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Polarimetry in the PACE Mission: Science Team Consensus Document

PACE Science team

National Aeronautics and
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PREFACE

Introduction

Based on the PACE Science Definition Team report, the PACE Project designated the Ocean Color Instrument (a radiometer) as the mission's primary instrument and determined threshold science requirements based only on imaging radiometry. At the same time, the PACE Project identified a multi-angle imaging polarimeter (MAP) as a desirable addition and proceeded to investigate different options to add such an instrument to the mission, while staying with the mission's design-to-cost constraints.

Working in parallel to the PACE project, the first PACE Science Team formed a subgroup that focused on defining MAP's science value to the mission. The subgroup invited a series of speakers to give webinars describing different MAP concepts and the scientific rationale behind each. The webinars were open to all PACE Science Team members and their affiliates. Four webinars were presented by Otto Hasekamp (SRON) speaking on SPEX, Brian Cairns (NASA GISS) speaking on RSP, David Diner (NASA JPL) speaking on MSPI, and J. Vanderlei Martins (UMBC) speaking on HARP. The breadth of concepts and complementary science resulting from such concepts, supplemented by published literature, provided the background for this report.

The polarimetry subgroup of the PACE Science Team then worked to document the state of the science of polarimetry as applied to (a) the remote sensing of aerosol and cloud parameters, (b) atmospheric correction over oceans, and (c) characterizing hydrosol properties. The goal was to justify the addition of a polarimeter to the PACE mission and to define the instrument requirements that would best meet the science objectives. The group found consensus in the value of including a MAP on PACE, and in defining many, but not all, of the instrument requirements. Both consensual and points of disagreement are documented in the report.

The polarimeter subgroup was formed in February 2015. The webinar series spanned the period April 30 to May 30, 2015. Discussion and writing the report continued through July, and the report was submitted to NASA Headquarters on July 23, 2015.

Submitted by Emmauel Boss and Lorraine A. Remer

Polarimetry in the PACE mission.

Science Team Consensus Document

July 23, 2015

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The PACE (Pre- Aerosol, Clouds, and ocean Ecosystem) Science Team was asked by NASA Headquarters to assess the importance of including a polarimeter in the PACE mission concept, in addition to and complementary with the planned Ocean Color Imager (OCI), and the relationship between different polarimeter features and specific PACE science goals. We note that the information that Headquarters requested is central to the funded research being actively pursued by members of the science team, with results expected in the third year of their research. Yet, because of the time-sensitive nature of the request, the science team has attempted to consolidate the knowledge accessible at this point in time. Greater detail and additional evidence will be available at the conclusion of the science team's endeavors.

1. Executive Summary

The first goal of PACE mission science is to open new vistas in aquatic biogeochemistry by measuring non-chlorophyll pigments, separate chlorophyll and colored dissolved organic matter (CDOM) and characterize phytoplankton taxonomy. PACE science will follow aquatic biochemistry into ecosystems in coastal regions, estuaries, tidal wetlands and lakes. PACE's second science goal is to extend aerosol and cloud data-records begun by the passive EOS-era instruments, as an aerosol- cloud-climate continuation mission. Besides PACE, NASA has no plans for multi-angle radiometry to continue the MISR record nor for multi-angle polarimetry to continue the PARASOL record. A multi-angle polarimeter on PACE will reduce risk towards meeting the first goal and enable the realization of the second.

The overarching consensus of the PACE Science Team is to **strongly endorse** the inclusion of a polarimeter in the PACE mission. This consensus opinion is based on the following three reasons:

- The science team has identified atmospheric products related to both clouds and aerosols that can only be obtained with a multi-angle polarimeter, and the addition of such an instrument will yield a substantial benefit to the mission science return. An extensive body of literature and on-going studies support this statement.
- The science team agrees with evidence showing that multi-angle polarimetry provides information for the simultaneous retrieval of "remote-sensing reflectance" (R_{rs}) and aerosol properties. Alternatively, multi-angle polarimetry can enhance traditional methods of atmospheric correction with the PACE radiometer, particularly in challenging situations near coastlines and inland water bodies, by better defining aerosol models with accurate retrievals of particle complex refractive index and absorption characteristics. Sufficient evidence exists to support this statement with confidence.
- Although few published studies exist, the science team is encouraged by preliminary theoretical and observational studies that show that polarimetry can aid in the characterization of hydrosols (particles suspended in the water), but more studies are needed.

Polarimetry opens a entirely new dimension in retrieving properties of atmospheric constituents over the ocean, in achieving optimum atmospheric correction (AC), and in retrieving the intrinsic optical properties (IOPs) of the ocean. The reasons for this are that photopolarimetry (1) offers *three* observables per viewing angle (intensity, degree of polarization, and direction of polarization), while radiometry offers only intensity; (2) exhibits meaningful angular information not observed in radiometry; and (3) is more sensitive to the physical and chemical properties of (inorganic) particles than radiometry.

We have reached these conclusions based on current literature and also four webinars given by Otto Hasekamp (SPEX), Brian Cairns (RSP), David Diner (MSPI) and Vanderlei Martins (PACS). Each webinar was given an hour slot, of which about 30 minutes were slides and presentation, and 30 minutes were discussion. In addition, there have been several follow-up telecons to identify consensus. All webinars, some slide presentations and some email threads have been posted to the science team FTP site. Participation in the webinars, discussions and access to the FTP site were open to an extended science team consisting of PIs, Co-Is, and any collaborators identified by the PI.

In many cases there is no simple mapping of a particular polarimeter feature to a specific scientific capability, as the same science can often be achieved by different combination of polarized and unpolarized channels, spatial resolution, angular range and density, swath width etc.

There is consensus that:

- Multi-angle photopolarimetric imaging is an essential polarimeter feature for most PACE science goals and highly desirable for ALL of them. For the remainder of this document, the term "polarimeter" implies a multi-angle observing instrument measuring both intensity and polarization, and it evaluates the multi-angular radiometric and polarimetric remote-sensing capabilities of such an instrument.
- A minimum of five view-angles, spanning an angular range of at least $\pm 60^{o}$ (measured from the ground) should be sufficient to characterize aerosols and for atmospheric correction. This statement is based on studies made over land targets. It may be possible to decrease the number of view angles for the specific purpose of atmospheric correction over ocean, but the state-of-the-science is not ready to justify the decrease at this time. Five viewing angles are also sufficient to retrieve information about ice cloud-scattering phase functions. Fifty angles or more are needed to characterize liquid cloud droplet-size retrievals.
- The target uncertainty in the degree of linear polarization (DoLP) is 0.005 to fully characterize aerosol properties, including aerosol size distribution, the real part of the refractive index, and single scattering albedo.
- Polarimeter swath should be as wide as possible while still meeting accuracy requirements and providing adequate angular sampling. It is preferable, but not necessary, for the polarimeter swath to match the swath of the PACE spectral radiometer. Swath widths less than 400 km still hold some value for characterizing atmospheric constituents, but provide little value for atmospheric correction over ocean.
- Strong consensual statements about importance of different spectral ranges cannot yet be stated. Discussion of different spectral capabilities is given in Section 3.0.

In Section 2.0 we justify the statements made above. In Section 3.0 we discuss instrument requirements in greater detail.

2. Justification for a Multi-angle Imaging Polarimeter in the PACE Mission

2.0. Characterization of Aerosol and Cloud Properties

Heritage sensors have provided a gradation of capability in retrieving characteristics of aerosol and cloud properties. MODIS, OMI, VIIRS, etc., provide a single-angle, multi-spectral radiometric image that can be used to retrieve a minimal set of aerosol and cloud properties. The next step in the gradation have been sensors that include multi-angle views of the same image. These sensors: MISR, AATSR, CHRIS/PROBA, and POLDER have demonstrated the added value of multi- angle imaging radiometry for characterization of aerosols and clouds. The variation in spectral radiance with view zenith or scattering angle enhances atmospheric path radiance relative to surface reflection, enabling aerosol retrievals over a wide range of surface types, and it provides sensitivity to the particle-scattering phase function, allowing categorical distinction of aerosol type into spherical non-absorbing, spherical absorbing, and non-spherical classes (Kahn and Gaitley, 2015). At moderately high (sub-km) spatial resolution, multi-angle imagery can also be used stereoscopically to retrieve aerosol plume and cloud-top heights and height-resolved atmospheric motion winds (Nelson et al., 2013; Marchand et al, 2007; Horvath, 2013). Presently, the near-surface wind speed is ancillary information in the modeled surface reflectance that has to be obtained from reliance on a global forecast model at a relatively coarse spatial resolution. Multi-angle observations provide two approaches for assessing the near-surface wind speed, either by measuring the angular extent of the sun-glint pattern or by observing cloud-track winds, which tend to be highly correlated with near-surface winds for low clouds.

These multi-angle radiometers have served as a stepping stone to better understand and utilize the remote-sensing strengths of a multi-angle photopolarimeter that we propose for PACE.

There is strong consensus within the aerosol community that a multi-angle polarimeter is part of the essential next step in improving our understanding of the global aerosol system, reducing uncertainty in estimates of aerosol forcing of climate, improving knowledge of aerosol-cloud processes and advancing space-based air quality monitoring and forecasting, and documenting important aerosol events. Though, as noted above, multi-angle radiometry is an important step up from the single-look, MODIS-like instruments, polarimetry allows for more accurate retrieval of particle properties from space than from either MODIS-like or MISR-like instruments. The extended capability of polarimetry to retrieve aerosol properties from space has already been demonstrated using measurements by POLDER, despite its relatively low polarimetric accuracy (Dubovik et al. 2011; Hasekamp et al., 2011). Currently, PACE and the European 3MI are the only planned instruments with multi-angle capability that could continue the NASA MISR aerosol record, and go beyond MISR to provide the required precise characterization of aerosol and cloud properties obtained from a multi-angle polarimeter.

A multi-angle polarimeter inversion is very different from the types of retrievals applied to radiometers for the past 15 years. Heritage aerosol retrievals must use *a priori* assumptions about the aerosol and surface properties plus a pre-calculated look-up table in order to retrieve at most aerosol loading and some information about aerosol type and height for general aerosol conditions. In contrast, the simultaneous inversion of multiple wavelengths, angles, and polarization states (with a minimum of constraints) can retrieve aerosol optical thickness, particle shape, size distribution, and complex refractive index for two aerosol-size modes, while simultaneously retrieving parameters of the surface beneath (Chowdhary et al., 2001; Mishchenko et al., 2007; Waquet et al., 2009; Knobelspiesse et al., 2012, Wu et al., 2015.)

Figure 1 shows an example of how radiometry alone is unable to distinguish between different refractive indices, but polarimetric radiances can differentiate them (Chowdhary et al., 2001). These characterizations are critical for aerosol radiative forcing studies, chemical transport model assessments and air quality applications. Retrievals of the multi-angle measurements of the kind envisioned for a PACE polarimeter can be used for a variety of applications, based on the heritage of multi- angle radiometers described above [Diner et al., 2010; Kahn et al., 2007; Marchand et al.,2010], all of which have significant applications for societal benefit. Multi- angle photopolarimetry improves upon radiometry in reducing the number of *a priori* assumptions required for aerosol retrieval and allows a more physical characterization of the scene.

Airborne versions of multi-angle polarimeters have been collecting data and producing retrieved parameters for over a decade (Chowdhary et al. 2001, 2002, 2005). These examples have shown that not only can a multi-angle polarimeter retrieve the expected aerosol properties in the traditional scenes expected of a remote sensing retrieval; but because aerosols and clouds have different polarimetric signatures, aerosols above clouds, below thin cirrus clouds, and within a broken cloud field can also be characterized, at least in some situations (Knobelspiesse et al., 2011; Waquet et al., 2013; Davis et al., 2013; Peers et al. 2015). This increases the availability of the aerosol characterization and provides a more accurate global picture of aerosol forcing. Because aerosol physical and optical properties are known to be different in the vicinity of clouds, global aerosol characteristics measured by MODIS-like instruments are clear-sky biased. This would also be true of a PACE OCI without the benefit of simultaneous polarimetric observations.

Photopolarimetry can match MODIS-like retrievals of liquid cloud droplet effective radius while also providing additional information about droplet size distribution width. Distribution width is especially important for identifying factors contributing to the onset of precipitation. A narrow and wide cloud droplet size distribution may have the same effective radius, but only the wide size distribution contains droplets large enough to initiate collision/coalescence processes that produce precipitation. Cloud droplet size distribution can be retrieved from the polarization measurements of a cloudbow, illustrated in Figures 2 and 3. A cross section through the polarized cloudbow oscillating bands can be fit to theoretical patterns calculated for a variety of effective radii and size distribution width.

Radius is sensitive to spacing of the cloudbow bands, and width is sensitive to the amplitude of the oscillations (Figure 3). The information that can be obtained from the cloud bow has been extended by Alexandrov et al. (2012b) who developed the "rainbow Fourier transform" technique that is capable of retrieving the droplet size distribution itself. Furthermore, based on this approach, Alexandrov et al. (2012b) developed the rainbow Fourier transform technique that is capable of retrieving properties of multiple modes in droplet size distributions. Breón and Goloub (1998) pioneered the retrieval of effective cloud droplet-size distribution using polarization with POLDER, requiring cloud microphysical homogeneity over 100 km. Since then, different polarimeter designs with hyperangle capability in at least one channel can view the same small cloud with upwards of 50 view-angles per pixel and retrieve size distribution-width for clouds as small as fair-weather cumulus (Alexandrov et al., 2012; Diner et al., 2013).

Polarimetry can also provide accurate retrievals of cloud thermodynamic phase (liquid or ice) through the detection of the cloudbow, which is only produced by perfectly spherical liquid drops (Goloub et al., 2000; van Diedenhoven et al., 2012). Since we cannot rely on traditional methods to determine cloud phase based on thermal infrared measurements, the inclusion of a PACE multi-angle polarimeter will greatly enhance mission capability with respect to cloud science.

For ice clouds, multi-directional polarization measurements provide information about the shape and scattering properties of ice crystals (van Diedenhoven et al., 2012b; 2013; Cole et al. 2014). Uncertainties in scattering properties of ice crystals, in particular their asymmetry parameter, and variation therein are the main causes of uncertainties in retrieving ice cloud optical thickness and ice effective radius using traditional MODIS-like methods (van Diedenhoven et al., 2014). These traditional methods would be applied to PACE OCI data in the absence of coincidental polarimetric observations.

Finally, multi-directional polarization measurements at two wavelengths with sufficiently contrasting contributions from Rayleigh scattering provide information on cloud top heights (Buriez et al. 1997; van Diedenhoven et al., 2013). Such methods would be complimentary to the Oxygen A-band cloud height retrievals anticipated for OCI, which cannot rely on traditional MODIS-like methods for retrieving cloud top heights that use thermal infrared measurements.

There are some limitations to using polarimetry for aerosol and cloud characterization. All aerosol and cloud retrieval procedures using polarimetry require measurements over specific ranges of scattering angles, depending on the retrieval approach. The ranges and values of scattering angles that would be measured by a polar-orbiting instrument will vary with solar and viewing geometries. Thus, the availability and quality of derived products will vary with location and time, especially for the outer portions of an instrument's swath.

Matching the PACE OCI swath with uniform high-quality aerosol and cloud retrievals across all cross-track view angles is impossible. Furthermore, the algorithms used to fully exploit the advantages of polarimetry for aerosol retrievals are complex, requiring effort to develop and maintain. Moreover, existing approaches are currently computationally costly, although we expect computational power to increase substantially by the time the PACE mission launches.

In summary, the potential PACE mission benefits of multi-angle polarization in characterizing aerosol and cloud properties are substantial, proven and documented.

2.1. Enhancement of Atmospheric Correction Capabilities

The PACE mission promises to advance the state of ocean color science beyond the current generation of sensors by estimating the amount of photosynthetic pigments and other suspended and dissolved water constituents using hyperspectral measurements from ultraviolet (UV), visible, and near infrared (NIR) wavelengths, and by targeting ecosystems in coastal regions, estuaries, tidal wetlands, and lakes. Achieving these objectives, in particular proper identification/discrimination of phytoplankton groups, requires the best accuracy possible on water-leaving radiance (L_{wn}) or remote-sensing reflectance (R_{rs}) retrievals. Since the radiance scattered by the atmosphere and reflected by the surface is about ten times the radiance scattered by the water body, the accuracy of the R_{rs} retrievals is squarely limited by uncertainty in the atmospheric correction. The performance of the present atmospheric correction algorithms is good, but not accurate enough—especially in the coastal zone and over inland waters where water and air properties are highly variable and intricate, aerosols are absorbing, and the proximity of land introduces further difficulty.

The shortcoming of conventional atmospheric correction methods in regions with complex marine and atmospheric compositions suggests an opportunity for a multi- angle polarimeter to supplement OCI R_{rs} retrievals, particularly at short visible-UV wavelengths and in cases where the water surface in the NIR cannot be considered black, and will, therefore, significantly reduce the risks for meeting many PACE mission objectives. As indicated in Section 2.1, measurements of the wavelength dependence and polarization of the scattered radiance in the NIR and shortwave infrared (SWIR) provide a determination of the aerosol physical properties, i.e., size distribution and refractive index. This information may be used to constrain the domain of possible aerosol types in a classic atmospheric correction scheme or, if sufficiently accurate, to directly compute the aerosol-scattering effect. The sensitivity of polarized radiance to aerosol type has also the potential to improve inversion schemes that aim at retrieving simultaneously atmosphere and ocean properties.

The capabilities expected of the PACE OCI, including expanded spectral range and hyperspectral wavelengths, also offer an alternative or complementary path towards an enhanced atmospheric correction. Spectral measurements in the Oxygen A-band may provide information about aerosol vertical structure (affects the perturbing atmosphere signal, especially when aerosols are absorbing), as demonstrated by Duforêt et al. (2007) and Dubuisson et al. (2009). The retrieved R_{rs} may also be corrected for Raman scattering contributions, which may reach 20% in clear oceanic areas (40% of the world ocean). In small spectral intervals, where solar irradiance exhibits sufficiently large variations and Raman scattering can be assumed constant, the Raman signal can be separated from the elastic signal. These proposed enhancements to traditional methods are under investigation in parallel with polarimeter studies. Here, we only comment on the preliminary results of the multi-angle polarimeter investigations.

Preliminary studies of the polarized ocean-color signal, both theoretical (Figure 4) and with measured data (Figure 5) suggest that polarimetry is able to achieve a level of atmospheric correction at minimum equal to heritage methods and will likely add significant capability. The theoretical work expresses the improvement in retrieved normalized water-leaving reflectance ($[\rho_w(\lambda)]_N$) uncertainty with the use of multi-angle instruments and polarimetrically sensitive multi-angle instruments in addition to OCI. The work, based upon the information theory originally described in Rodgers (2000), shows that the uncertainty associated with a retrieval from a multi-angle radiometer would be only 20–35% of the uncertainty of a retrieval with the information content of an OCI. The information content from a multi-angle polarimeter further reduces the uncertainty to 5–20% of the OCI uncertainty. Details of the analysis are given in the caption of Figure 4.

The observational evidence is presented by L_{wn} retrievals applied to AirMSPI measurements taken over a SeaPRISM site off the coast of California. AirMSPI is a multi-angle polarimeter flying on the high-altitude NASA ER-2 with 20 km of atmosphere between it and the ocean below. The SeaPRISM site on an offshore platform provides spectral L_{wn} measured just above the ocean surface. Comparisons between the AirMSPI retrievals with the SeaPRISM ground truth show that spectral L_{wn} is retrieved much more accurately with multi-angle and polarization capability than when a more limited retrieval is made with just one angle and no polarization. Details of the data collection, retrievals and analysis are given in Figure 5. The results of both the theoretical and observational studies of Figures 4 and 5 show that polarimetry will make a positive difference to the PACE mission atmospheric correction, especially in complex scenes where a priori assumptions could break down.

He et al. (2014) provide further evidence of the advantages of including polarimetry for atmospheric correction over ocean. They describe a method for retrieving L_{wn}, using parallel polarization radiance (PPR = I + Q), where I and Q are the first two components of the Stoke's vector. Their results, both from simulations and from application to POLDER data, demonstrate that using PPR provides two important enhancements to ocean color retrieval. First, it reduces the sun glint at moderate to high solar zenith angles. Second, it boosts the ocean color signal relative to the total radiance received by satellite at large view angles. These advantages are explained by the compensating effect between the total radiance and the polarization. For example, as view zenith angles increase, because of the increasing long path length through the atmosphere, the total radiance received by the satellite increases, causing the relative ocean color signal reaching the satellite to decrease. Meanwhile, the magnitude of Q increases with path length, but in the negative sense, which offsets the increase in I, and slows down the increase in PPR with path length through the atmosphere. Figure 6 illustrates this enhancement due to polarimetry.

Use of multi-angle polarimetry for atmospheric correction can take many paths including simultaneous retrievals of atmosphere and ocean, using polarimetry to better define the atmospheric state and constrain a traditional retrieval, or as in He et al. (2014), increase the signal-to-noise ratio (SNR) of the ocean color signal in specific challenging geometries. While multi-angular information alone may also improve atmospheric correction in the presence of absorbing aerosols (Thieuleux, 2002), multi-angle polarimetry offers the most information for the enhancement of atmospheric correction for the PACE mission.

With improved atmospheric correction provided through multi-angle polarimetry, it is expected that in-water optical properties will be better retrieved in magnitude and spectral shape, resulting in more accurate biogeochemical estimates for chlorophyll, particulate organic and phytoplankton carbon, and bulk size distribution parameter, and assisting in the separation of the contribution of dissolved organic material and non-algal particles to the total absorption.

2.2. Characterization of Hydrosols

Light scattered by oceanic particles in the underwater environment is polarized analogous to light scattered by atmospheric aerosols (Kattawar 2013; Chowdhary et al. 2012; Lotsberg and Stamnes, 2010). Thus, additional information can be obtained from polarimetric remote-sensing data in the inversion of ocean color measurements—information that can then be used to derive additional oceanic properties (Harmel 2016). Established ocean color remote sensing techniques are limited to obtaining the remote-sensing reflectance, R_{rs}, from which the absorption coefficient a and backscattering coefficient b_b can be retrieved using:

$$R_{rs} \propto b_b/(a+b_b)$$

Other ocean color products such as phytoplankton particle-size distribution (PSD) are then derived from a and b_b. On the other hand, remote sensing measurements of the polarized water-leaving radiance (or reflectance) are sensitive to *additional* microphysical properties of hydrosols such as their composition (e.g. refractive index) and their shape. Better characterization, and therefore, knowledge of these additional properties should lead to improved methods for determining pigment concentration and perhaps taxonomy, especially in optically complex waters. Polarization measurements also provide *independent* means to validate the retrieval of PSD from R_{rs} measurements.

A simple illustration of the potential of using polarimetry synergistically with the OCI is shown in Figure 7. This figure clearly illustrates the sensitivity of degree of linear polarization (DoLP, *i.e.* fraction of total light intensity that is linearly polarized) to variations in water types. The clear water in this figure shows low (high) DoLP values in the blue and green (red), while the opposite occurs for the more productive water. Adding CDOM in the more turbid water increases the DoLP in the blue even more. This is similar to the "Umov effect" reported for bright celestial bodies, where bright objects tend to exhibit lower DoLP due to multiple scattering thus causing the DoLP spectrum to resemble a "flipped" R_{rs} spectrum.

Note also the chlorophyll absorption and fluorescence peaks in the productive waters, which again show negative correlation between reflectance and DoLP values (higher DoLP values at wavelengths with higher the chlorophyll absorption, and lower DoLP values at wavelengths of strong chlorophyll fluorescence) (see also Tonizzo et al., 2009).

Polarization signatures also allow for the distinction between organic and inorganic particles. That is because inorganic particles exhibit higher scattering coefficients, thereby increasing multiple scattering, which reduces the DoLP. For example, Chami and McKee (2007) suggest that it is possible to retrieve the suspended particulate matter (SPM) from DoLP measurements at the Brewster angle. Using theoretical modeling they showed that an empirical based inversion approach could retrieve the concentration of inorganic particles from underwater polarized radiance measurements regardless of the phytoplankton content in coastal waters.

Several other studies have shown the sensitivity of polarized light in the ocean to variations in IOPs and biochemical properties (Chowdhary et al., 2012; Ibrahim et al., 2012; Chami and Platel, 2007). For example, Chami and Platel (2007) used neural network computations to study whether variations in the direction and polarization of marine reflectance could be used to retrieve IOPs. They showed that adding polarization channels improves the retrieval of the IOPs (including the scattering coefficient) by 65–75%, while including directional reflectance improves it by 15–60%, compared to using only scalar reflectance in the retrieval of IOPs. In shallow waters, polarization measurements can also provide additional constraints to separate signals from water constituents and various surface and benthic features (Gilerson et al., 2013).

Top of the Atmosphere (TOA) simulation studies of polarized light over oceanic waters have shown that this light remains sensitive to the scattering properties of the ocean (Chowdhary et al., 2005, 2006, 2012). Over low production (open ocean) waters, where the phytoplankton particles and CDOM covary and are the primary optically significant waterborne constituents, the TOA polarized reflectance is somewhat sensitive to the variations of the chlorophyll-*a* concentration (Chl) (Chowdhary et al., 2012), depending on the wavelength and geometry of observations. In Ibrahim (2015), it was shown that the TOA DoLP is moderately sensitive to IOP changes in open oceans in the green portion of the spectrum.

Sensitivity decreases towards the blue portion of the spectrum due to the contribution of molecular scattering, and towards the red portion of the spectrum due to water absorption. The IOP information content of DoLP observations at the TOA increases over bright coastal waters, where this DoLP becomes much more sensitive to the variations in the properties and abundance of hydrosols. A sensitivity study (Ibrahim, 2015) shows that it is possible to retrieve *new* macro- and micro-physical properties of hydrosols (i.e. the attenuation and scattering coefficients, refractive index, and particle abundance), and to obtain independent retrievals of hydrosol PSD, from DoLP measurements. Relationships between the DoLP at the TOA and hydrosol IOPs, represented as the ratio between the attenuation and absorption coefficients (c/a), suggest additional information regarding the nature of suspended and dissolved water constituents that is not represented within unpolarized radiometric signals (Figure 8).

Thus, a spaceborne polarimeter, given appropriate spectral channels and sensitivity, offers promising tools to retrieve new information on marine hydrosols and hence help in distinguishing types of marine particles. Such capabilities have been originally demonstrated for polarimetric observations obtained by the POLDER satellite instrument over a coccolitophore bloom and over turbid waters (Loisel et al., 2008). Observations by a polarimeter with a higher accuracy and finer spatial resolution polarimeter may extend POLDER's results for hydrosol retrievals to waters with more complex composition. Combined radiometer/polarimeter inversions are expected to enlarge the number of parameters retrieved for the ocean as well as improve standard products.

The ideas presented in this section are preliminary, and it is unclear how much additional hydrosol information could be realized from a spaceborne polarimetric instrument in real-life situations. Fieldwork with airborne polarimeters under varying environmental conditions will bring important new information to the table, especially when compared with ship borne instruments. Specifically, measurements made during the 2014 SABOR field experiment that are currently being analyzed, and those to be made in the NAAMES experiment over the next five years, will add significantly to our experience and put these preliminary results to the test.

3. Discussion of Instrument Features

Below we discuss in outline form the important features of a multi-angle polarimeter for the science described in the preceding sections. Work is on-going to better map specific features to scientific capability. The following lays out the possibilities as best we can with the information available now.

3.0. Polarimetric Accuracy

- The target uncertainty in degree of linear polarization (DoLP) for instruments to fully characterize aerosol properties is 0.005, including aerosol size distribution, the real part of the refractive index, and the single-scattering albedo.
- The POLDER level of DoLP uncertainty of 0.02 can still achieve some aerosol characterization, and can likely aid in constraining aerosol models for atmospheric correction, following the traditional atmospheric correction algorithm.
- Polarimetric cloud retrievals generally use polarized reflectance instead of DoLP. The accuracy of polarized reflectance is mainly determined by the instrument's radiometric accuracy. Accuracy similar or better than that of POLDER are sufficient for retrievals of ice and liquid cloud properties. In terms of DoLP accuracy, 0.02 is sufficient for characterization of cloud

properties, but compromises the capability to accurately determine aerosol absorption above clouds.

- Unknown is how polarimetric accuracy will affect joint atmosphere-ocean retrievals or characterization of hydrosols. Preliminary estimates suggest that accuracy should be equivalent as for aerosol characterization (0.005) in order to distinguish aerosol and hydrosol polarimetric signatures.

3.1. Radiometric SNR

- SNR of 1000 for an albedo of 0.5 with the sun at zenith for spectral and polarized radiance.
- Dynamic range of radiometry: Up to an albedo of one for the sun at zenith so as to not saturate over clouds or sun glint.
- Current SNR of POLDER is insufficient to characterize hydrosols, except in very specialized regimes (Loisel et al, 2008).

3.2. Spatial Resolution

- If all else is equal, finer resolution is better, but polarimetric accuracy and SNR have priority over spatial resolution in order to fully characterize aerosol properties.
- For aerosol, we have seen concepts in the range 0.3–6 km at nadir. These appear to satisfy the aerosol and cloud needs of the instrument developers.
- The issue of distinguishing between clouds and aerosols in a moderately large pixel (e.g., 6 km) appears to have solutions based on the very different polarization signals of clouds and aerosols. These studies have been applied to polarimeter-only retrievals. It is unclear how this capability would map to joint OCI/polarimeter retrievals.
- Because we expect atmospheric/aerosol properties to have larger spatial scales than ocean IOPs, for atmospheric correction, it will be possible to decouple pixel resolution of the polarimeter from that of the OCI. For optimal scientific return, the different views of the multi-angle polarimeter will need to be registered to a common grid, then they can be super-sampled to match the radiometer footprint. This approach still allows retrieval of water-leaving radiances at the native OCI resolution. The OCI radiometer can help with identifying clouds within a larger polarimeter footprint.
- We note that there are concepts that feature some capability for at least one non- polarized channel to have pixel spatial resolution as fine or finer than the radiometer and may offer aid to the radiometer in cloud masking.
- Hydrosol retrievals, especially in coastal regions, will require higher spatial resolution compared with aerosols due to the shorter correlation scales for water features. While it may not be possible to match the resolution of an OCI for all pixels, a subsample with an OCI image having a spatial resolution of one km or better would be compatible with ocean color retrievals.

3.3. Swath Width

- The PACE science team recommends at least a 400 km swath width for aerosol and cloud retrievals. The science driver for imagery is to characterize aerosol events and regional/seasonal targets, as well as to obtain global statistics. Swath widths less than 400 km still hold some value for characterizing atmospheric constituents on a global basis.
- For atmospheric correction and hydrosols, there is consensus that the polarimeter swath should be as wide as possible while still meeting accuracy requirements and providing adequate sampling of scattering angle. It is preferable to match the radiometer swath, but even if the

swaths do not match, the polarimeter still adds significant value to mission science for both atmospheric and oceanic purposes.

- We note that far-from-nadir views may have degraded capability in making retrievals due to higher Rayleigh scattering, introducing noise, reduced the range of observed scattering angles, and larger pixel sizes.

3.4. Angles

- By angles, we mean the number of view angles of the same ground or atmospheric target following ATSR, MISR, and RSP multi-angle view heritage.
- For aerosol and atmospheric correction, five viewing angles paired with a wavelength range of 410 nm–1600 nm appears to be sufficient based on a study of aerosol retrievals over land. See Figure 9. Other studies vary on the specifics, but it appears that 5 or 7 view angles should be sufficient to characterize aerosols and for atmospheric correction. But this may depend on the complementary spectral information. This statement is based on studies made over land targets. It may be possible to decrease the number of view angles for the specific purpose of atmospheric correction over ocean, but the state-of-the-science is not ready to justify the decrease at this time. Additional angles help in minimizing glint and characterizing surface roughness/wind speed.
- To fully characterize cloud-top droplet size distribution, a greater number of angles (~50–60) for at least one polarized wavelength are needed. However, only five angles are needed to retrieve ice-particle phase function. Choice of wavelength is important.
- The cloud thermodynamic phase can be retrieved from polarimetric angular information, given ~10–15 angles for at least one wavelength. There are spectral means to retrieve phase as well, if measurements are made in SWIR channels with contrasting values of ice/water imaginary index of refraction.
- The above assumes the angular density is distributed across a wide angular range of viewing angles (~ ±60° as measured at the ground) to obtain a broad range of scattering-angle measurements of the same target and to minimize glint.
- There is no information on the angular requirements for hydrosol retrievals.

3.5. Wavelengths

- Strong consensual statements about the importance of different spectral ranges cannot yet be stated.
- However, there is movement towards a statement that aerosol characterization requires a polarized "deep blue" channel, such as 412 nm, plus three to four additional channels through the VNIR spectral range. This configuration can also retrieve cloud top height in the absence of thermal wavelengths.
- There is evidence that a polarized 1600 nm channel adds significant capability for aerosol characterization. The same somewhat-limited evidence shows that if 1600 nm is included, there is no need for a polarized 2100 nm channel.
- Aerosol layer height is important to characterize, both for atmospheric products and atmospheric correction. There are several methods to retrieve this parameter that are still areas of active research by the PACE science team. These include the uses of O_2-A bands, inversions using combinations of polarized UV and VNIR channels, and combinations of polarized VNIR (including 410 nm) and SWIR channels.
- Multi-directional polarization measurement at blue wavelengths or shorter allows retrieval of cloud top heights. Multi-angle, stereo-derived cloud heights would extend the MISR climate

data record. Cloud height and physical thickness can also be retrieved if an un-polarized O_2-A band is added to the OCI measuring capabilities. Adding a water vapor channel (e.g. 940 nm) to the OCI instrument provides similar, but less readily useable, information and would extend the existing use of such a capability from MODIS.

- For clouds, SWIR channels will be important, but they may not need to be polarized. Having a 2.25-micron channel in addition to a 2.1 or 1.6 channel may allow retrieval of cloud thermodynamic phase, even without angular information.
- To make best use of a hyperangle channel for cloud microphysical retrieval, the hyperangle channel must be polarized and should be in the VNIR range.
- An unpolarized cirrus channel (1.38 µm or 1.88 µm) would allow thin (sub-visual) cirrus detection and some optical property quantification, while a polarized cirrus channel would also allow thin cirrus-phase function retrievals.
- For hydrosols, a polarized red channel holds the most promise due to minimal atmospheric interference and not too much absorption by water.
- For calibration purposes, not science questions, the science team finds significant value in matching polarimeter channels to PACE radiometer channels, if neither the PACE radiometer or polarimeter are hyperspectral. Central wavelengths should match in as many channels as possible, and if full spectral response function could match, gas correction algorithms might be compared.
- There is no agreement within the science team on how much capability polarized UV channels add for aerosol characterization. There is possibility that polarized UV channels will provide additional information that will help separate aerosol absorption from aerosol layer height in the satellite-measured signal. However, the benefits of polarized UV channels may be offset by the uncertainty introduced by the high Rayleigh scattering in this spectral range.

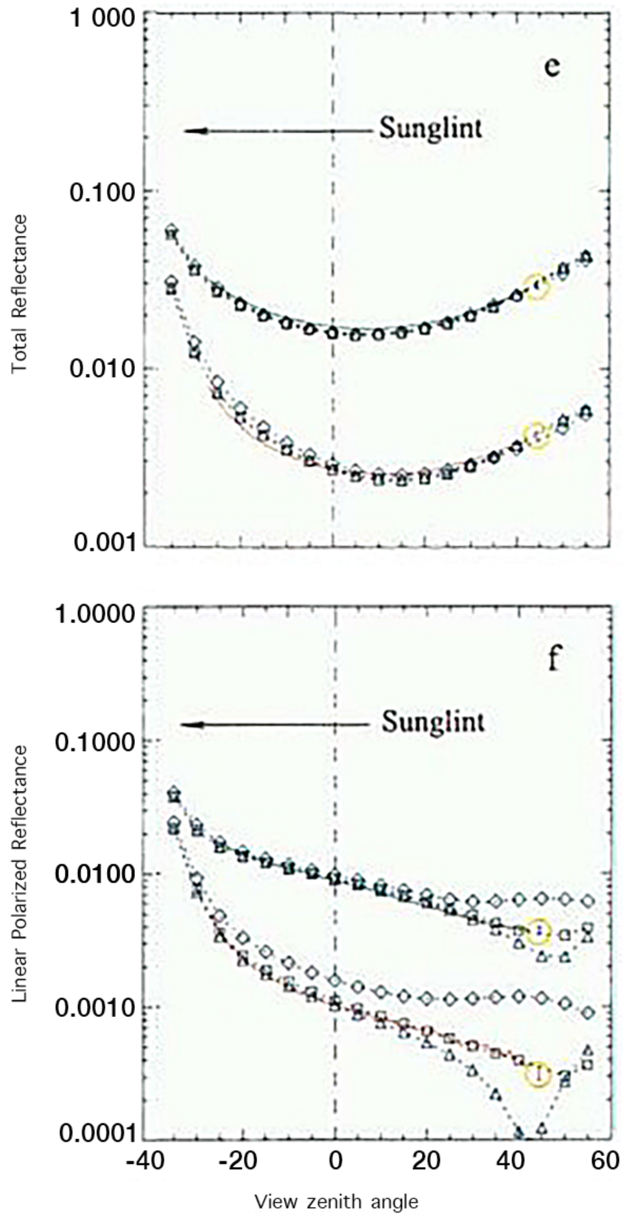

Figure 1. RSP data taken over the ocean off the coast of California (solid curves) and results of simulations (symbols).

The upper and lower panels are for the total and polarized radiances, respectively. Green and red curves depict 0.865 and 2.250 μm data, respectively. Curves depict the data obtained over the Santa Barbara Channel. Squares show fits obtained with a bimodal aerosol model. Triangles (diamonds) demonstrate the result of increasing (decreasing) the coarse mode refractive index by 0.03 (0.09) and adjusting the optical thickness so that the total radiances could still be reproduced.

Yellow circles highlight measurement error bars. Note that the measured total reflectance fits a range of real part of the refractive index that spans 1.42 to 1.54, but that the polarized reflectance is sensitive to these perturbations. Note also the role that view angle plays in fitting modeled parameters to measurements. Taken from Chowdhary et al., 2001.

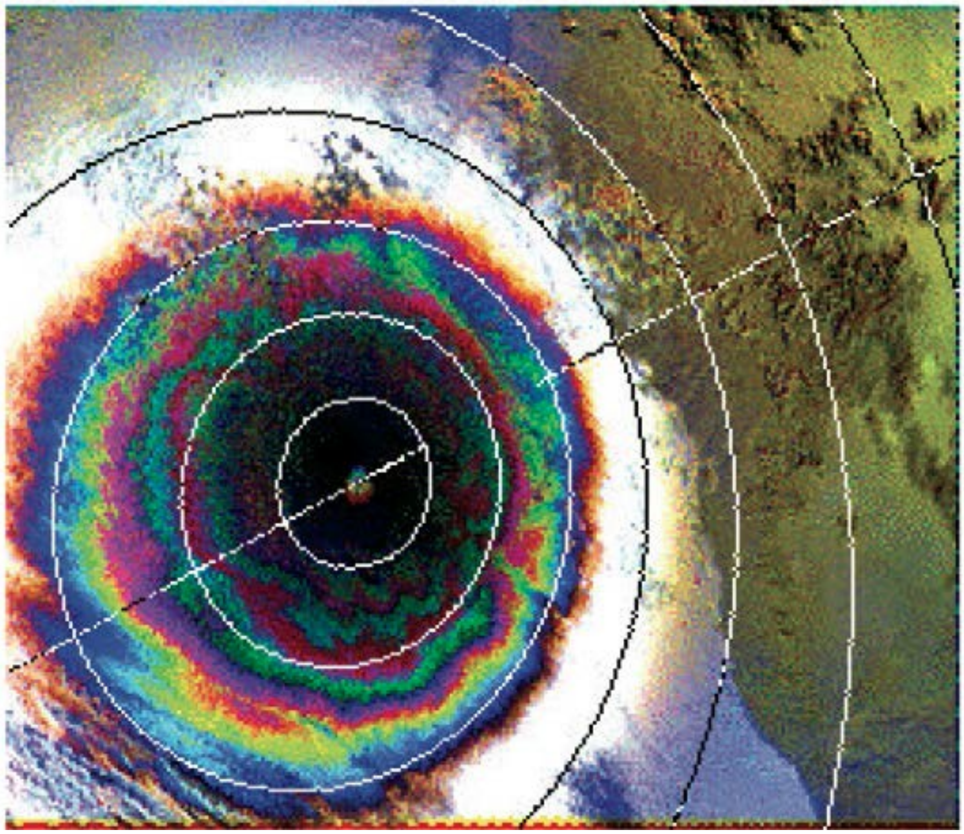

Figure 2. Polarized reflectance from POLDER showing cloudbow bands over a scene containing a stratus cloud. Image from Breón and Goloub (1998).

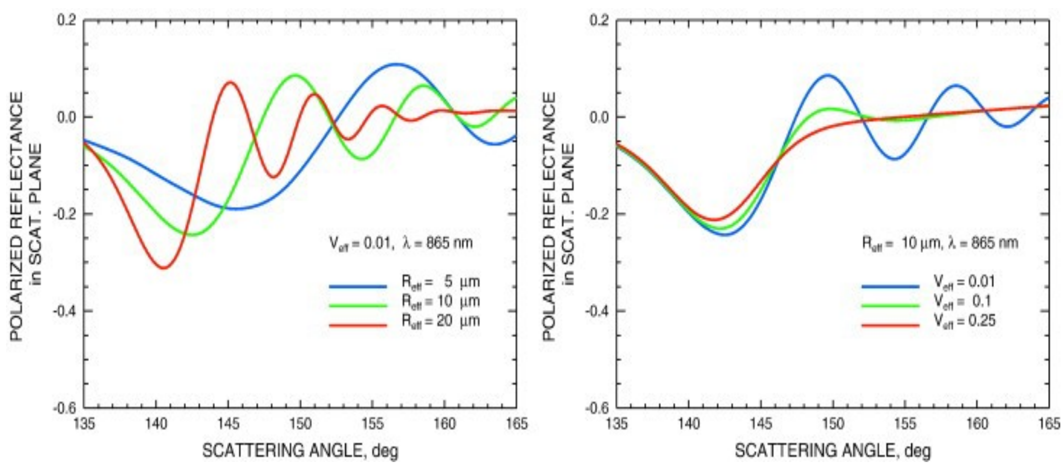

Figure 3. Theoretical calculations of polarized reflectance through a cloudbow showing the bright and dark bands. On the left, different colored curves depict clouds of the same droplet size distribution width (V_{eff}), but different effective radii (R_{eff}). On the right, curves denote clouds of the same effective radius, but different widths. From Alexandrov et al. (2012).

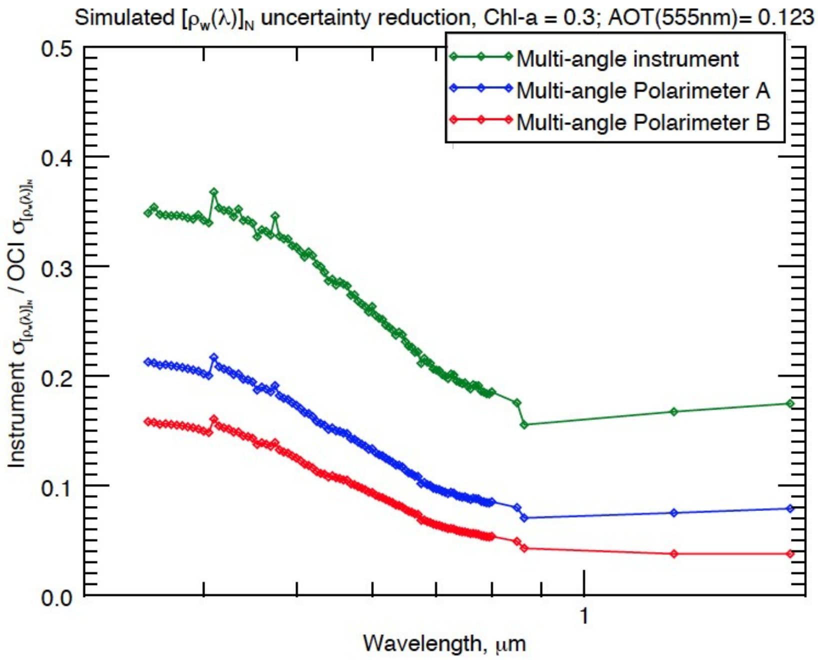

Figure 4. This figure expresses the improvement in retrieved normalized water-leaving reflectance ([ρw(λ)]N) uncertainty with the use of multi-angle instruments and polarimetrically sensitive multi-angle instruments in addition to OCI. Values are the ratio of tested instrument [ρw(λ)]N uncertainty to OCI [ρw(λ)]N uncertainty as predicted by a radiative transfer simulation information content analysis (Knobelspiesse et al, 2012, based upon the information theory originally described in Rodgers, 2000).

This analysis assumes an unconstrained simultaneous retrieval of aerosol and ocean optical properties and does not quantify modeling errors, retrieval algorithm convergence success, or the improvements shown in validation due to observationally justified atmospheric correction constraints. We presume, however, that the impact of these effects is similar for the different tested designs, which is why we have chosen to present these results relative to OCI.

This analysis was performed for a variety of scene types; shown here is a simulation that used a Chl-*a* concentration of 0.3 mg/m^3, and a maritime aerosol AOT (0.555µm) of 0.123. The simulated OCI instrument has 95 channels ranging in wavelength from 0.35 µm to 2.13 µm and a vicarious calibration based radiometric uncertainty of 0.3%. The Multi-angle Instrument has five viewing angles between 50º fore and aft in the along-track direction and five channels from 0.41µm to 2.25µm. Like OCI, a radiometric uncertainty of 0.3% is assumed.

The Multi-angle Polarimeter A has the same characteristics as the Multi-angle Instrument, plus polarization sensitivity in every channel and viewing direction. The polarimetric uncertainty of these measurements is 1%. The Multi-angle Polarimeter B has 10 view angles between 55º fore and aft in the along-track direction and the same channels as the Multi-angle Instrument and the Multi-angle Polarimeter A. However, the 0.865µm channel has 50 viewing angles between 50º fore and aft in the along-track direction, and the polarimetric accuracy is tightened to 0.5%.

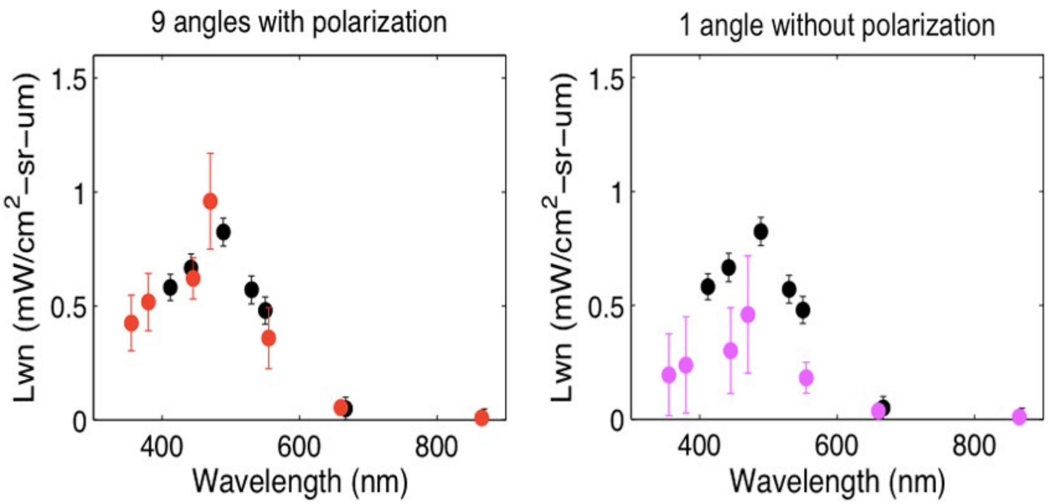

Figure 5. From Kalashnikova PACE ST presentation January 2015. Colored symbols: Mean and spread of AirMSPI normalized water-leaving radiance (Lwn) retrieval results based on 8 initial guesses, using an optimization-based multi-pixel retrieval algorithm (Dubovik et al., 2011). AirMSPI data were acquired February 6, 2013 over the AERONET-OC SeaPRISM station.

Black symbols: SeaPRISM observations with error bars denoting the PACE SDT uncertainty target. The left-hand figure contains results derived from observations at 9 angles; radiances at 355, 385, 445, 470, 555, 660, and 865 nm; and polarization in the 470, 660, and 865 nm bands. It shows that multi-angle radiometry and polarimetry appear capable of retrieving accurate L_{wn} *without the need for prescribed aerosol or surface reflectance constraints, even at a mid-visible AOD of ~0.25. The right-hand figure contains results derived from multispectral observations at a single angle without polarization, and shows that without additional information there is an increased bias and modeling uncertainty in the retrieved* L_{wn}.

The forward radiative transfer calculations were performed using a Markov chain approach developed for a coupled atmosphere/surface system (Xu et al.,2011; 2012). The ocean water-leaving radiance was modeled as a depolarizing Lambertian surface reflection model, plus a polarizing part modeled by the Cox-Munk model (Cox and Munk, 1954; Mishchenko et al., 1997). Atmosphere and surface properties were retrieved simultaneously, and surface reflectance was retrieved independently at each wavelength.

Current satellite retrievals mitigate random and systematic errors over open ocean by invoking standardized models for ocean surface spectral reflectance and aerosol scattering. However, in more complex waters, or when aerosol absorption is present at short wavelengths, traditional retrieval assumptions break down. The left-hand figure does not prescribe either an aerosol model or any surface spectral constraints, indicating that multi-angle and polarimetric imagery provides the necessary additional information in the more general scenario.

The right-hand panel does not invoke any of the enhanced capabilities, including expanded wavelength range, expected of the PACE OCI, and therefore suggest a worse retrieval than could actually be obtained by the radiometer alone.

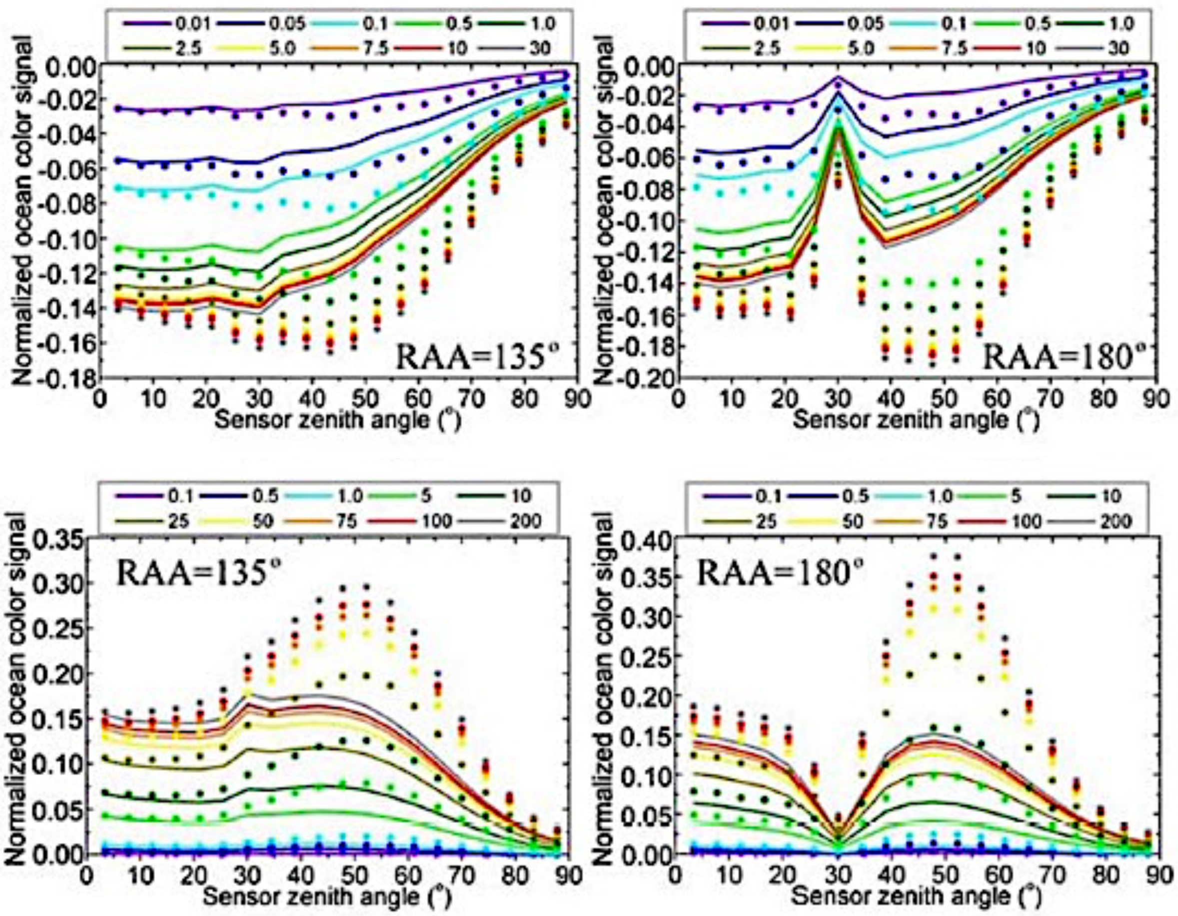

Figure 6. Comparison of the simulated normalized ocean color signal for the total radiance (solid lines) and the parallel polarization radiance, PPR = I + Q, (points) at the top-of-atmosphere for different chlorophyll concentrations (top) and total suspended matter (bottom). For this example, solar zenith angle is 30°. RAA is the relative azimuth angle between the solar incident and sensor viewing angles. For specific geometries PPR provides enhanced measurable signal at the top-of-atmosphere compared with the radiance alone. From He et al. (2014).

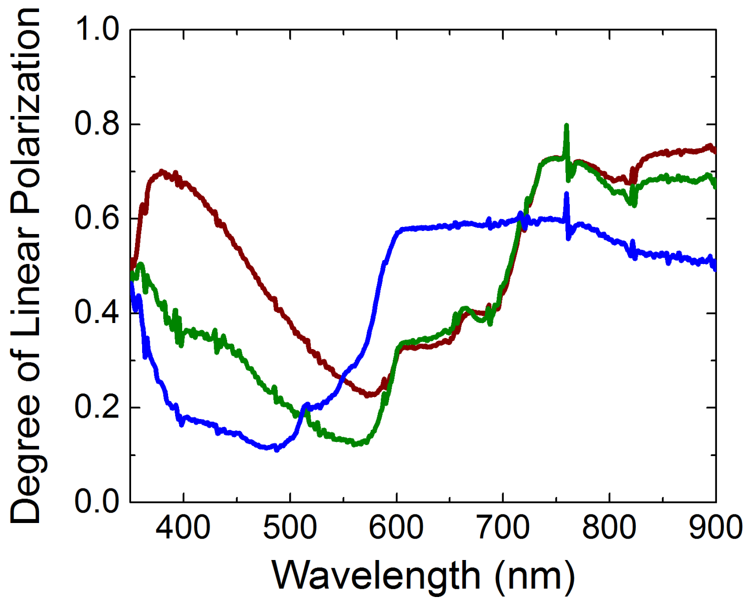

Figure 7. Illustration of the degree of linear polarization (DoLP) measured above the surface of different water types in South Florida: Clear water (blue curve), biologically productive water (green curve), and productive water with high amounts of CDOM (brown curve).

Measurements were made above the water surface with a hyperspectral polarimeter covering a wavelength range of 350–1100 nm (nominal, 380–900 nm useful), at a spectral resolution (FWHM) of 3 nm, and with a fine spectral sampling-interval of 0.8 nm. The view angle is 50º (near Brewster's angle) and oriented 90º to the sun. The water varied from clear near the Keys to turbid in Florida Bay near the shoreline. These data are "raw" polarization data, in that no corrections for surface reflections have been applied. Also note that view angle is critical in these data.

Measurements at 135º to the sun often show very low DoLP. These are preliminary data. The main spectral polarimetric features are discernible. The high-frequency fluctuations indicate that absolute spectral calibrations could be improved.

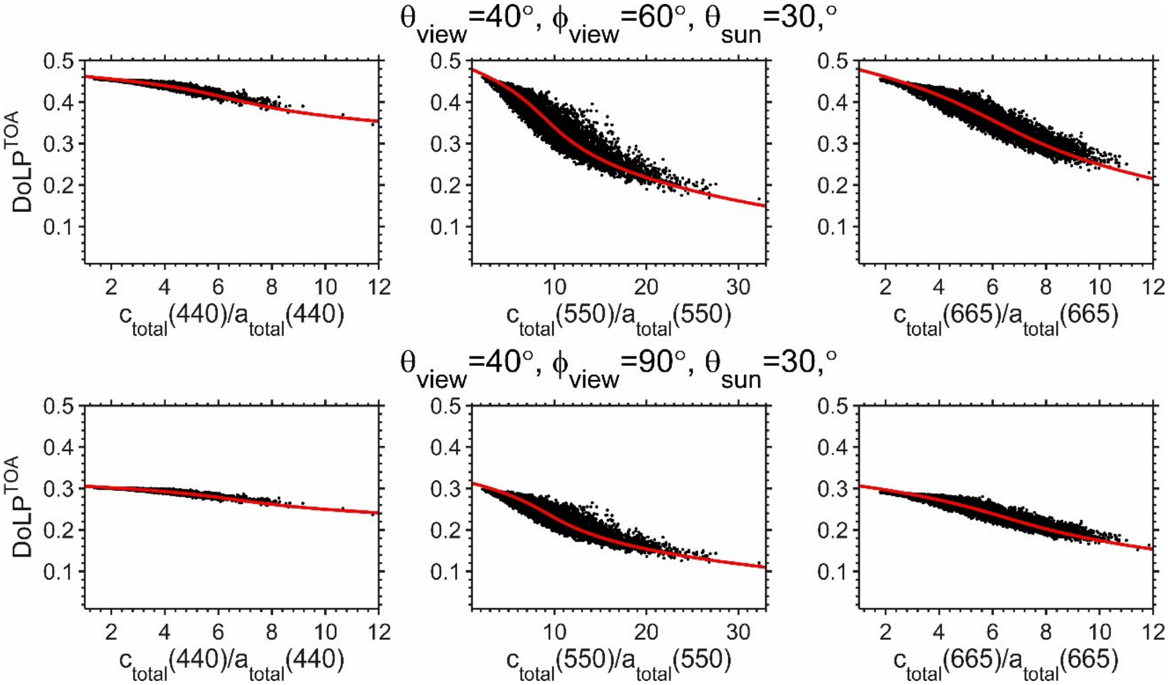

Figure 8. The relation between DoLPTOA, simulated for τ = 0.1, and c/a for Case II waters at the TOA at three wavelengths, at 40° viewing zenith angle and for sun relative azimuth angle of 90° and 60°. Sun zenith angle is fixed at 30°. There is no sensitivity to the changes of IOPs at the 440 nm due to the significant Rayleigh contribution of molecules in the atmosphere. At 550 nm and 665 nm, the changes of DoLP is more significant with varying IOPs.

The dynamic range of DoLP variability is also a function of sun and viewing angles. Such results show the possibility of IOP retrieval using polarimetry at selected bands. A careful assessment of ocean's polarized signature is mandatory for the polarimeter design. More comprehensive studies are required for band selection, radiometric sensitivity, and illumination/viewing geometry factors, (Ibrahim, 2015).

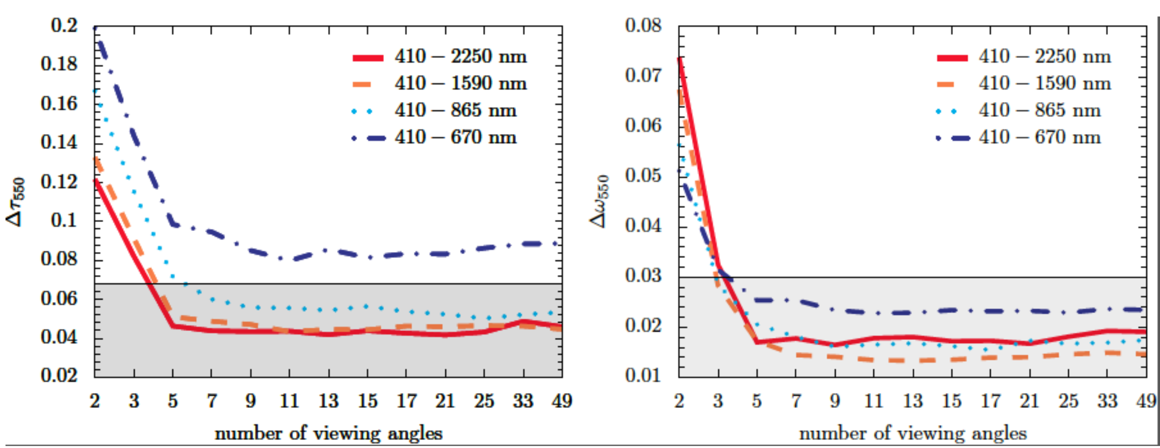

Figure 9. From Otto Hasekamp webinar presentation. Theoretical retrieval accuracy as function of number of view angles for different spectral ranges for AOD_550 on the left and SSA on the right. The shaded gray area shows the target retrieval accuracy for aerosol characterization.

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