Atmospheric correction in the presence of absorbing aerosols, and enhancement quantification from multi-angle, polarimetric observations

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Collaborators: David Diner and Oleg Dubovik

Jet Propulsion Laboratory
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What we proposed to do?

Goal: Justify the added value of a polarimeter to PACE, and refine requirements for the multi-angular, UV to shortwave infrared, oxygen A-band, and polarimetric sensing capabilities for atmospheric correction.

- **Objective 1:** Determine requirements for a polarimeter instrument to compensate for the effects of aerosols through theoretical studies and polarimetric retrieval development.
- **Objective 2:** Assess the practicality of the requirements for polarimetric observations of aerosol and ocean properties with field data analysis of Airborne Multisangle SpectroPolarimetric Imager (AirMSPI) observations.
- **Objective 3:** Determine the potential of mineral dust characterization for investigating how ocean ecosystems respond to dust deposition.

Main accomplishments

JPL-led
JPL-contributed

- ## Objective 1:

Davis, A. B., O. V. Kalashnikova, and D. J. Diner, Aerosol Layer Height over Water from Oxygen A-band: Mono-Angle Hyperspectral and/or Bi-spectral Multi-Angle Observations, in review, *Remote Sensing*, 2018

Seidel, F. C., P.-W. Zai, M. J. Garay, D. J. Diner, and O. V. Kalashnikova, Sensitivity of the Ocean Water Reflectance Factor and Polarization to Aerosol Optical Depth, in preparation for *Applied Optics*, 2018

Merlin, G., J. Riedi, L. C.-Labonnote, C. Cornet, **A. B. Davis**, P. Dubuisson, M. Desmons, N. Ferlay, and F. Parol, Cloud Information Content Analysis of Multi-Angular Measurements in the Oxygen A-Band: Application to 3MI and MSPI, *Atmos. Meas. Tech*. 9, 4977-4995, 2016**,** doi:10.5194/amt-9-4977-499

- ## Objective 2:

Xu, F., O. Dubovik, O., P.-W. Zhai, D. J. Diner, O. V. Kalashnikova, F. C. Seidel, P. Litvinov, A. Bovchaliuk, M. J. Garay, G. van Harten, and A. B. Davis: Joint Retrieval of Aerosol and Water-leaving Radiance from Multispectral, Multiangular and Polarimetric Measurements over Ocean, *Atmos. Meas. Tech.*, 9, 2877-2907, 2016, https://doi.org/10.5194/amt-9-2877-2016

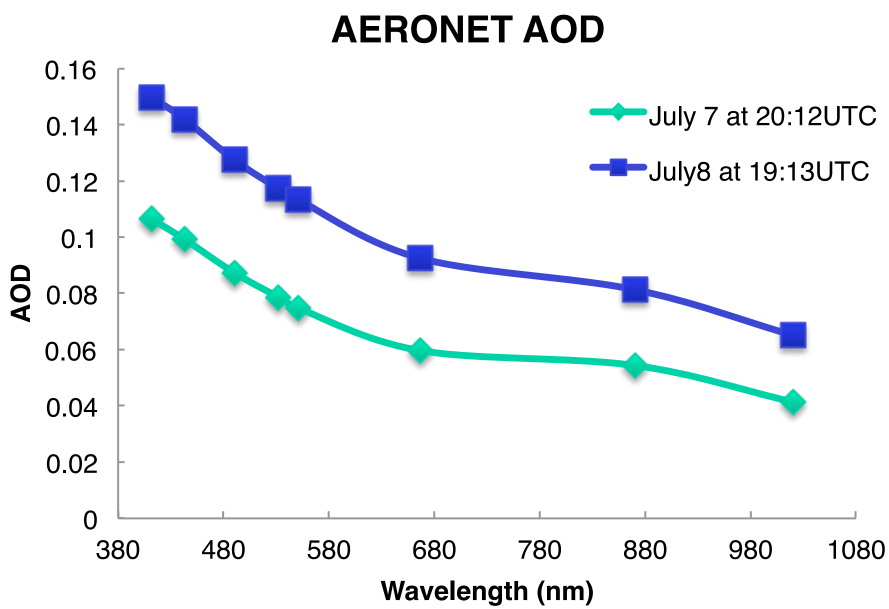
Xu, F., G. van Harten, D. J. Diner, O. V. Kalashnikova, F. C. Seidel, C. J. Bruegge, and O. Dubovik, Coupled Retrieval of Aerosol Properties and Land Surface Reflection Using the Airborne Multiangle SpectroPolarimetric Imager, *J. Geophys. Res. Atmos.*,122, 7004-7026, 2017, doi:10.1002/2017JD026776

- ## Objective 3:

Li, W., H. Al-Eskary, K. P. ManiKandan, M. A. Qurban**, M. J. Garay, and O.V. Kalashnikova**, Synergistic Use of Remote Sensing and Modeling to Assess an Anomalously High Chlorophyll-a Event during Summer 2015 in the South Central Red Sea, *Remote Sensing*, 9, 778, 2017, doi:10.3390/rs9080778.

PACE-related polarimetric data collection

- JPL/Caltech teams successfully completed the Imaging Polarimetric Assessment and Characterization of Tropospheric Particulate Matter (ImPACT-PM) field campaign in July 2016
- Polarimetric data were collected over the USC SeaPrism AERONET ocean site on July 7 and 8, 2016
- Results of SPEX data analysis (in collaboration with the AirMSPI team) were presented at the Fall 2017 AGU meeting



ER-2 instruments:

- **AirMSPI-1**
- **CPL**
- **SPEX**

Role	Name
JPL PI	**Olga Kalashnikova**
Caltech PI	**John Seinfeld**

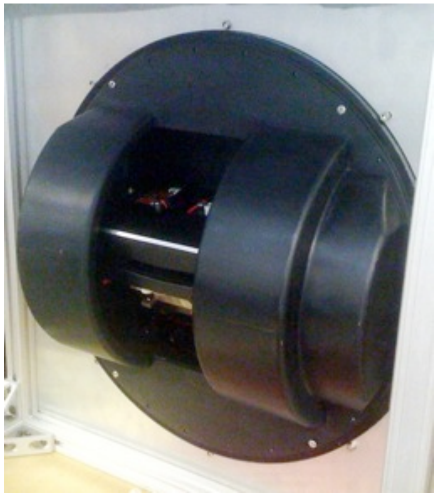
ER-2 Targets: July 7, 2016: 20:11:06 UTC; July 8, 2016: 19:15:10 UTC

Objective 1

Theoretical sensitivities:

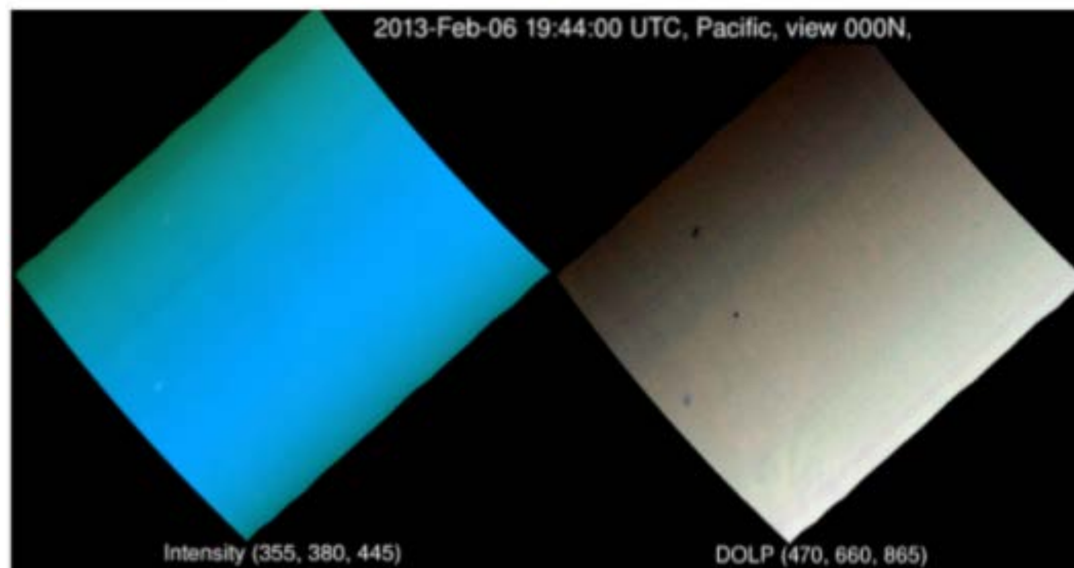
- Explored the value of multi-angular and polarimetric information for water leaving radiance (L_{wn}) and aerosol absorption (SSA) retrievals
- Explored the value of multi-angular and polarimetric oxygen A-band observations for determining aerosol layer height and thickness
- Quantified the impact of aerosol optical depth (AOD) on Remote Sensing Reflectance (Rrs), Hemispherical Directional Reflectance Factor (HDRF) and Degree of Linear Polarization (DoLP) for open ocean water (Case-1)

Using AirMSPI-1 to explore the value of a polarimeter

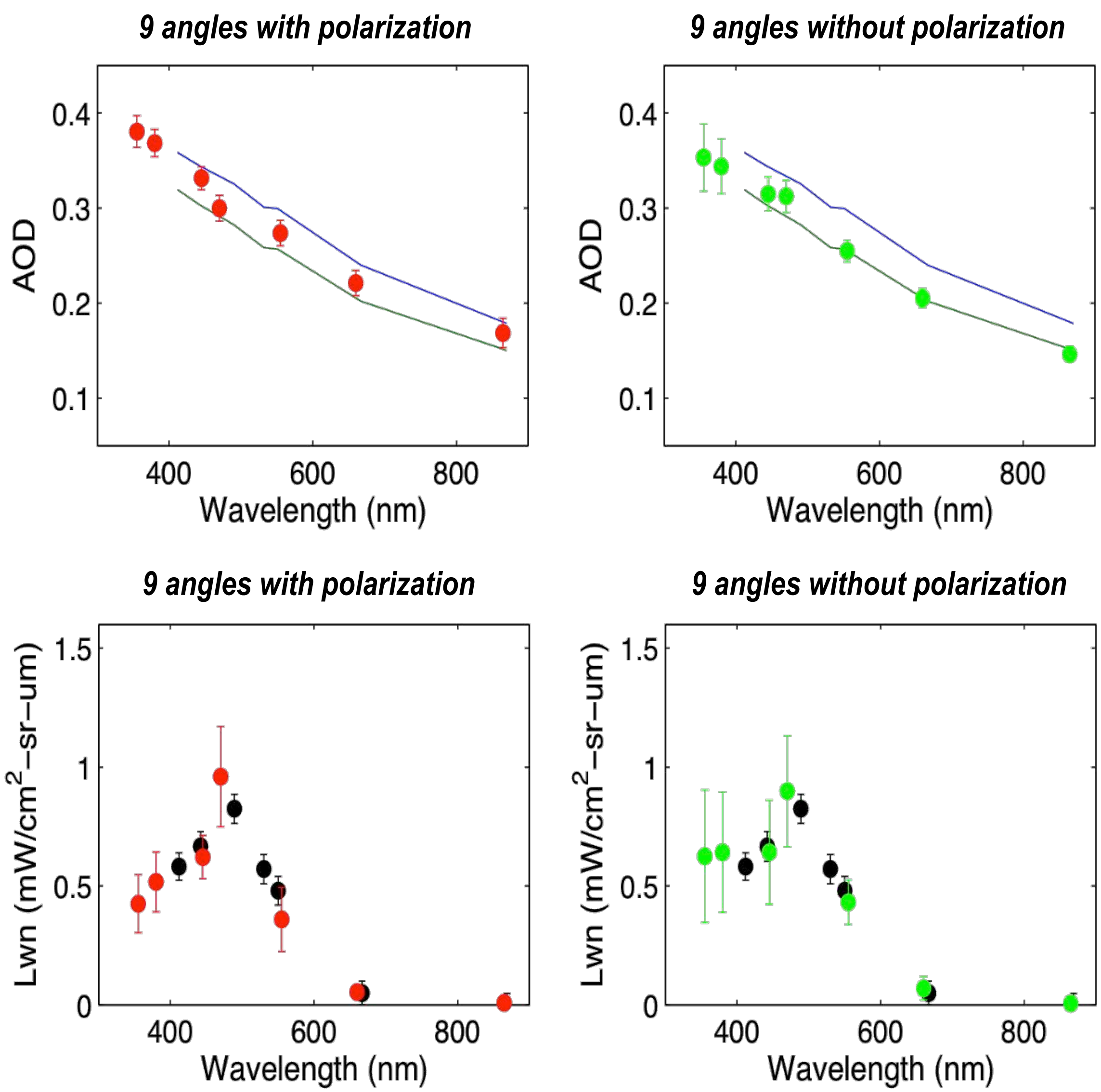


AirMSPI data were acquired over the USC SeaPRISM AERONET-OC site on the Eureka platform on February 6, 2013

Spectral bands	355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarized)
Flight altitude	20 km
Multiangle viewing	Between ±67° using single-axis gimbal



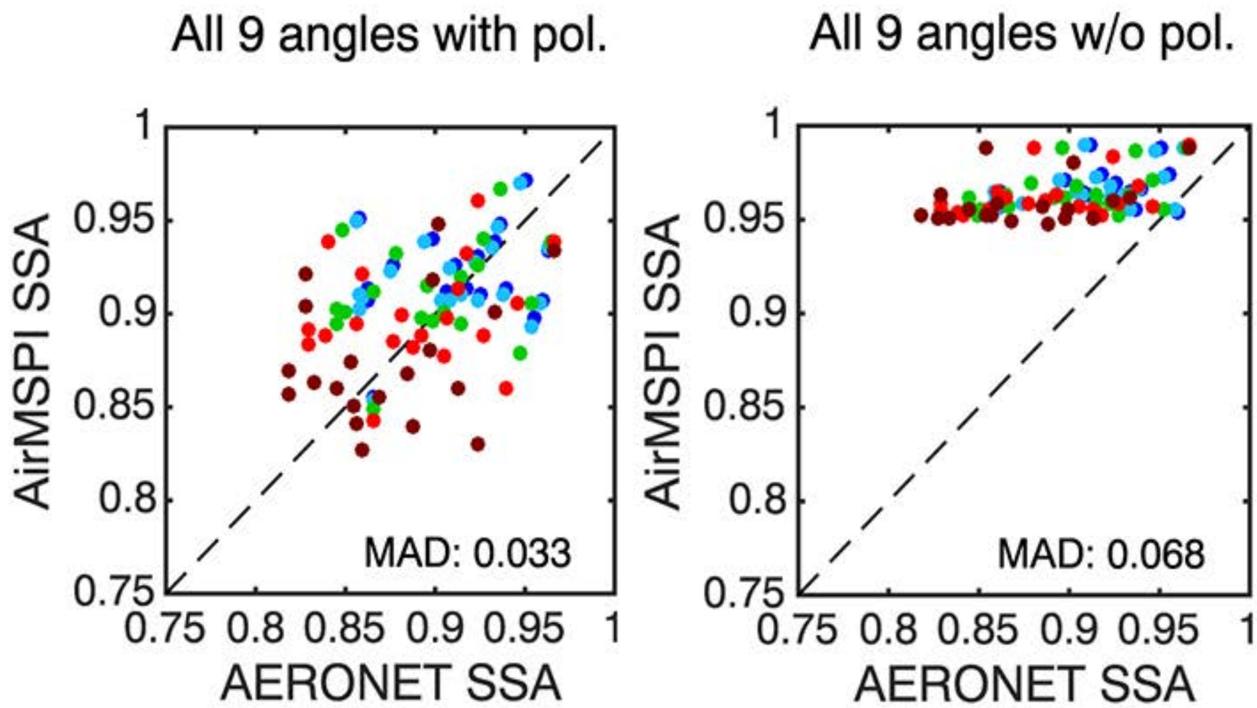
Using AirMSPI-1 to explore the value of a polarimeter



- Colored dots and bars: Mean and spread of AirMSPI retrieval results based on 8 initial guesses for 19:43 UTC on February 6, 2013
- Blue and green lines and black points: SeaPRISM observations at 19:08 and 20:08 UTC
- Results show that AOD and L_{wn} retrievals agree better with AERONET when polarimetric information from the 3 AirMSPI bands is included

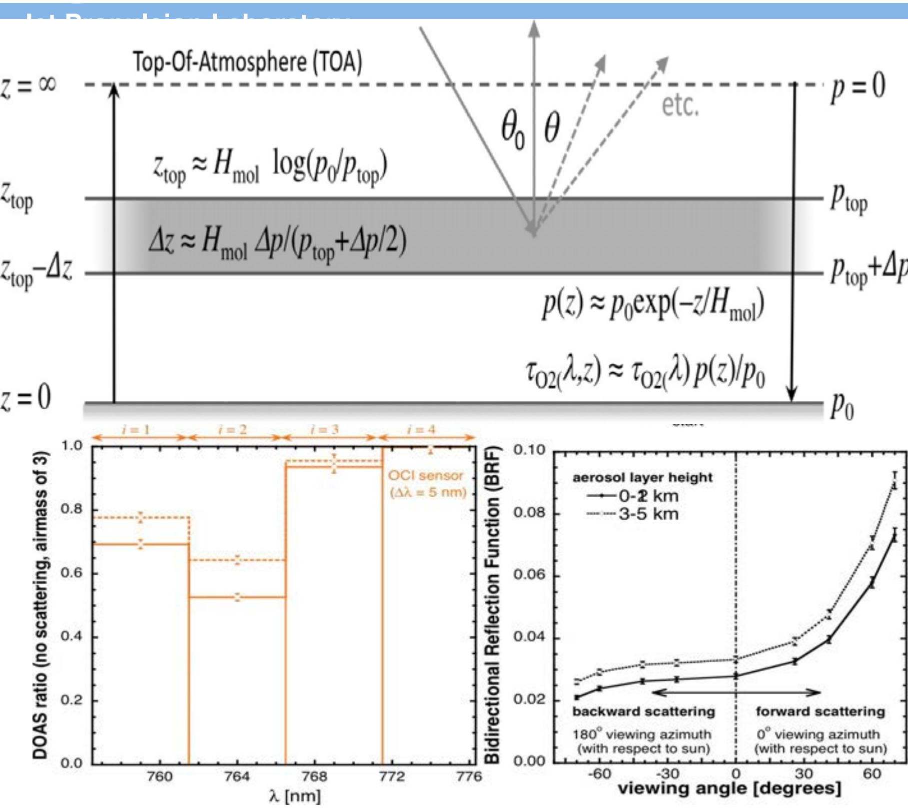
Sensitivity of AirMSPI-retrieved SSA to number of viewing angles and polarization features

Xu et al., 2017



Polarization features are the most beneficial for constraining aerosol SSA; the multi-angular features are helpful for separating aerosol and surface, and for improving water leaving radiance retrievals in the presence of aerosols

Aerosol layer height from O_2 A-band: Spectroscopy and/or multi-angle?



Top: ***Model atmosphere with a scattering aerosol layer embedded in absorbing O_2 gas.*** **Bottom Left**: ***Distinguishing low and high aerosol layers with PACE's spectroscopy.*** **Bottom Right**: ***Same but with multi-angle radiometry. Noise is small enough for both approaches to be used successfully.***

Davis A. B, O. V. Kalashnikova, D. J. Diner, Aerosol layer height over water from O_2 A-band: Mono-angle hyperspectral and/or bi-spectral multi-angle observations, Remote Sensing (2017), under review. Preprints. doi:10.20944/preprints201710.0055.v1

Anthony welcomes questions!

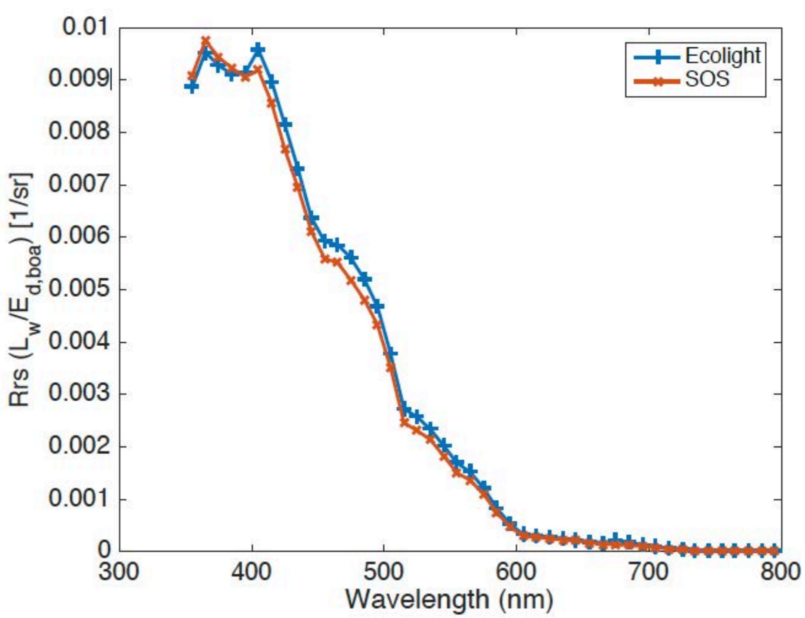
Scientific Question: PACE will have unprecedented spectral coverage extending into the UV where vital new information on marine biology can be harvested … on condition that the impact of the atmosphere can be accurately predicted and mitigated. In particular, this will call for locating absorbing aerosols in the atmospheric column since they can be either low, near their sources, or lofted to high altitudes in the course of long-range transport. We bring di-oxygen "A-band" absorption to bear on this mission-critical task.

Data & Results: We use synthetic data from an analytical solution of the 1D radiative transfer problem that predicts PACE's mono-directional hyper-spectral signals from the Ocean Color Instrument (OCI) as well as multi-angle bi-spectral signals for the likes of NASA's Multi-Angle Imager for Aerosols (MAIA) investigation from JPL. Our information content analysis supports retrieval of aerosol layer height, but not of its geometrical thickness, at least for optically thin aerosols. Working in tandem, such sensors can improve precision of aerosol height retrieval, but generally won't enable geometrical thickness retrieval.

Significance: Our study of aerosol layer height retrieval supports NASA's PACE mission and proposed MAIA investigation, for ocean- and human health, respectively.

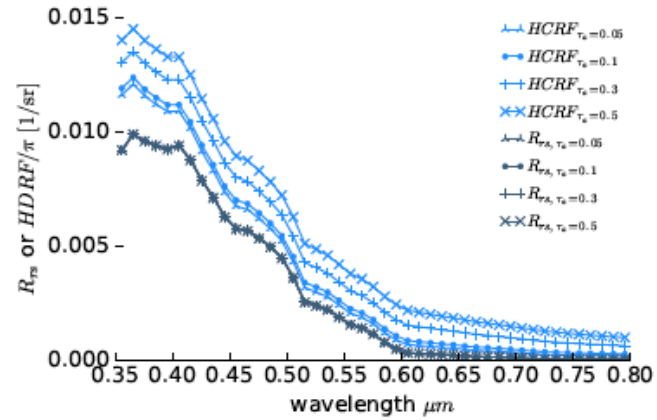
Supported by the NASA's PACE Science project.

Sensitivity of the ocean water reflectance factor and polarization to aerosol optical depth

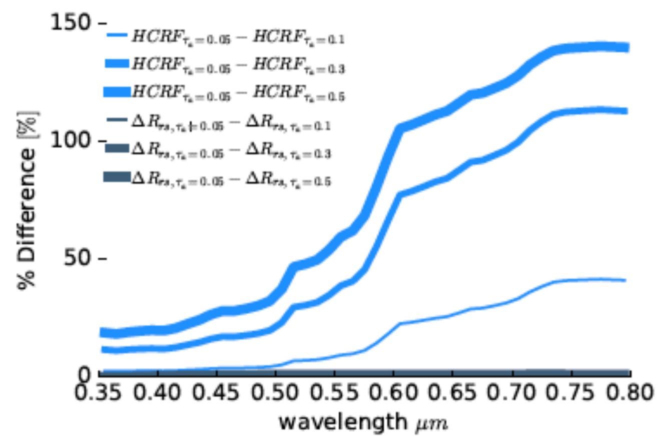


Intercomparison of remote sensing reflectance (R_{rs}) simulated with two independent radiative transfer codes by Zhai et al, 2010 (SOS, red line) and EcoLight (by C. Mobley, personal communication, blue line).

Seidel et al., in preparation



Spectral dependence of HDRF (light blue) similar to what would be observed by a satellite sensor and R_{rs} (dark blue) a theoretically derived parameter for different AOD values



Percent differences in HDRF and R_{rs} showing that changes in AOD can significantly affect satellite observations of ocean reflectance even if the absolute differences are small

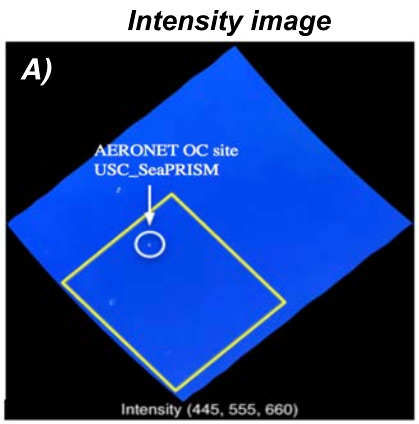
Objective 2

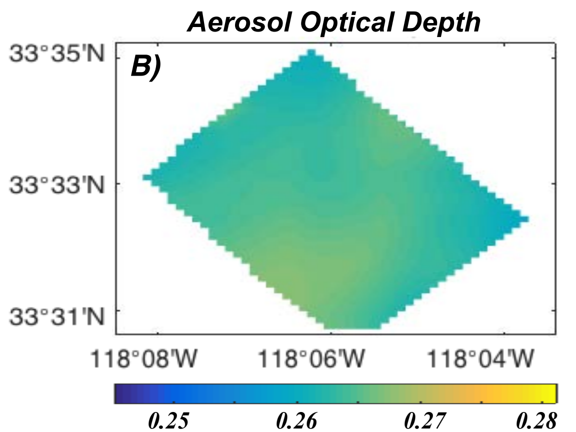
Retrieval development and retrievability studies:

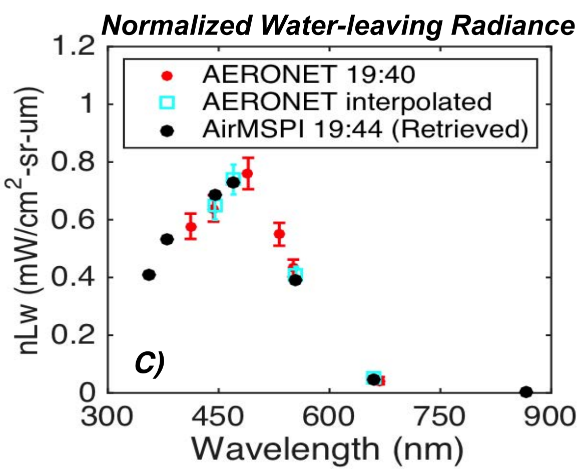
- Developed an optimized & coupled aerosol-ocean retrieval algorithm; tested water leaving radiance retrievals on cases of AirMSPI observations of open ocean (Case-1) waters
- Developed an optimized & coupled aerosol-land surface retrieval algorithm; evaluated aerosol property retrievals using AirMSPI observations and AERONET

Joint Retrieval of Aerosol and Water-leaving Radiance from Multi-spectral, Multi-angular & Polarimetric Observations

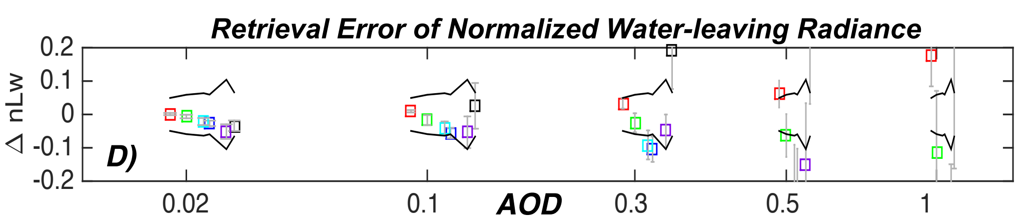
Jet Propulsion Laboratory







(A): AirMSPI image of AERONET Ocean Color site - USC_SeaPRISM;
(B): Retrieved AOD;
(C): Retrieved nLw;
(D): Retrieval error of nLw in different bands (colored dots) vs PACE requirement (black line) in the existence of dust aerosols



Scientific Challenge: Remote sensing of ocean productivity and ecosystem health requires accurate retrieval of water-leaving radiances, which is challenging for turbid waters and absorbing aerosols. While multi-spectral, multi-angular and polarimetric measurement technologies are available to deal with these challenges, a reliable retrieval algorithm that takes full advantage of the observations is required.

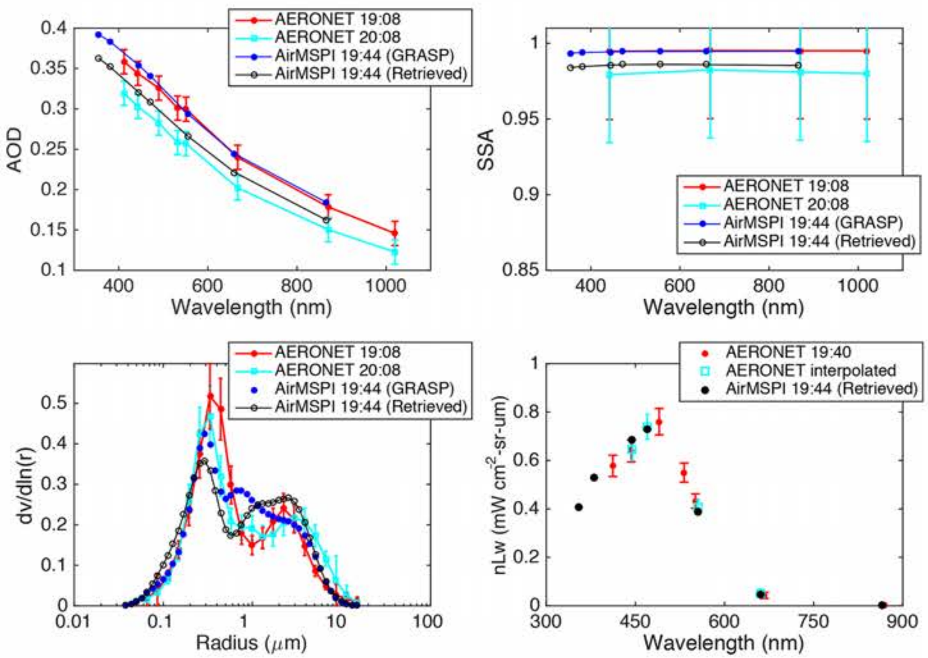
Contribution: An optimized & coupled aerosol-ocean retrieval algorithm has been developed. Verification tests and case studies using observations from JPL's Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) show the retrieval error of water leaving radiance meets PACE requirements when the mid-visible optical depth of weakly absorbing and dust aerosols is less than ~0.3 and ~0.1, respectively.

Xu, F., Dubovik, O., Zhai, P.-W., Diner, D. J., Kalashnikova, O. V., Seidel, F. C., Litvinov, P., Bovchaliuk, A., Garay, M. J., van Harten, G., and Davis, A. B.: Joint retrieval of aerosol and water-leaving radiance from multispectral, multiangular and polarimetric measurements over ocean, Atmos. Meas. Tech., 9, 2877-2907, https://doi.org/10.5194/amt-9-2877-2016, 2016.

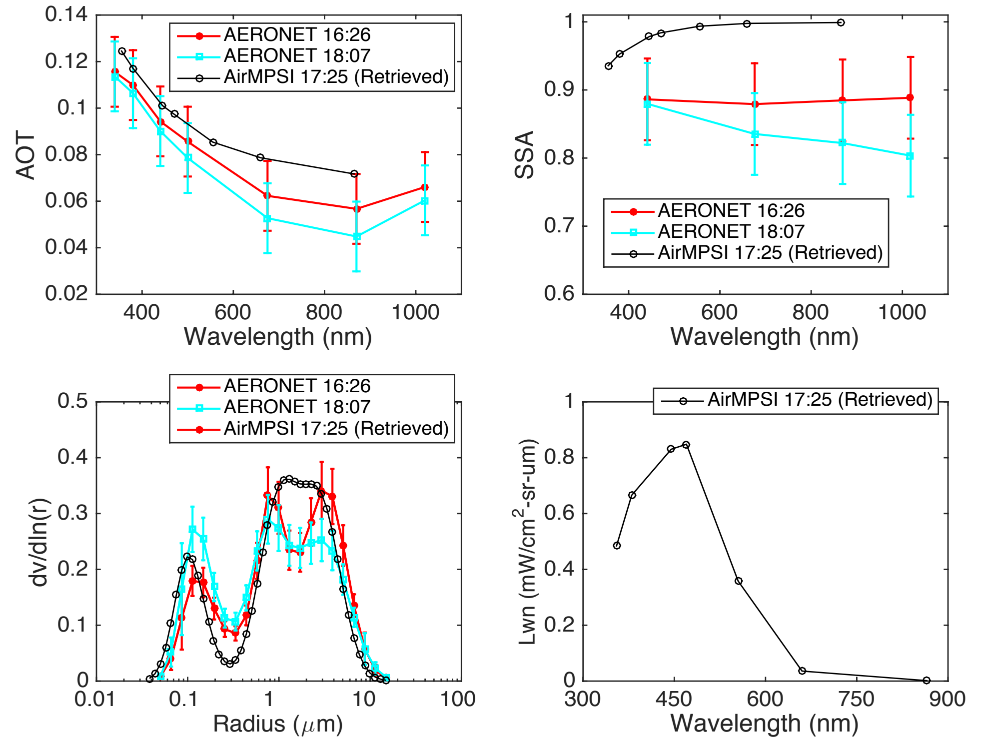
Supported by the NASA's PACE project.

Joint Retrieval of Aerosol and Water-leaving Radiance from Multi-spectral, Multi-angular & Polarimetric Observations

SeaPRISM, Feb. 6, 2013, 19:44 UTC
(from Xu et al., 2016)



Monterey, Apr. 28, 2014, 17:25 UTC

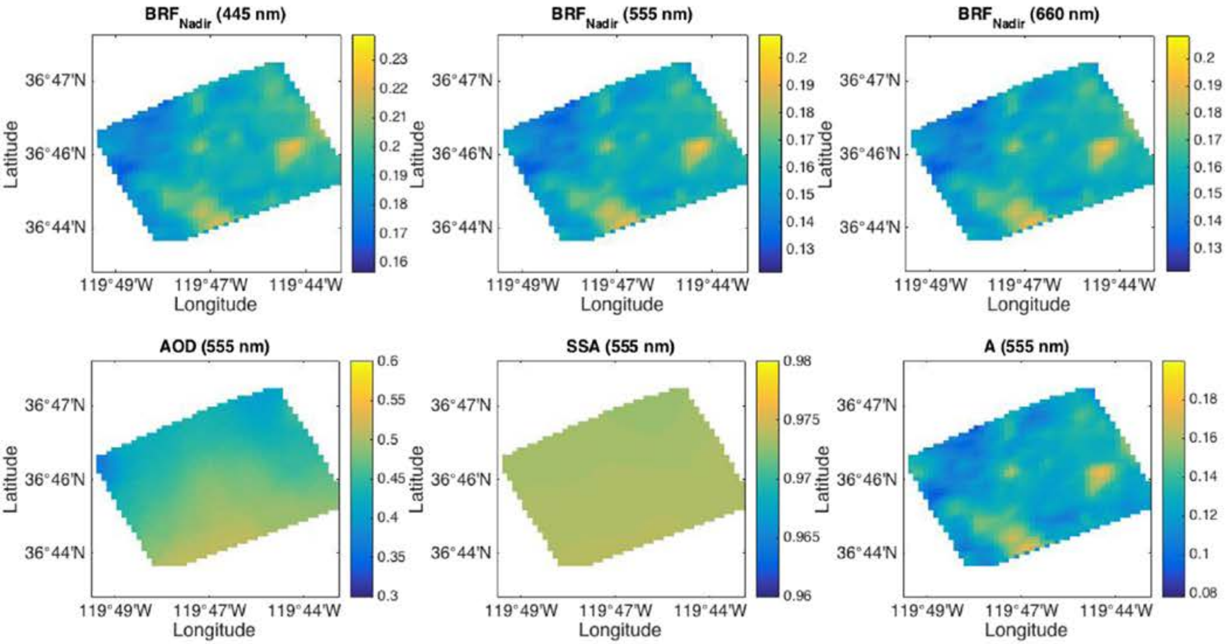


- February 6, 2016 case study of AOD, SSA, size distribution and nL_w over the AERONET USC SeaPRISM OC site compares favorably to AERONET's reported values;
- Aerosol property accuracy decreases at low AODs in the case of AirMSPI observations over AERONET Monterey site.

Coupled retrieval of aerosol properties and land surface reflection using multiangle, spectropolarimetric measurements

Jet Propulsion Laboratory

Feng Xu, JPL



Upper panel: The left, middle, and right panels give the images of bidirectional reflectance factor (BRF) at blue (445 nm), green (555 nm), and red (660 nm) bands, respectively. BRF is defined as $\pi I_{meas} d^2/\mu_0 E_0$, where I_{meas} is the measured radiance, d is the Earth-Sun distance, μ_0 is the cosine of solar zenith angle, and E_0 is the exo-atmospheric solar irradiance;
Lower panel: Retrieved AOD, SSA, and surface albedo (A) maps at 555 nm in the left, middle, and right panels, respectively, with patch resolution 0.5 km.

Xu, F., G. van Harten, D. J. Diner, O. V. Kalashnikova, F. C. Seidel, C. J. Bruegge, and O. Dubovik (2017), Coupled retrieval of aerosol properties and land surface reflection using the Airborne Multiangle SpectroPolarimetric Imager, J. Geophys. Res. Atmos.,122, 7004-7026, doi:10.1002/2017JD026776

Supported by the NASA's ACCDAM program, ACE pre-Phase A formulation, and the PACE project.

Scientific question: What are the requirements on the retrieval quality of polarimetric measurements for the simultaneous retrievals of aerosol optical/ microphysical properties and surface reflection?

Scientific Contribution: We developed an optimized & coupled aerosol-surface retrieval algorithm for JPL's Airborne Multiangle Spectro-Polarimetric Imager (AirMSPI).

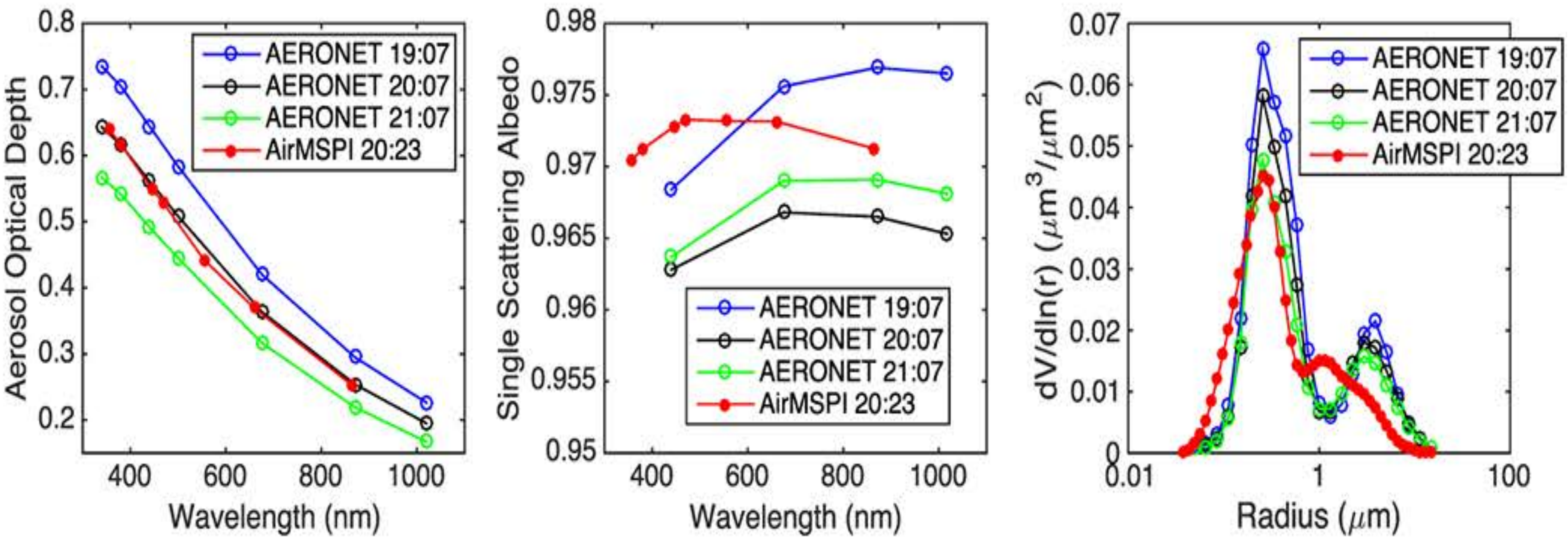
Results were verified against AERONET reference data using 27 datasets acquired during four NASA field campaigns. Aerosol optical depth (AOD) and single scattering albedo (SSA) retrieval errors are found to be around 0.025 and 0.04 respectively at the blue band (445 nm).

Significance: **Polarimetric measurements significantly improve the retrieval of aerosol optical and microphysical properties.**

- We identify the best angular combinations for 2-, 3-, 5-, 7-angle observations from the retrieval quality assessment of various angular combinations.
- Target revisits help better determine aerosol property and surface reflection.

Coupled retrieval of aerosol properties and land surface reflection using multiangle, spectropolarimetric measurements

The Fresno AERONET site on January 6, 2012, *(from Xu et al., 2017)*



Results from the paper were used in the PACE report on Aerosols

Objective 3

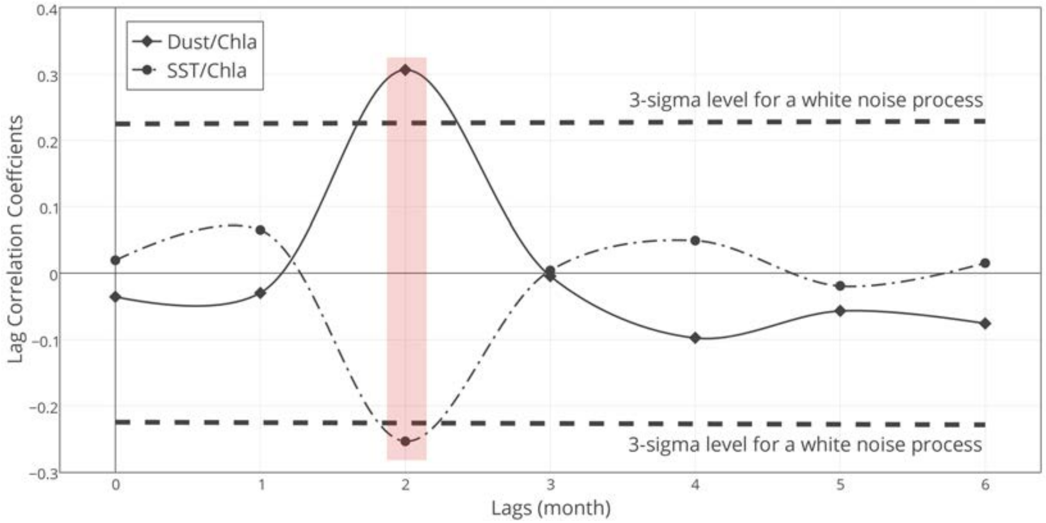
Determine the potential of mineral dust characterization for investigating how ocean ecosystems respond to dust deposition:

- Evaluated an anomalously high chlorophyll-*a* event during Summer 2015 in the South Central Red Sea
- Identified significant 2-month lag correlations between dust event anomalies and chlorophyll-*a* anomalies as well as sea surface temperature (SST) anomalies and chlorophyll-*a* anomalies

Assessment of anomalously High Chlorophyll-a Event during Summer 2015 in the South Central Red Sea

Jet Propulsion Laboratory

Wenzhao Li, Chapman University



Monthly lag correlation between dust aerosol optical depth (DAOD) and Chl-a (solid) and SST and Chl-a (dot-dashed). Dashed lines show the limits of three standard deviations for a white noise process. The red box shows that the 2-month lag correlations exceed this level for both relationships.

Li, W., H. El-Askary H., K. P., ManiKandan, M. A. Qurban, M. J. Garay and O. V. Kalashnikova, Synergistic Use of Remote Sensing and Modeling to Assess an Anomalously High Chlorophyll-a Event during Summer 2015 in the South Central Red Sea, Remote Sens. 2017, 9(8), 778; doi:10.3390/rs9080778

The JPL team work was supported by the ROSES PACE Science Team (P. Bontempi) award to Olga Kalashnikova.

Scientific question: What are possible causes of anomalous chlorophyll-*a* events in the Red Sea, and how is dust activity in the region contributing?

Finding: Our analysis suggests that a combination of factors controlling nutrient supply contributed to the anomalous phytoplankton growth. These factors include horizontal transfer of upwelling water through eddy circulation and possible mineral fertilization from atmospheric dust deposition. A lag cross correlation showed a statistically significant 2-month lag between dust AOD anomalies and SST anomalies and chlorophyll-*a* anomalies.

Significance: **We suggest that in the South Red Sea region, high dust activity could contribute to the phytoplankton growth or indicate conditions controlling nutrient supply.**

Summary

- **Objective 1:** Information content analysis of multiangle polarimetric observations show that polarimetric information improves retrievals of AOD and water leaving radiance, and allows the retrieval of aerosol absorption; oxygen A-band observations support retrieval of aerosol layer height, but not of its geometrical thickness, at least for optically thin aerosols.
- **Objective 2:** An optimized & coupled aerosol-surface retrieval algorithm for both land and ocean was developed for JPL's Airborne Multiangle Spectro-Polarimetric Imager (AirMSPI); demonstrated good agreement between AirMSPI retrievals and AERONET observations of aerosols and ocean surface reflectance.
- **Objective 3:** Identified a statistically significant 2-month lag correlation between dust anomalies and chlorophyll-*a* anomalies, suggesting links between dust activity and phytoplankton growth or atmospheric effects on conditions controlling nutrient supply.
- **New collaborative work:** Analysis and validation of SPEX observations collected at USC SeaPRISM site in July 2016 is work in progress led by the SPEX team (Initial SPEX results were presented at the Fall 2017 AGU meeting).

Thank you!

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