# Polarization and multi-directional views for aerosol and cloud remote sensing

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# What is polarization ?

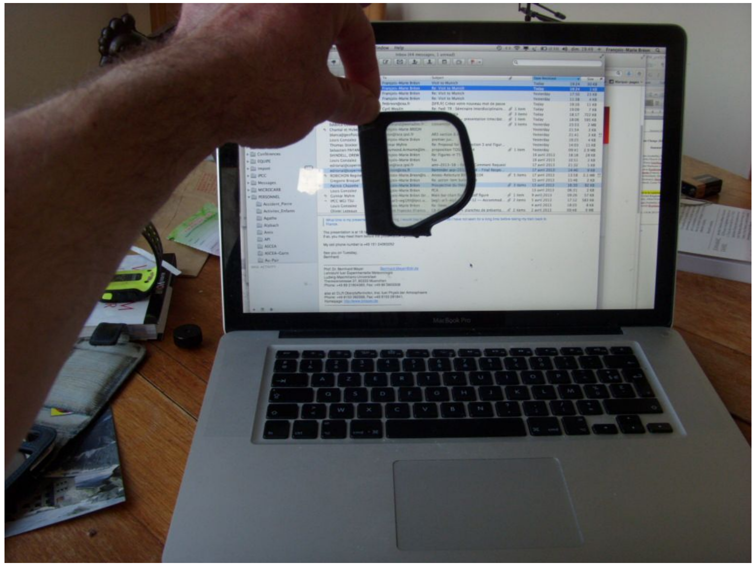
Light is an electromagnetic wave.

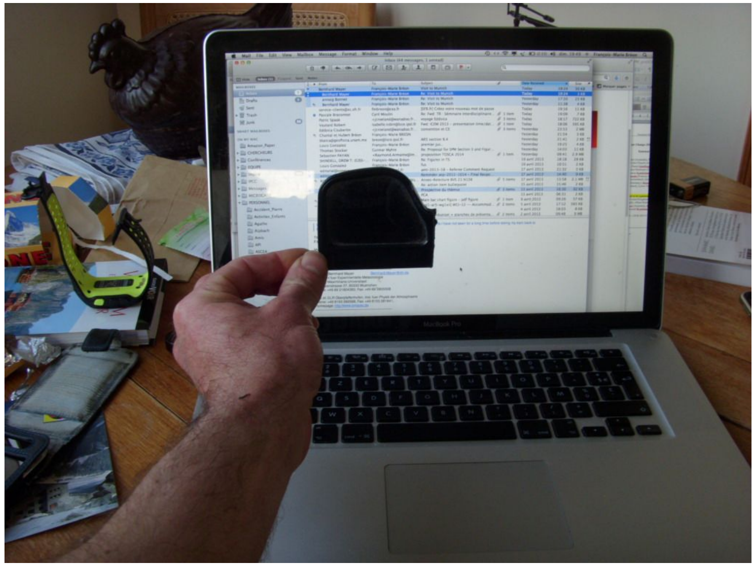
Usually, the electric field is randomly oriented.

It may get preferentially oriented after a scattering or reflexion process

In such case, the light is said “polarized”

A polarizer let through the light waves that have the electric field parallel to the polarizer direction





Obviously, my screen generates fully polarized light !

# Natural processes that polarize light

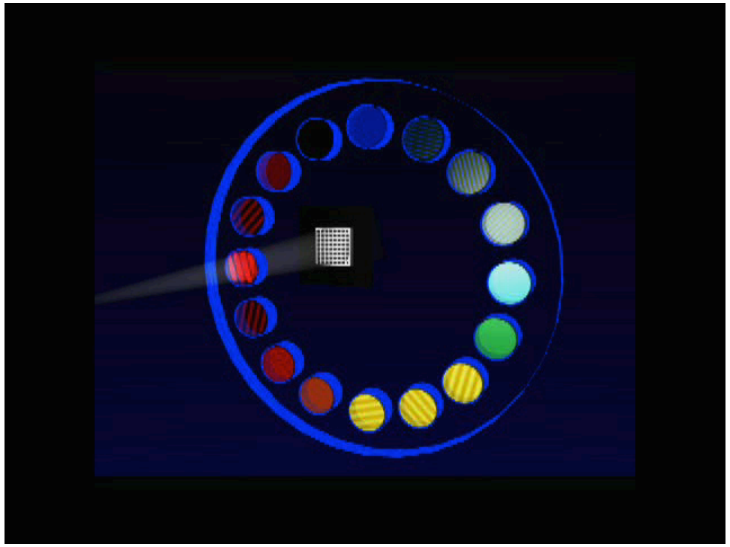
Molecular scattering polarize sunlight, depending on the scattering angle. Skylight is highly polarized !

Specular reflexion generates polarization depending on the incidence angle. Full polarization for incidence at the Brewster angle (≈50°)

Scattering by aerosols and clouds generate polarized light depending on aerosol and droplet characteristics.

The measurement of polarization provides additional information to identify the presence and type of scattering particles in the atmosphere

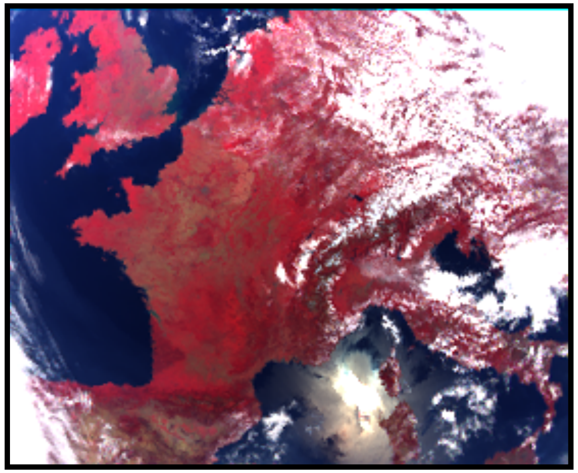
# Parasol polarization measurements

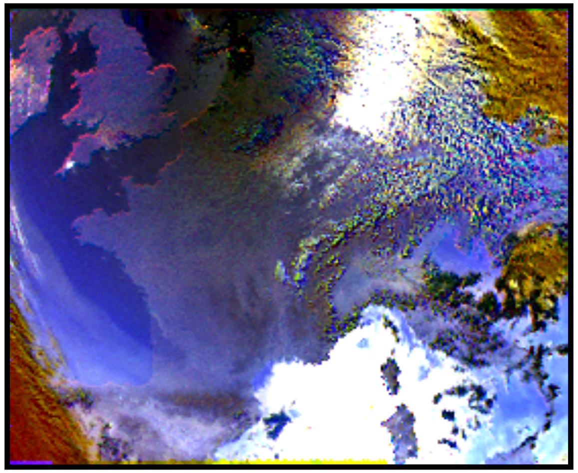


Three successive measurements with polarizer turned by step of 60°

Inversion of radiometric model yield linear polarization parameters [I, Q, U]

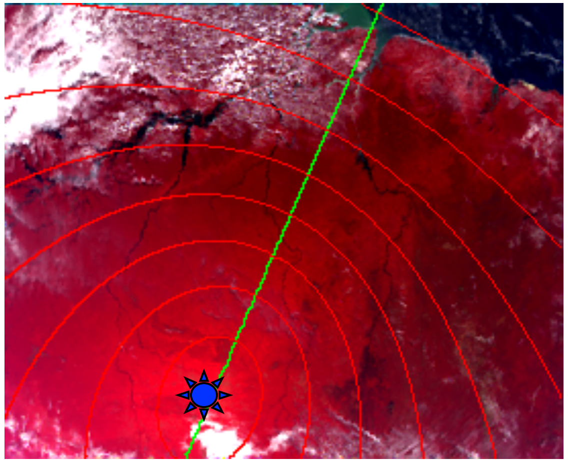
Three spectral bands 490, 670, 865 nm

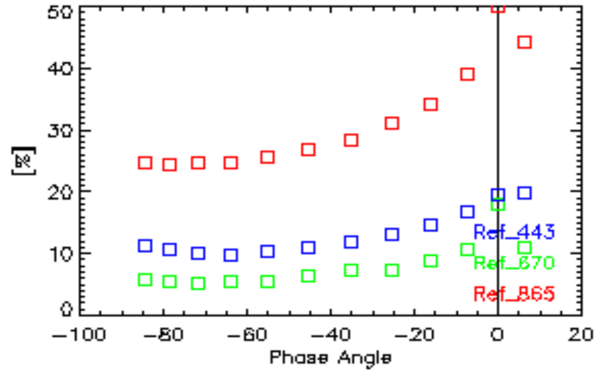


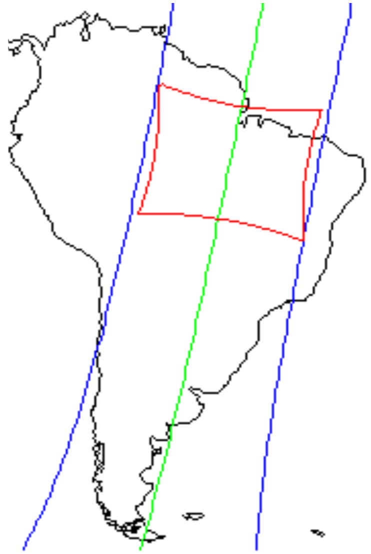


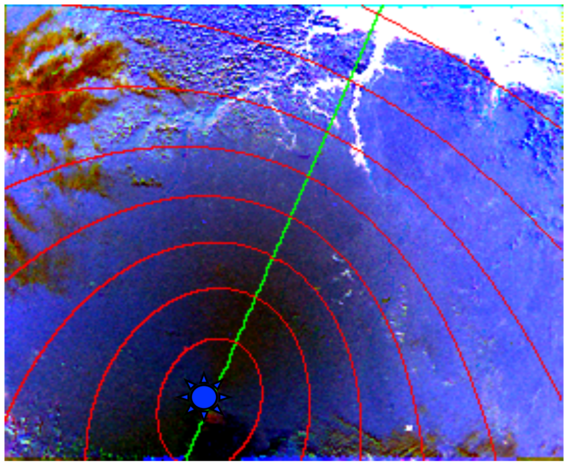
Rough correction for molecular scattering. Three colour composites

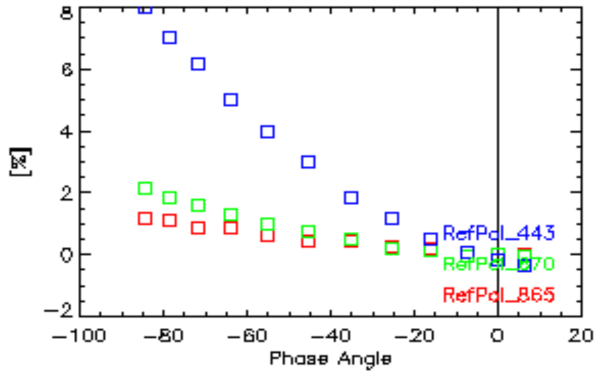
# Vegetation (Amazonian)



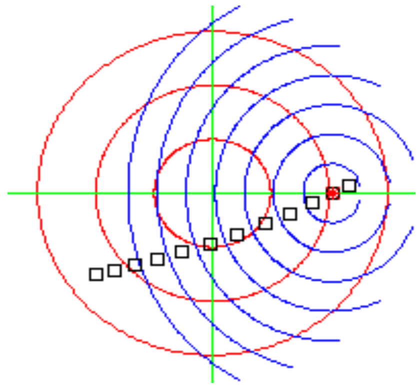


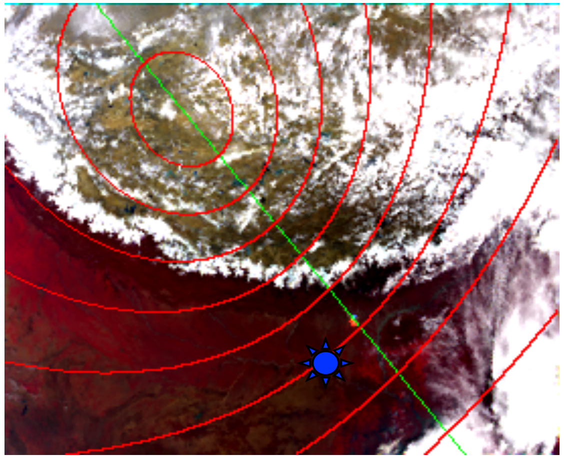


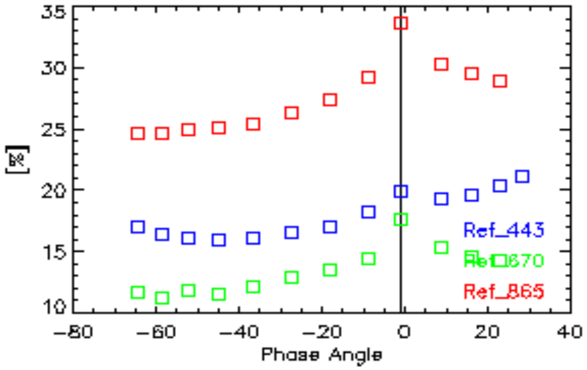


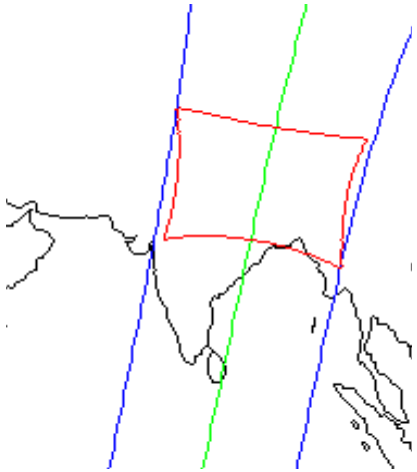

$$R_P(\theta_s,\theta_v,\varphi) \approx \frac{F_P\left(\frac{\pi-\gamma}{2}\right)}{4\left(\cos\theta_s+\cos\theta_v\right)}$$

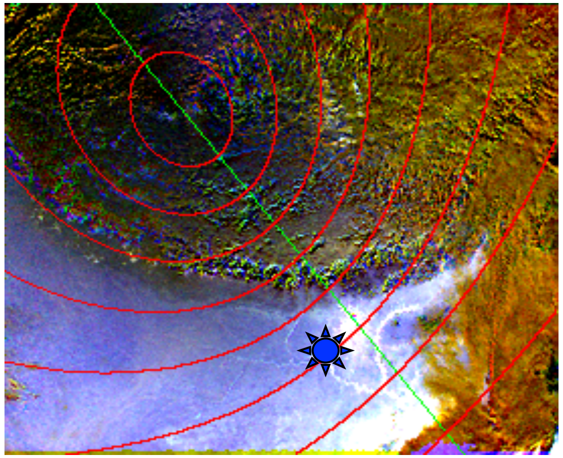


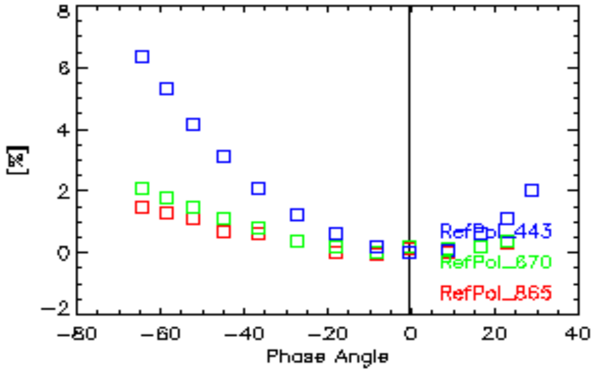
# Aerosols over the Ganges Valley

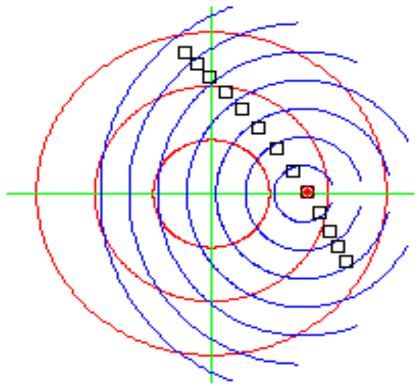




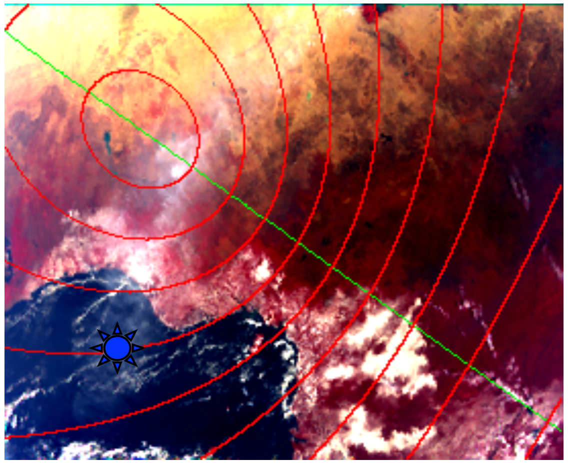


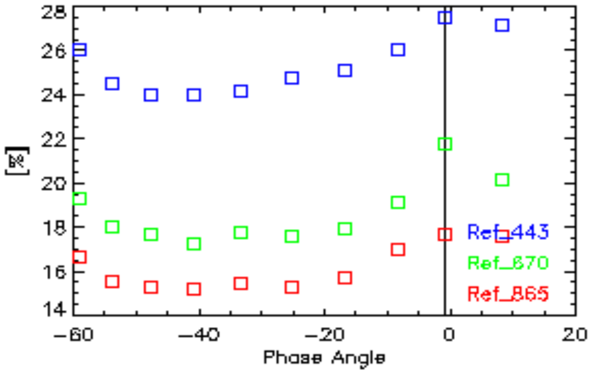


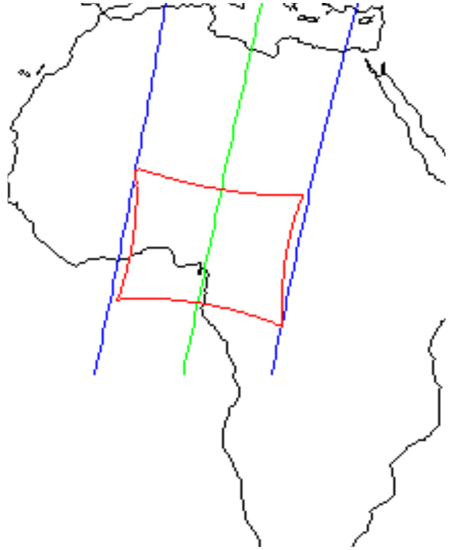



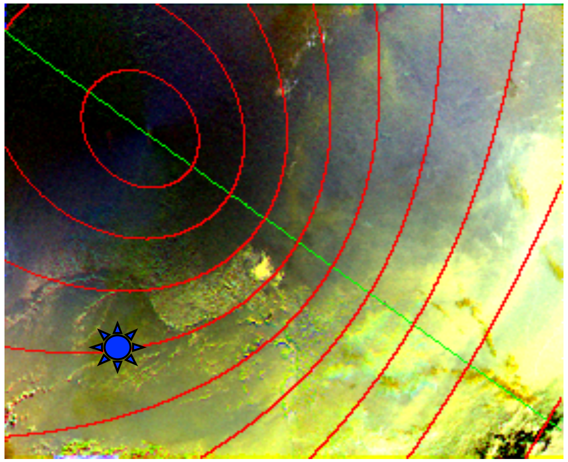
$$R_P(\theta_s,\theta_v,\varphi) \approx \frac{P_P(\gamma)}{4\left(\cos\theta_s + \cos\theta_v\right)}\left(1-\exp\left(-m\,\tau_a\right)\right)$$

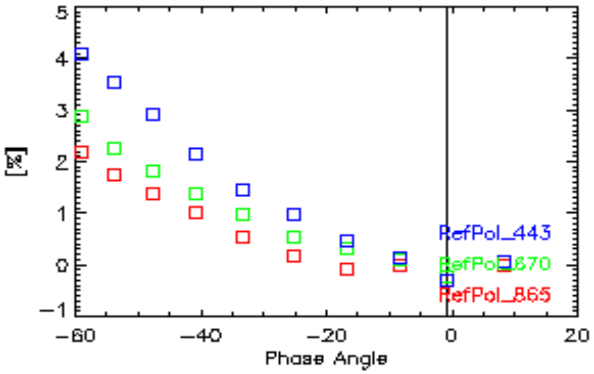
# Biomass Burning Aerosol

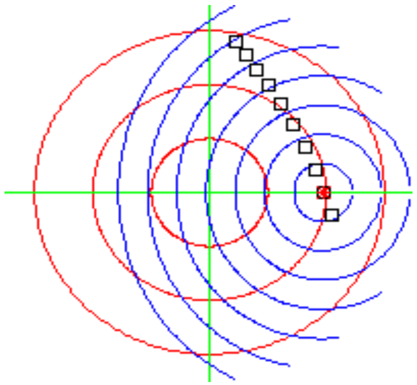




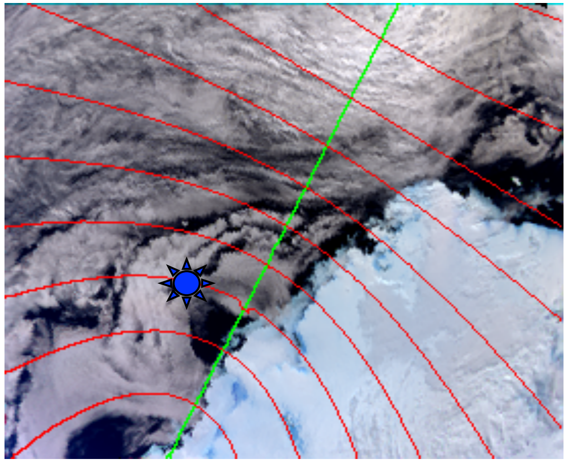



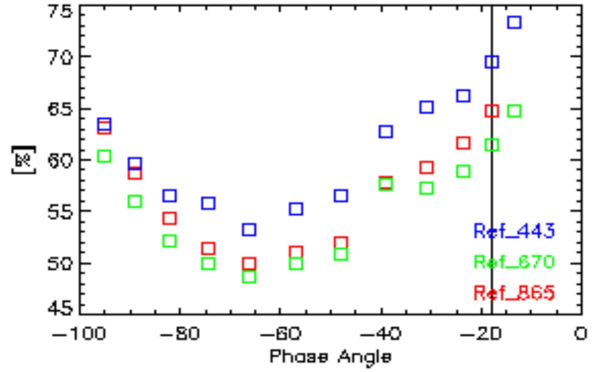


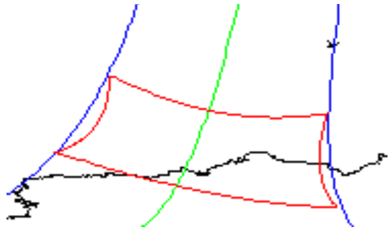


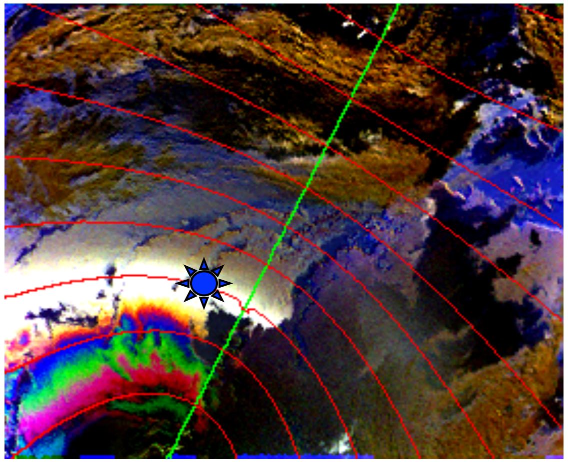



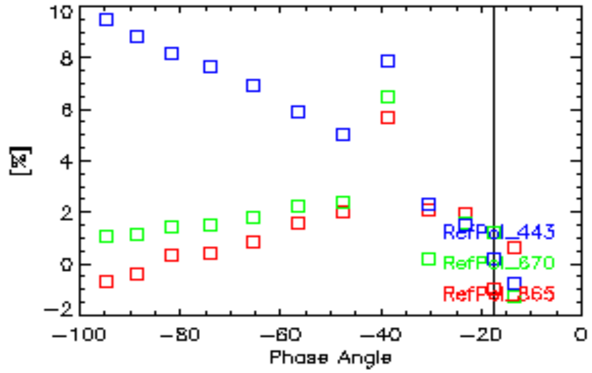
# Antarctic + Cloud Bow

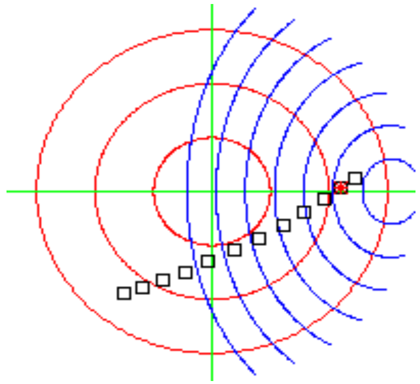








# Surface BPDFs

We have analyzed polarization measurements and derived typical models for the polarized reflectance of land surfaces.

BPDF characteristics are very different than those of BRDFs

Minimum at backscatter. Increases with phase angle

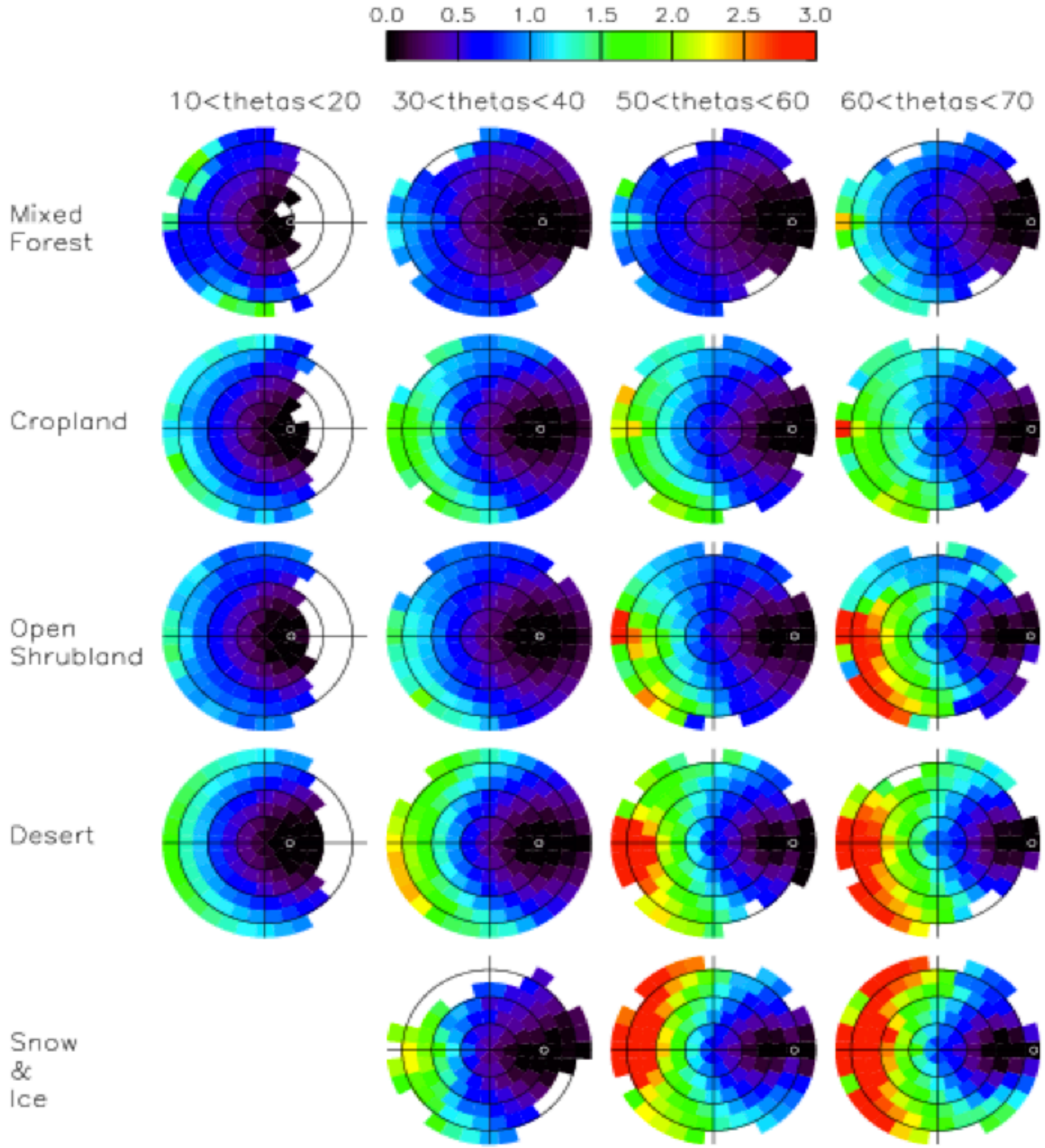
Varies from ≈0 to a few percent

Forest < crops < bare soil < snow

Appears Spectrally neutral

Generated by specular reflection

Did not find any useful information about the surface that can be derived from polarization, and that cannot be obtained more easily




Maignan et al., *Rem. Sens. Env.*, 2010

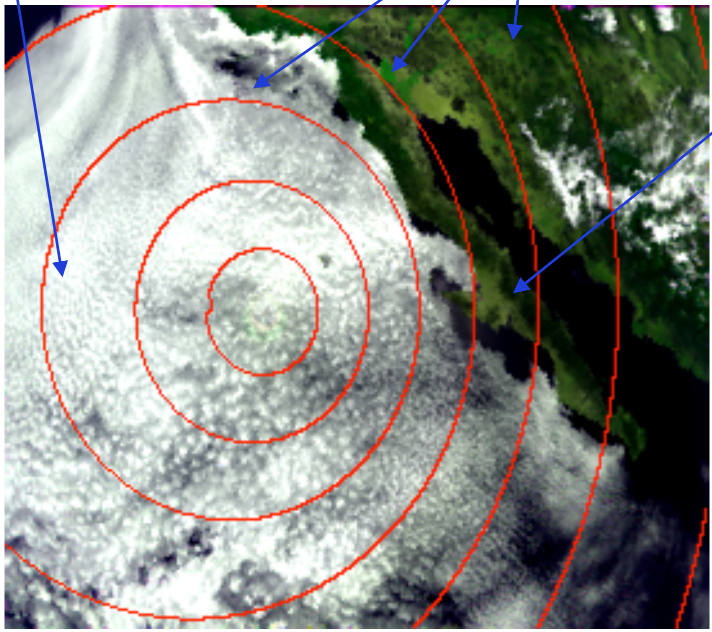
# Cloud Droplet Radius
# from Multidirectional polarisation measurements

# Liquid phase clouds

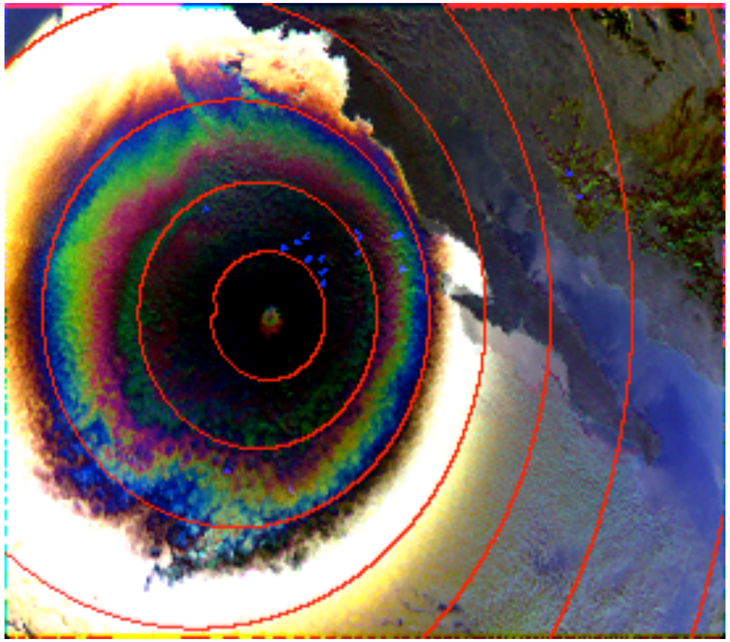
Stratocumulus cloud field

Scattering angle

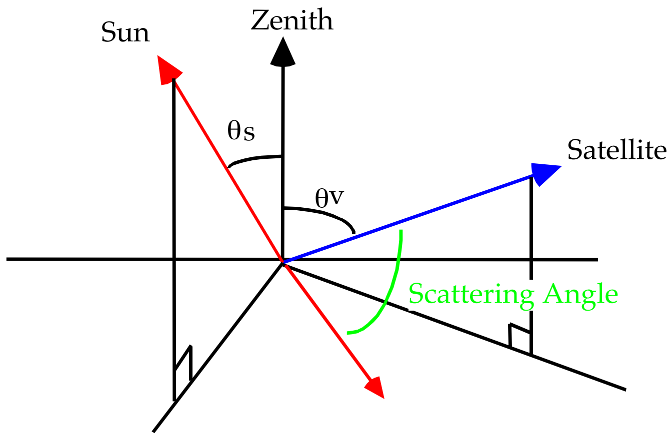
Baja California



3-color composite 443-670-865 nm

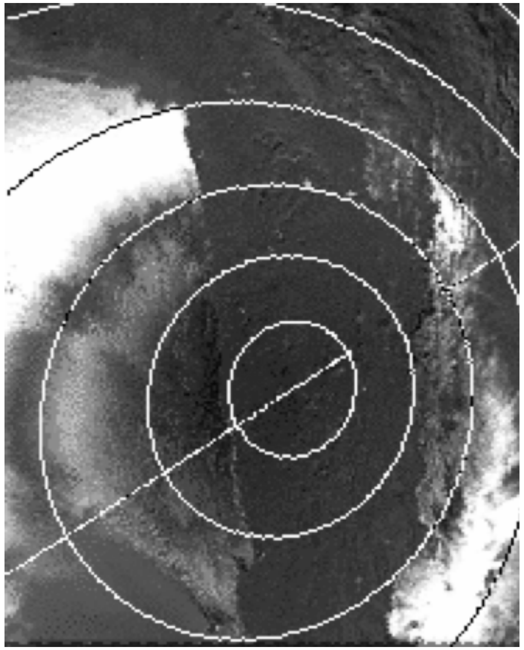


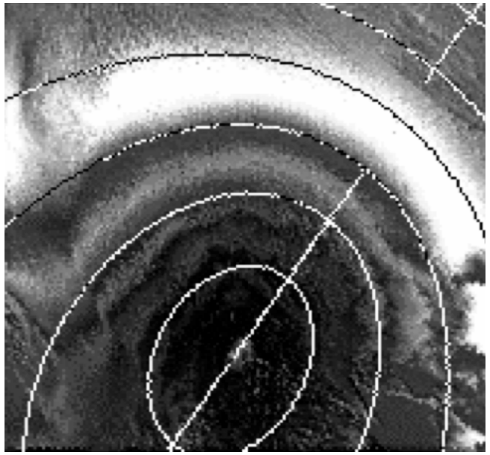
Same scene in polarized light

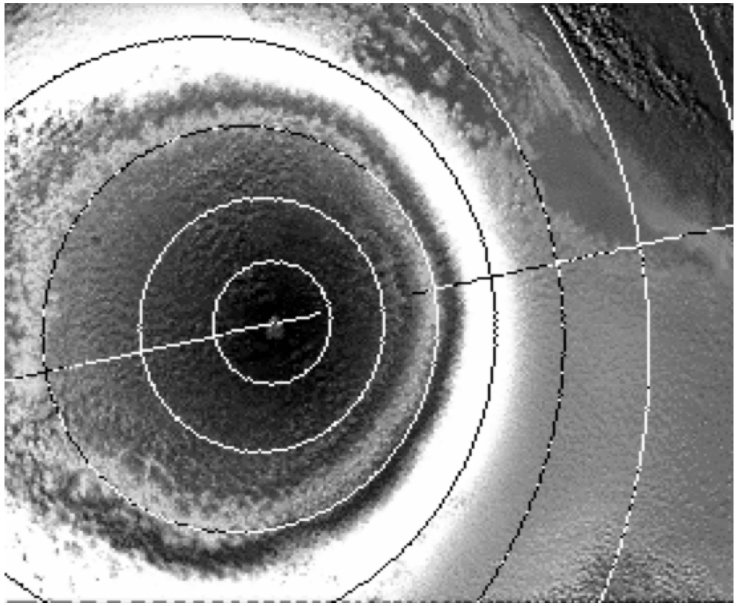



In some cases, clouds fields show specific features in polarized light for scattering angles between 140 and 170°

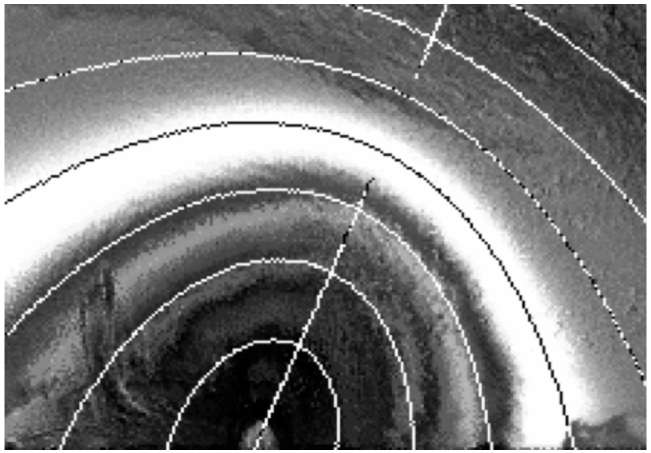
# Many such examples...

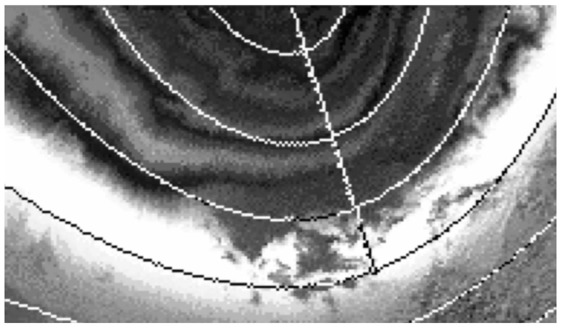


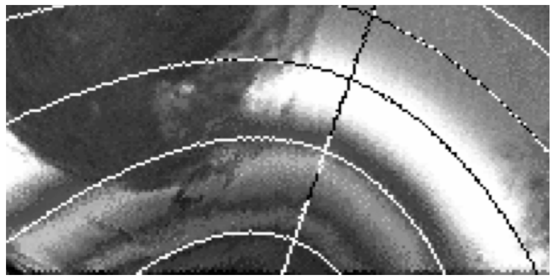




The position of color bands relative to the scattering angle is variable !



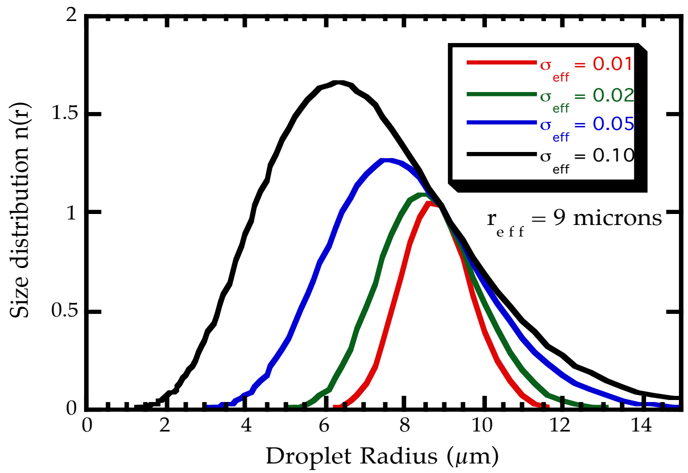




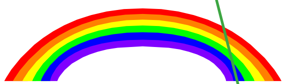
# Droplet polarized phase function

Size distribution :

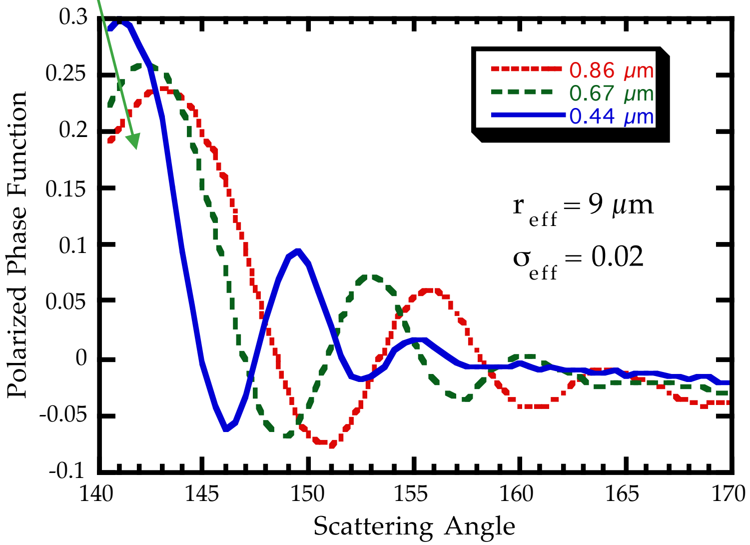
$$n(r) = \left(\frac{r}{r_{eff}}\right)^{-3} \exp\left[\frac{1}{\sigma_{eff}}\left(\ln\left(\frac{r}{r_{eff}}\right) - \frac{r}{r_{eff}} + 1\right)\right]$$



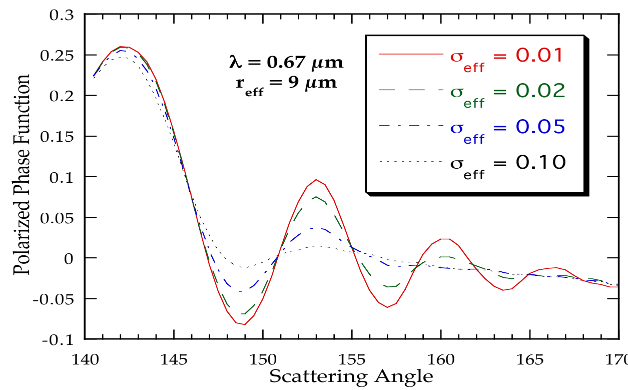

Rainbow



Spectral signature :




Dampening for wider size distributions:

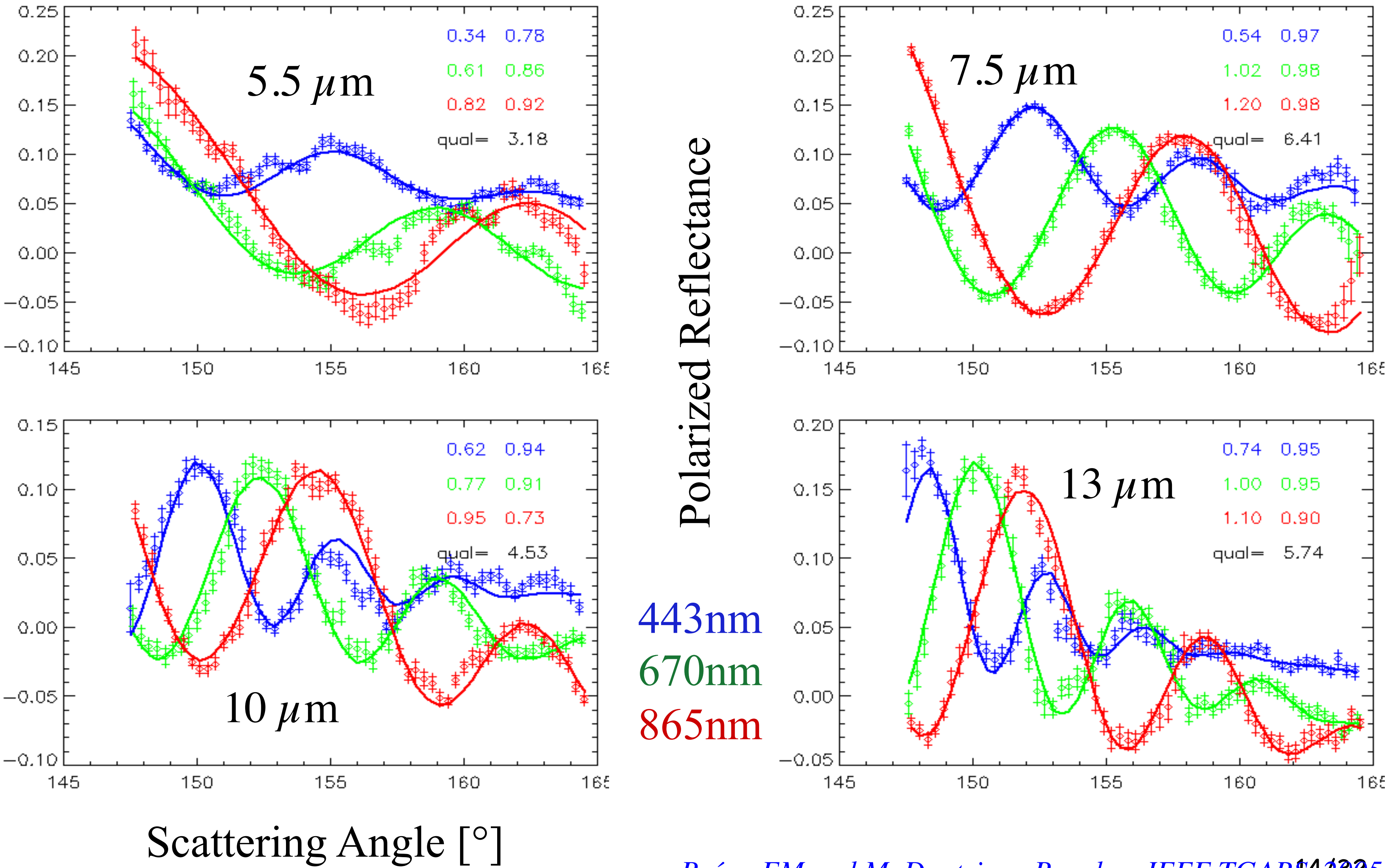



The polarized phase function shows oscillations that explain the observed features. Angular position of maxima and minima depend on wavelength and effective radius. Such feature require a narrow size distribution.

Polarized reflectance mostly generated by single scattering

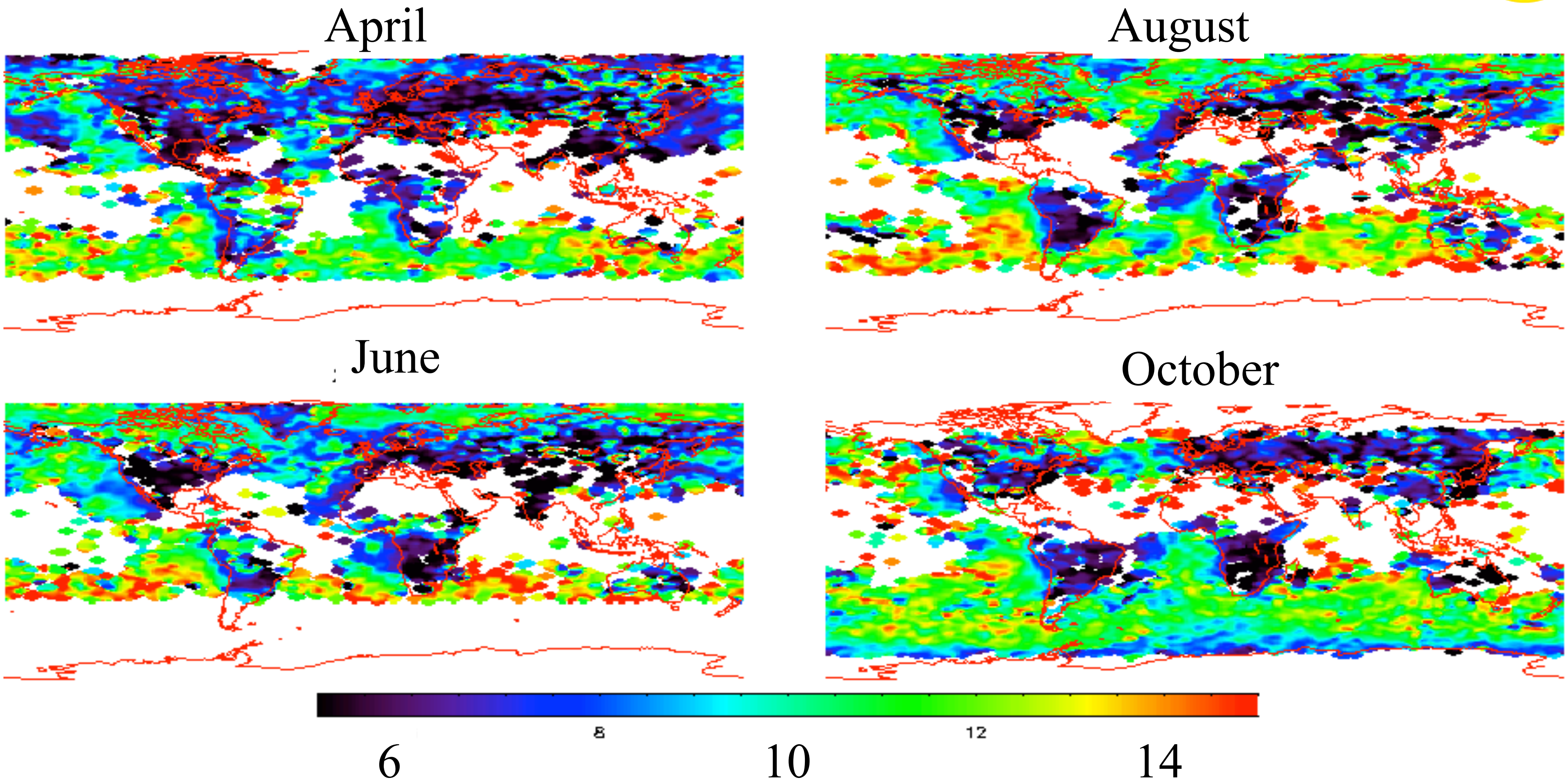
*Bréon FM and Ph Goloub, GRL, 1998*

# Measurement-model fit




*Bréon FM and M. Doutriaux Boucher, IEEE TGARS, 2005*

# Retrieved spatial distributions of CDR

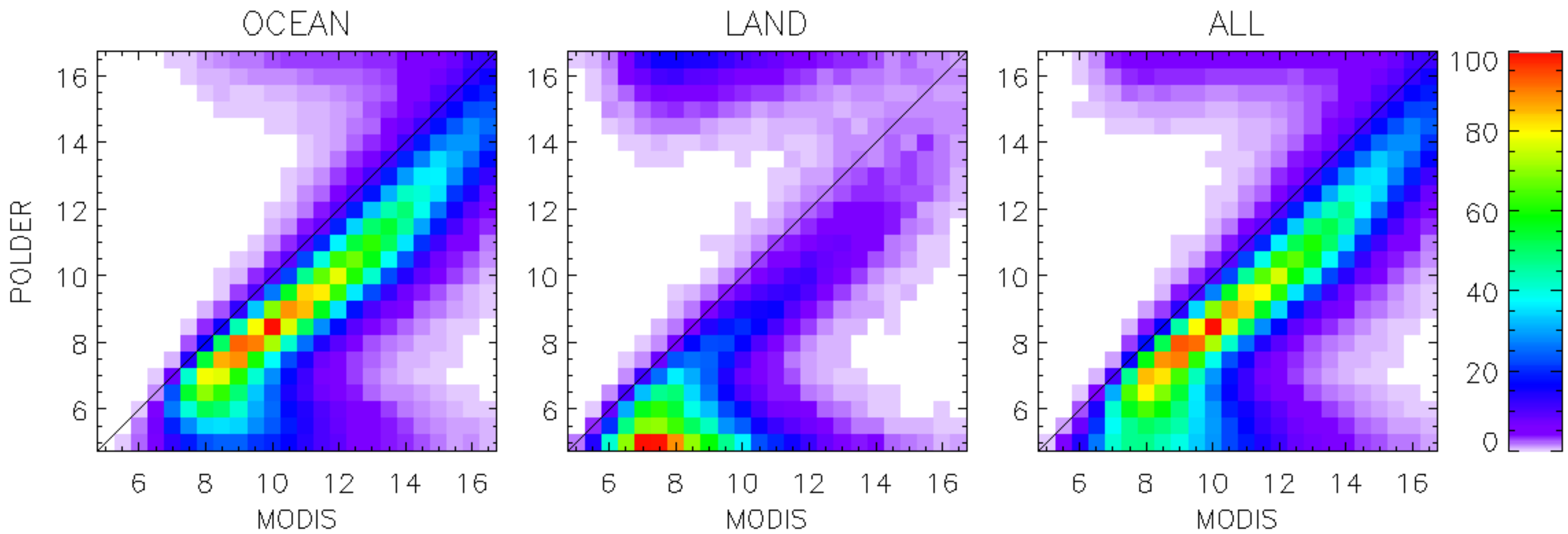



Poor sampling because of limitations on viewing geometry, extended cloud field and narrow size distribution.

Shows smaller droplets over continents, and in particular polluted areas

*Bréon FM and S. Colzy, GRL, 2000*

# Comparison with MODIS

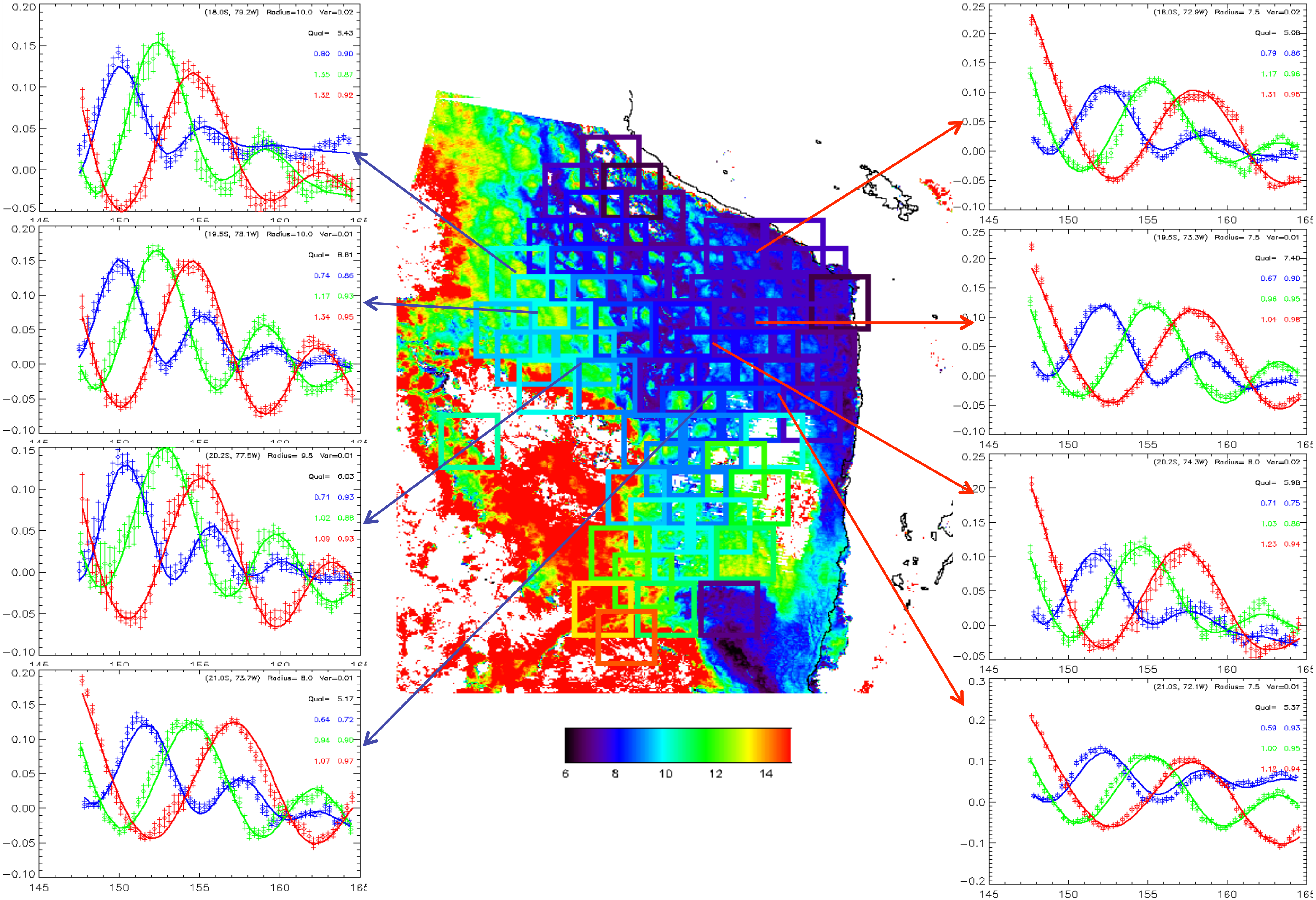



Excellent correlation over the Oceans

Poor correlations for small droplets [in particular found over land surfaces]

Bias of 2 $\mu$m (POLDER < MODIS).

- CDR at the very cloud are smaller than deeper in the cloud ?
- Spatial heterogeneity ?
- Size distribution different than assumed ?



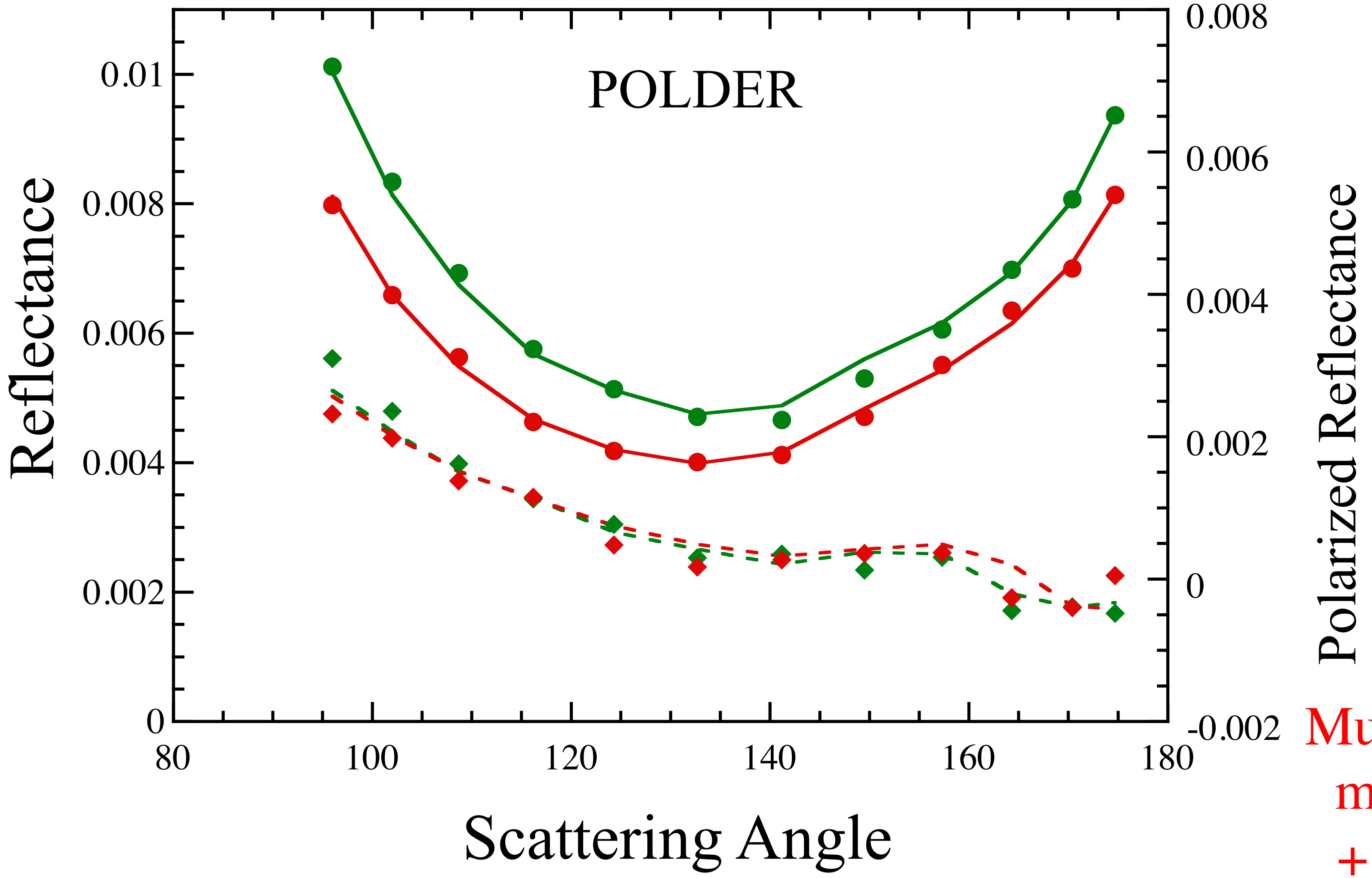
(18.0S, 79.2W) Radius=10.0 Var=0.02
Qual= 5.43
0.80 0.90
1.35 0.87
1.32 0.92
(19.5S, 78.1W) Radius=10.0 Var=0.01
Qual= 8.81
0.74 0.86
1.17 0.93
1.34 0.95
(20.2S, 77.5W) Radius= 9.5 Var=0.01
Qual= 6.03
0.71 0.93
1.02 0.88
1.09 0.93
(21.0S, 73.7W) Radius= 8.0 Var=0.01
Qual= 5.17
0.64 0.72
0.94 0.90
1.07 0.97
(18.0S, 72.9W) Radius= 7.5 Var=0.02
Qual= 5.08
0.79 0.86
1.17 0.96
1.31 0.95
(19.5S, 73.3W) Radius= 7.5 Var=0.01
Qual= 7.40
0.67 0.90
0.96 0.95
1.04 0.98
(20.2S, 74.3W) Radius= 8.0 Var=0.02
Qual= 5.98
0.71 0.75
1.03 0.86
1.23 0.94
(21.0S, 72.1W) Radius= 7.5 Var=0.01
Qual= 5.37
0.59 0.93
1.00 0.95
1.12 0.94
145 150 155 160 165
6 8 10 12 14

# CDR with polarization. Conclusions

- Multidirectional polarization provides an alternative (to spectral) method for the estimate of CDR
- Advantage of polarization : Measures the single scattering, which provides a near-direct measurement of the scattering phase function
- Requires specific conditions (geometry and cloud properties) so that its statistic is poor
- Measurements have shown that the CDR distribution is not as expected, in particular over stratocumulus clouds.
- Bias with MODIS. Several hypothesis. My best hypothesis is that evaporation at cloud top makes droplets smaller than deeper into cloud. Polarization sensitive to the very cloud top.
- Still not clear why MODIS shows large spatial variability in CDR when Parasol retrieval indicates a more homogeneous CDR field

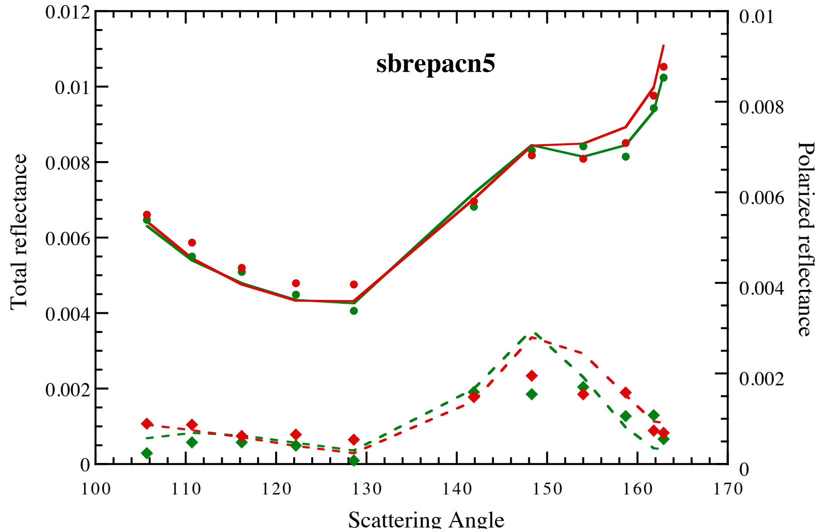
# Atmospheric Aerosols
# from Multidirectional polarisation measurements

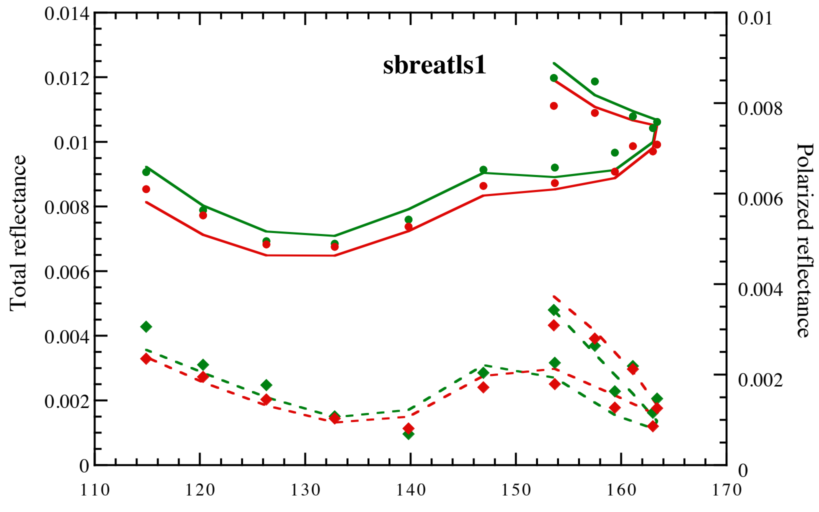
# Aerosols over the oceans: Information content



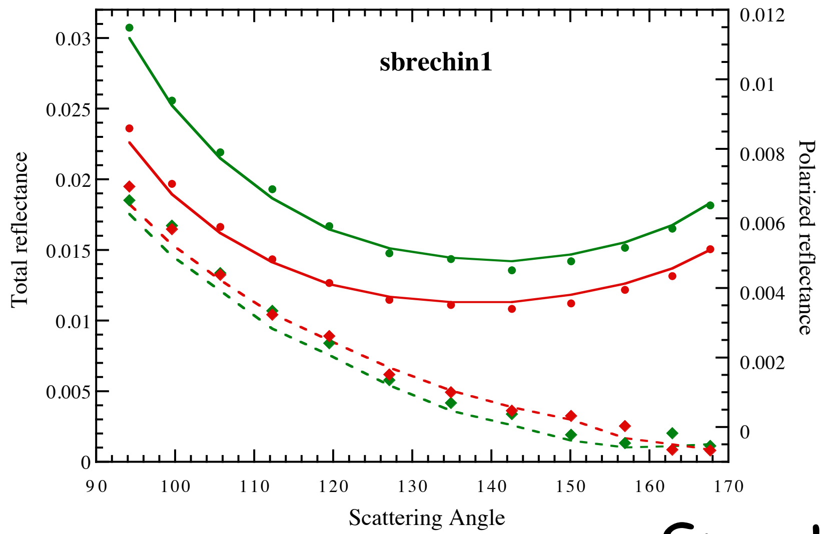

Multi-directional measurements + Polarization

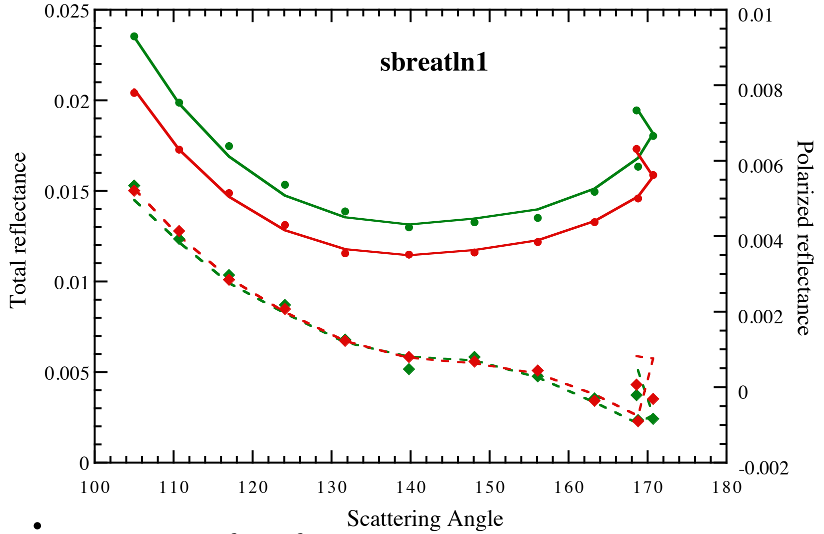
# Aerosol Inversion over the oceans




**Large to small particles**

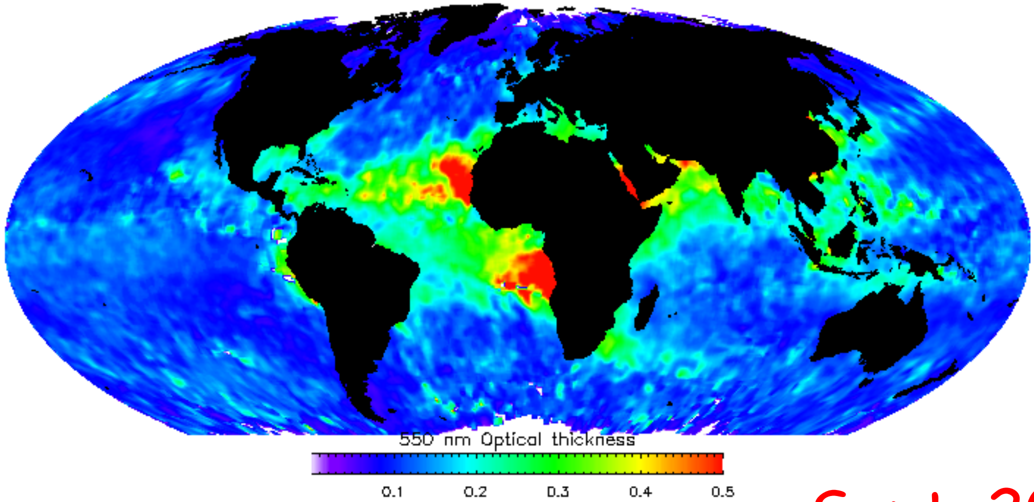



Spectral effect increases
150° arc decreases

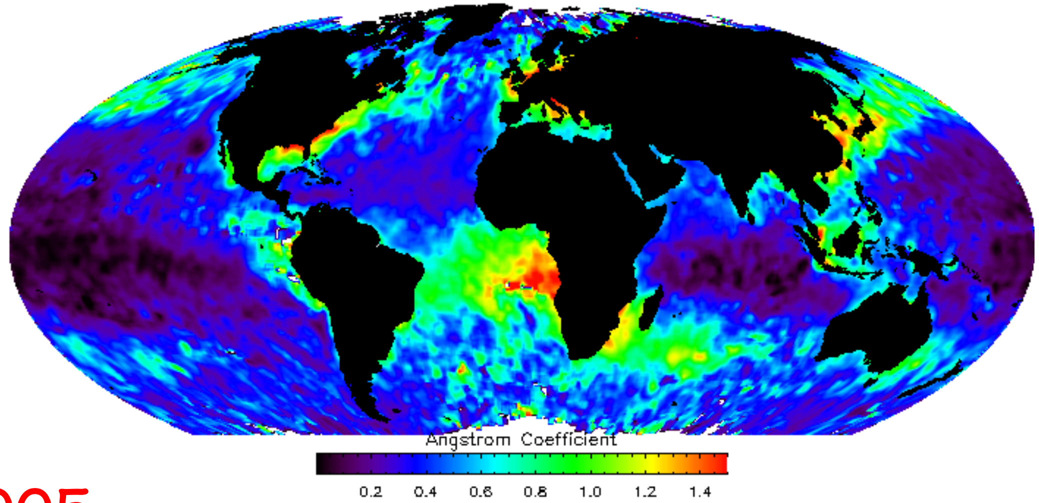
*Deuzé JL. et al., GRL, 1999*
*Deuzé JL. et al., JGR, 2000*

# Main Parasol products over the oceans

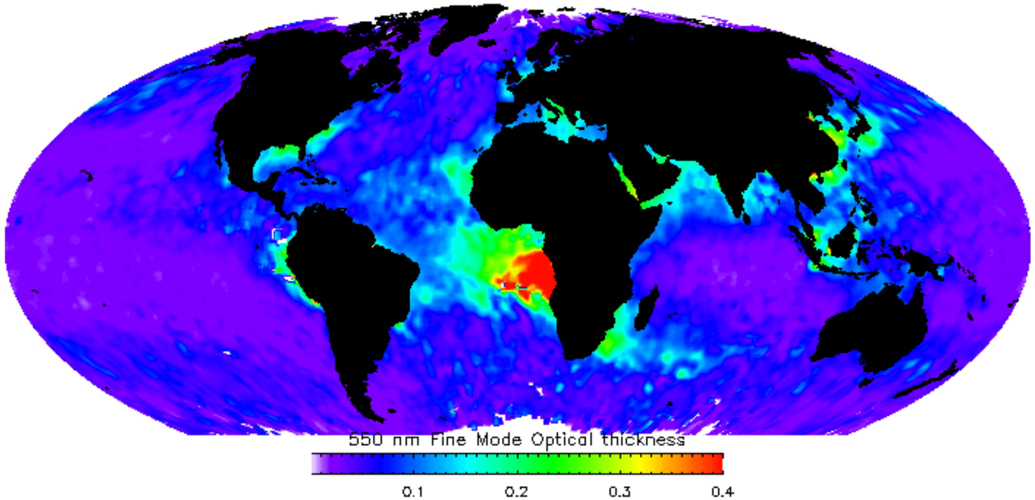



Total Optical Thickness

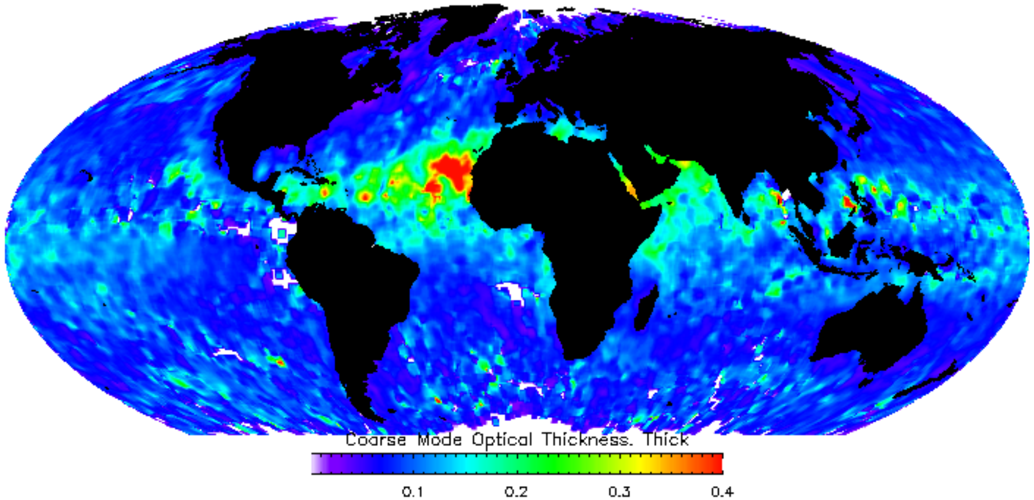
Sept. 2005




Angström Coefficient



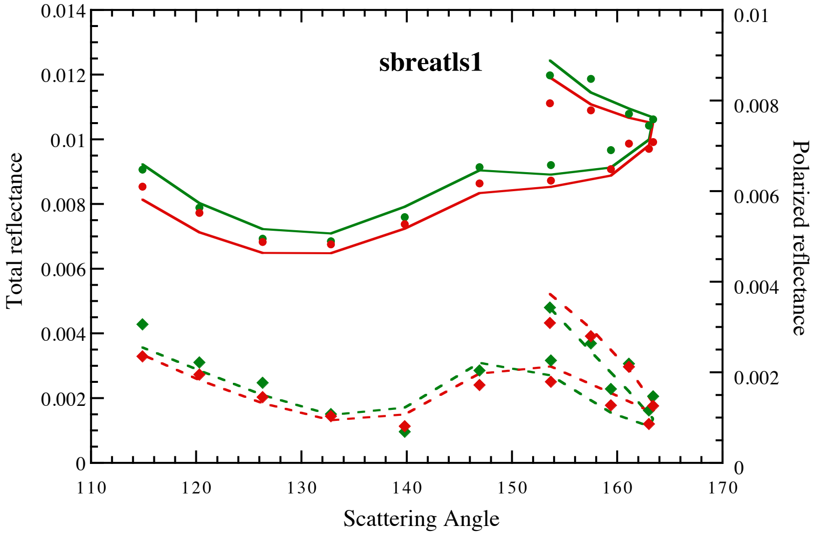

Fine Mode Optical Thickness

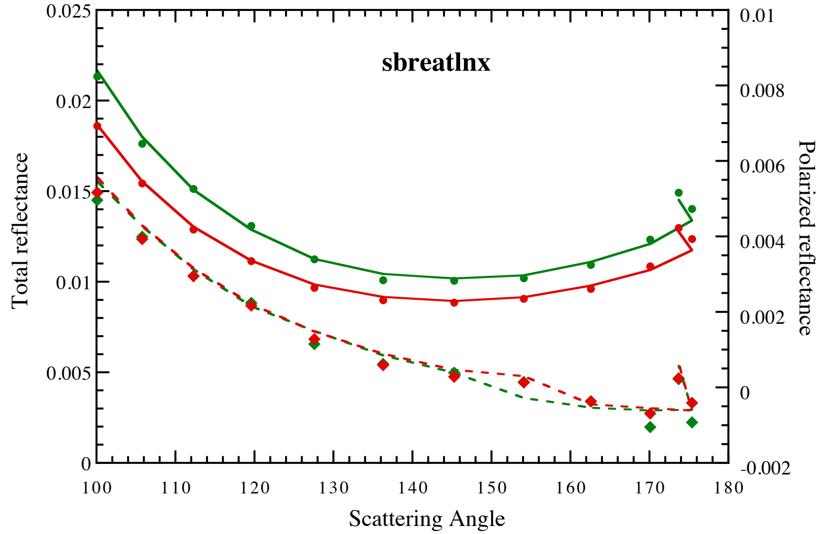



Coarse Mode Optical Thickness

+ Effective radii, info on scattering phase function and quality indices

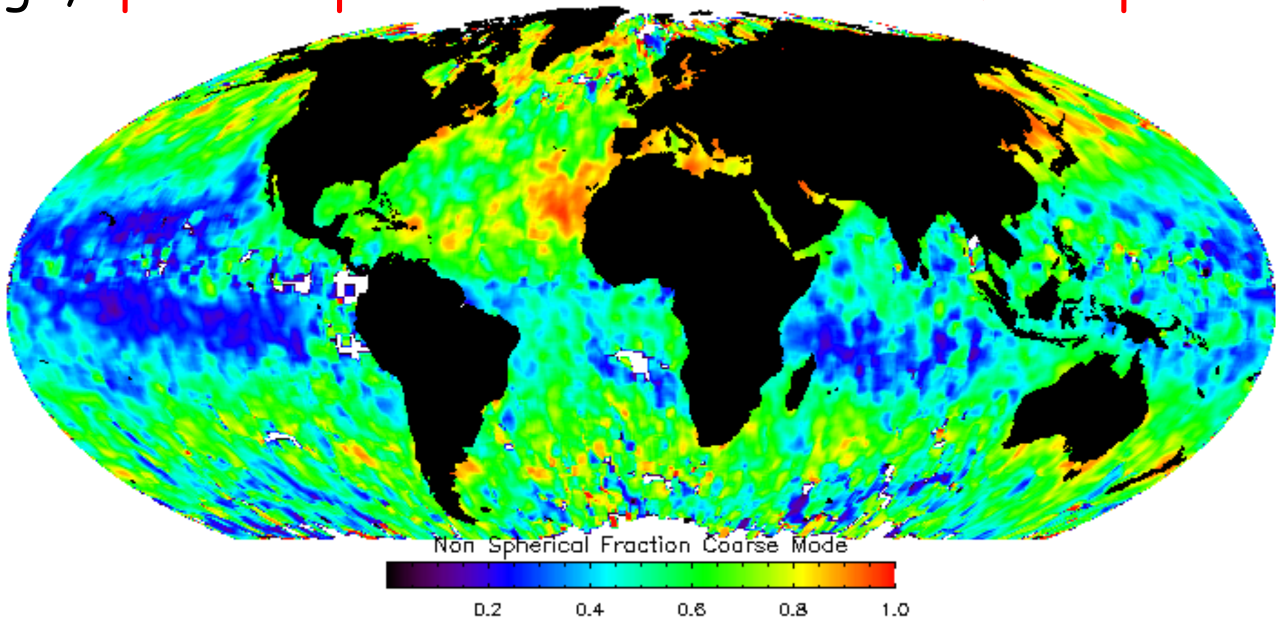
# Identification of non spherical particles




150° arc indicates the presence of large, spherical particles

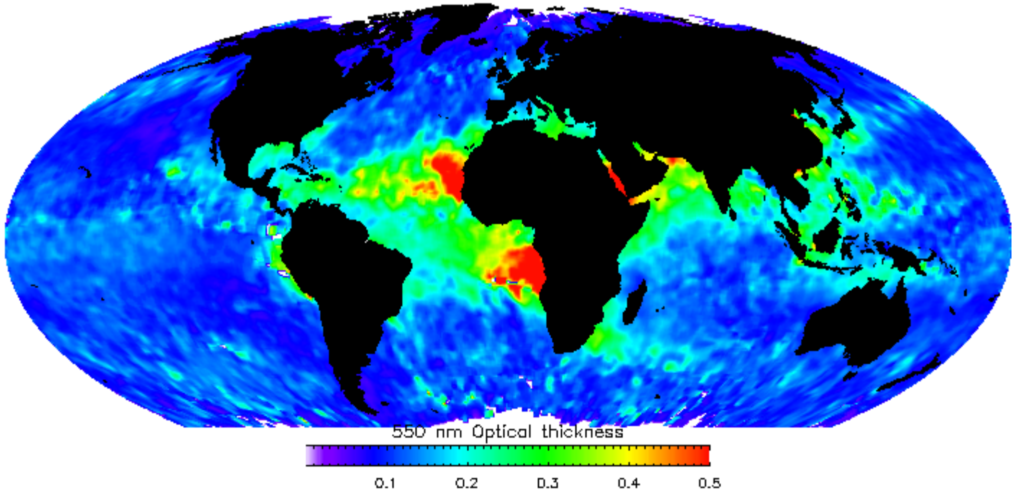
Small spectral effect but no Arc: Non spherical particles.



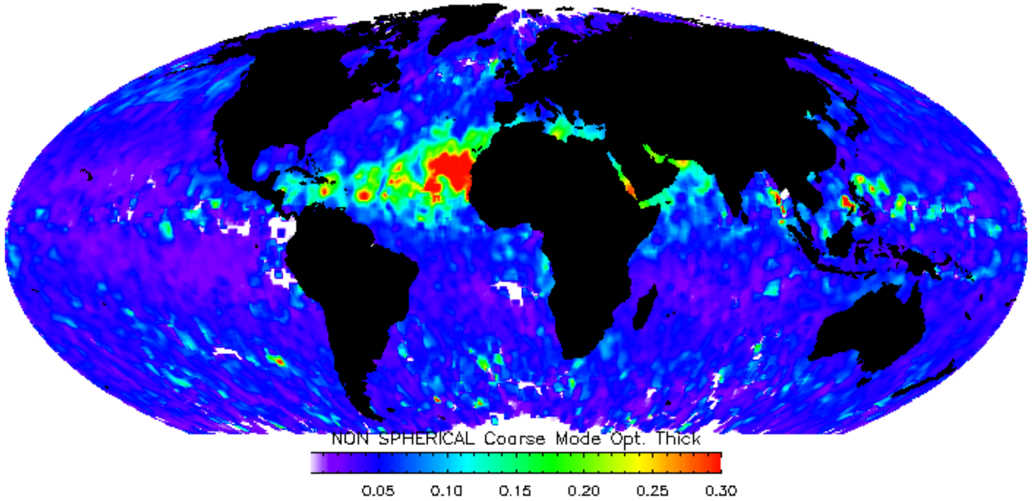

**Fraction of non-spherical particles in coarse mode**

*Herman M. et al., JGR, 2005*

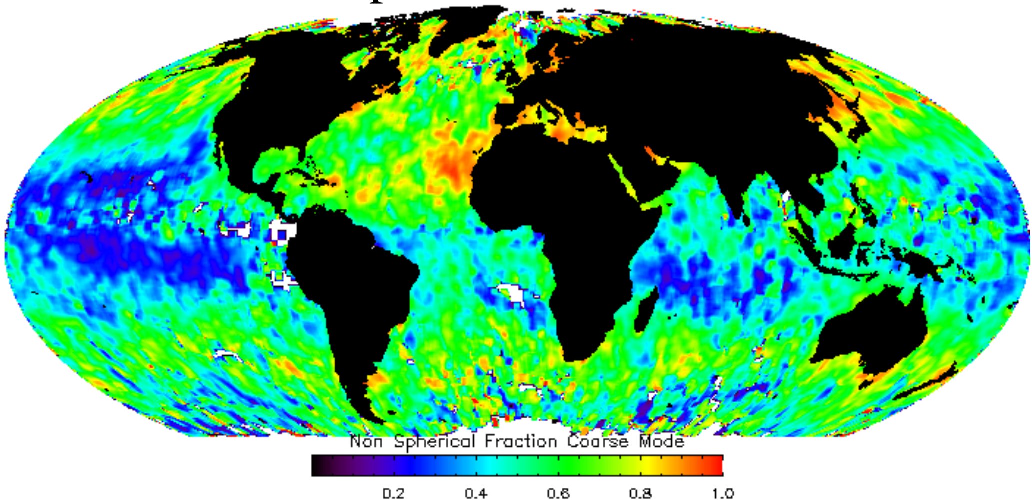
# Aerosol non-sphericity (2/2)



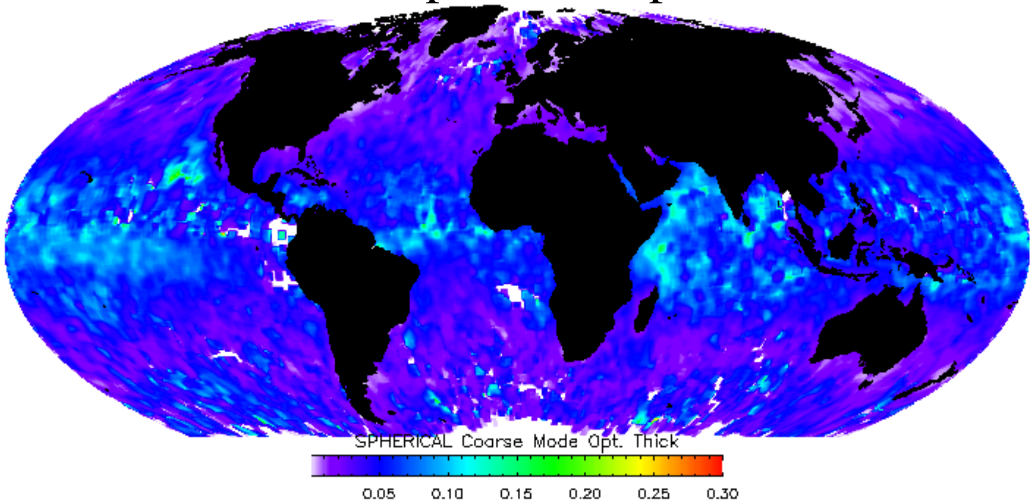

Total Optical Thickness




Coarse mode Non-Spherical Optical Thickness




Fraction of non spherical in Coarse Mode

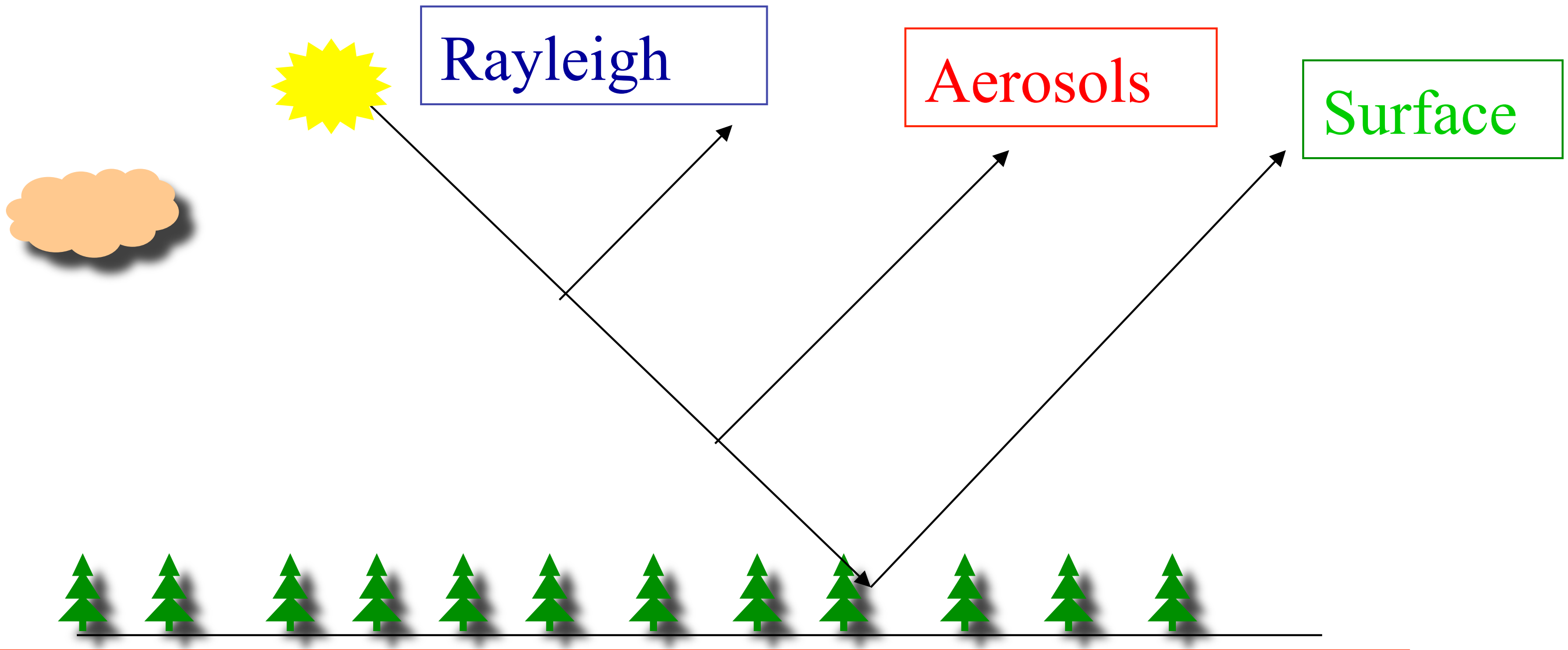



Coarse mode Spherical Optical Thickness

Non spherical particles downwind of dust sources. Spherical particles where hydrated, sea-salts are expected.

# Over land…

Why is polarization so useful for aerosol remote sensing over land ?

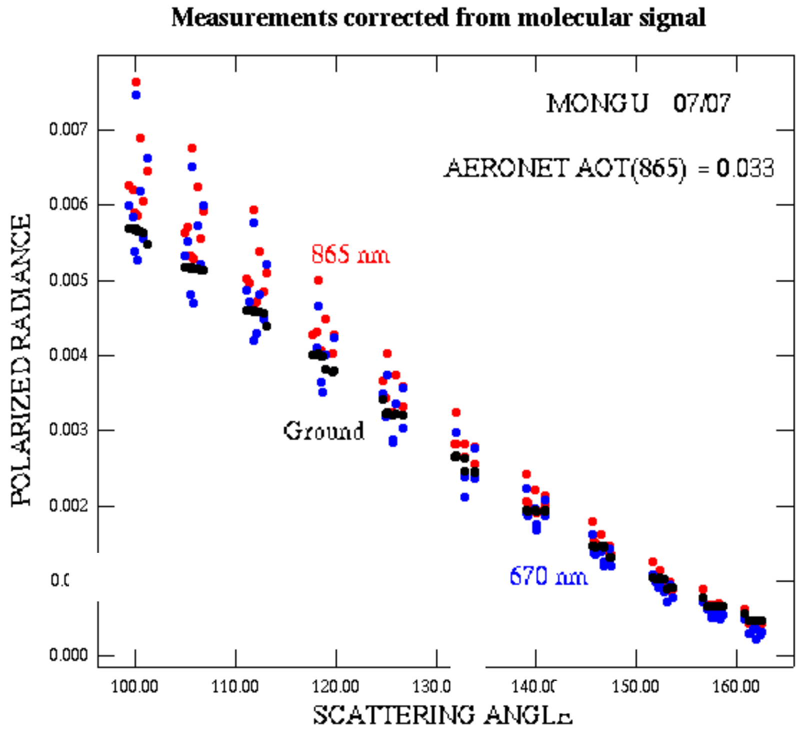


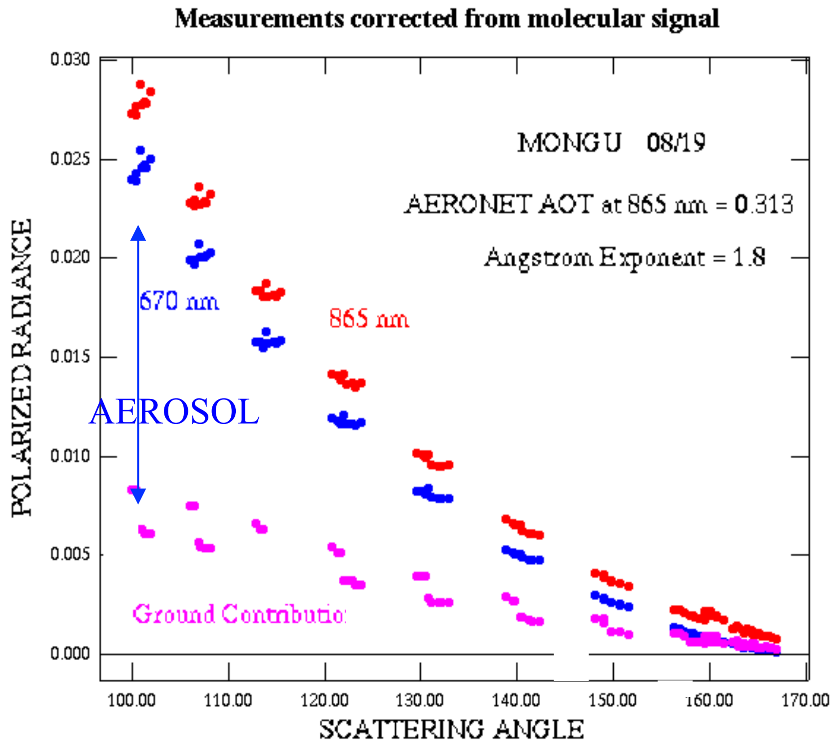

$$L_p^{meas}(\lambda,\theta_s,\theta_v,\varphi,z_{pixel}) = L_p^{aer+mol}(\mathrm{mod},\delta_a) + L_p^{sol} \times e^{-m(c_m\delta_m + c_a\delta_a)}$$

$L_p^{sol}$

- is small compared to atmospheric contribution
- is spectrally neutral
- is rather uniform (varies little with surface type)
- can be roughly estimated from surface classification

# Aerosol reflectance is highly polarized




**Clear atmosphere (AOT=0.03) : the reflectance at TOA is close to the surface values**

**Hazy atmosphere : large aerosol contribution, $1.0\times10^{-2}$ at 110°-120° for AOT=0.31**

**Illustration for Biomass Burning Aerosols**

Deuzé et al., 2001

# Aerosol inversion over land

Based on the hypothesis that surface polarized reflectance is small and varies little

Parameterization of the surface polarized reflectance (semi empirical model as a function of surface type and NDVI; *Nadal&Bréon, 1998*)

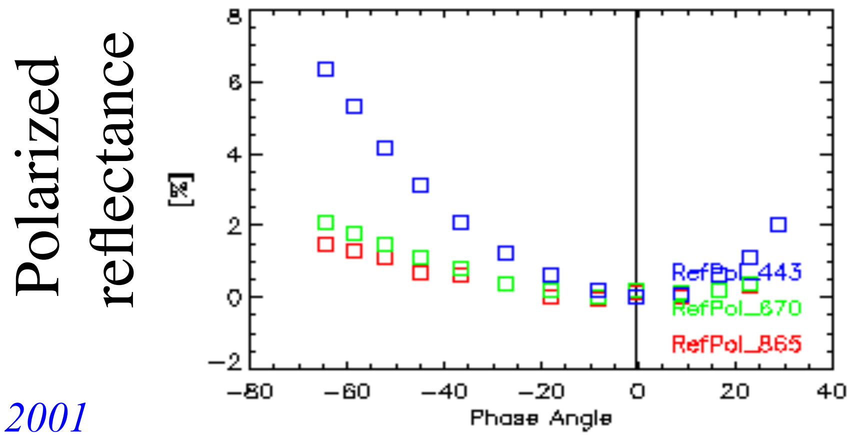
Model + optical thickness estimate based on measured polarized reflectance at 670 and 865 nm.

Works well for “small” aerosol (sulfates, biomass burning) over vegetated areas

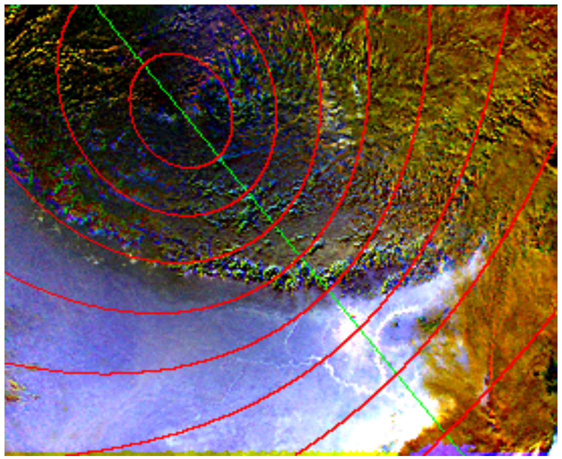
BUT…

Does not work for coarse aerosols (desert dust)

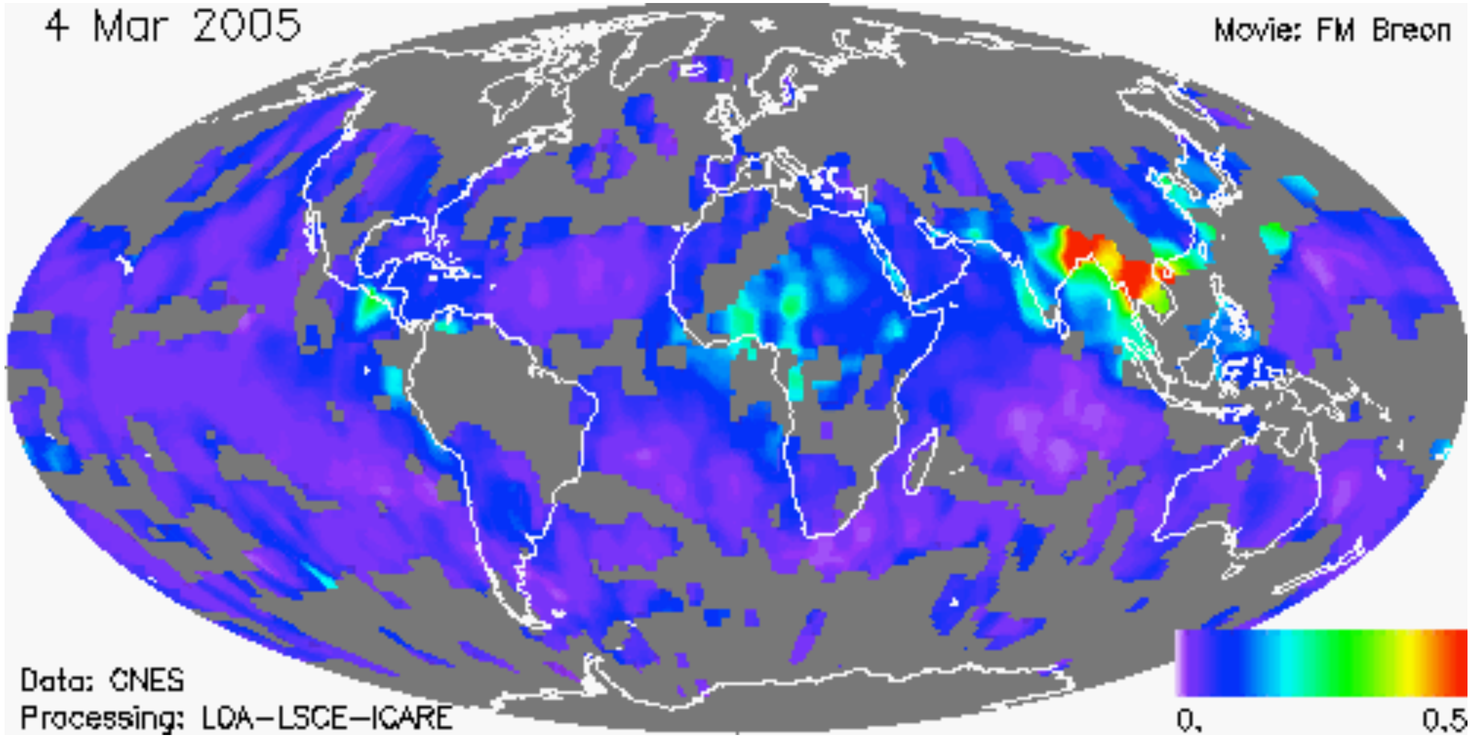
Does not work over desert or snow due to their larger polarized reflectance




*Deuzé JL et al., JGR, 2001*



# Fine mode optical thickness




Fine mode optical Thickness 550 nm

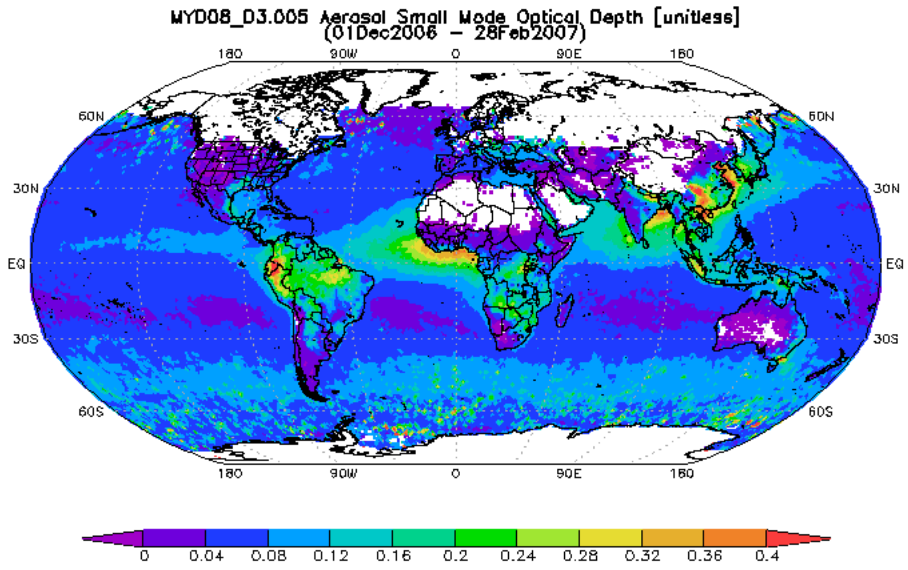
Aerosol load by sub-micronic particles (fine mode)
Over land: based on multi-directional polarized measurements
Over the ocean : Uses both reflectance and polarized meas.

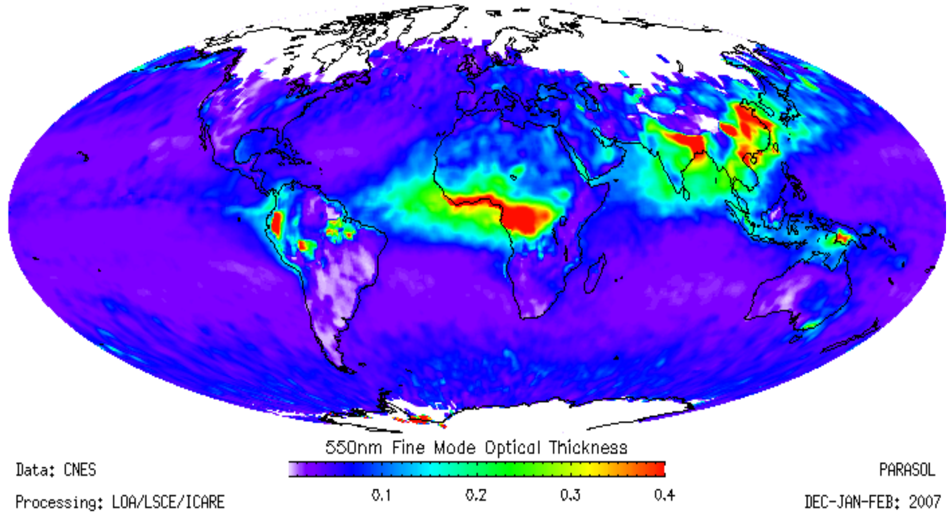
Note annual cycle of biomass burning activity, pollution over China, Galapagos volcanic eruption late October 2005

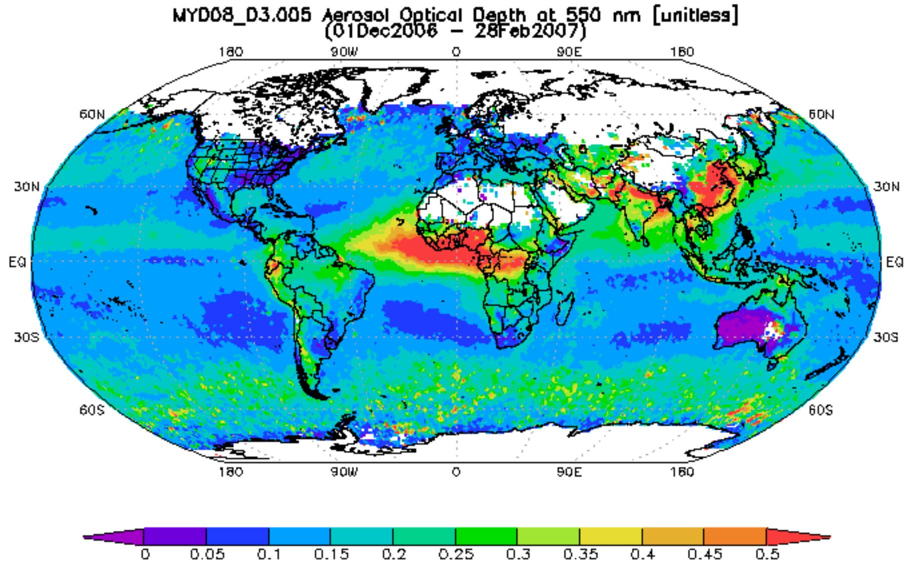
# Parasol-MODIS comparison. 3: DJF 2007

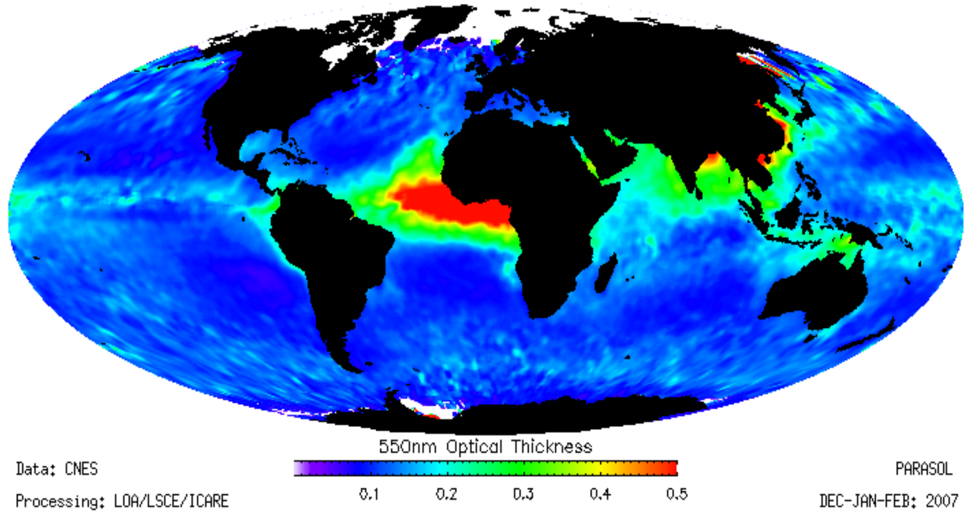
MODIS

Parasol



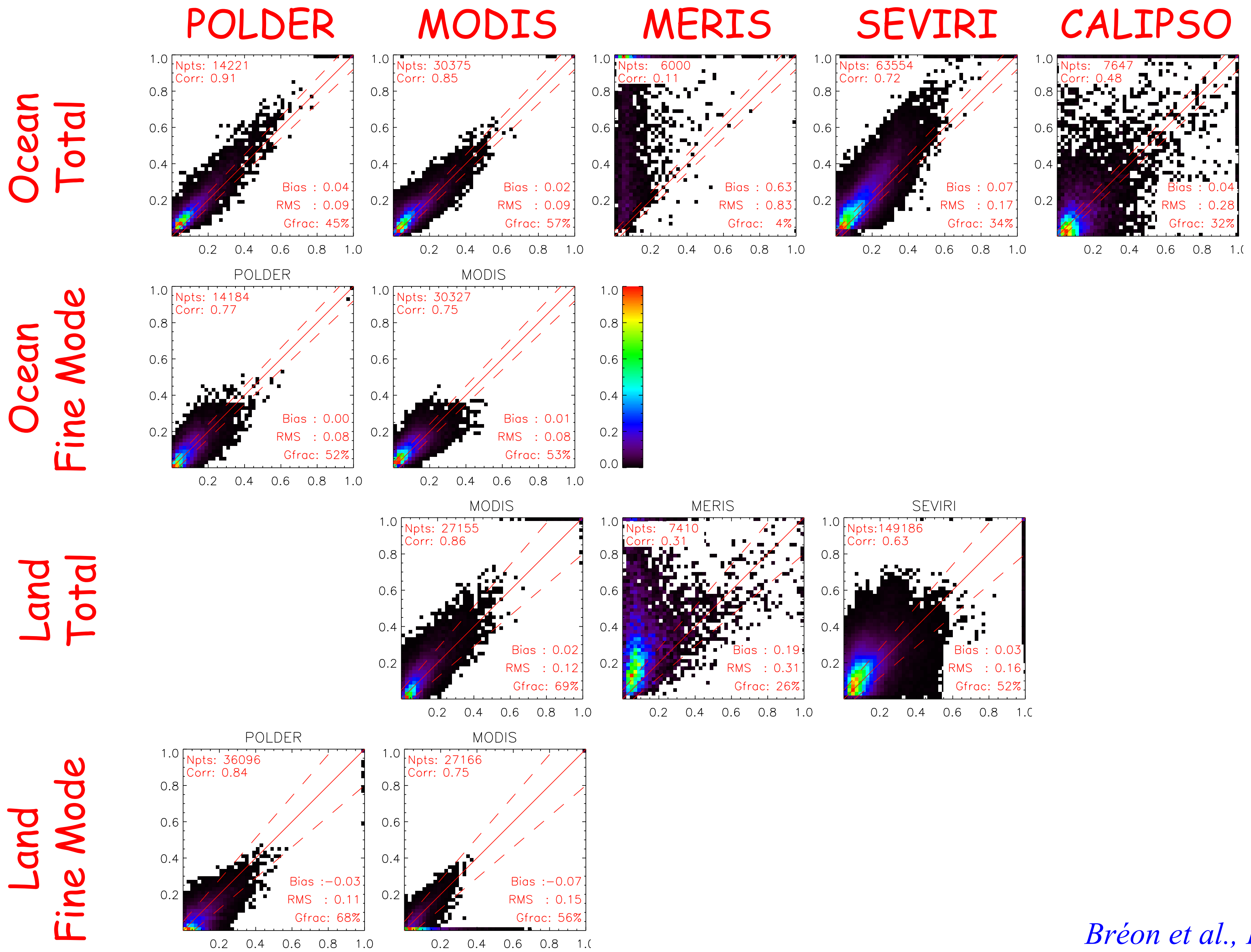




**Tanre et al. 2008**

# Validation against Aeronet




*Bréon et al., RSE, 2011*

# Parasol concept for aerosol : Pros and con

Multispectral + multidirectional + Polarization measurements provide a lot of constrains for the aerosol model retrieval

Depending on the target location with respect to the satellite, the range of scattering angle varies

Multidirectional acquisition reduces the glint issue.

Spatial resolution of POLDER. Limits daily coverage in the presence of broken clouds (a problem in the tropics, in particular for Parasol afternoon views).

Surface contribution to the measured polarized reflectance. Although small, the surface contribution is not fully negligible

A longer wavelength polarized channel would help constraining the surface polarization contribution. Airborne measurements indicate that the surface polarized reflectance is spectrally neutral. => Was to be done by Glory mission. 3MI

# Prospects

POLDER onboard PARASOL remains the only instrument in space that measures the polarization state of the reflected sunlight

The GLORY mission has been developed by NASA to measured aerosols and CDR, on the basis developed using POLDER observations, but the launch failed and the satellite was lost

An "advanced" version of the POLDER instrument with higher spatial resolution and extended spectral range has been developed. It is referred to as 3MI and will be flown onboard European operational weather satellites (MetOp-SG).