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 ($\approx 50^\circ$)

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
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)

\[ R_p(\theta_s, \theta_v, \varphi) = \frac{F_p\left(\frac{\pi - \gamma}{2}\right)}{4(\cos \theta_s + \cos \theta_v)} \]
Aerosols over the Ganges Valley

\[ R_p(\theta_s, \theta_v, \varphi) \approx \frac{P_p(\gamma)}{4(\cos \theta_s + \cos \theta_v)} \left(1 - \exp(-m \tau_a)\right) \]
Biomass Burning Aerosol
Antarctic + Cloud Bow
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 $\approx 0$ 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.

Cloud Droplet Radius
from Multidirectional polarisation measurements
Liquid phase clouds

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

3-color composite 443-670-865 nm

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!
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

Scattering Angle [°]

5.5 µm

7.5 µm

10 µm

13 µm

443nm

670nm

865nm

Bréon FM and M. Doutriaux Boucher, IEEE TGARS, 2005
Retrieved spatial distributions of CDR

April

August

June

October

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, GR, 2000
Excellent correlation over the Oceans
Poor correlations for small droplets [in particular found over land surfaces]
Bias of 2 µm (POLDER < MODIS).
- CDR at the very cloud are smaller than deeper in the cloud ?
- Spatial heterogeneity ?
- Size distribution different than assumed ?
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

- **Meteosat**: One channel, one direction, no constrain on aerosol model.
- **VHRR**: Two channels, one direction.
- **MODIS**: Many channels, one direction.
- **MISR**: Multi-directional measurements.
- **POLDER**: Multi-directional measurements + Polarization.

The graph shows the relationship between scattering angle and reflectance/polarized reflectance for POLDER data.
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

Angström Coefficient

Fine Mode Optical Thickness

Coarse Mode Optical Thickness

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

Sept. 2005
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
Non spherical particles downwind of dust sources. Spherical particles where hydrated, sea-salts are expected.
Why is polarization so useful for aerosol remote sensing over land?

\[ L_{p,\text{meas}}(\lambda, \theta_s, \theta_v, \varphi, z_{\text{pixel}}) = L_{p,\text{aer+mol}}(\text{mod}, \delta_a) + L_{p,\text{sol}} \times e^{-m(c_m\delta_m + c_a\delta_a)} \]

- \( L_{p,\text{sol}} \)
  - 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, $1.0 \times 10^{-2}$ at $110^\circ$-$120^\circ$ 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
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

Tanre et al. 2008
Validation against Aeronet

Bréon et al., RSE, 2018/32
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).