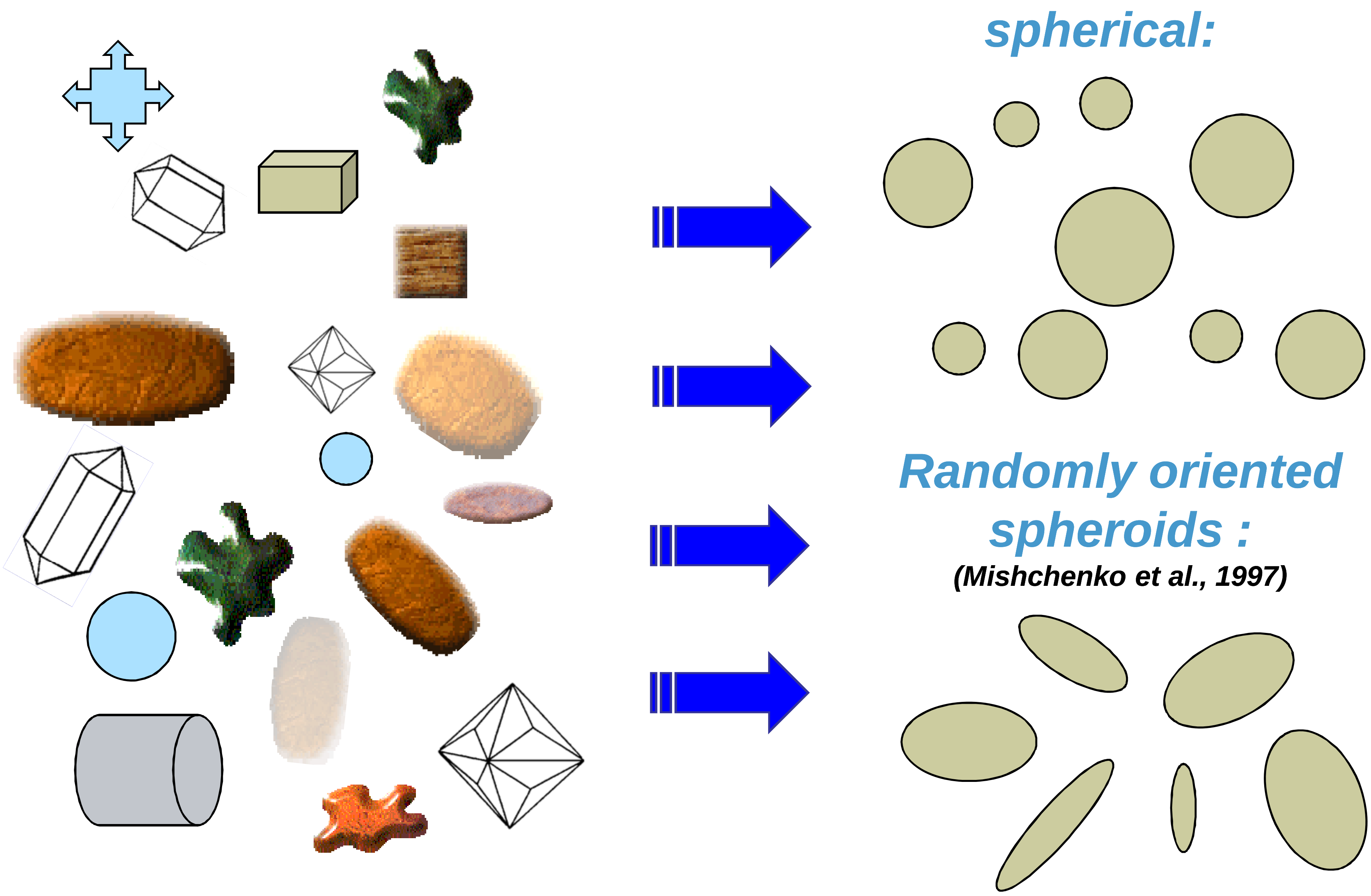
Nonsphericity biases







AERONET model of aerosol



CONCLUSIONS:

1. Achivements:

- the retrieval is rather elaborated;
- the retrieval provides not only the main set of parameters but also extended set secondary products;
- the results are provided together with error estimates
- the model and accuracy is verified in sensitivity studies
- useful climatologies were developed;

2. Perspectives:

- more efficient use of polarimetric measurements
- updating model of non-spherical fraction
- deriving aerosol composition
- combining photometric data with other co-incident observations

AERONET retrieval products: - V1 - V2 - V3

Directly retrieved parameters:

- dV/dlnR - size distribution; *(- dynamic errors)*
- $C(t,f,c)$, $R_v(t,f,c)$, $\sigma(t,f,c)$, $R_{eff}(t,f,c)$ - integral parameters of dV/dlnR
- $n(\lambda)$ and $k(\lambda)$ at 0.44, 0.67, 0.8, 1.02 μm; *(- dynamic errors)*
- $C_{spherical}$ - fraction of spherical particles *(- dynamic errors)*

Indirectly retrieved/estimated parameters:

♣ *popular:*

- ω_0 - at 0.44, 0.67, 0.8, 1.02 μm; *(- dynamic errors)*
- $P_{11}(\Theta,\lambda)$ *(- dynamic errors)* and $<\cos(\Theta)>$;
- $P_{12}(\Theta,\lambda)$ and $P_{22}(\Theta,\lambda)$ - ??? *(- dynamic errors)*
- $F^{\downarrow}_{TOA}(\lambda)$ and $F^{\downarrow}_{BOA}(\lambda)$ - down ward spectral fluxes
- $F^{\uparrow}_{TOA}(\lambda)$ and $F^{\uparrow}_{BOA}(\lambda)$ - upward spectral fluxes

♣ *not well-known / under-developed:*

- $S(\lambda)$ - lidar backscattering-to-extinction ratio; *(- dynamic errors)*
- $\delta(\lambda)$ - lidar depolarization ratio ; *(- dynamic errors)*
- $F^{\downarrow}_{TOA}$ and $F^{\downarrow}_{BOA}$ - down ward broad-band (visible) fluxes;
- $F^{\uparrow}_{TOA}$ and $F^{\uparrow}_{BOA}$ - upward broad-band (visible) fluxes;
- ΔF_{TOA} and ΔF_{BOA} - radiative forcing
- ΔF^{Eff}_{TOA} and ΔF^{Eff}_{BOA} - radiative forcing efficiency

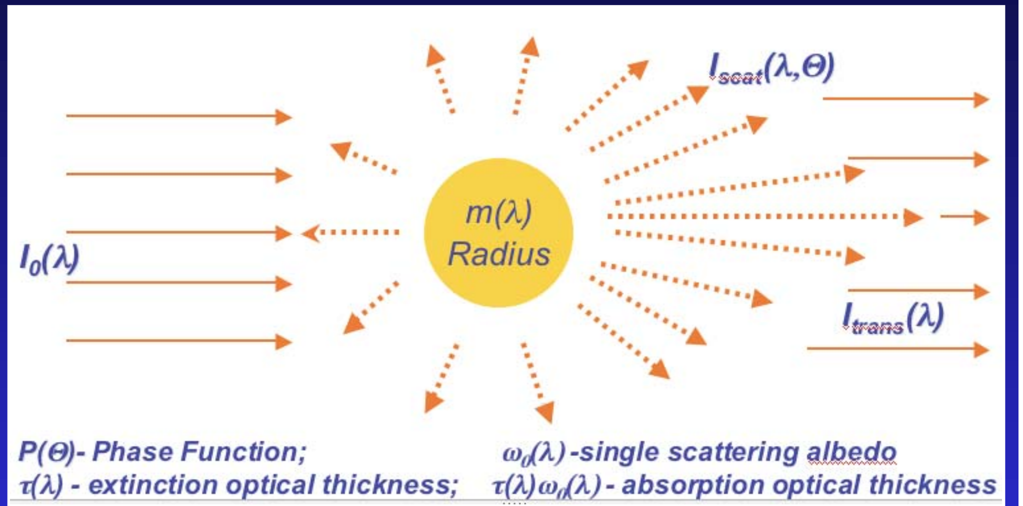
Aerosol single particle scattering:

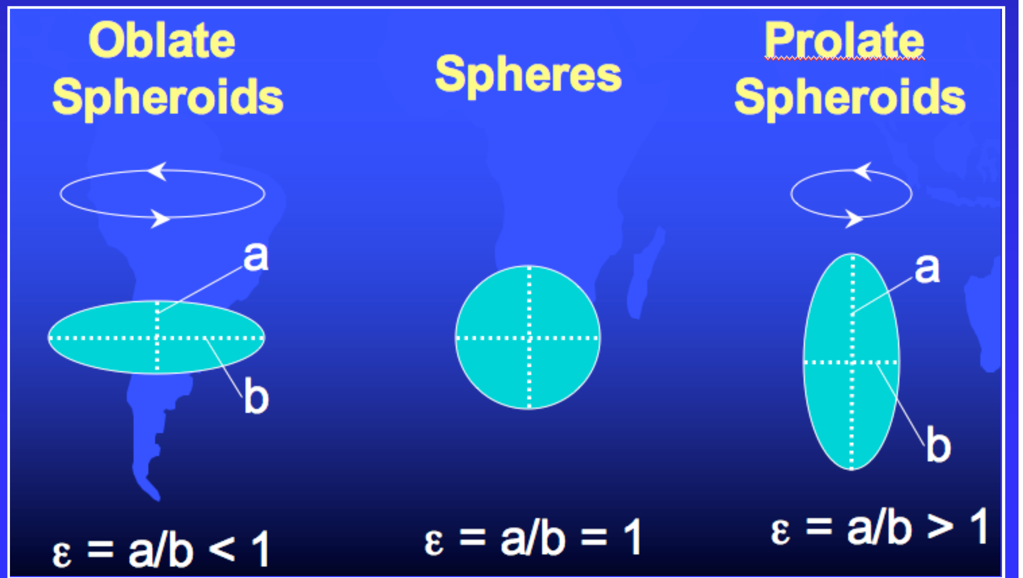
ASSUMPTIONS in the retrievals:

EACH AEROSOL PARTICLE

- <u>sphere or spheroid (!!!);</u>
- homogeneous;
- $1.33 \leq n \leq 1.7$
- $0.0 \leq k \leq 0.5$

-n and k spectrally dependent *(but smooth)*

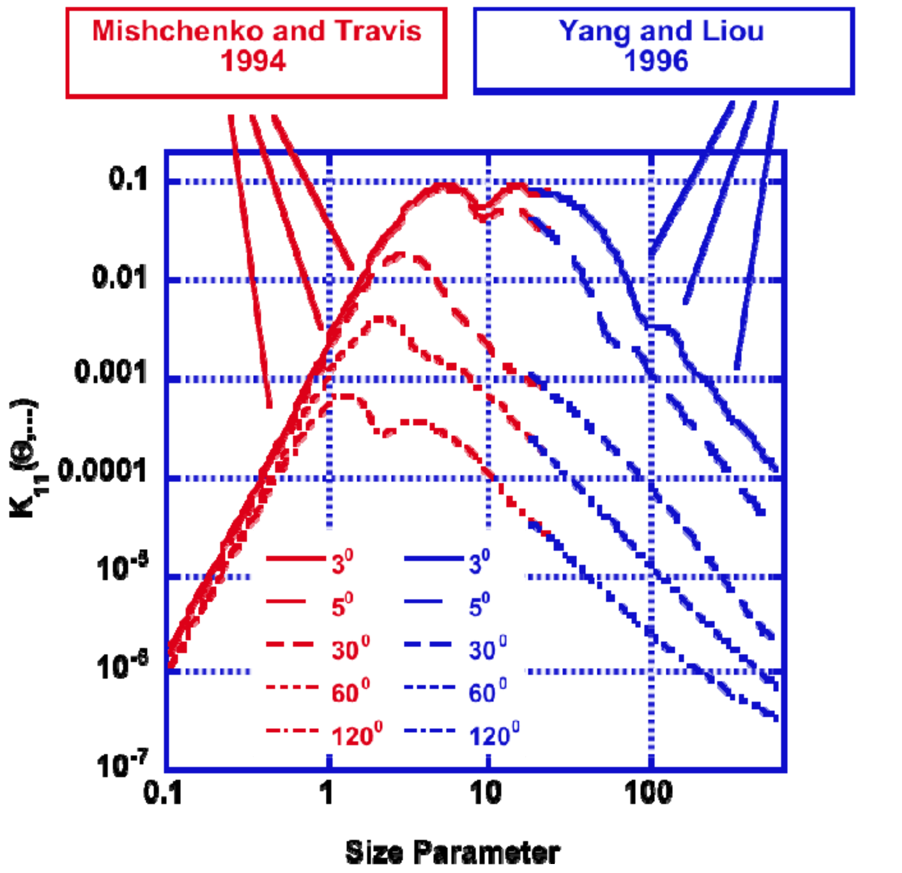


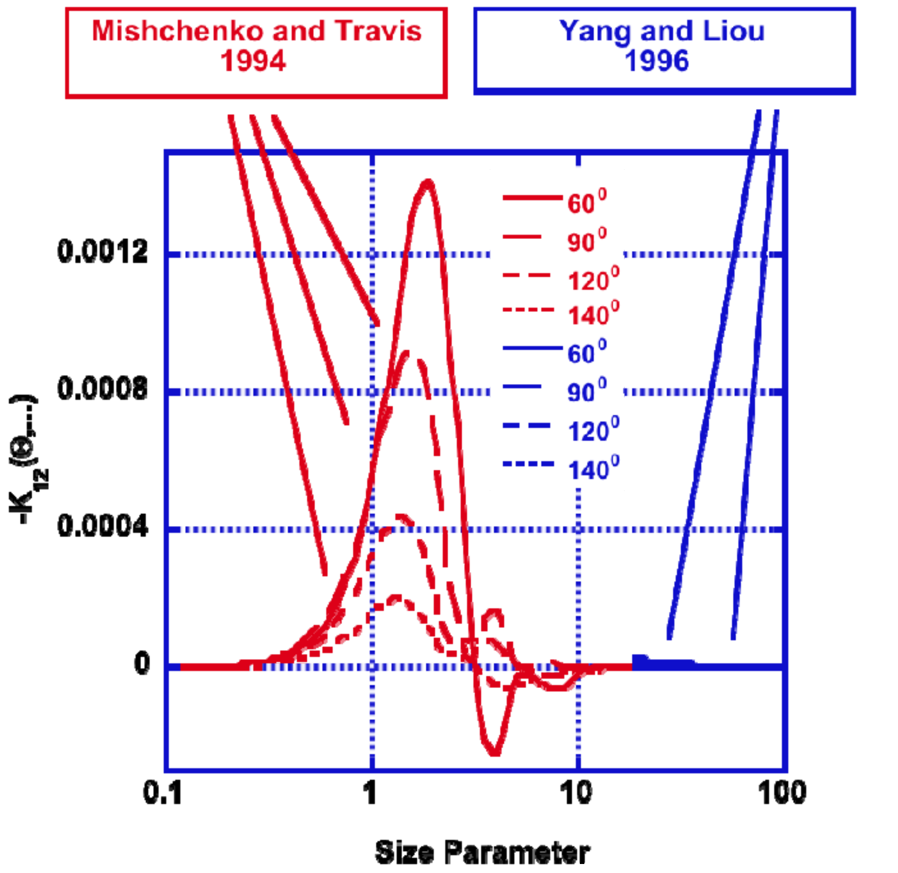


Computational challenge of using spheroids model

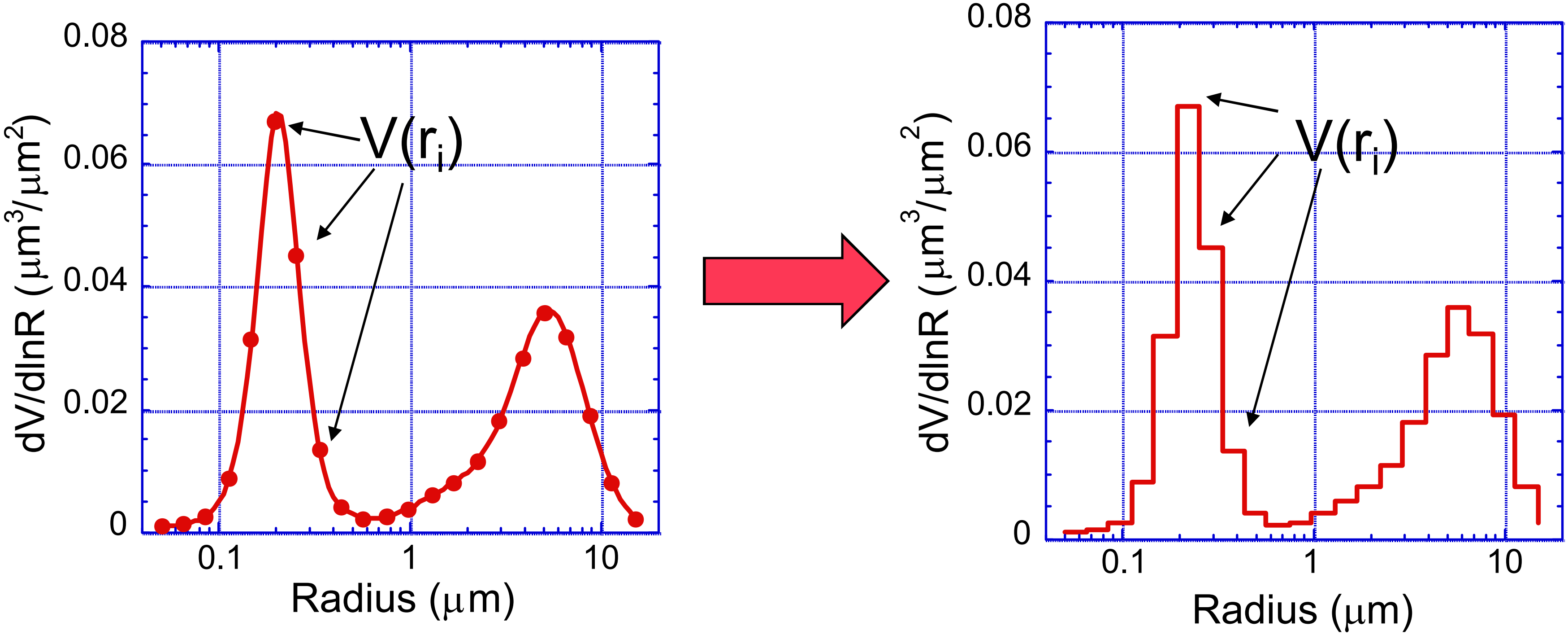
Strategy: using two complementary methods

Example for prolate spheroids with aspect ratio ~ 2.75





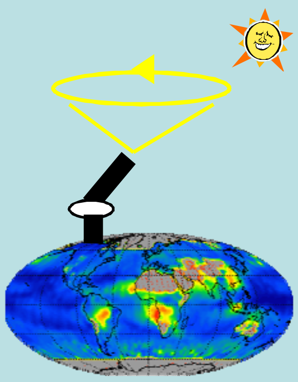
Modeling Spheroid Polydispersions



$$\tau(\lambda) = \int_{\varepsilon_{min}}^{\varepsilon_{max}} \int_{r_{min}}^{r_{max}} K_\tau(\lambda;k;n;\varepsilon;r) N(\varepsilon) V(r)\, dr\, d\varepsilon \approx \sum_j \sum_i N(\varepsilon_j) V(r_i) \int_{r_i - \Delta/2}^{r_i + \Delta/2} K_\tau(\lambda;k;n;\varepsilon_j;r_i)$$

$\boxed{\mathbf{K}(\lambda;k;n;\varepsilon_j;r_i)}$ - Kernel look-up table for fixed r_i (22 points)
($1.33 \le n \le 1.7$; $0.0 \le k \le 0.5$, $0.3 \le \varepsilon \le 3.0$)

spheroid kernels data base for operational modeling !!!

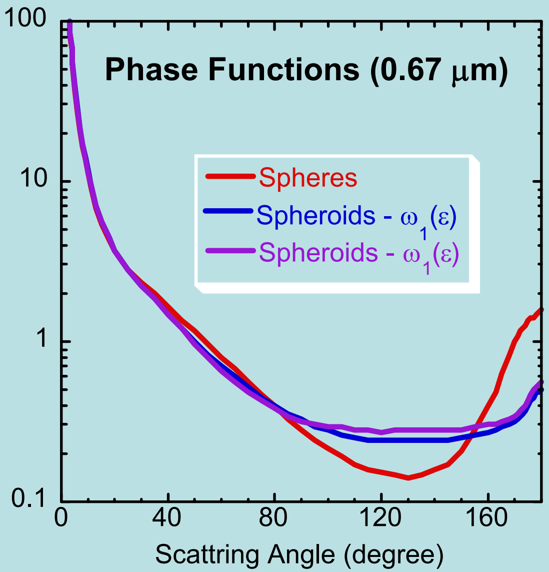


K - pre-computed kernel matrices:
Input: n and k

Input: ε_i (N_p =25),
$V(r_i)$ (N_i =22 -41)

Basic Model by Mishchenko et al. 1997:
- randomly oriented homogeneous spheroids
- $\omega(\varepsilon)$ - size independent shape distribution

$$\tau(\lambda),\mathbf{F}_{11},\dots,\mathbf{F}_{44} \approx \sum_{(i;p)} \mathbf{K}_{ip}\left(\dots;\lambda;n;k\right) N\left(\varepsilon_p\right) V\left(r_i\right)$$



Time: < one sec.
Accuracy: < 1-3 %
Range of applicability:
$0.012 \le 2\pi r/\lambda \le 625$ (41 bins)
$0.3 \le \varepsilon \le 3.0$ (25 bins)
$1.33 \le n \le 1.7$
$0.0 \le k \le 0.5$

Output: $\tau(\lambda)$, $\omega_0(\lambda)$, $F_{11}(\Theta)$, $F_{12}(\Theta)$, $F_{22}(\Theta)$, $F_{33}(\Theta)$, $F_{34}(\Theta)$, $F_{44}(\Theta)$

Optics ⟷ Microphysics

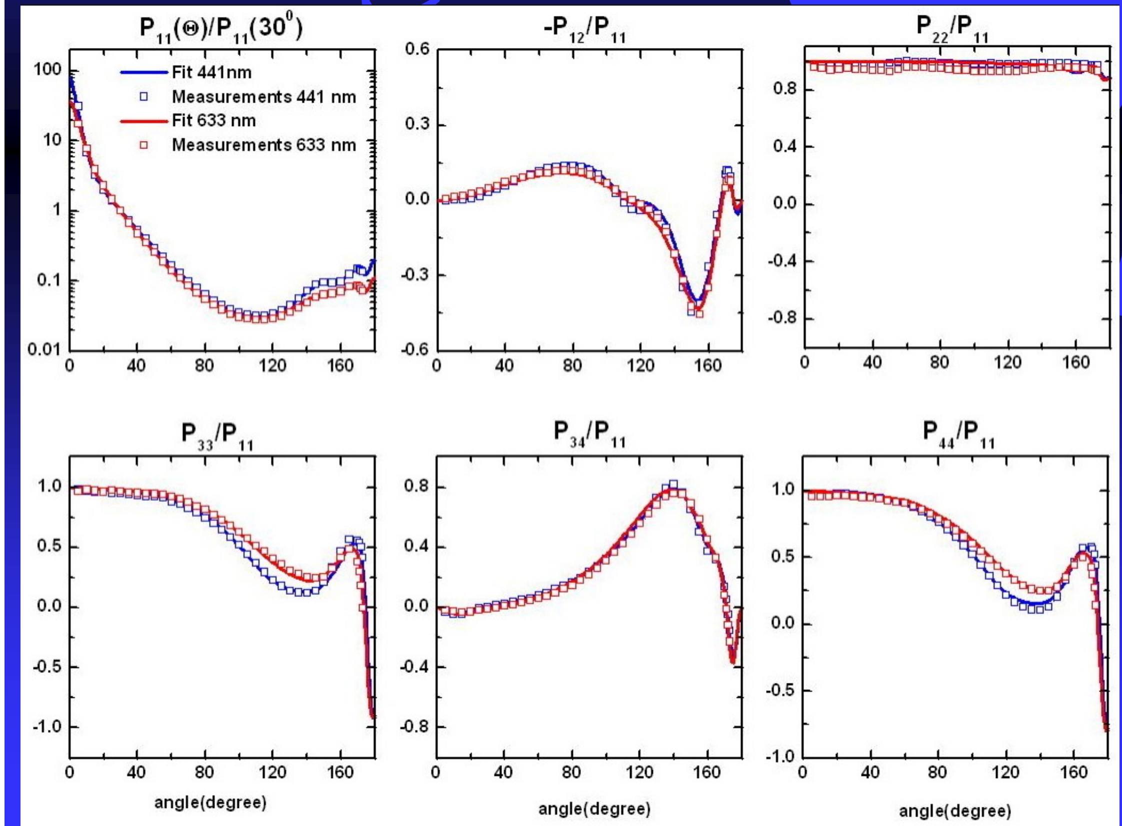
Dubovik et al. (2006)

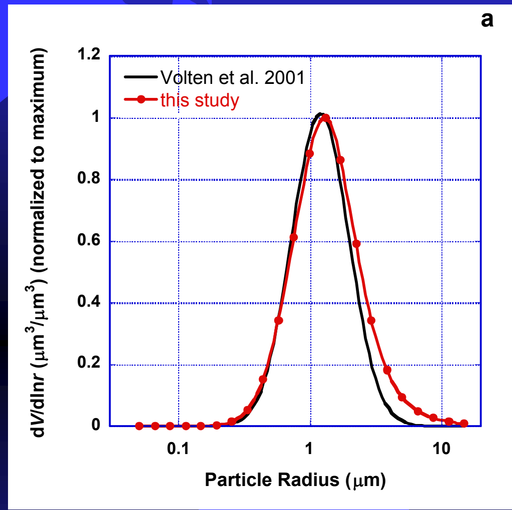
Water Droplets:

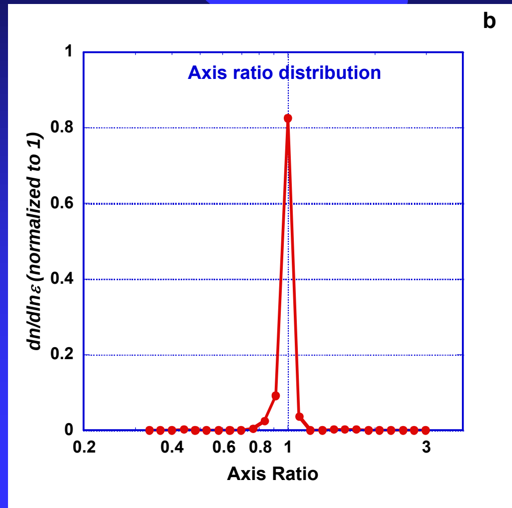
$n \approx 1.34\text{-}1.35$

$k \approx 0.0006 - 0.007$

Volten, Munoz et al.

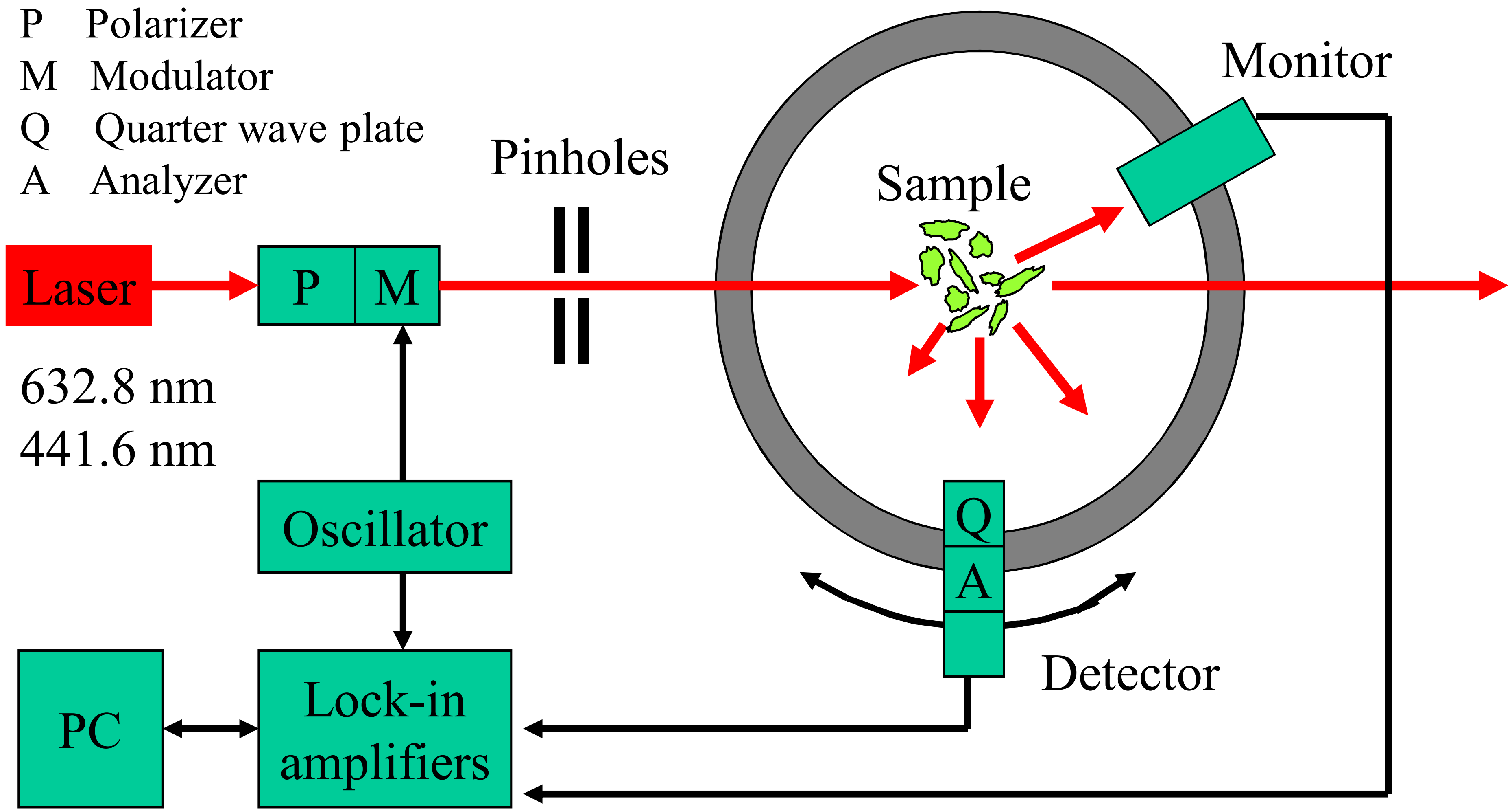






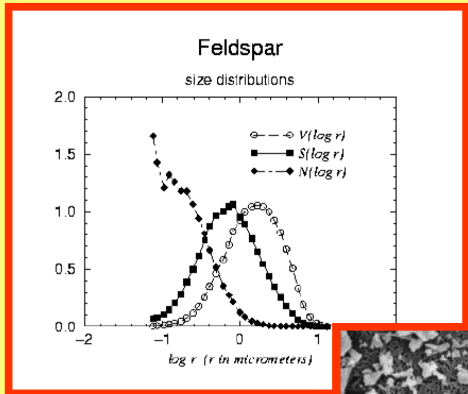
Measurement

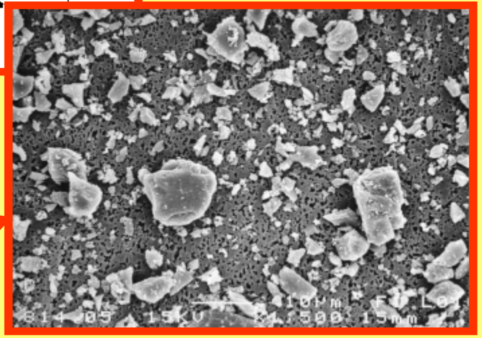
$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{scatt} \propto \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{in}$$



H. Volten, O. Munoz,
J. Hovenier,…

Facts and Figures





name of sample feldspar

origin crushed piece of Feldspar rock from Finland

main constituents K-feldspar, plagioclase, quartz

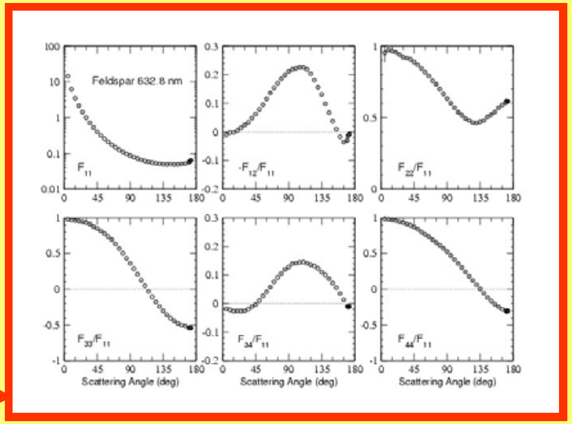
particle size distributions measured with laser diffraction

r_{eff} =1.0 micrometer, v_{eff} =1.0

particle shape irregular (SEM image)

refractive index estimated to be in the range:
1.5-1.6 - i0.001-0.00001Ê

colorÊ light pink to white powder

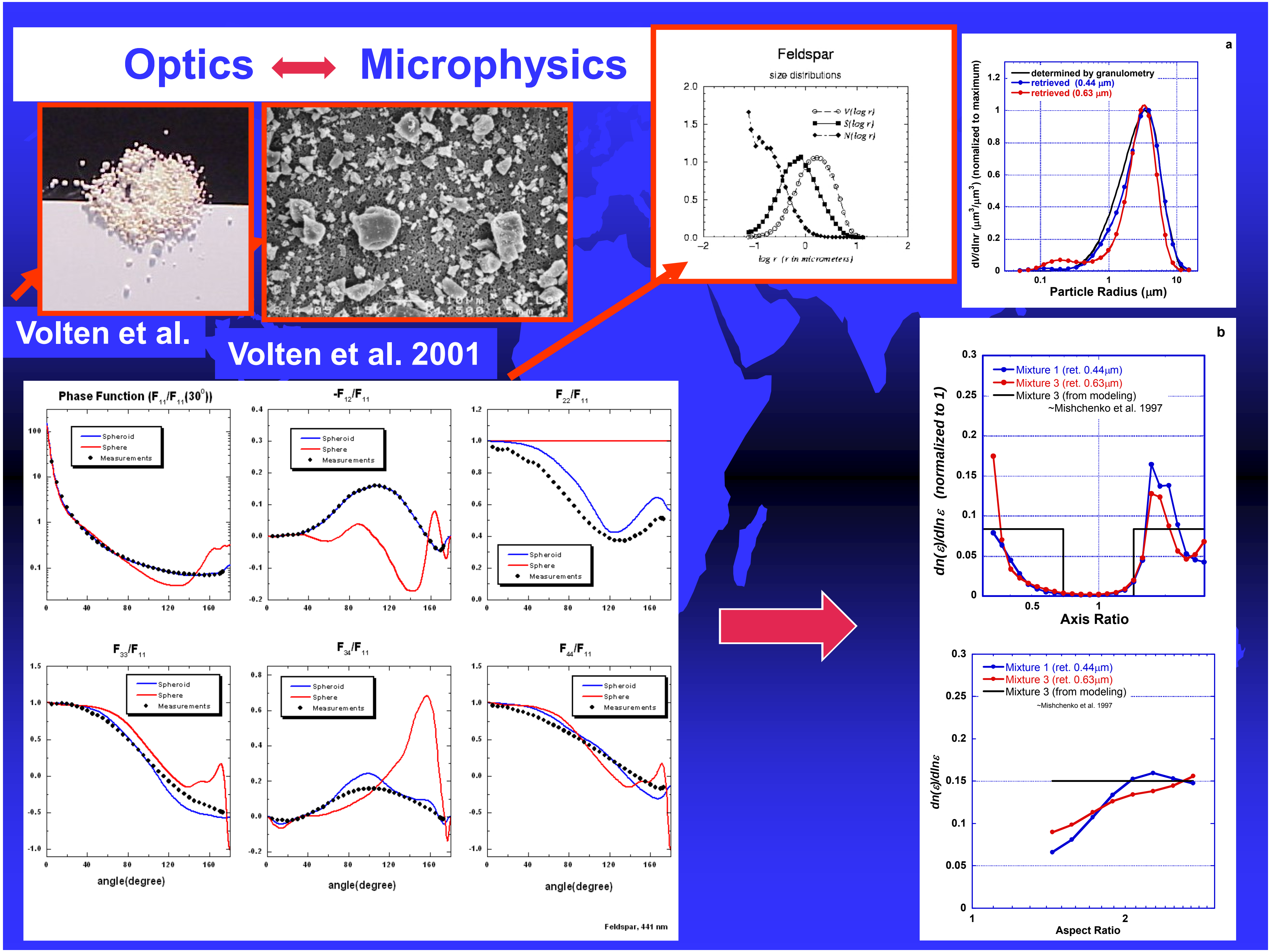


scattering matrix from 5-173 degrees scattering angle

wavelength 441.6 nm (figure)
632.8 nm (figure)

article Scattering matrices of mineral particles at 441.6 nm and 632.8 nm.
Volten H, Mu–oz O, Rol E, de Haan JF, Vassen W, Hovenier JW, Muinonen K, Nousiainen T.
Journal of Geophysical Research, 106, 17375-17401,2001

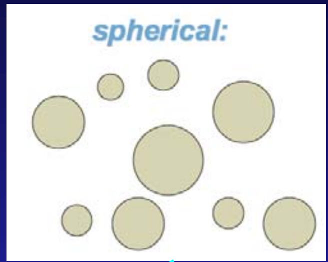
http://www.astro.uva.nl/scatter

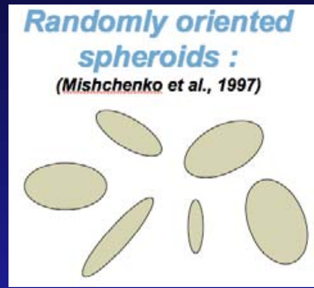


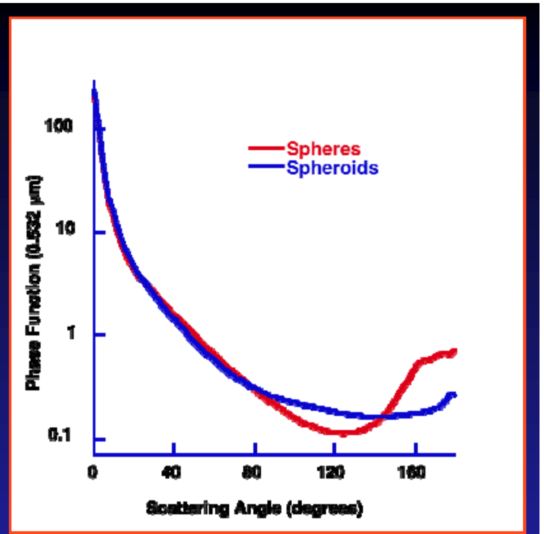
Optics
Microphysics
Volten et al.
Volten et al. 2001
Feldspar
size distributions
V(log r)
S(log r)
N(log r)
log r (r in micrometers)
a
determined by granulometry
retrieved (0.44 μm)
retrieved (0.63 μm)
dV/dlnr (μm³/μm³) (normalized to maximum)
Particle Radius (μm)
b
Mixture 1 (ret. 0.44μm)
Mixture 3 (ret. 0.63μm)
Mixture 3 (from modeling)
~Mishchenko et al. 1997
dn(ε)/dln ε (normalized to 1)
Axis Ratio
dn(ε)/dlnε
Aspect Ratio
Phase Function (F11/F11(30°))
-F12/F11
F22/F11
F33/F11
F34/F11
F44/F11
Spheroid
Sphere
Measurements
angle(degree)
Feldspar, 441 nm

Mixing of particle shapes

retrieved

$C \times$ 

$+ (1\text{-}C) \times$ 



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

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