Measurements and analysis of directional effects and polarization properties of suspended particulate matter (phytoplankton and inorganic matter)

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Objectives

- Investigate the directional intensity and polarization signature of hydrosols (phytoplankton, suspended minerals…).
- Improve the modeling of the scattering properties of particles.
- Better predict the remotely sensed signal by a satellite ocean color sensor.
- Increase the performance of inverse ocean color algorithms.
- Towards polarization-based remote sensing for polarimetric satellite missions (PACE, NASA; 3MI/sentinel 5, EUMETSAT/ESA scheduled for 2020).

Principles

Light radiation is fully described by its intensity (I) and polarization (Q, U, V)

$$\begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Scattered light *Mueller matrix* *Incident light*

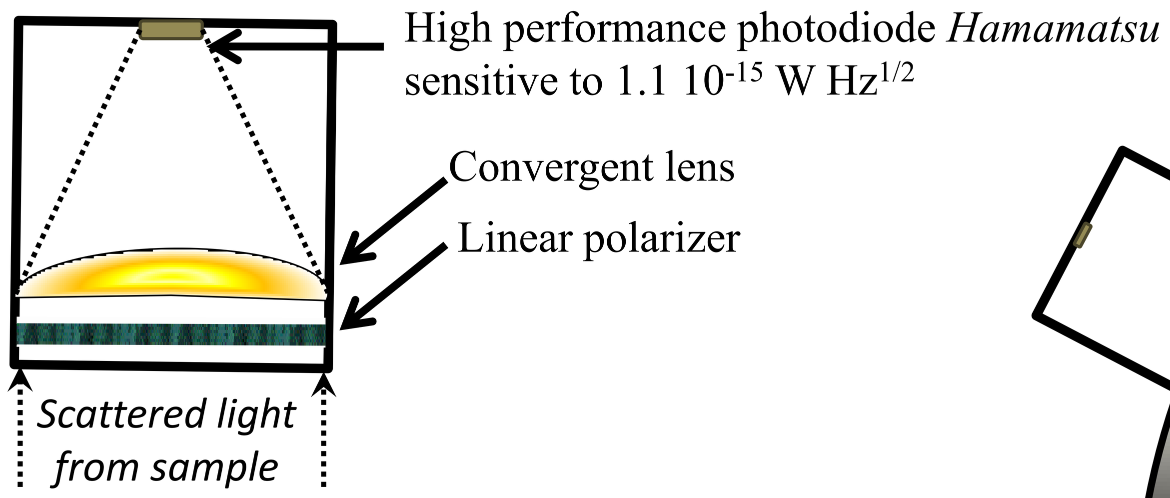
$$VSF(\Theta) = b m_{11}(\Theta)$$

VSF: Volume Scattering Function (m^{-1} sr^{-1})
b: scattering coefficient (m^{-1})
Θ: scattering angle

VSF mainly used to characterize hydrosol characteristics.
Polarization signature (Mueller matrix) gives supplementary information to help characterize hydrosols and their impacts on light field.

Rotating detector

The box rotates to perform measurements for various polarizer orientations.

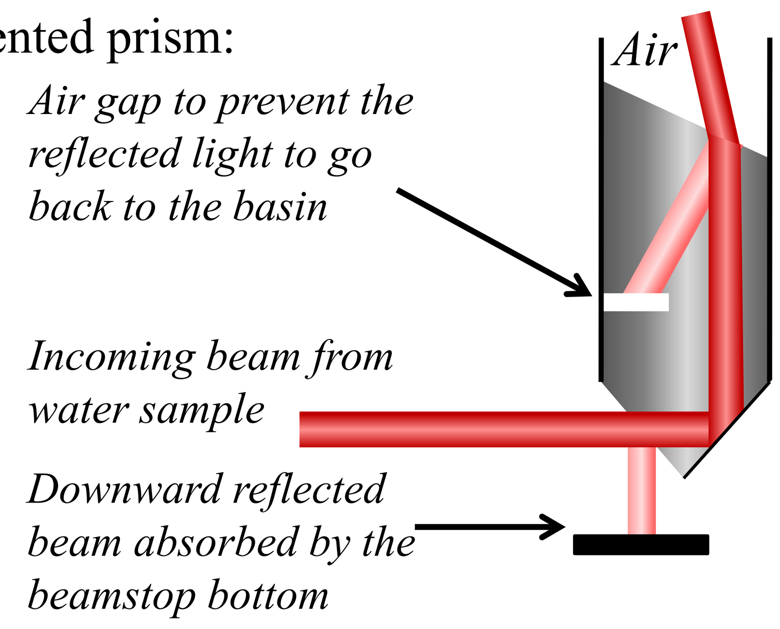


Prisms

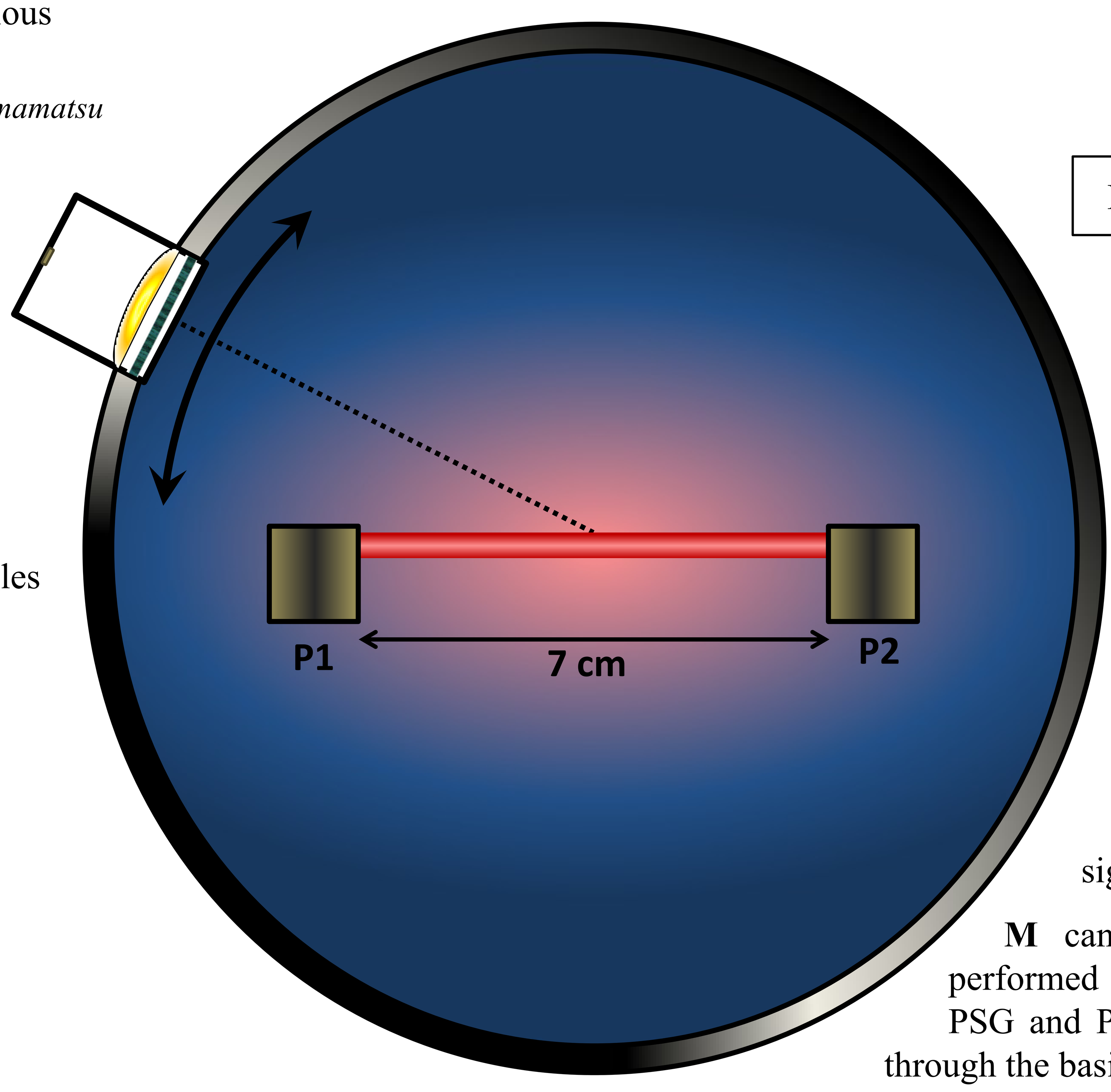
Double periscopic optical system allowing measurements over a wide range of scattering angles (from **1° to 179°**)

P1: periscopic system to bring the laser polarized source into the scattering plane.

P2: patented prism:

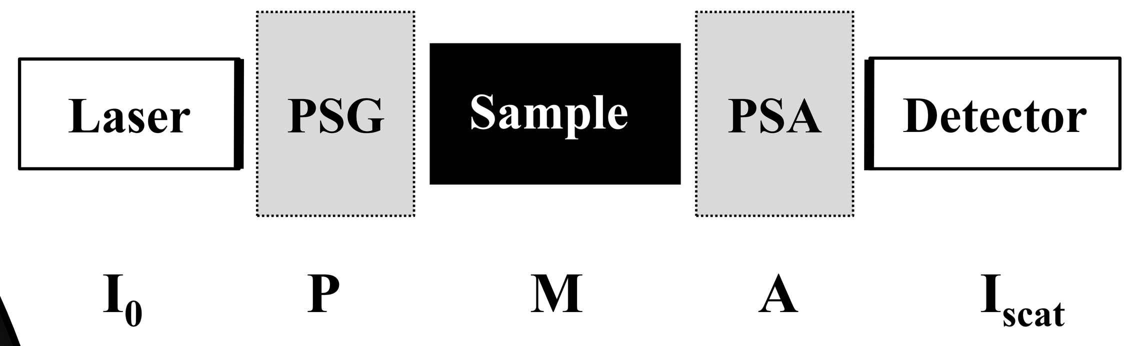


POLVSM instrument



Mueller matrix retrieval

PSG: Polarization State Generator
PSA: Polarization State Analyzer



$\mathbf{I_0}$ is the Stokes vector of the laser source.
M is the Mueller matrix of the sample.
A and **P** are the Mueller matrices of PSA and PSG

$$I_{scat} = \mathbf{A} \mathbf{M} \mathbf{P}^T \mathbf{I_0}$$

$$\mathbf{P}(\theta) \text{ or } \mathbf{A}(\theta) = \frac{1}{2}\begin{pmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \end{pmatrix}$$

θ is the orientation angle of the polarizer with respect to the scattering plane.

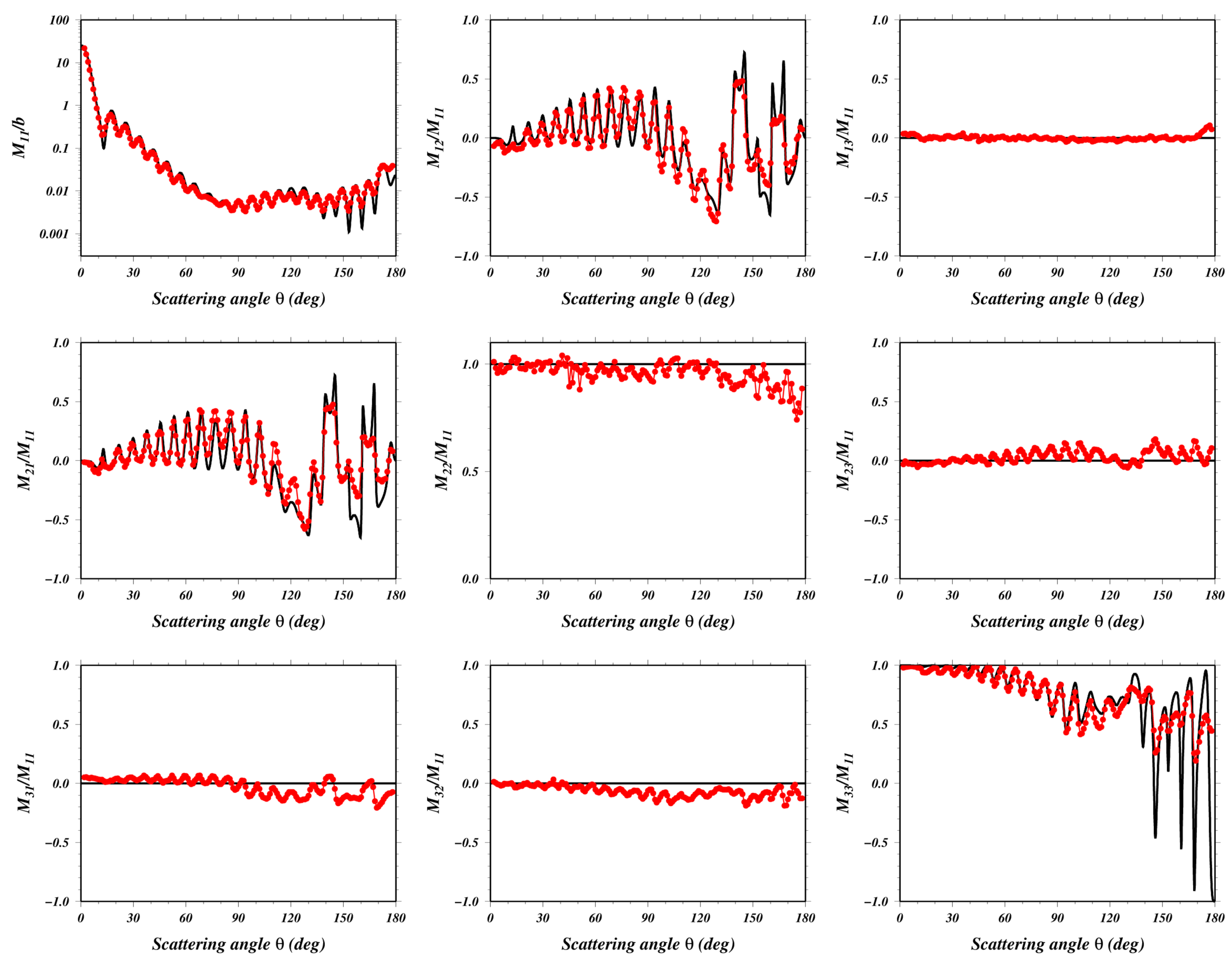
The detector is capable of measuring intensity signal I_{scat} only (first term of the Stokes vector $\mathbf{I_{scat}}$).

M can be retrieved from a series of measurements performed for a specific combination of orientations of PSG and PSA including calculation of the signal attenuation through the basin (*Chami et al., 2014*):

$$\hat{\mathbf{M}} = \mathbf{A}_{sys}^{-1} \mathbf{I}_{sys} \mathbf{P}_{sys}^{-1}$$

where $\mathbf{A}_{sys}$ and $\mathbf{P}_{sys}$ stand for matrices accounting for the system of equations generated by the combination of polarizers' orientations

Validation and calibration with mono-disperse beads



Calibration procedure consists of converting the measured raw signal into geophysical units, namely m^{-1} sr^{-1}.

This procedure is based on beads (e.g., 3μm) measurements whose scattering properties are theoretically known

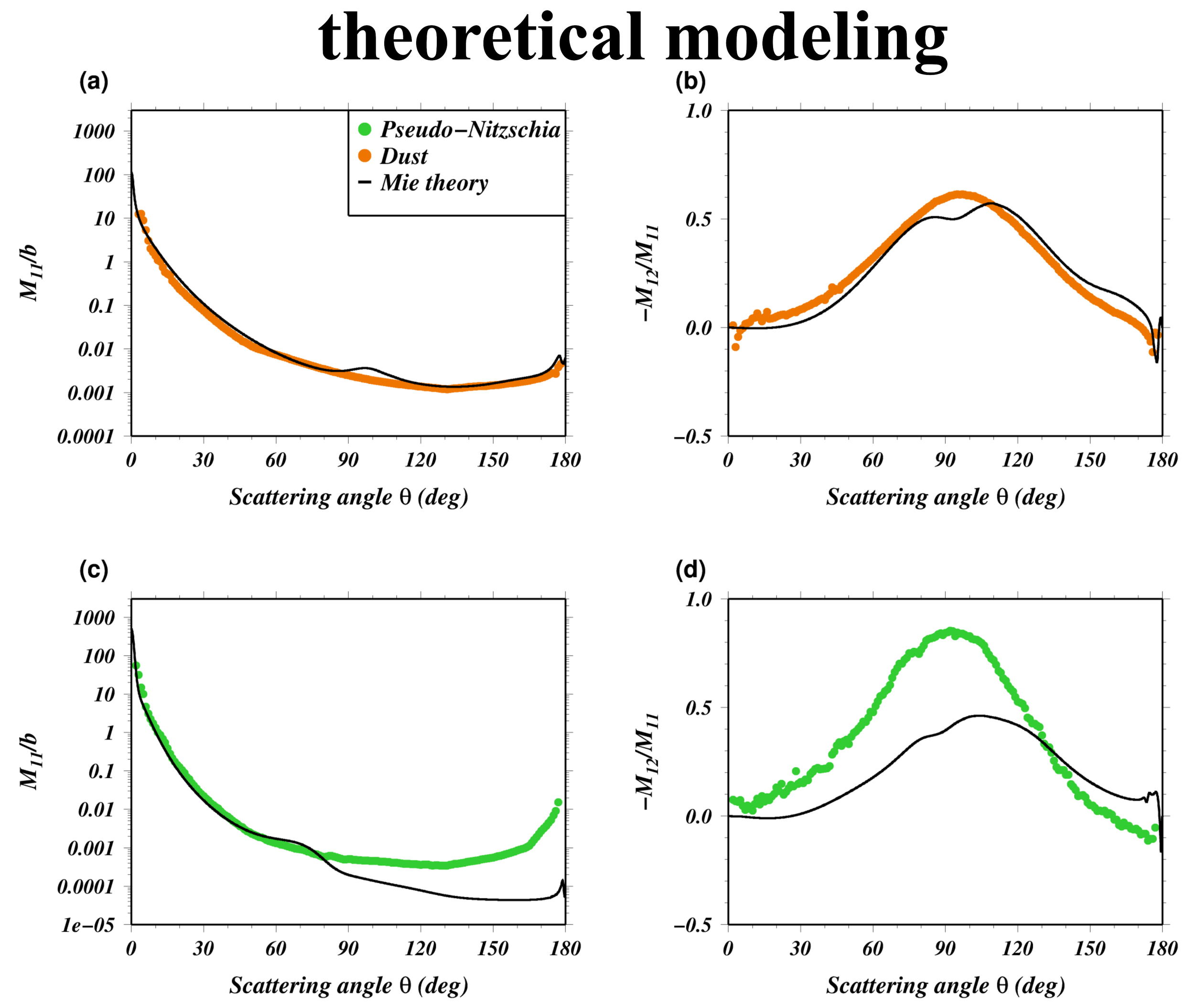
$$m_{11}^{calibrated} = C_0 m_{11}^{uncalibrated} \quad \text{in } m^{-1} \; sr^{-1}$$

$$C_0 = \frac{\int_{\theta=\theta_{min}}^{\theta_{max}} M_{11}^{theory}(\theta)\sin\theta \, d\theta}{\int_{\theta=\theta_{min}}^{\theta_{max}} M_{11}^{uncalibrated}(\theta)\sin\theta \, d\theta} \approx \frac{b^{theory}}{b^{uncalibrated}}$$

The procedure was repeated for various beads concentrations and showed:

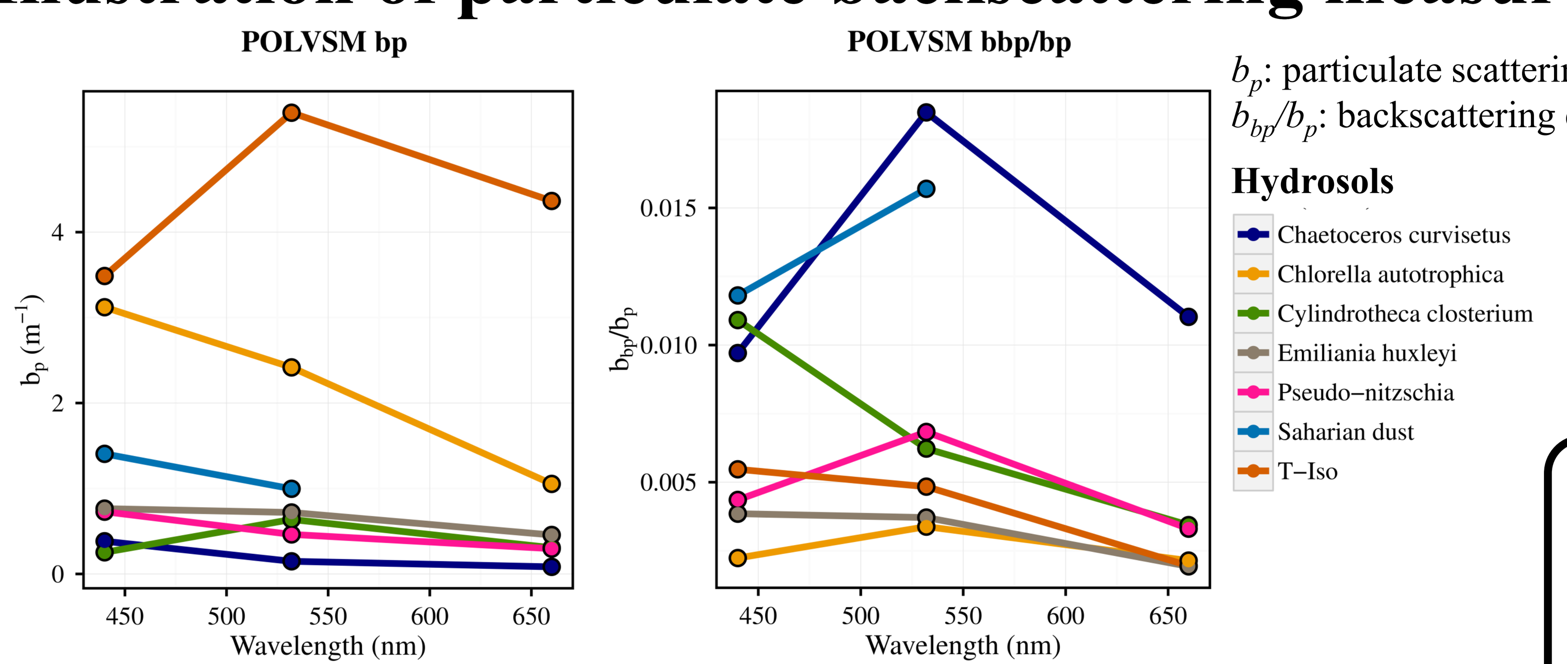
Uncertainty ≤ 4.5%
Detection limit: b=0.05 m^{-1}

Comparison of natural samples with theoretical modeling



- Mie theory reproduces efficiently the measured VSF and degree of polarization for dust-like inorganic hydrosols sample (despite the non-sphericity of these dust grains)
- More sophisticated modeling is needed to predict the directional and polarized signature of phytoplankton (impacts of heterogeneous internal structure of living cells)
- **Importance of angularly resolved measurements of the Mueller scattering elements to gain understanding on light scattering by marine particles with ramifications for light distribution in the water column, identification of algal species, decoupling absorption and scattering signals and ocean color remote sensing from space from radiometric and polarimetric sensors.**

Illustration of particulate backscattering measurements



b_p: particulate scattering coefficient
b_{bp}/b_p: backscattering efficiency

→*Retrieved values in agreement with previous studies and phytoplankton literature*

Acknowledgments

The POLVSM project was funded by the French space agency (CNES), the *Université Pierre et Marie Curie*, the *Institut Universitaire de France* and the CNRS . Optical system and mechanical pieces were developed and constructed at the *Observatoire Océanologique de Villefranche* (**Edouard Leymarie, Alexandre Thirouard, Eric Tanguy, Dominique Delhommeau**) and the *Observatoire Côte d'Azur* (**Alain Roussel, Paul Girard, Serge Bonhomme**) .We wish to thank **Sophie Marro** for her great help about cultures of the phytoplankton species. The reference of the patent of the prism P2 is FR2936871.

References

Chami, M., A., Thirouard, T., Harmel, "*POLVSM (POLarized Volume Scattering Meter) instrument: an innovative device to measure the directional and polarized scattering properties of hydrosols*", **Optics Express**, Vol. 22, Iss. 21, pp. 26403–26428 (2014)