On the Use of Space-based Polarimetric Measurements for Ocean Colour Remote Sensing – Heritage and Perspective

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Abstract

The polarization of the light within the water body has been already documented, and very well described from in-situ measurements. This signature mostly results from the process of scattering by all the constituents of the water body, the molecular water itself, but also hydrosols, including phytoplankton and non-algal particles, as well as water surface reflection and refraction. Mie scattering calculations demonstrated the sensitivity of Polarization with the chemical and physical properties of marine particles (nature and quantity of particle, refractive index, size, shape...).

As roughly for the scalar radiance, the marine polarised radiance once propagated to the top-of-atmosphere layer remains small and contributes to less than 10-20% of the total polarized radiance depending on the water types, aerosols and wavelengths.

Observation of the polarization from space have been experienced based on POLDER sensors. While for open ocean, the atmospheric correction or the accuracy of the estimation of the surface wind speed could be improved, it was possible to retrieve a significant water leaving polarized reflectance for bright waters. Alternatively, a new approach proposes to analyse the parallel polarized contribution with respect to the observing meridian plane, which reduces significantly the perturbing contribution from surface reflection.

Despite these past studies, the potential of polarization from spaced-borne measurements remains largely un-exploited for ocean colour purposes. The 3MI mission, a POLDER follow-on improved instrument on-board EPS-SG, will offer beyond 2021 the opportunity for a long-term time series acquisition in fully operational framework. Applications to marine analysis will be therefore possible. Other polarimetric information could also be available from SGLI/GCOM-C, OCI/PACE or DPC/GF-5.

Polarisation in the water body

Many studies have analysed the polarization in the atmosphere, especially for the molecular scattering and the characterization of aerosol and cloud particles. But not so many studies have been published for polarization of the light field in the ocean.

It can be mentioned analysis of the theory on the polarization of light in the ocean [Chandrasekhar (1950), Kattawar (1994)], the elliptical polarization of submarine illumination [Ivanoff and Waterman (1958)], the polarization due to scattering of in-water constituents [Chandrasekhar (1950); Ivanoff et al. (1961); Timofeyeva (1970); Morel (1973); Chang et al. (1999), Chami and Mc Kee (2007), Chami (2007); Chami and Platel (2007); Harmel et al. (2012), Liu et al. (2017)], the measurements of the Mueller matrix element of constituent [Beardsley (1968), Voss and Fry (1984)], the radiative transfer computation in the water body [Chandrasekhar (1950); Kattawar and Adams (1989); Chami et al. (2001); Chowdhary et al. (2006); Zhai et al. (2017)], or the ocean colour remote sensing using the polarisation [Loisel et al. (2008); He et al. (2014)].

The polarization of the light can be seen as an additional dimension to the spectral information usually considered. Consequently, compared to scalar radiance, measurements that include the polarimetric characteristics of the light provide more intrinsic information about the particulate scattering.

The scattered light is in general partially polarized according to the proportion defined by the degree of polarization, P with P = sqrt(Q²+U²+V²) / I
where [I, Q, U, V] is the Stokes vector characterizing the light with I representing the intensity of the light, Q and U describing the linear polarization state (quantity and privileged orientation), and V describing the elliptic polarization state. It is usually assumed V is negligible in the atmosphere-ocean system [Mishchenko (2014)]. In that case, P become the degree of linear polarization.

Theoretical computations

It is demonstrated, for instance based on simple Mie scattering computations, the dependence of polarization to the chemical and physical properties of particles. This observation is valid for atmosphere as well as for the water body. The molecular scattering shows a very strong polarization for a 90° scattering angle, decreasing when moving to smaller/greater angles. When particles are added, the position of the peak of polarization, as well as its intensity, change depending on the size, refractive index, and concentration of particle. For large particles, P decreases strongly. For this reason, the measurement of P provides an information on the relative proportion between small size and large particles in the observed field. The multi-scattering and scattering by non-spherical particles tend to lower also P.
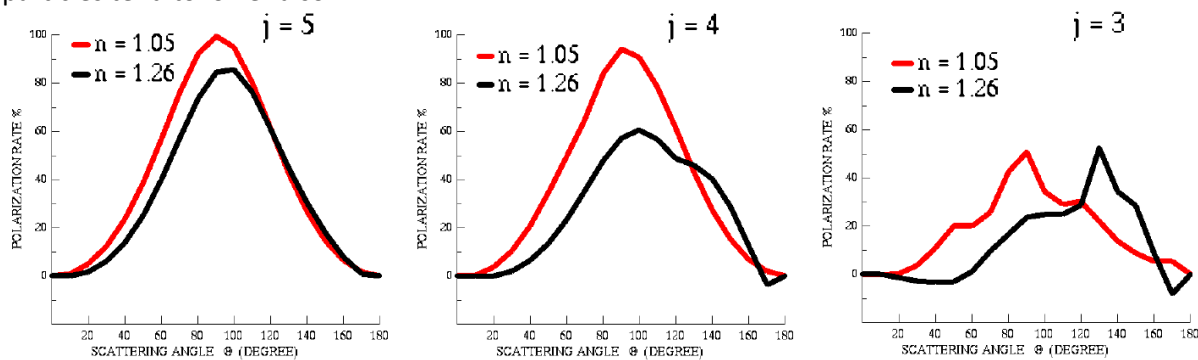
In-situ measurements

Historical in-situ measurements from Ivanoff et al. (1961) or Morel (1973). The degree of linear polarization at 90° scattering angle, P(90), can be directly linked to the ratio total scattering coefficient β by pure sea water scattering coefficient β_w.
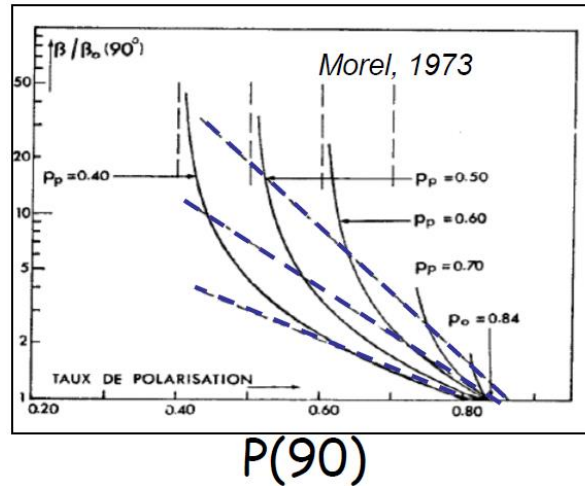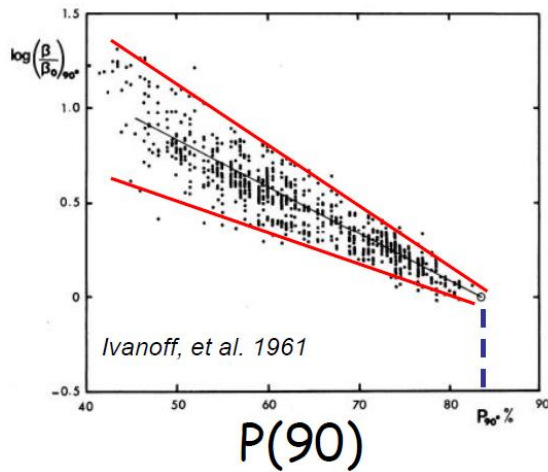
$$P(90) = - A \log (\beta (90)/\beta_w(90)) + 0.84$$
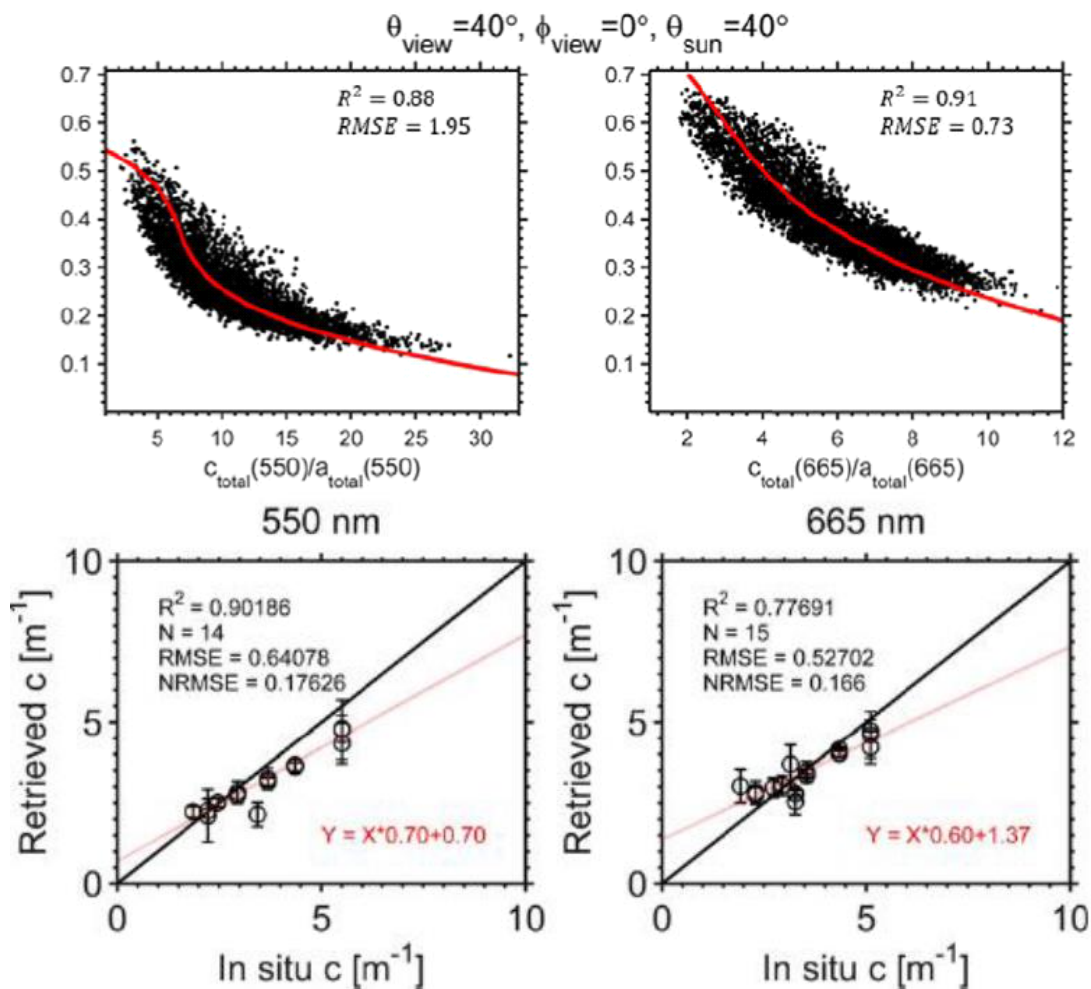
Pure sea water

Degree of polarization at 90°

This relationship can be extended to very turbid waters by

$$P(\theta) = P_p(\theta) + \beta_w(\theta)/\beta(\theta) (P_w(\theta) - P_p(\theta))$$

Very turbid waters

P(90)

Morel, 1973

P(90)

For coastal waters, the degree of linear polarization P has theoretically been related to the ratio the attenuation to absorption ratio, c/a, allowing the assessment of the particulate backscattering to scattering ratio, b_{bp}/b_p, (as bb and a are inverted) as shown by Ibrahim et al. (2016). These findings were confirmed by in-situ measurements.


$\theta_{view} = 40°$, $\phi_{view} = 0°$, $\theta_{sun} = 40°$

$R^2 = 0.88$
$RMSE = 1.95$

$c_{total}(550)/a_{total}(550)$

550 nm

$R^2 = 0.91$
$RMSE = 0.73$

$c_{total}(665)/a_{total}(665)$

665 nm

$R^2 = 0.90186$
$N = 14$
$RMSE = 0.64078$
$NRMSE = 0.17626$

$Y = X*0.70+0.70$

In situ c [m^{-1}]

$R^2 = 0.77691$
$N = 15$
$RMSE = 0.52702$
$NRMSE = 0.166$

$Y = X*0.60+1.37$

In situ c [m^{-1}]

In addition some relationship is observed between P and bbp/bp as documented by Loisel et al. (2006).

Theoretically — Experimentally
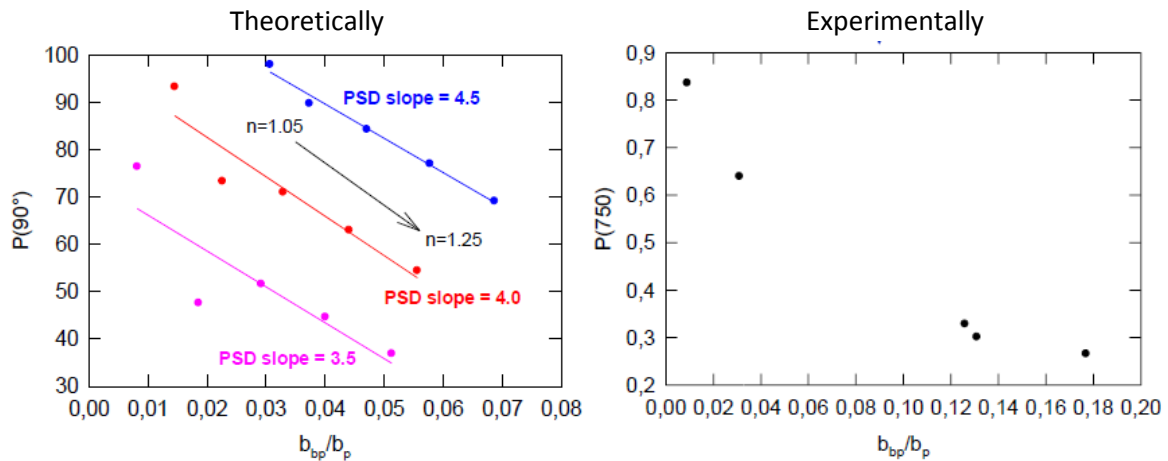
Difficulty above surface and from space

Numerous theoretical studies but few field measurements have demonstrated the potential of polarimetric observations above the sea level to assess pertinent information on the bulk particulate matter. Two main aspects contribute to limit the polarized signal as observed from space. First, viewing geometries associated to a space view correspond at the sensor level to scattering angles in general above 100°. But this scattering angle once transposed below the sea surface is significantly increased. Therefore, space observations are mostly associated to backscattering conditions in the water body, and it was explained before that a large part of the polarized signature is observed around 90° of scattering angle as illustrated in the following figure.
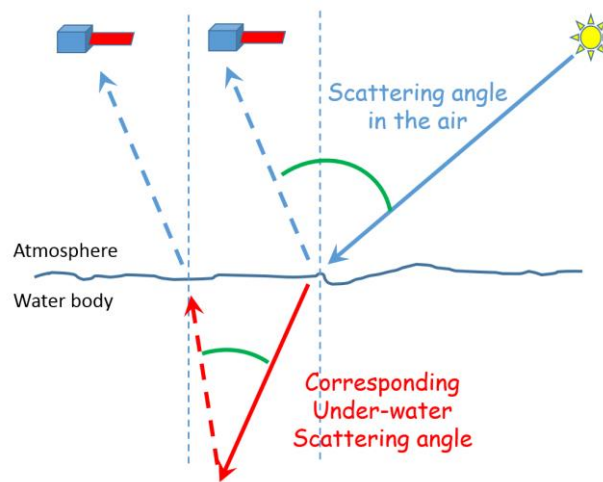

Secondly, as for natural light observations, the skylight and its reflection by the sea surface is the dominant part of the signal observed from space (Fougnie et al. 1999, Harmel and Chami 2008).

In these conditions, what about ocean colour applications as we are dealing with a quite small signal ?

For waters dominated by phytoplankton particles (PDW), the water leaving polarized signal contributes less than 9% to the TOA polarized reflectance (Zhai et al. 2017).

In open waters, Harmel and Chami (2008) have shown the TOA polarized reflectance is not really sensitive to the biomass concentration. Of course it depends partly on the sensor radiometric resolution. But the polarized reflectance can be used for improved aerosol detection and atmospheric correction, including the skylight reflection and sunglint.
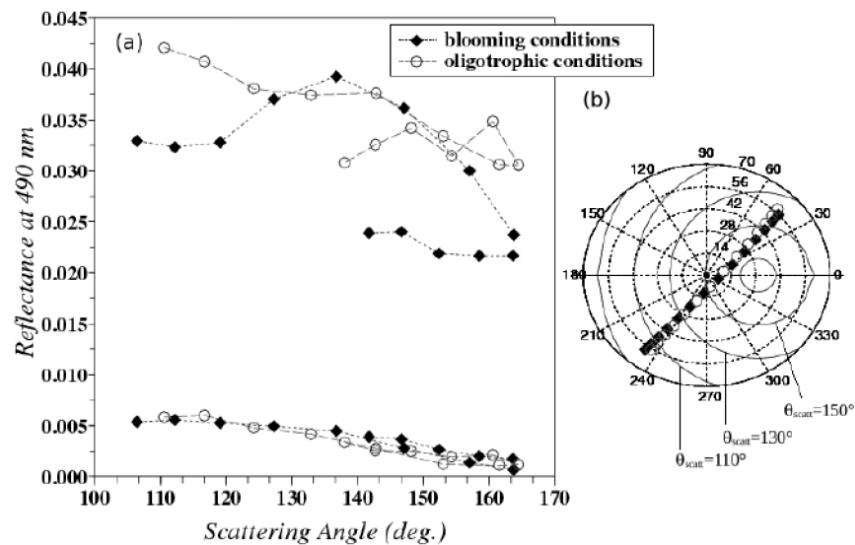
For waters dominated by non-algae particles (NDW), the polarized water leaving contribution can be as much as 20% in the wavelengths range from 470 to 670nm. For wavelengths shorter tan 450nm or longer than 865nm, the water leaving contribution to the TOA polarized reflectance is in general smaller than 5% (Zhai et al. 2017).

From bright waters in absence of aerosols, Loisel et al (2008) has shown water leaving polarized reflectance can be retrieved from space (POLDER2 as example) over bright waters.
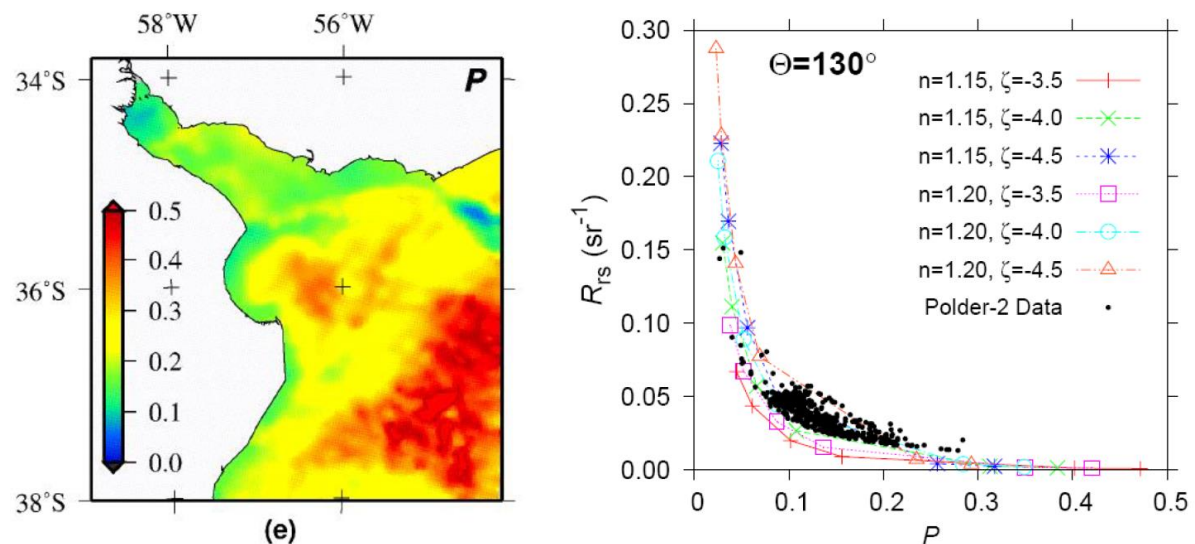

News approaches can be foreseen to exploit the polarimetric measurements from space. He et al (2014), have proposed a new simple concept for ocean colour satellite remote sensing using parallel polarization radiance (PPR) instead of the traditional radiation intensity. This parallel component is defined with respect to the meridian plane. Then, perpendicular and vertical components are defined by PPR = I+Q and VPR = I-Q

The reflected signal at the interface is lower for PPR than for VPR, the dominant part of the reflected skylight being polarized in the vertical direction. Then, for some specific geometries, the reduction of the skylight and sunglint reflected signal can be very significant (He et al. 2014, Fougnie et al. 1999), especially in the case of high solar zenith angles.

He et al. (2014) introduced the concept of normalized ocean colour signal, difference total TOA signal minus background signal, normalized by the background signal. The background signal is considered to be the atmospheric contribution plus the pure seawater component. For the PPR parameters, it gives : I_PPR(N) = (I_PPR-I_PPRb) / I_PPRb where b is for background.

The normalized polarized ocean colour signal has a significantly higher magnitude at the top of the atmosphere compared to the total radiance. Thus, there is a great potential for improving ocean colour detection from satellite.
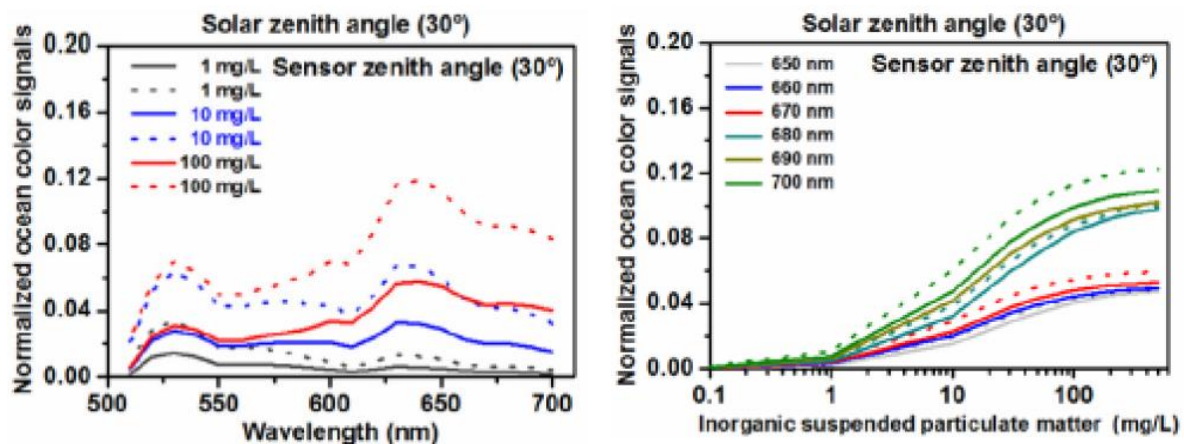
Measurements from space

Historical measurements are available from the POLDER family of missions (Deschamps et al., 1994): POLDER1 on-board ADEOS-1 (Nov. 1999-Jun. 1997), POLDER2 on-board ADEOS-2 (Apr. 2003-Oct. 2003), and POLDER-3 on-board PARASOL (Dec. 2004 – Dec. 2013) satellites, which were mainly designed to measure the radiative and microphysical properties of clouds and aerosols.

POLDER instruments cover the spectral range 443 to 910nm (1020nm for PARASOL) with 9 spectral bands. 3 of them are polarized. The spatial resolution is about 6x6km² at nadir. The multi-viewing capabilities are also a very valuable information while up to 14 different viewing conditions are available for any ocean target.

A generation of space-based polarimetric missions is coming. These instruments are dedicated to measuring the polarimetric properties of radiation. The CNSA Directional Polarimetric Camera (DPC - 2019) mission, the NASA Phytoplankton, Aerosols, Clouds and Ecosystems (PACE - 2022) mission and the EUMETAT Multi-viewing Multi-Channel Multi-polarisation Image (3MI - 2022). These news sensors could be, and must be, exploited in a near future.

Perspective with 3MI

3MI is follow-on instrument of POLDER (Fougnie et al. 2018). A spectral extension to the SWIR domain, as well as 410nm is provided. The polarimetric information (Stokes vector) will be available for 9 spectral bands. The spatial resolution will be 4km at nadir, and the instantaneous swath is 2200-ALTx2220-ACT km². Sub-pixel information based on METimage, a 500m resolution imager on-board

the same platform, will be provided on level-1 products (Lang et al. 2018). It is also expected a slightly better radiometric resolution than POLDER.

The concept is optimized to provide polarization, directionality and spectral signature at the same time as described in Fougnie et al. (2018). The availability of various viewing directions is particularly useful to optimize the retrieval of the surface contribution while the skylight signal, as well as sunglint, vary strongly with viewing geometries.
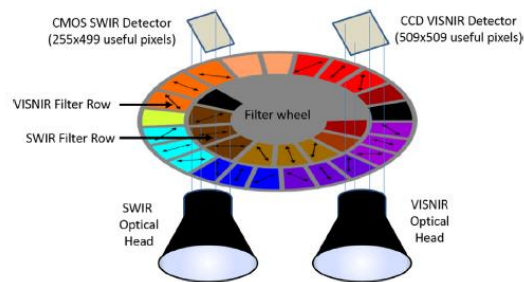
Band name	Spectral domain	CWL (nm)	FWHM (nm)	Polar
3MI-1	VISNIR	410	20	P
3MI-2	VISNIR	443	20	P
3MI-3	VISNIR	490	20	P
3MI-4	VISNIR	555	20	P
3MI-5	VISNIR	670	20	P
3MI-6	VISNIR	763	10	NP
3MI-7	VISNIR	765	40	NP
3MI-8	VISNIR	865	40	P
3MI-9	VISNIR	910	20	NP
3MI-10	SWIR	1370	40	P
3MI-11	SWIR	1650	40	P
3MI-12	SWIR	2130	40	P
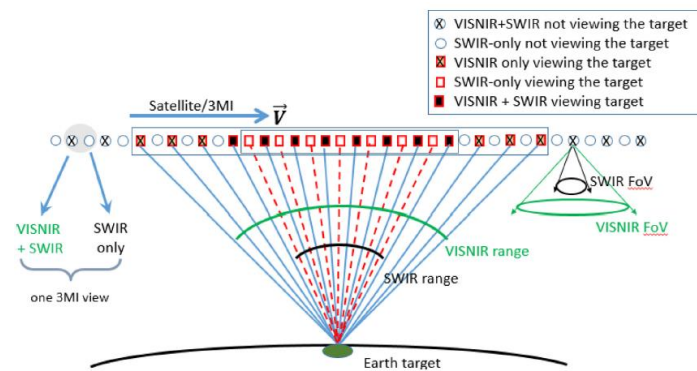
The following Figure provides the typical above-water scattering angle distribution (minimum, maximum, as well as total range) that will be available from 3MI measurements.
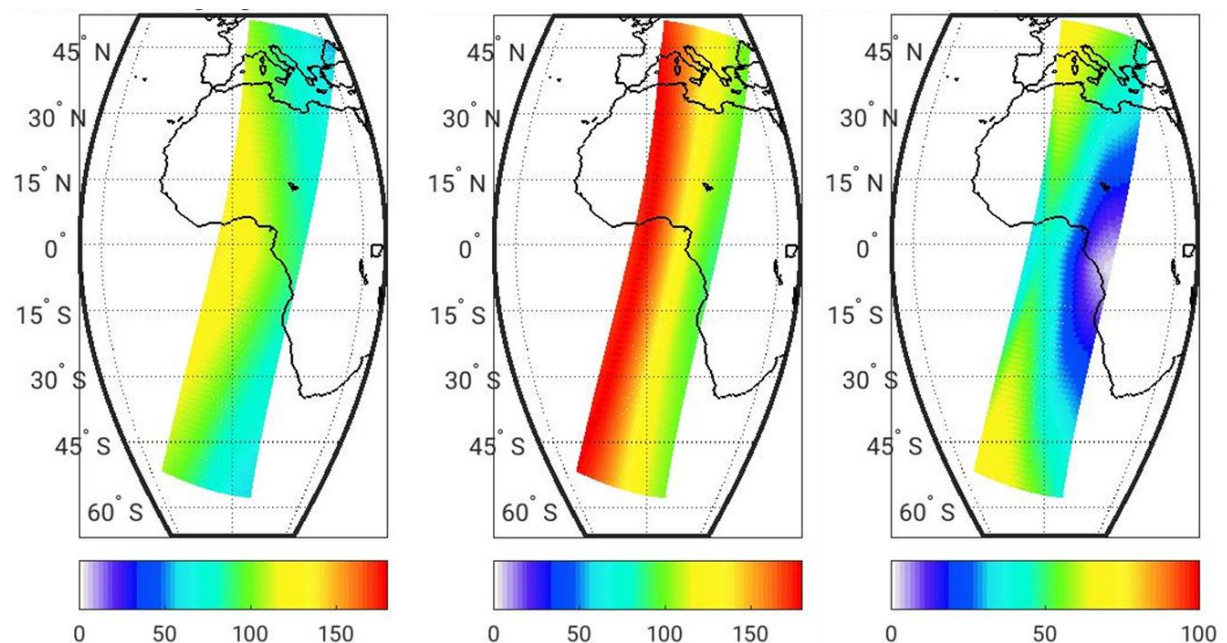
3MI is a mission devoted to aerosol and cloud characterization in the EPS-SG European program. It will deliver level-1 data, as well as associated atmospheric level-2 products, on near real time baseline, products being available 100 minutes after sensing. The availability of data is a very good added value if the use of such measurements is considered for near real time application, especially for coastal applications. This easily opens the door to synergistic use in combination of low-orbiting system fully developed for ocean colour needs, such as Sentinel-3/OLCI, but also in combination of high temporal revisit imaging from geostationary orbit, for instance using MTG/FCI in the case of the European geographical area.

Conclusion

Polarimetric measurements, alone or in combination with high-temporal revisit geostationary or polar-orbiting ocean colour imagers, offer great potential for advancing quality and value of satellites ocean colour observation. A series of polarimeters, scheduled to be launched in the coming years, will provide measurements to support these developments. 3MI, one of them, will in addition provide these data in a near real time baseline, allowing important synergistic uses with other sensors fully dedicated and designed for ocean colour (e.g. Sentinel-3/OLCI…)

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