

Brian Cairns

Fall AGU Town Hall

12 December 2019, San Francisco

PACE



Plankton, Aerosol, Cloud, ocean Ecosystem

Legacies:

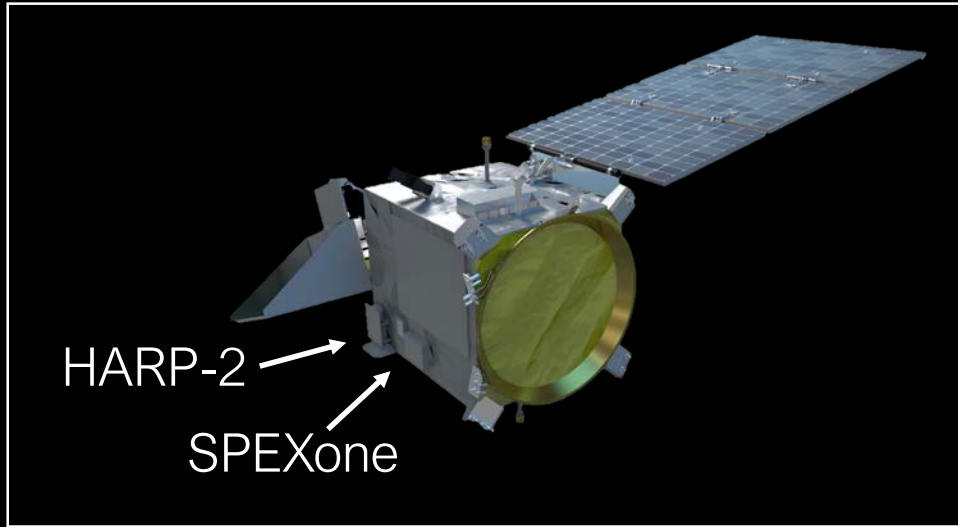
- CZCS
- SeaWiFS
- POLDER
- MODIS
- MISR
- VIIRS
- others

Town Hall agenda:

- mission update
- programmatic
update & future
science teams
- contributions to
atmospheric
science
- Q&A







Mission Characteristics

Orbit

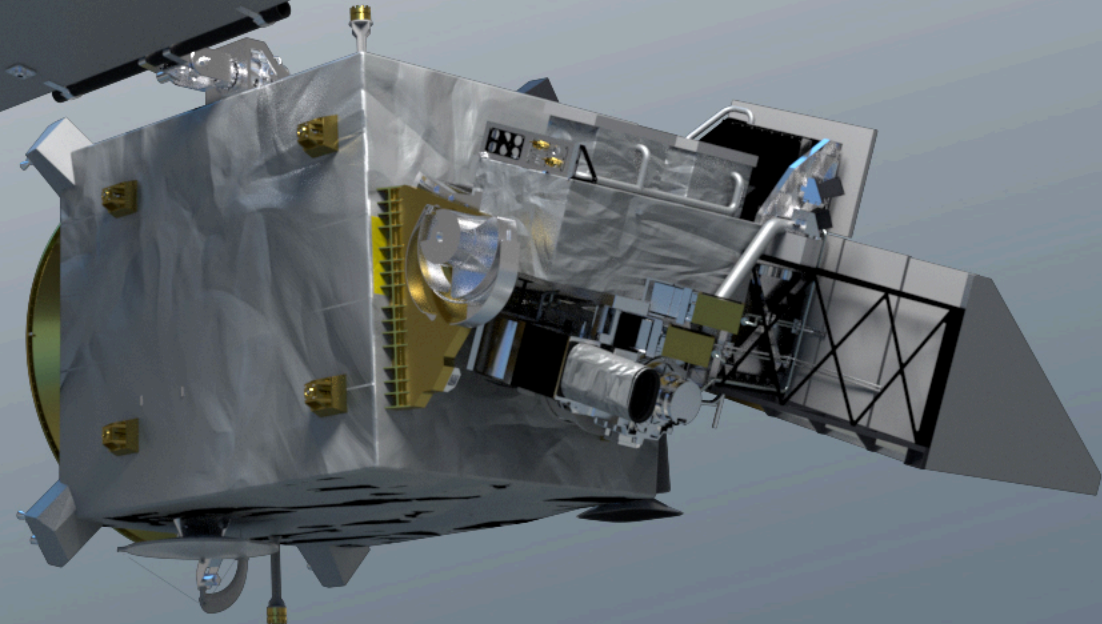
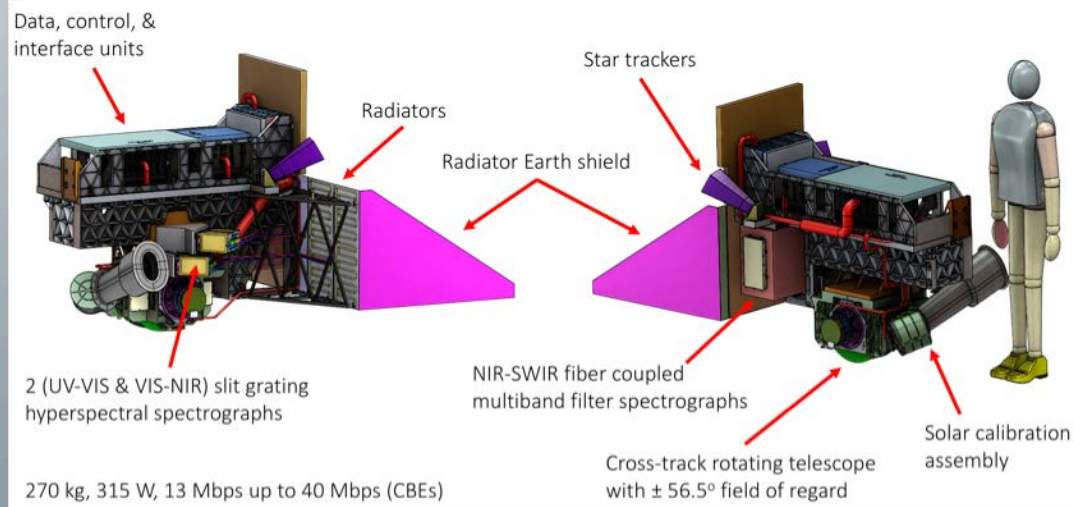
- 676.5 km altitude
- Polar, ascending orbit
- Sun synchronous
- 98° inclination
- 13:00 local Equatorial crossing

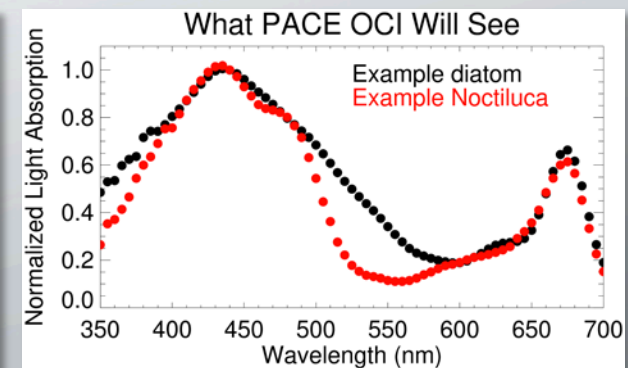
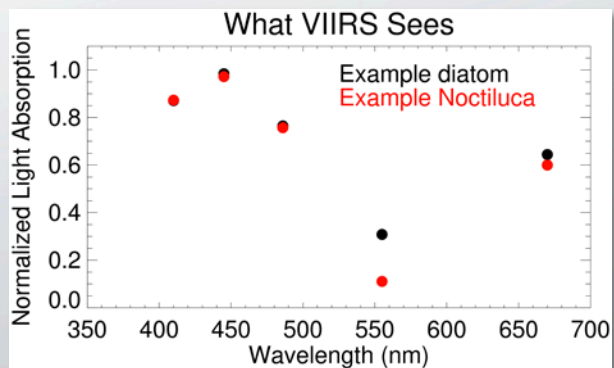
Cost, Schedule, Lifespan

- \$845M Design-to-Cost
- Category 2, Class C
- Dec 2022 launch
- 3-year design life
- 10-years of fuel

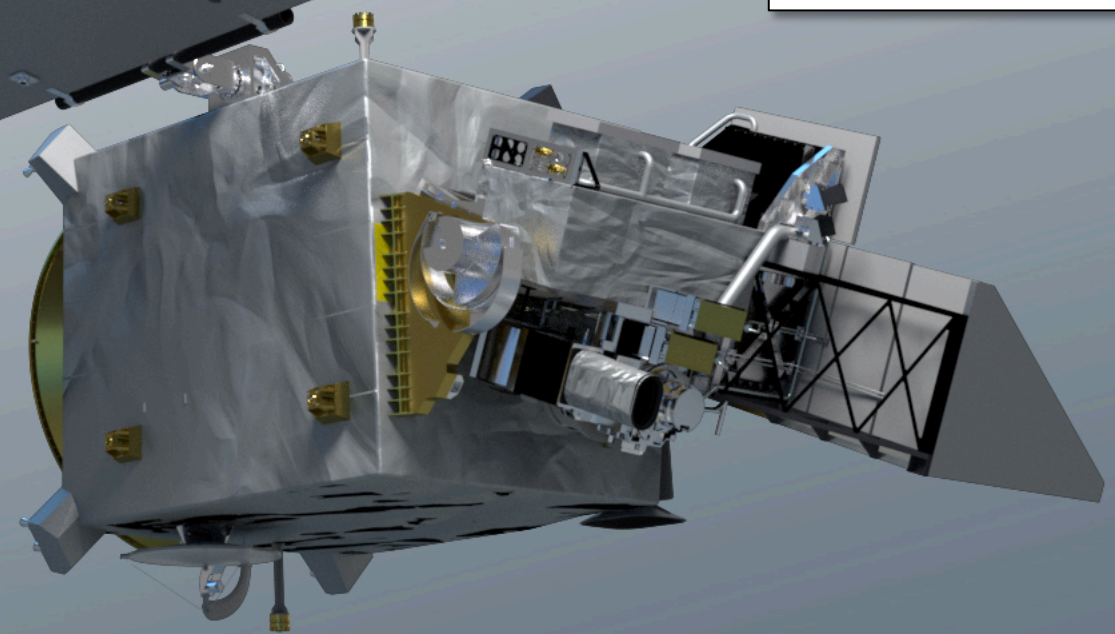
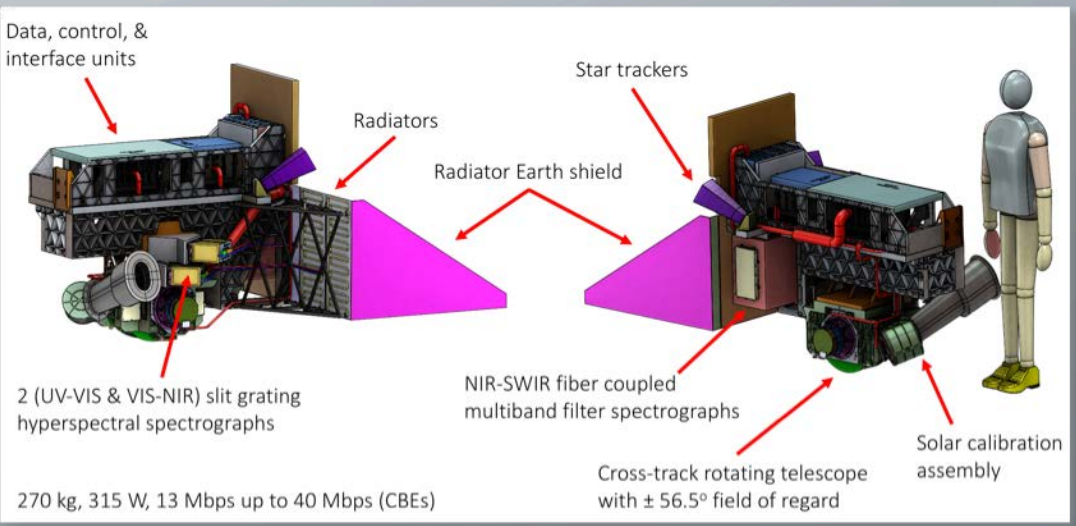


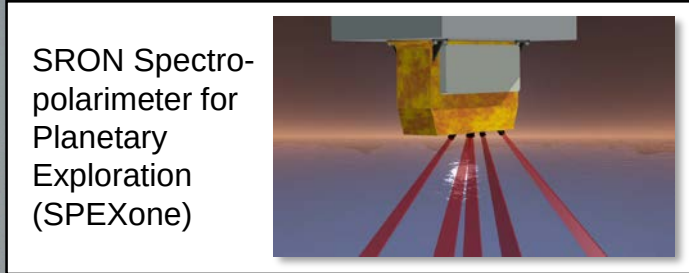
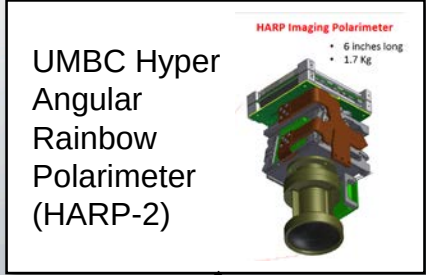
- 340 – 890 nm at 5 nm resolution
- Plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- 1 – 2 day global coverage
- Ground pixel size of 1 km² at nadir
- $\pm 20^\circ$ fore/aft tilt to avoid Sun glint
- Twice monthly lunar calibration
- Daily on-board solar calibration
- Performance that meets or exceeds heritage
- Built at NASA Goddard Space Flight Center





PACE OCI in 2017 Decadal Survey Program of Record

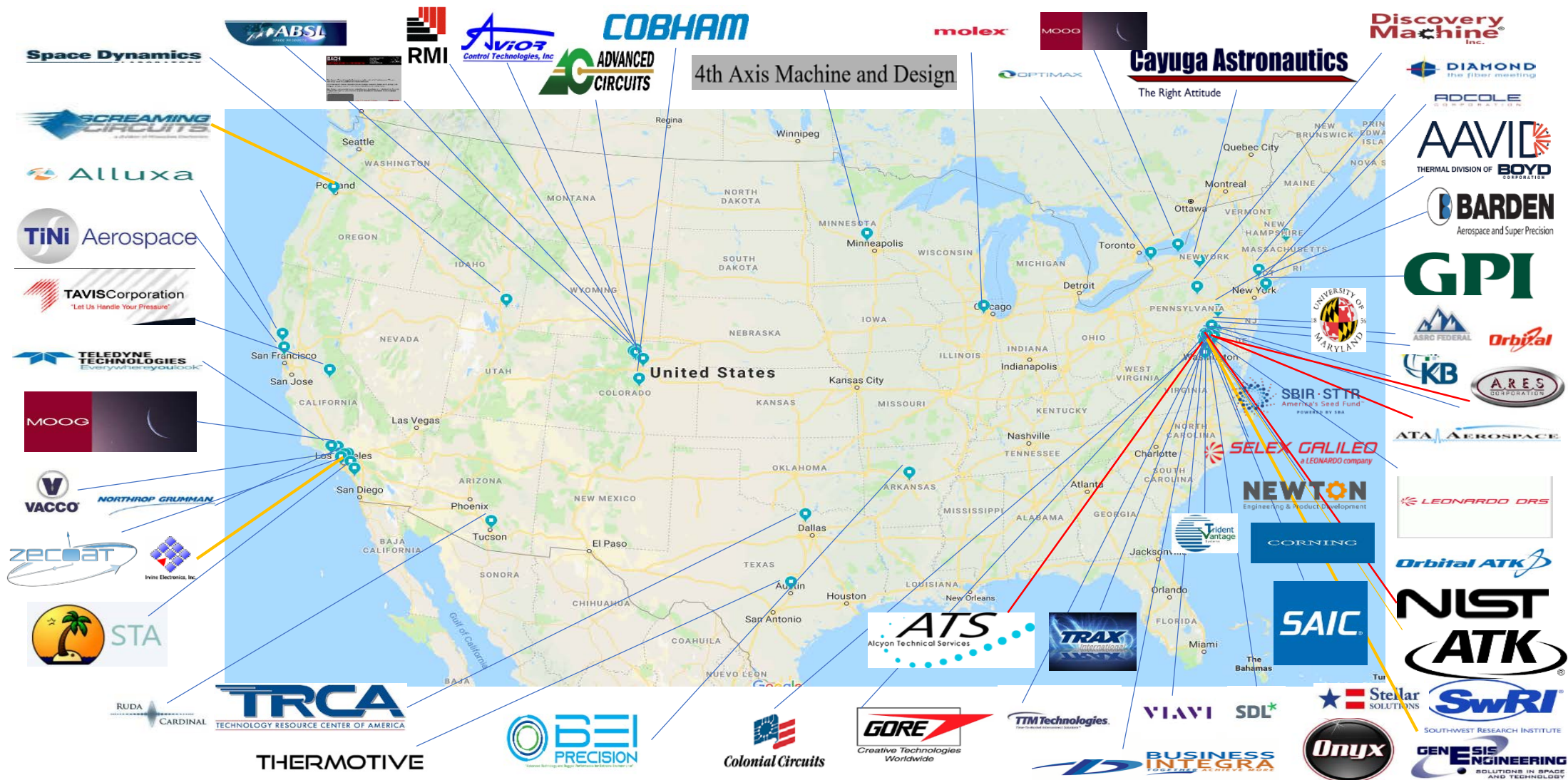




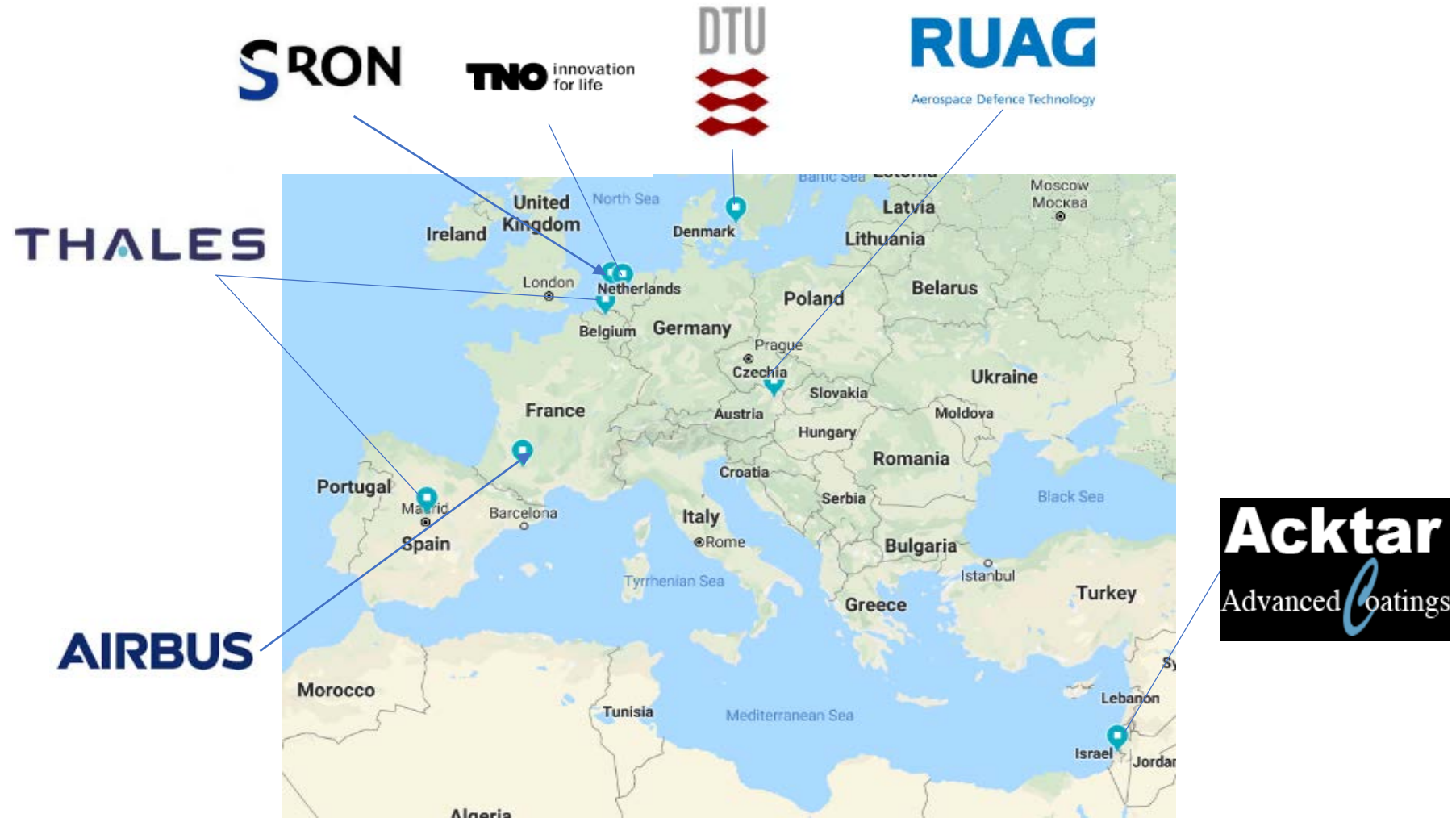
PACE polarimeters *NOT* in 2017 Decadal Survey Program of Record

	HARP-2	SPEXone
UV-NIR range	440, 550, 670, 870 nm	Continuous from 385-770 nm in 5 nm steps
SWIR range	None	None
Polarized bands	All	Continuous from 385-770 nm in 15-45 nm steps
Number of viewing angles [degrees]	10 for 440, 550, 870 nm; 60 for 670 nm [spaced over 114°]	5 [-57°, -20°, 0°, 20°, 57°]
Swath width	±47° [1556 km at nadir]	±4.5° [106 km at nadir]
Global coverage	2 days	30+ days
Ground pixel	3 km	2.5 km
Heritage	AirHARP, Cubesat	AirSPEX

Who's working on PACE (in the USA as of 2019)?



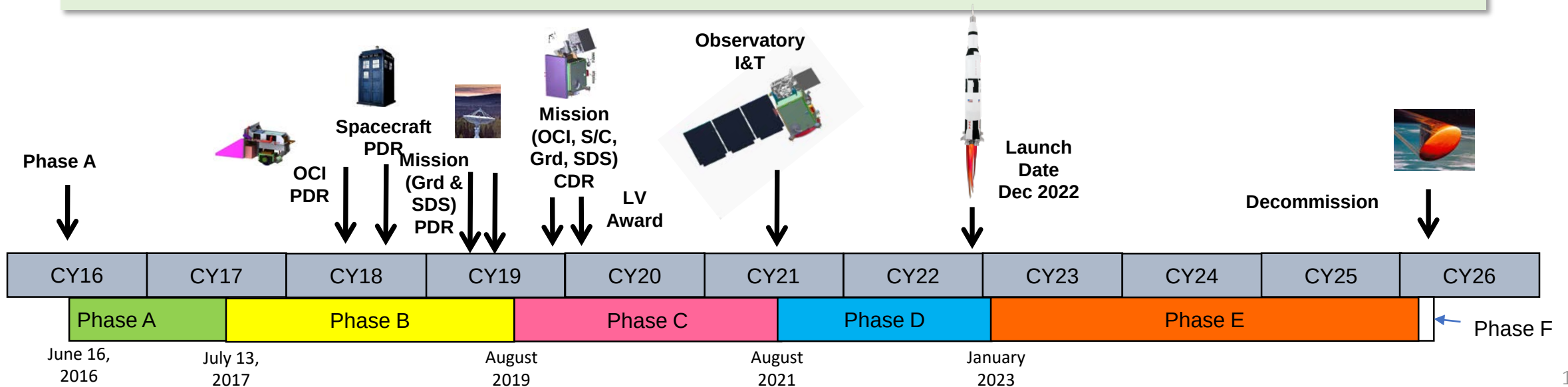
Who's working on PACE (internationally as of 2019)?



Looking forward: the mission's coming year(s)

Phase C – final design and fabrication (**D** – AI&T, launch; **E** science ops)

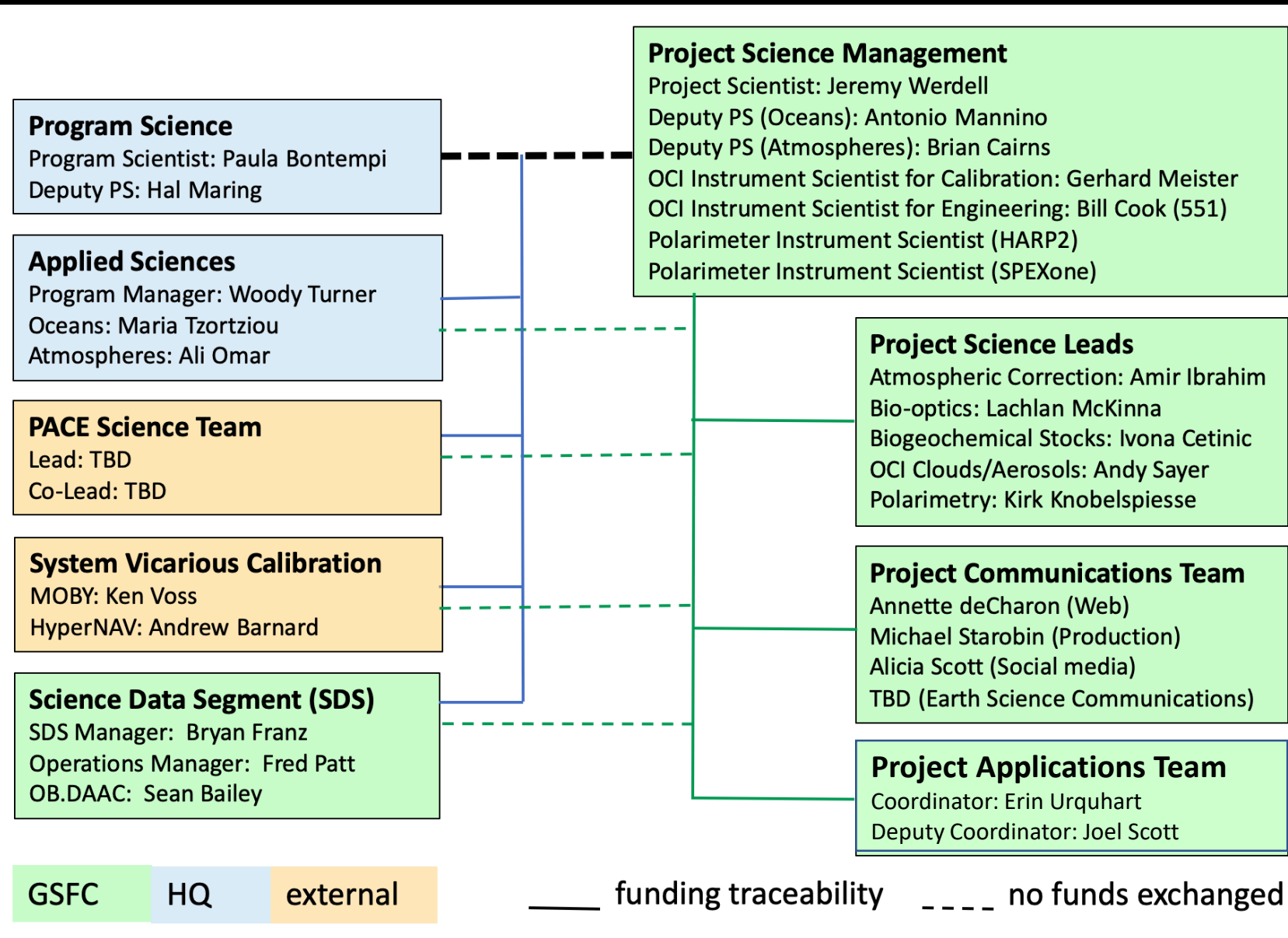
- August 2019 – Q2 2021
- All mission elements must pass Critical Design Reviews (CDR)
- Instruments integrated, tested and ready for integration onto observatory
- Project & HQ Science + OBPG Science Data Processing:
 - respond to element issues (study, charge/retreat, provide therapy)
 - build science capabilities (plans for cal, val, algs, processing, documentation, etc.)



mission update

- Jul 13, 2017: KDP-B
- May 1-4, 2018: OCI PDR
- Jun 26, 2018: SPEXone PDR
- Aug 8, 2018: HARP2 PDR
- Sep 17-20, 2018: spacecraft PDR
- Feb 7, 2019: SPEXone CDR
- Mar 19-20, 2019: ground system (GS) PDR
- Apr 25, 2019: HARP2 CDR
- Jun 11-14, 2019: mission PDR
- Aug 15, 2019: KDP-C
- Aug 2019: Sys Vicarious Calibration award
- Sep 2019: PACE in draft appropriations bills
- Dec 2019: OCI CDR – **this week**
- Feb 2020: mission/spacecraft/GS CDR
- ...
- Fall/Winter 2020: polarimeter delivery
- Aug 2021: Phase D – integration & testing
- Dec 2022: launch
- Mar 2023: science operations

science update – mission organization



Programmatic update & future science teams

updates

2017 Decadal Survey - PACE appears in the “Program of Record” (POR)

- POR refers to OCI only
- polarimeters are *not* part of the POR – they are not required instruments

2 system vicarious calibration awards made through ROSES

- Marine Optical Buoy (MOBY) – Ken Voss, University of Miami; mooring
- HyperNAV – Andrew Barnard, Seabird Scientific; float

Science Team to be formed for 3 years; roughly CY 2020-2022 (launch in late 2022)

- Hyperspectral and/or SWIR aspects of OCI
- Multi-angle polarimetry (alone or with OCI)
- Applications (societal benefits) from the above

A.38: PACE Science and Applications Team

Release Date: March 14, 2019

Estimated Annual Budget Available: ~\$3.2M

Estimated Number of Awards: 12-20

Maximum Award Duration: Maximum 3 years

NOIs received May 15, 2019

Proposals Due: July 15, 2019

A Total of 52 Proposals were Received

Peer Review Panel: October 2019

Selection Announcement: November 2019

Potential Start Date for Awards: January 1, 2020

A.38: PACE Science and Applications Team

- To formulate a Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) **Science and Applications Team (SAT) for a three-year period (FY20-22)**.
 - Basic and applied research and applications, including theoretical and analytical studies, to develop:
 - OCI-analog hyperspectral data to develop an algorithm or approach for one or more ocean color, aerosol, and/or cloud data product or suite of products from OCI;
 - HARP-2- and/or SPEXone-analog multi-angle polarimetric data to develop an algorithm or approach for one or more ocean color, aerosol, and/or cloud data product or suite of products;
 - OCI-analog hyperspectral data and HARP-2/SPEXone-analog multi-angle polarimetric data to develop one or more cross-instrument ocean color, aerosol, and/or cloud data products; and
 - Applications derived from OCI-analog hyperspectral data and/or HARP-2/SPEXone-analog multi-angle polarimetric data for societal benefit.
- This solicitation seeks basic and applied research and applications that specifically exploit the unique capabilities of the PACE observatory. Proposals that do not consider the hyperspectral capabilities of OCI and/or multi-angle polarimetry, or that propose the creation of MODIS-like data products from PACE will be considered non-responsive.

NASA has a strict open access data policy. All data products resulting from funded proposals will be open and publicly available



Get Involved with PACE Applications



Current

- **Identify key stakeholders** and Early Adopters (expert test users) plus their data needs to promote the use of PACE data products
- **Assess the applications** that can be addressed with PACE retrievals
- **Provide feedback** on factors that might impact the value of PACE data for applications purposes

PACE Applied Sciences program POCs:

PACE Applications Coordinators:

Erin Urquhart and Joel Scott
erin.u.jephson@nasa.gov

NASA Applied Science Program:

Woody Turner, Maria Tzortziou & Ali Omar

Future

- Engage new user communities
- **Continuous collaboration with stakeholders** to ensure that their data product needs are met
- **Demonstrate the utility of PACE data products and PACE's practical use for societal benefit**

Consider joining the PACE Early Adopters Program



PACE contributions to atmospheric science

Plankton, Aerosol, Cloud and ocean Ecosystem (PACE) Instruments

(Primary) Ocean Color Instrument (OCI)

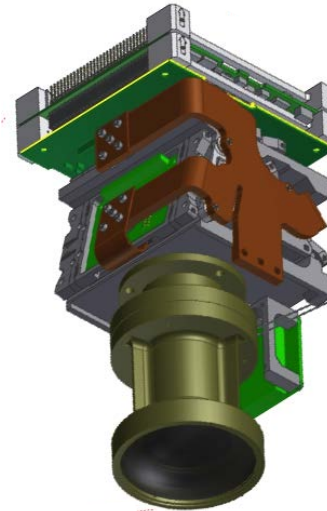
Wide swath, UV-VIS imaging spectrometer with SWIR channels designed for ocean color applications, useful for aerosols and clouds



OCI ETU FlatSat End-to-End
Electrical System Test

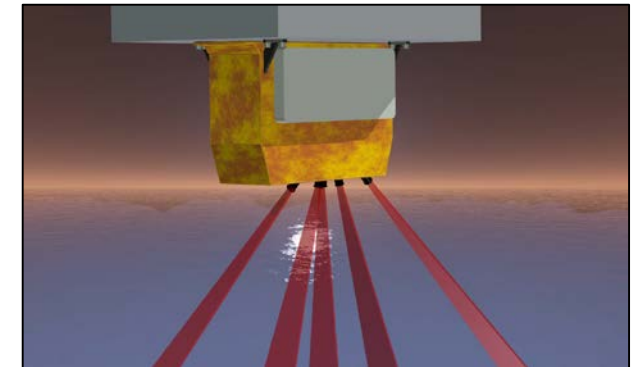
Hyper Angular Rainbow Polarimeter 2 (HARP2)

wide-swath multi-angle polarimeter, hyper angle capability



Spectro-Polarimeter for Planetary Exploration (SPeXone)

narrow-swath multi-angle polarimetric spectrometer



PACE key mission elements



SPEXone and HARP2 are '**contributed**' instruments

Requirements derive from **do no harm** philosophy alone

No requirements for successful data collection, science

Both originally designed as cubesat scale instruments

Polarimeters will be an excellent proof of concept for atmospheric correction, aerosol and cloud retrievals

Ocean Color Instrument (OCI)

Ocean Color Instrument – physical assembly

Scanning concept follows SeaWiFS and VIIRS heritage

Data, control, &
interface units

Radiators

Radiator Earth shield

Star trackers

2 (UV-VIS & VIS-NIR) slit grating
hyperspectral spectrographs

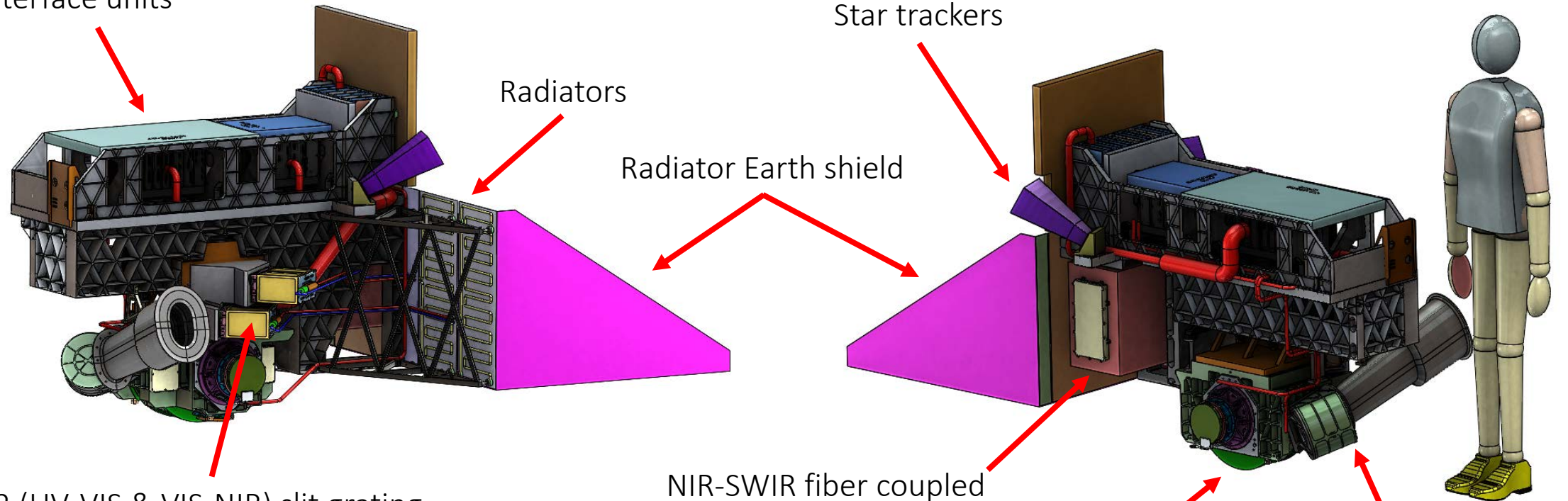
NIR-SWIR fiber coupled
multiband filter spectrographs

270 kg, 315 W, 13 Mbps up to 40 Mbps (CBEs)

Cross-track rotating telescope
with $\pm 56.5^\circ$ field of regard

Solar calibration
assembly

OCI is tilted by $\pm 20^\circ$ to avoid sun glint



OCI characteristics

SPECTRAL COVERAGE

Hyperspectral radiometry from the ultraviolet (320 nm) to near-infrared (885 nm) specified to 5nm spectral resolution

Shortwave (SW) infrared (IR) bands:
940, 1038, 1250, 1378, 1615, 2130, and 2260 nm

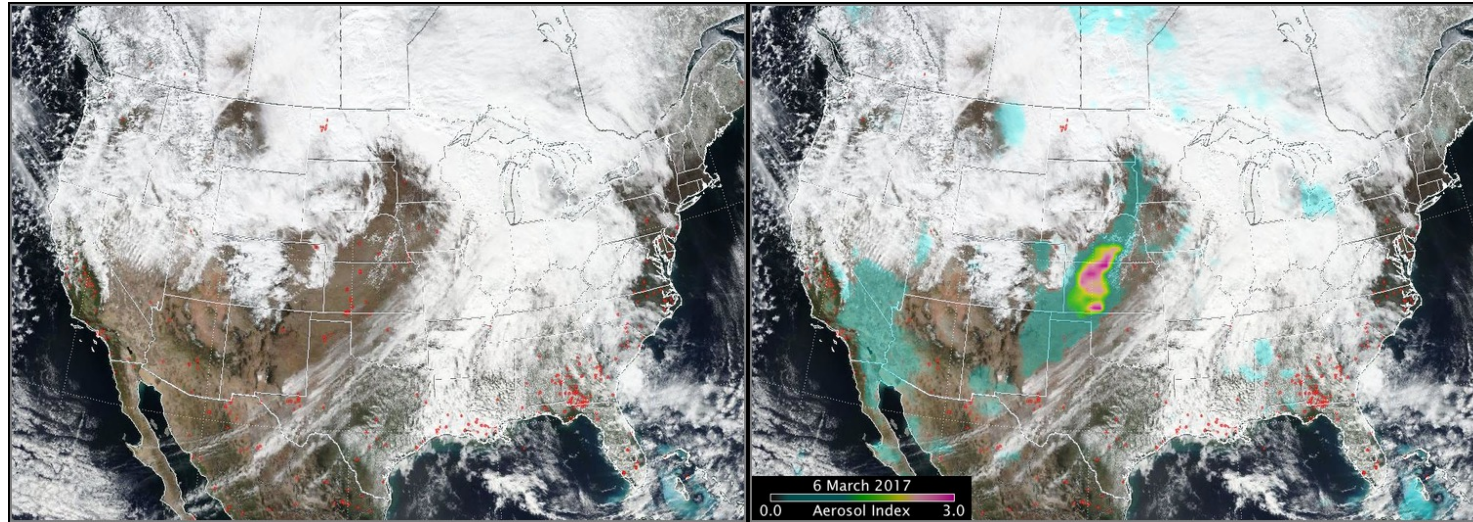
GSD of $1 \pm 0.1 \text{ km}^2$ at nadir

Twice-monthly lunar calibration & onboard solar calibration
(daily, monthly)

*MODIS on Terra (2000-) does not yet provide science-quality ocean data
**MODIS/VIIRS short-wave infrared bands are not optimized for oceans

SHORT-WAVE INFRARED Multi-band Aerosol/cloud properties

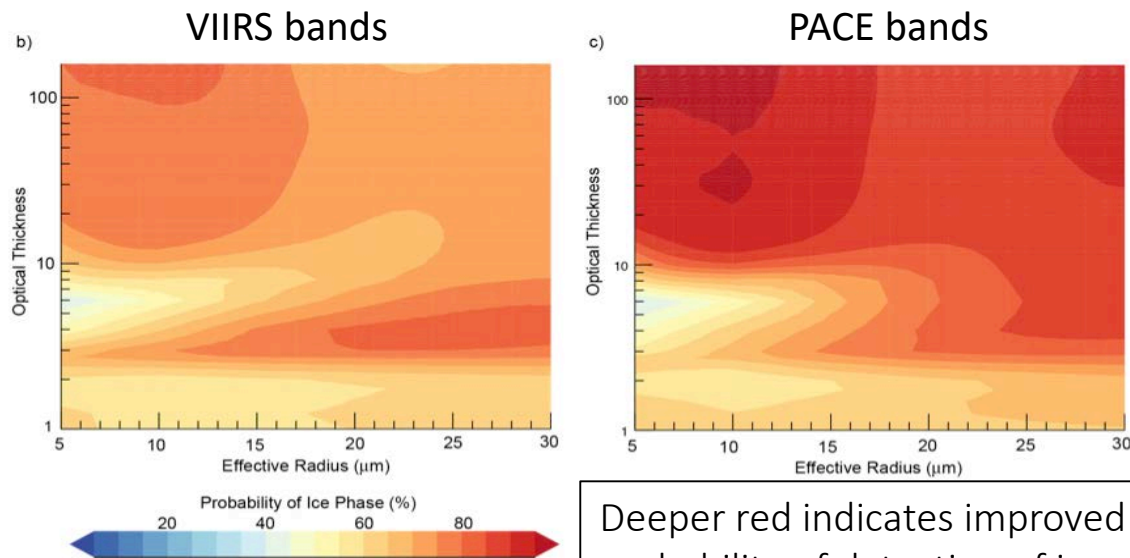
OCI atmospheric improvements over heritage



1 km resolution at nadir from UV to SWIR

UV + oxygen-A and B-bands provide opportunities for aerosol algorithms beyond heritage

VIIRS RGB + OMPS Aerosol Index



Deeper red indicates improved probability of detection of ice phase

Two 2- μm bands (VIIRS + MODIS) improve retrievals of cloud thermodynamic phase

AGU PUBLICATIONS

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1002/2017JD026493

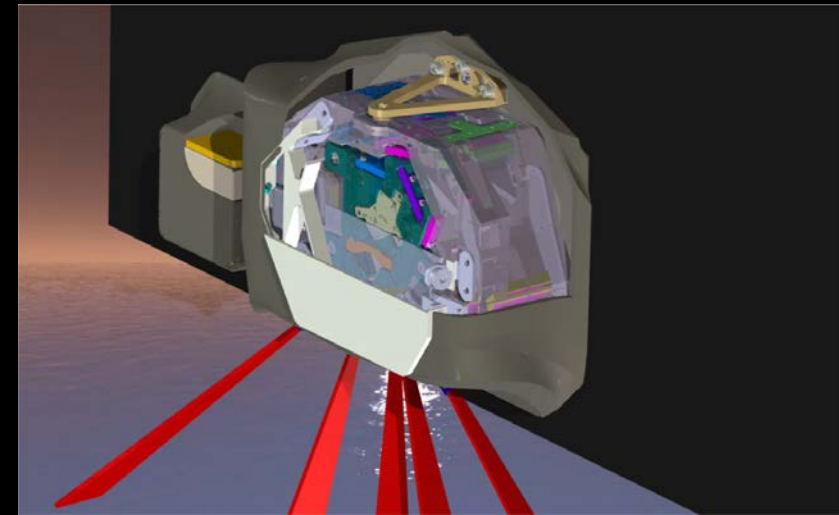
Characterizing the information content of cloud thermodynamic phase retrievals from the notional PACE OCI shortwave reflectance measurements

O. M. Coddington¹, T. Vukicevic², K. S. Schmidt^{1,3}, and S. Platnick⁴

Multi-angle polarimeters

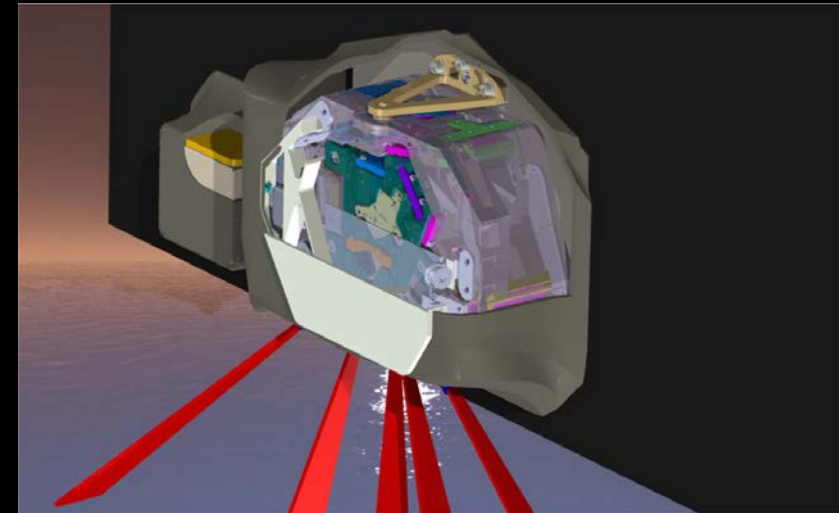
PACE pixel-level polarimetric aerosol products

- Aerosol microphysical retrievals
 - Over ocean, land, clouds (and snow?)
- Aerosol layer height
 - Blue/UV polarized observations (both) and O₂ absorption bands from SPEXone
- Surface characterization (BPDF)
- Separation of brown and black carbon into different products, differentiation between BrC and CDOM
- Aerosol above clouds, polarization and UV - SWIR



PACE pixel-level polarimetric cloud products

- Droplet size distributions at cloud tops
 - Accurate in 'challenging' conditions: broken, mixed phase, low optical depth, snow,
- Robust cloud-top phase detection
 - Detection of cloud is 'unambiguous' indication of liquid at tops
- Ice shape and scattering properties collocated with OCI retrievals
 - Constraining ice asymmetry parameter for OCI ice cloud retrievals
- SPeXone polarimetry O2 A band + UV adds potential for cloud top height, cloud fraction, physical thickness and CDNC



Polarimetry on PACE

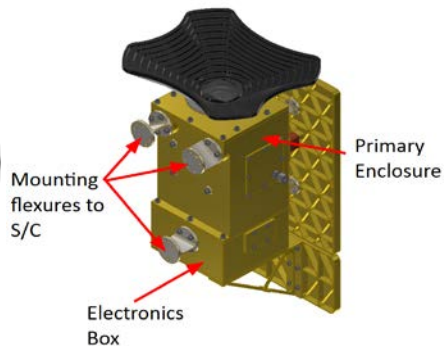
Two cubesat-sized *contributed* instruments



Spectro-Polarimeter for Planetary Exploration (SPEXone)

Contribution from the Netherlands (SRON, NSO, Airbus; TNO optics)

POC: Otto Hasekamp Hyperspectral (UV) + narrow swath + high accuracy



Hyper Angular Rainbow Polarimeter (HARP-2)

Contribution from University of Maryland Baltimore County

POC: Vanderlei Martins Hyperangular + wide swath

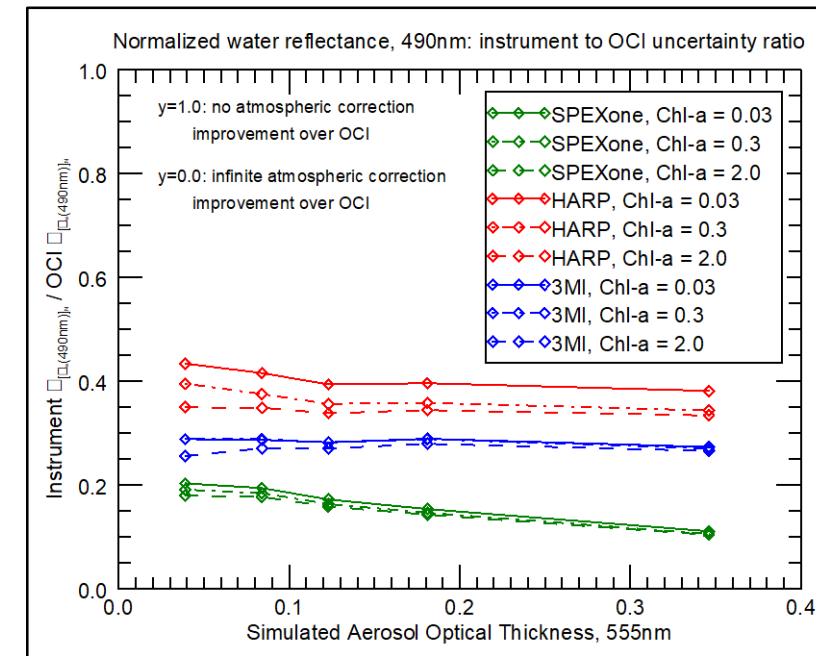
	SPEXone	HARP-2
Spectral range (resolution)	385-770 nm (hyperspectral 2 nm)	440, 550, 670 nm (10) + 870 nm (40 nm)
Polarimetric accuracy (DoLP)	0.002	< 0.01
# viewing angles	5 (-52°, -20°, 0°, 20°, 52°)	20 for 440, 550, 870 nm + 60 for 670 nm (114°)
Swath width	9° (100 km)	94° (1550 km)
Ground sample distance	2.5 km ²	2.5 km ²
Heritage	AirSPEX, SPEX/ASPIM	AirHARP, cubesat HARP for ISS

How will PACE polarimeters perform?

Radiative transfer simulations + information content analysis
(Knobelspiesse et al. 2012)

Right – atmospheric correction improvement: ratio of SPeXone/HARP2 water leaving reflectance uncertainty to OCI uncertainty. EUMETSAT 3MI for reference.

Below – aerosol retrieval improvement: degrees of freedom for signal for a simultaneous aerosol & ocean retrieval



Atmospheric
correction
improvement

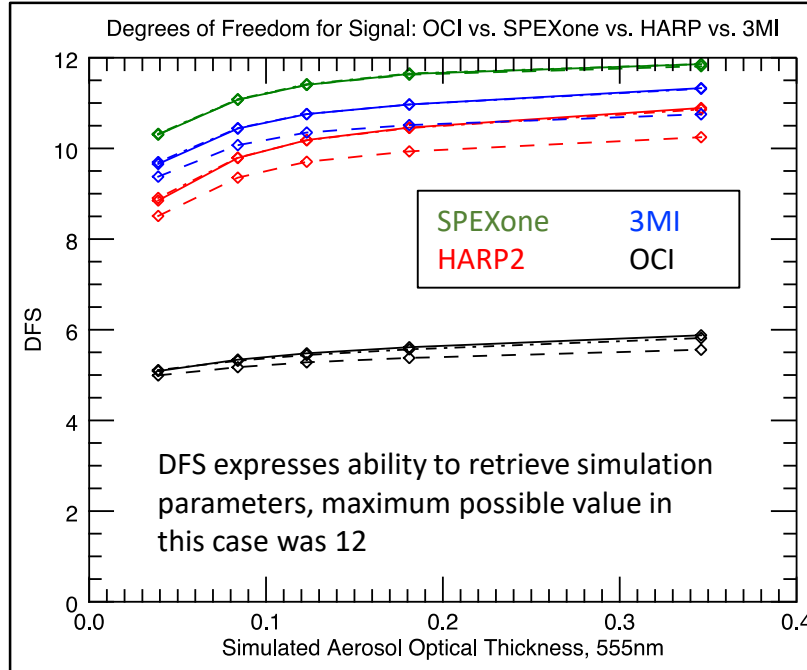
better



better



Aerosol
retrieval
improvement



Both offer dramatic improvement, comparable to 3MI

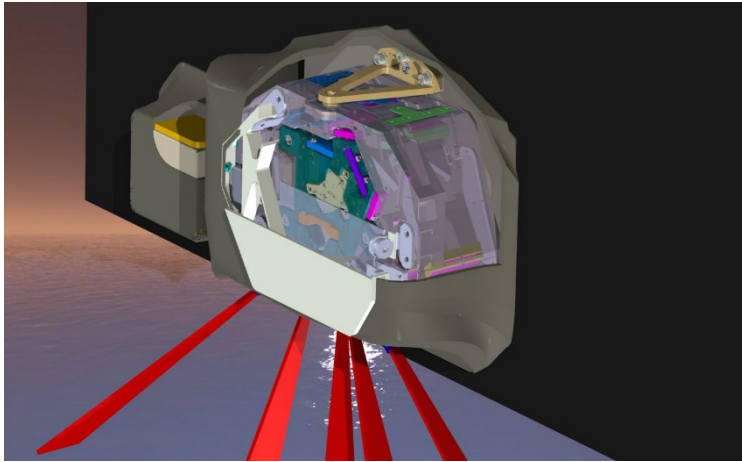
Other characteristics must also be considered, e.g. considerable swath width difference (SPeXone: 9°, HARP2: 94°).

Cloud property retrieval

Hyperangular capability of HARP2 can be used to retrieve droplet size distributions and to characterize ice particle roughness and aspect ratio, which reduces the uncertainty in ice particle size retrievals from OCI.

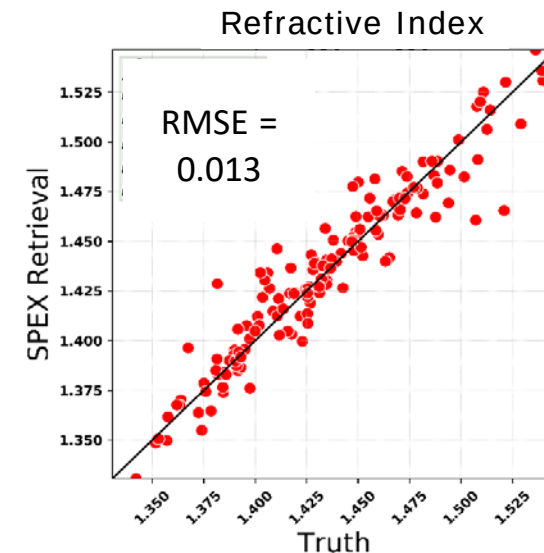
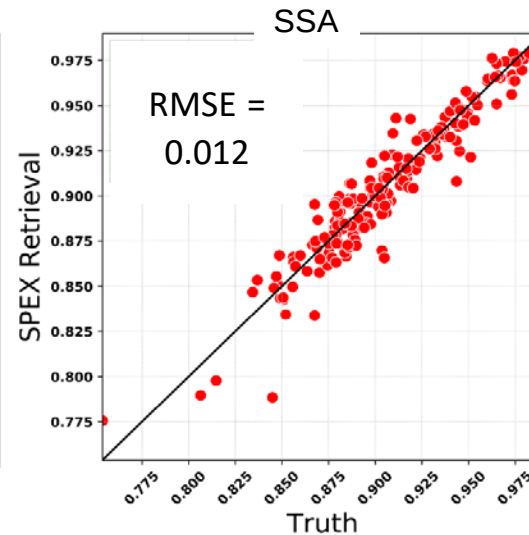
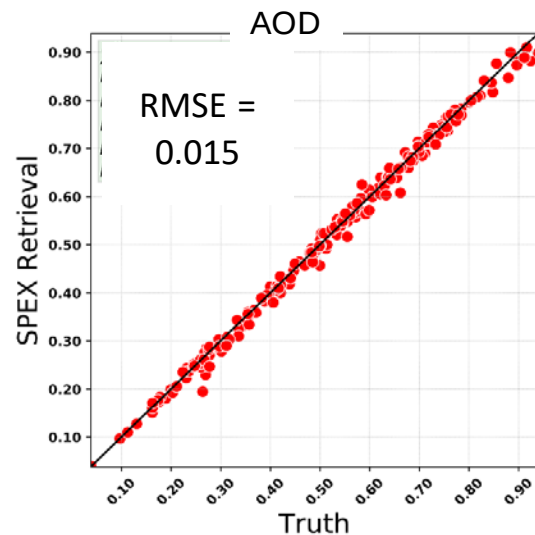
Operational algorithms must be created to exploit this information.

How will PACE polarimeters perform? – Examples from SPeXone



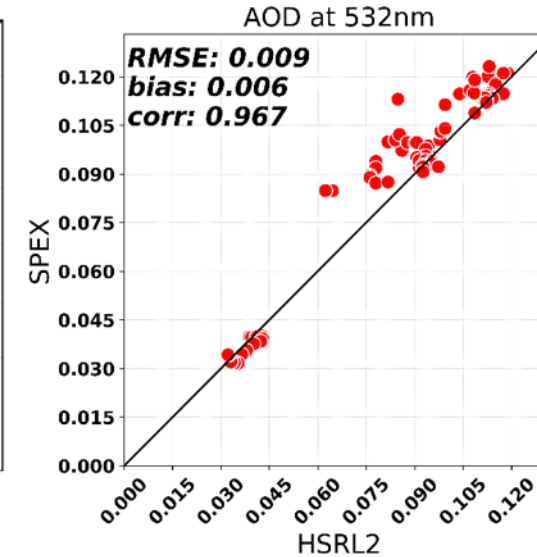
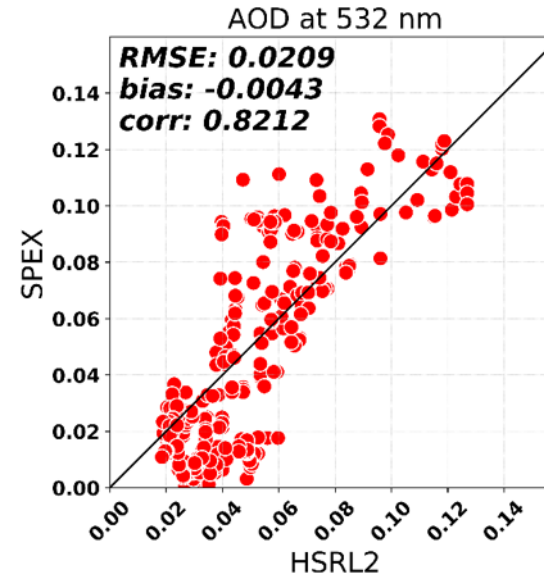
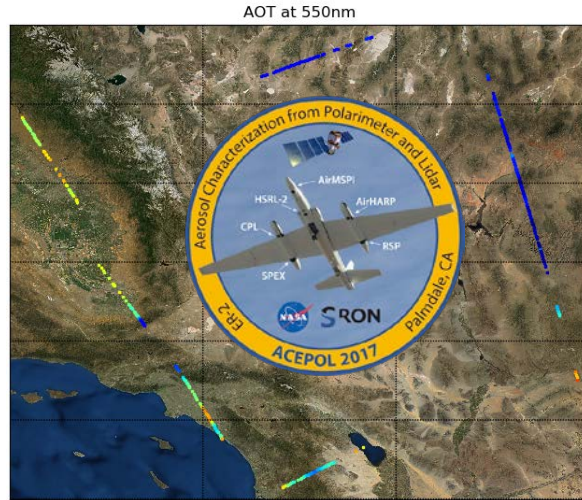
Parameter	Specification
viewing angles	+/-57°, +/-20°, 0°
spectral range	385-770 nm
spectral resolution intensity	2-5 nm
spectral resolution DoLP	15 - 40 nm
spatial resolution	5 x 5 km ²
polarimetric accuracy	0.003
radiometric accuracy	2%
SNR (dark ocean, SZA=70°)	300
swath	100 km

Synthetic retrievals demonstrate retrieval capability

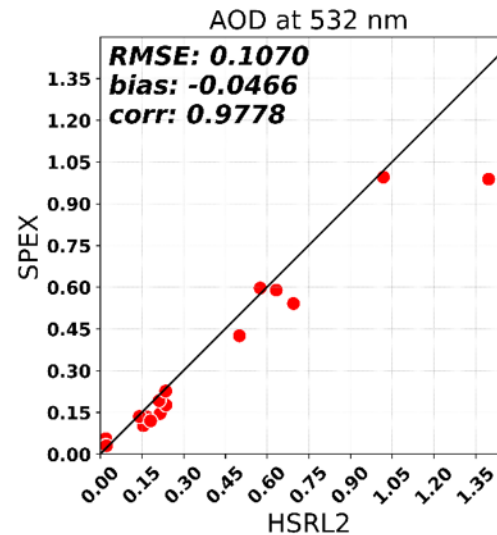


How will PACE polarimeters perform? – Examples from SPEX airborne in ACEPOL

Measurements at low AOD



Measurements of Smoke Plume

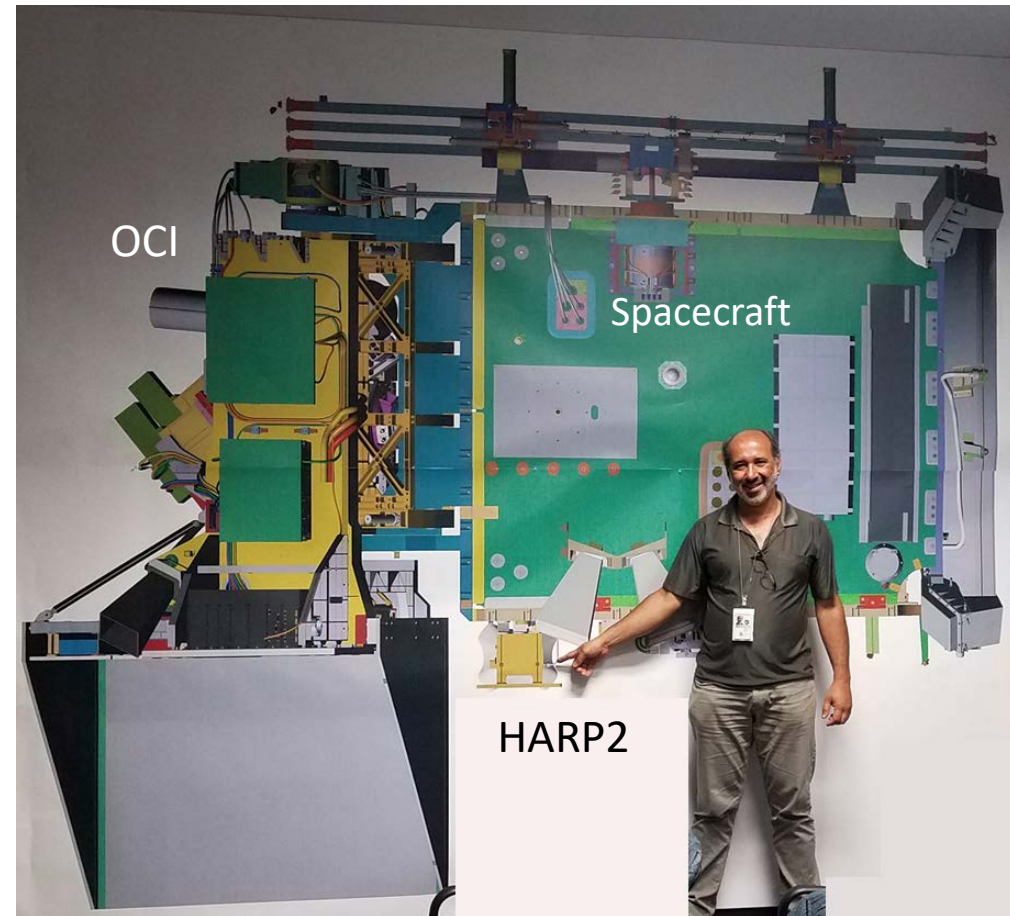
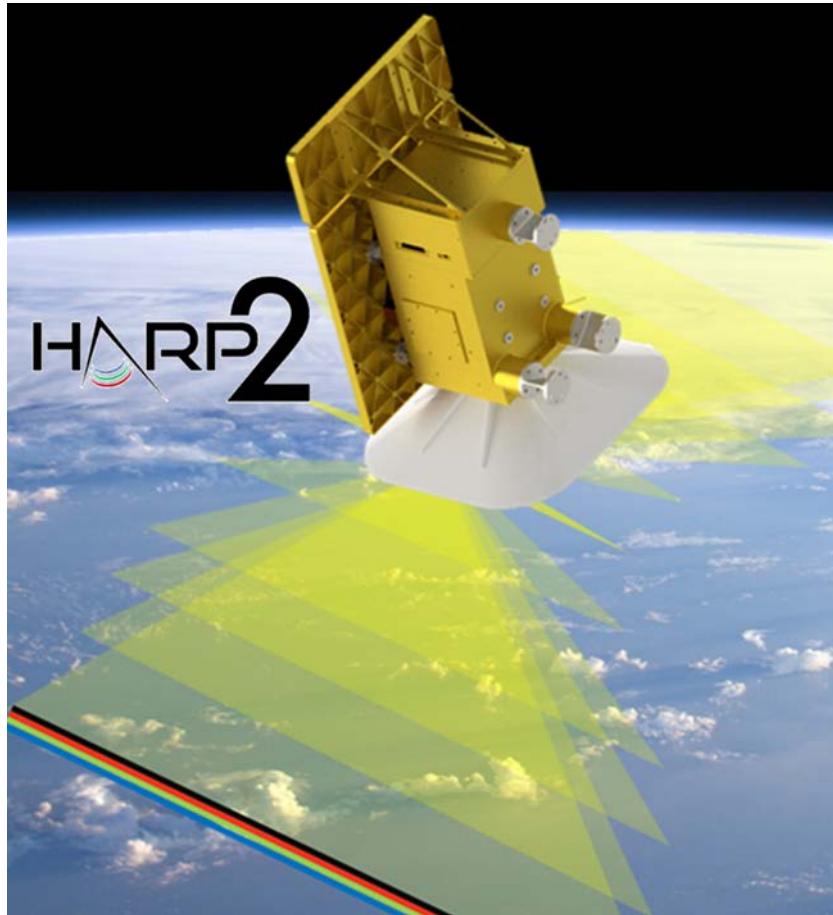


Smoke Properties

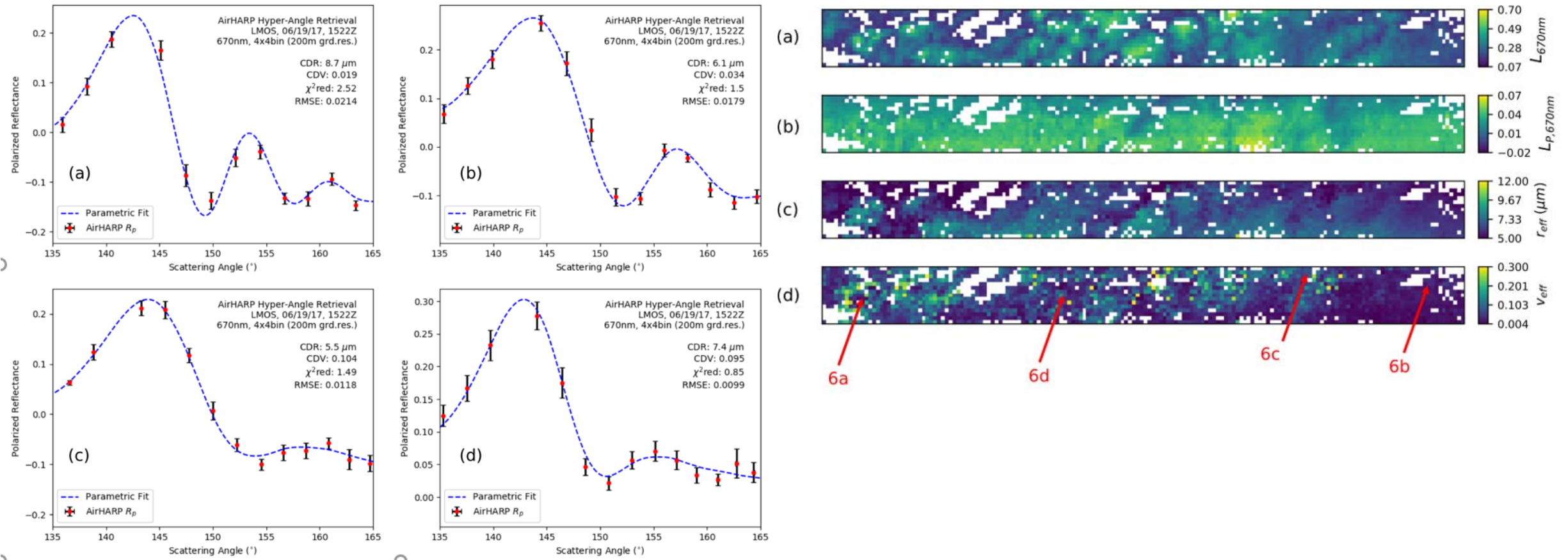
	SPEX	RSP
AOD _{fine}	0.52	0.50
AOD _{coarse}	0.03	0.03
r _{eff} (μm)	0.16	0.15
RRI	1.58	1.58
IRI	0.06	0.04
%sphere	97	84
SSA	0.79	0.85
ALH (km)	4.3	1.7

How will PACE polarimeters perform? – HARP2

- Global coverage in 2 days
- Synergy with Ocean color and SPEXOne polarimeters
- Hyperangular observations

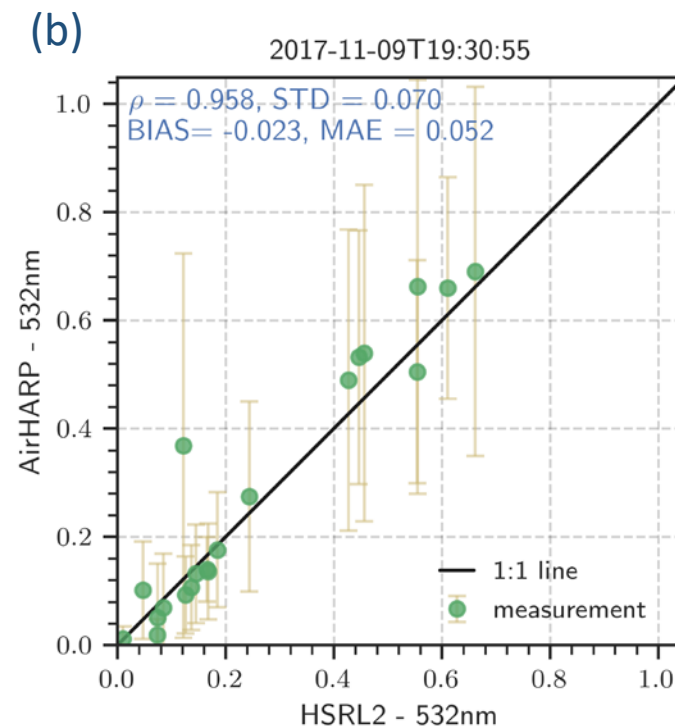
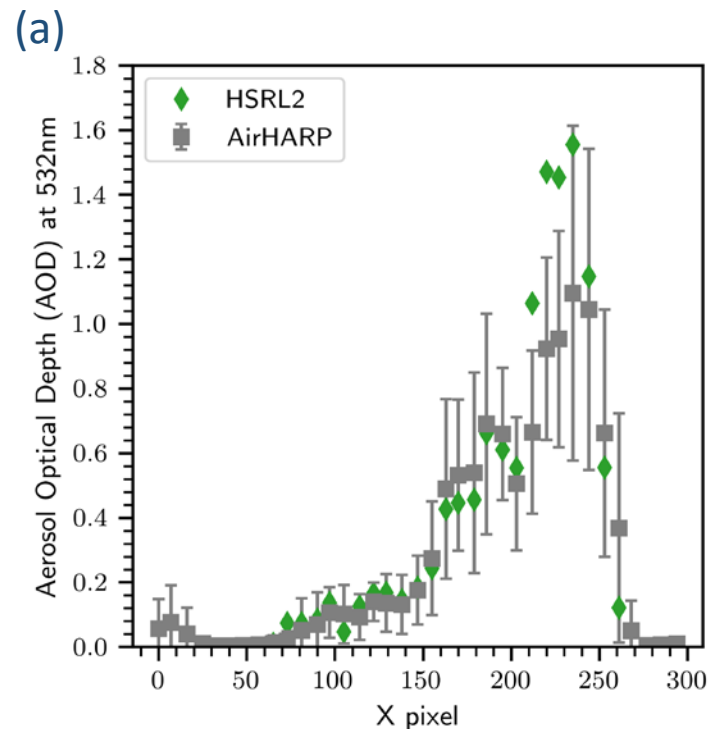
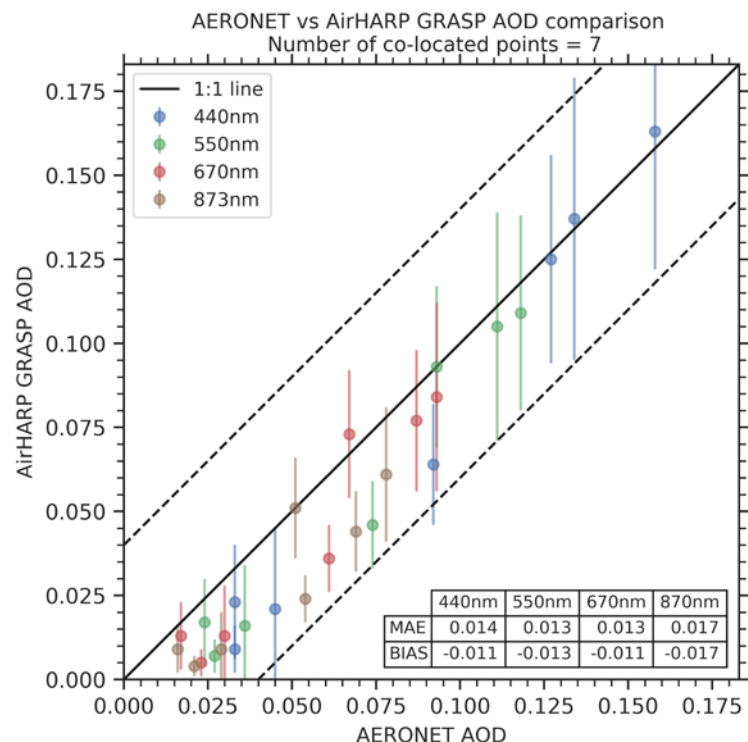


How will PACE polarimeters perform? – Examples from AirHARP



Brent A. McBride^{1,2,3}, J. Vanderlei Martins^{1,2,3}, Henrique M.J. Barbosa⁴, William Birmingham^{2,3}, and Lorraine A. Remer^{2,3}, **Spatial distribution of cloud droplet size properties from Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) measurements, AMTD 2019**

How will PACE polarimeters perform? – Examples from AirHARP



Figures show AOD comparisons with AERONET (above) and (a) AOD measured at 532nm by AirHARP versus HSRL2 AOD at 532nm for the forest fire scene on 09-11-17_07,31,00PM ; (b) Correlation plot for the HSRL2 AOD at 532nm vs AirHARP AOD at 532nm for the flight on 9th November 2017 over a smoke plume

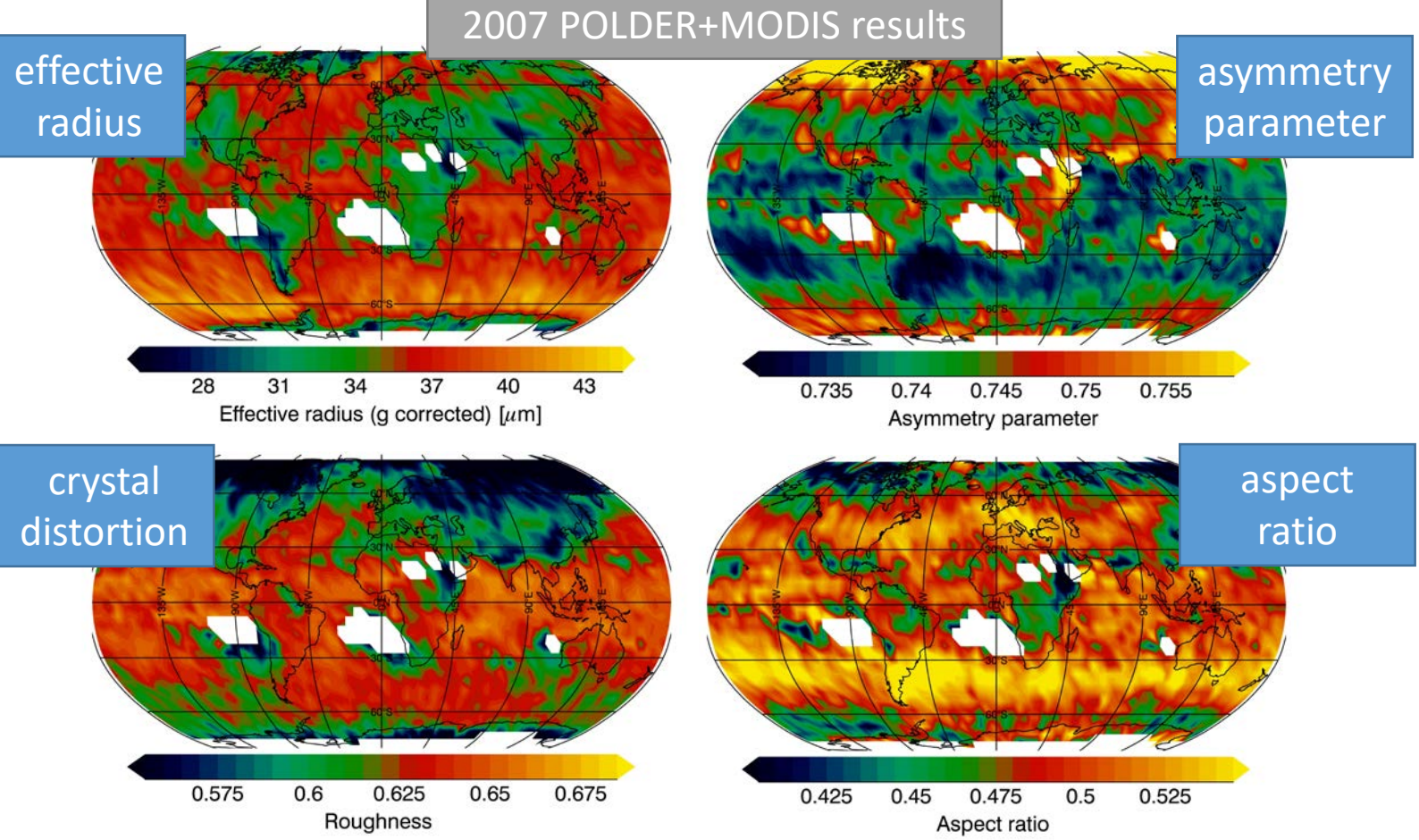
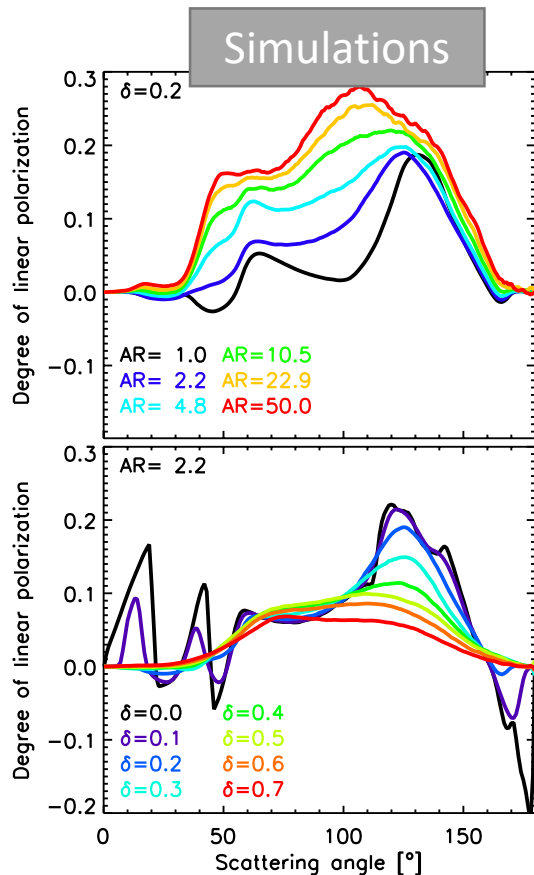


How will PACE polarimeters perform?

SPeXone + HARP2 + OCI: Polarimetric observations compliment OCI ice cloud retrievals

- Polarimetry allows retrieval of ice crystal aspect ratio and crystal distortion, which are fundamental properties determining the scattering asymmetry parameter
- Retrieving asymmetry parameter avoids the need to assume an ice optical model for optical thickness and effective radius retrievals from VIS/SWIR bands

van Diedenhoven et al.
(AMT 2012, JGR 2014)



How will PACE polarimeters perform?

SPeXone: highest accuracy, (hyper) spectral range includes UV, but has narrow swath.

Excellent for aerosol characterization and atmospheric correction, but utility of latter for OCI is limited by swath.

HARP2: broad swath, hyperangular, more limited spectra (no UV)

Good for aerosol characterization and atmospheric correction, can do latter for most of OCI swath. Excellent for cloud droplet size and ice particle shape/roughness retrieval, does so in entirely different manner than heritage dual-band OCI algorithms.

SPeXone + HARP2 + OCI: Hyperspectral + Hyperangle + highly accurate radiometric and polarimetric observations means PACE would have far greater information content than any single current instrument for ocean color, aerosol and cloud observations.

SPeXone and HARP2 both make all polarization measurements simultaneously which guarantees their level of accuracy no matter what scene is being observed. This is not the case for rotating filter band instruments (POLDER, 3MI) which use sequential observations that can be affected by "false polarization".

Learn more about PACE



<https://pace.gsfc.nasa.gov>
@NASAOcean (Twitter)
@NASAOcean (Facebook)
Technical Memo. series

A screenshot of the PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) website homepage. The header features the NASA logo and the text 'National Aeronautics and Space Administration'. Below this is the title 'PACE Plankton, Aerosol, Cloud, ocean Ecosystem'. A navigation bar includes links for HOME, ABOUT, MISSION, SCIENCE, APPLICATIONS, CAMPAIGNS, NEWS, and GALLERY. The main content area has a large image of a colorful, abstract representation of the ocean and atmosphere, with the text 'PACE Plankton, Aerosol, Cloud, ocean Ecosystem' overlaid. Below this is a section titled 'NASA Sets the PACE for Advanced Studies of Earth's Ocean and Atmosphere' with a paragraph of text. To the right of this text is a small video player showing a crowd of people. Below the text is a line graph titled 'NASA's long-term chlorophyll record is unparalleled' with a green line showing fluctuations. To the right of the graph are several small icons representing different organisms. Below the graph is the text 'PACE will show all chlorophyll is not created equal'. At the bottom, there is a section titled 'Why Do We Need PACE?' with a sub-header 'Ocean Ecology' and a paragraph of text. A small globe icon is visible on the right side of this section.

NASA/TM-2018-219027/ Vol. 3



PACE Technical Report Series, Volume 3

Ivona Cetinić, Charles R. McClain, and P. Jeremy Werdell, Editors

Polarimetry in the PACE Mission: Science Team Consensus Document

PACE Science team

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

backup

PACE mission

Key characteristics of the PACE observatory :

- The Ocean Color Instrument (OCI), single view hyperspectra, extending deep into the UV with SWIR bands similar to MODIS/VIIRS
- The Hyper Angular Rainbow Polarimeter (HARP-2), up to 60 views at 670 nm to observe cloud bows (and neutral points) at the pixel level
- The Spectro-polarimeter for Planetary Exploration (SPEXone), multi-angle polarimetry extending into the UV
- All instrument data provided on a common grid (L1C)
- 676.5 km altitude and 13:00 local Equatorial crossing time
- Sun synchronous, polar, ascending orbit with 98° inclination
- Fall 2022 launch, three-year design

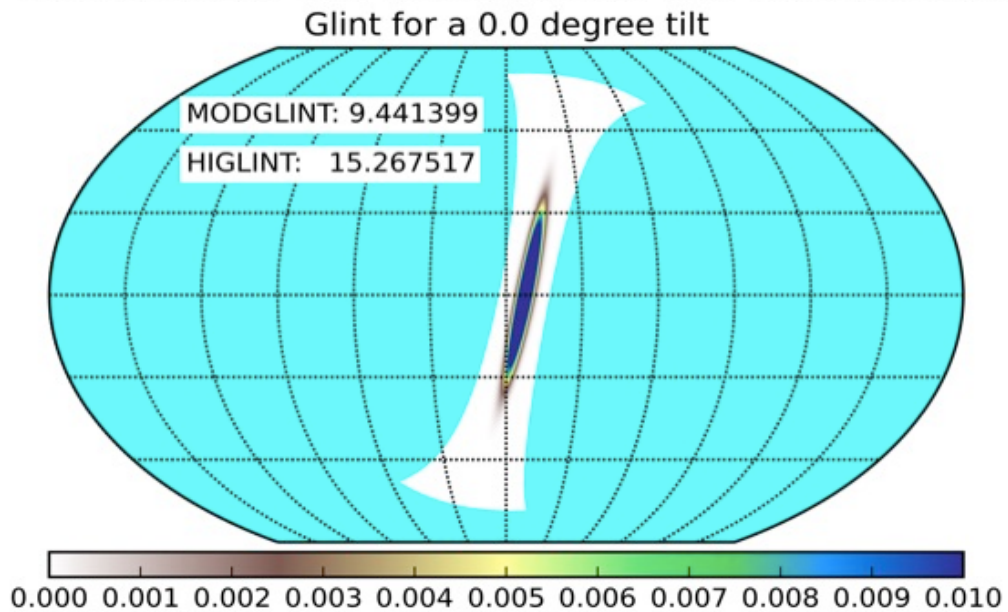
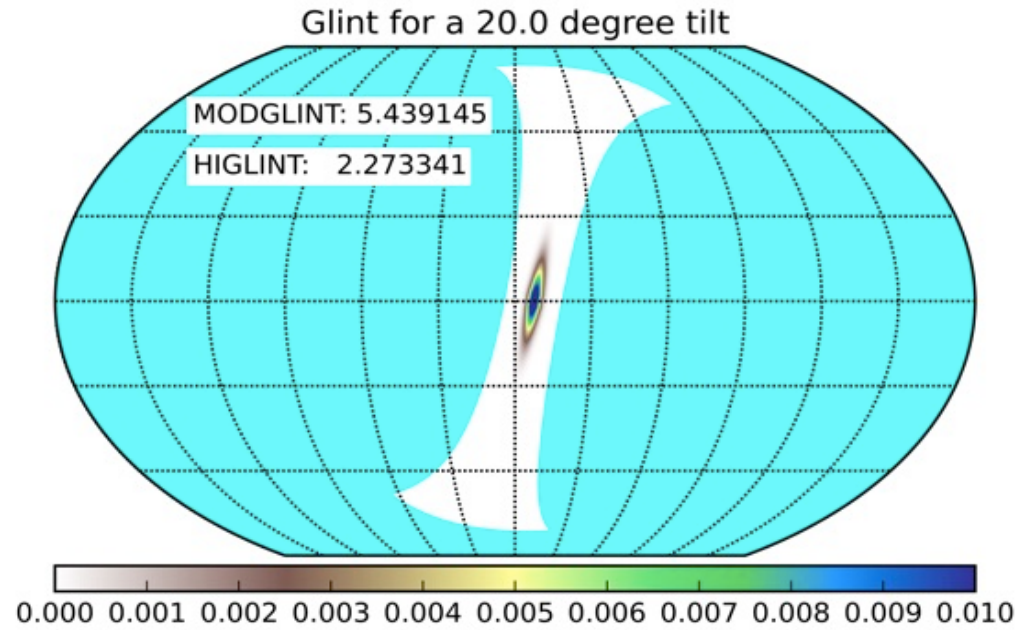
Lots of new and exciting opportunities to remotely sense the properties of aerosols and clouds

PACE Threshold aerosol and cloud product requirements

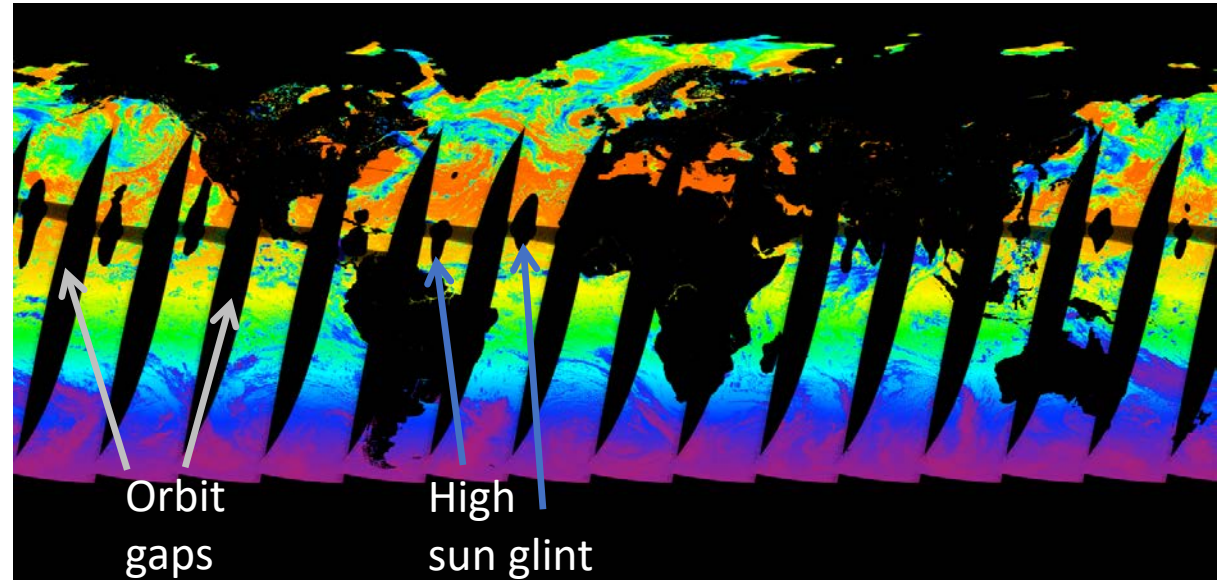
Data Product	Range	Uncertainty
Total aerosol optical depth at 380 nm	0.05 to 5	0.06 or 40%
Total aerosol optical depth at 440, 500, 550 and 675 nm over land	0.05 to 5	0.06 or 20%
Total aerosol optical depth at 440, 500, 550 and 675 nm over oceans	0.05 to 5	0.04 or 15%
Fraction of visible aerosol optical depth from fine mode aerosols over oceans at 550 nm	0.05 to 1	±25%
Cloud layer detection for optical depth < 0.3	NA	40%
Cloud top pressure of opaque (optical depth > 3) clouds	100 to 1000 hPa	60 hPa
Optical thickness of liquid clouds	5 to 100	25%
Optical thickness of ice clouds	5 to 100	35%
Effective radius of liquid clouds	5 to 50 µm	25%
Effective radius of ice clouds	5 to 50 µm	35%
Atmospheric data products to be derived from the above		
Water path of liquid clouds		
Water path of ice clouds		
Shortwave radiation effect		

These “heritage” requirements are to be met by OCI (alone)

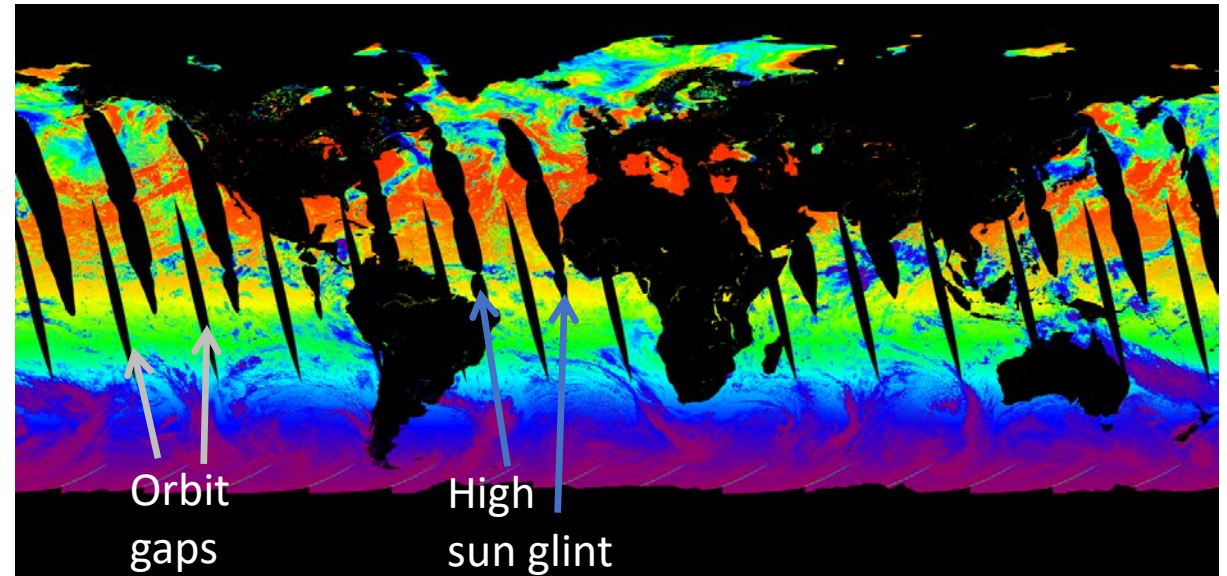
OCI is tilted 20° to avoid glint



SeaWiFS PAR - June 21, 2007 (with tilt)

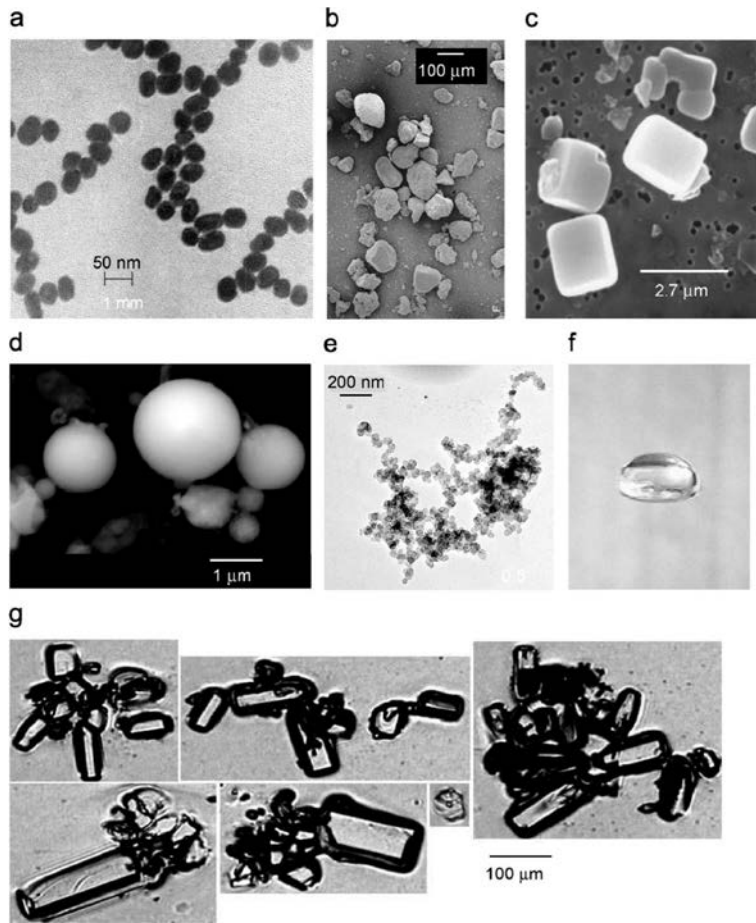


MODIS-Aqua PAR - June 21, 2007 (without tilt)



Multi-angle polarimeters on PACE

For multi-angle polarimetric observations to be beneficial for aerosol and cloud characterization and atmospheric correction they need the following capabilities:



Example atmospheric aerosols, particles that have a wide range of sizes, shapes and chemical compositions.

Spectral range

- Wide spectral range needed for accurate aerosol retrievals over land.

Swath width

- A broad, OCI-matching swath is desired for atmospheric correction

Angular range

- A wide view angle range observes scattering angles essential for aerosol size and complex refractive index retrieval.

Polarimetric accuracy

- High accuracy needed for best aerosol and cloud retrievals

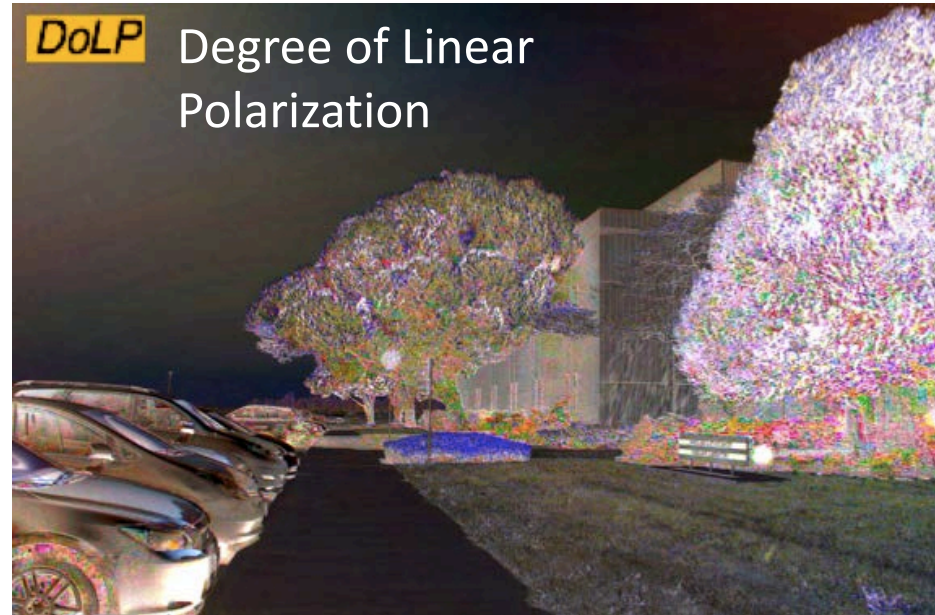
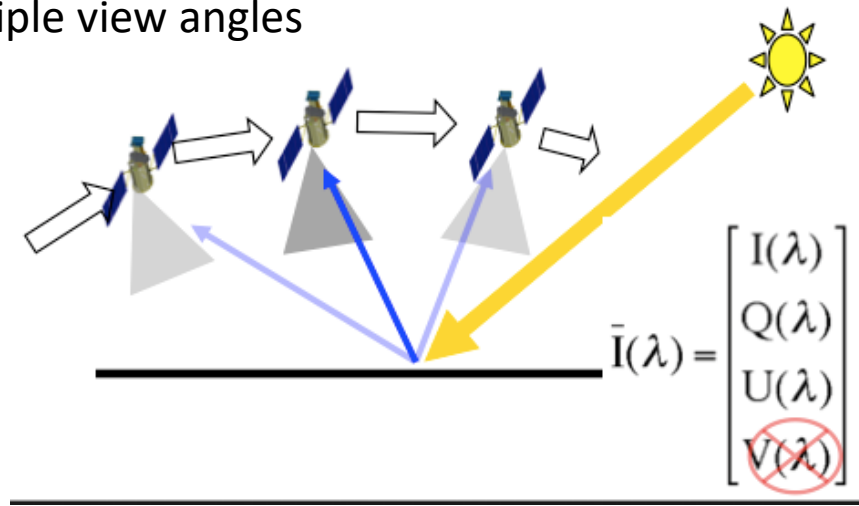
Number of viewing angles

- Aerosols: roughly five
- Ice clouds: roughly ten for crystal shape and roughness
- Liquid clouds: 40-60 view angles

Multi-angle polarimetry adds dimensions of information



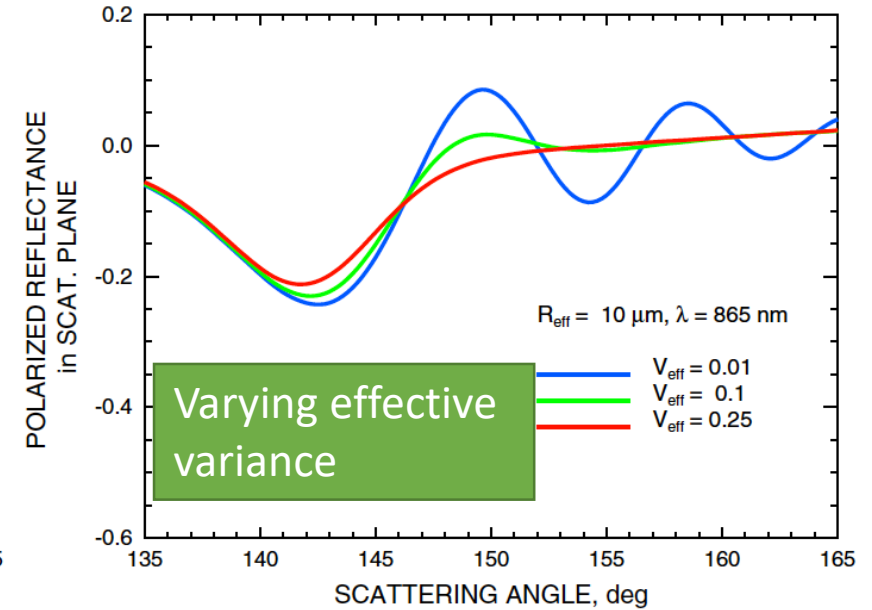
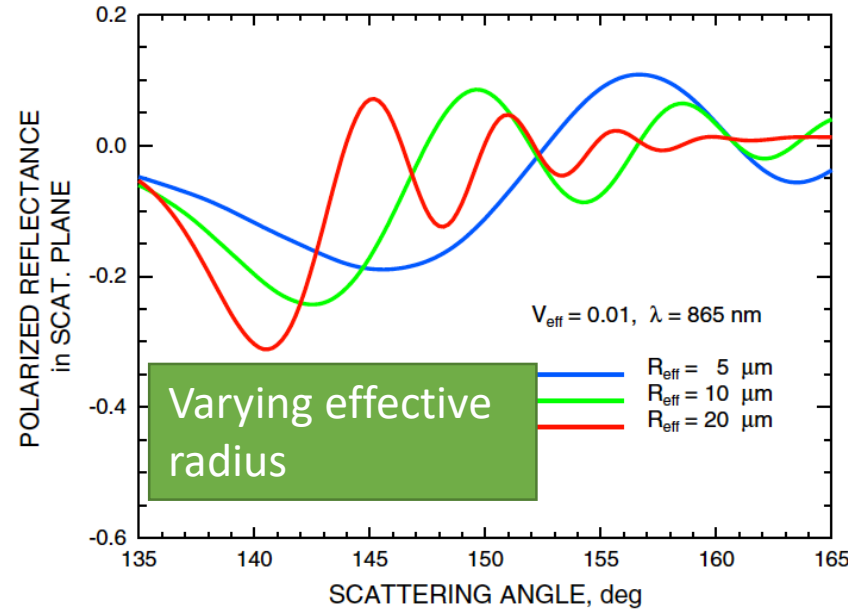
Multiple view angles



Droplet size distribution retrievals

Alexandrov et al., RSE 2012

Primary rainbow width and supernumerary bows structure depends on drop size distribution



Polarized reflectances can be approximated by Mie calculations and simple formula accounting for other effects

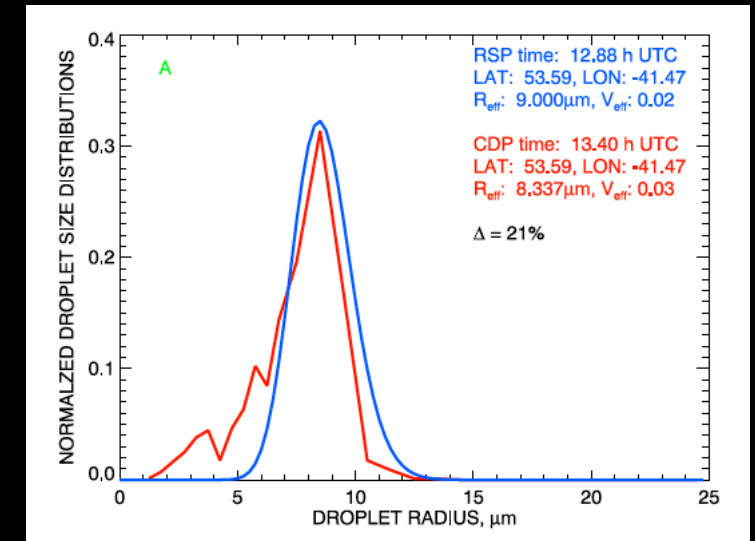
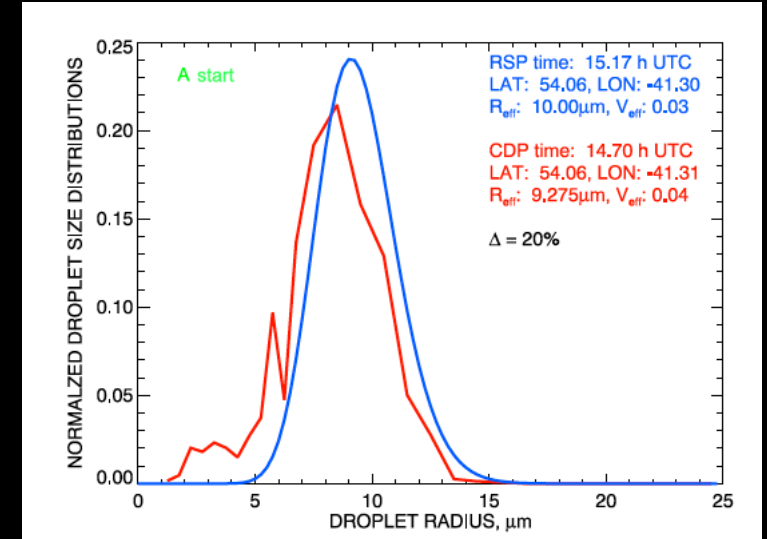
$$R_Q(\lambda, \Theta) = A(\lambda) P_{12}^{Mie}(\lambda, \Theta, r_e, v_e) + B(\lambda) \cos^2 \Theta + C(\lambda)$$

A, B, C are fit parameters accounting for optical thickness, multiple scattering, 3D effects, calibration, Rayleigh, ice, aerosols

Droplet size distribution retrievals

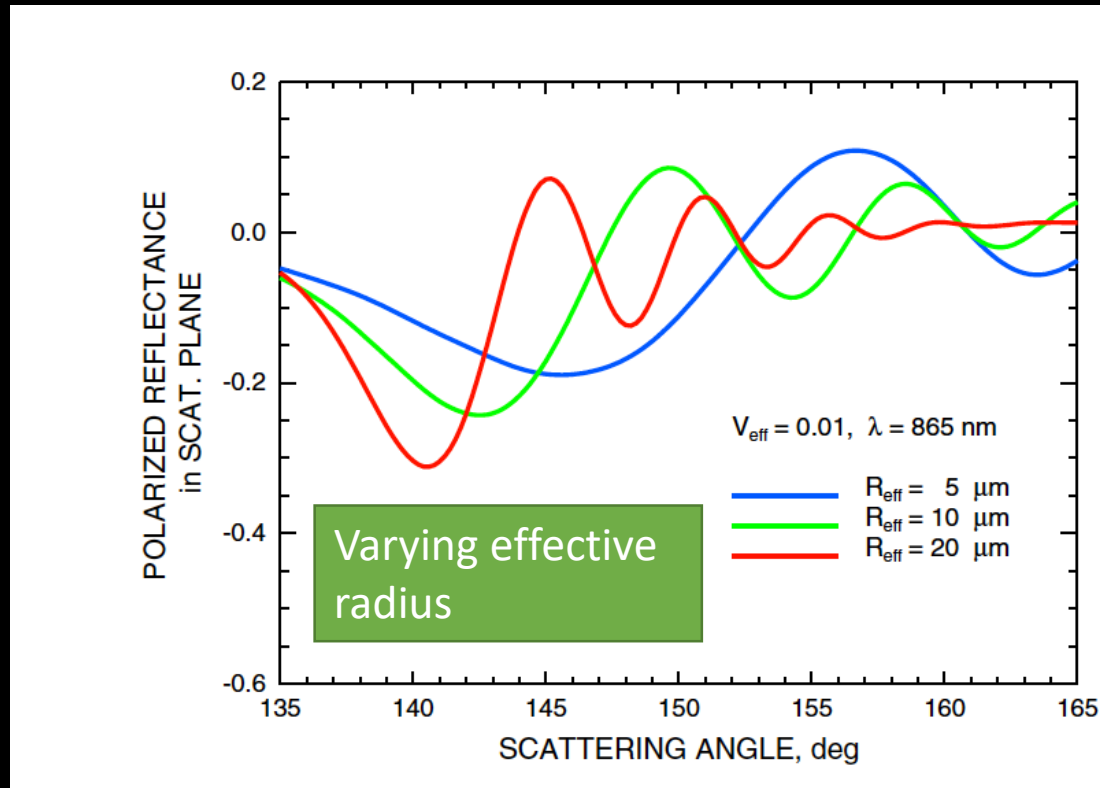
Expected uncertainties

- Effective radius:
 - 1-D and 3-D simulated measurements: <5%
 - RSP retrievals versus in situ: <10%
- Variance (for mono-modal situations):
 - 1-D and 3-D simulated measurements: 6-27%
 - RSP retrievals versus in situ: mostly <50%
- References:
 - Alexandrov et al., RSE, 2012, 2018
 - Miller et al., AMT, 2018
 - Shang et al., AMT 2015

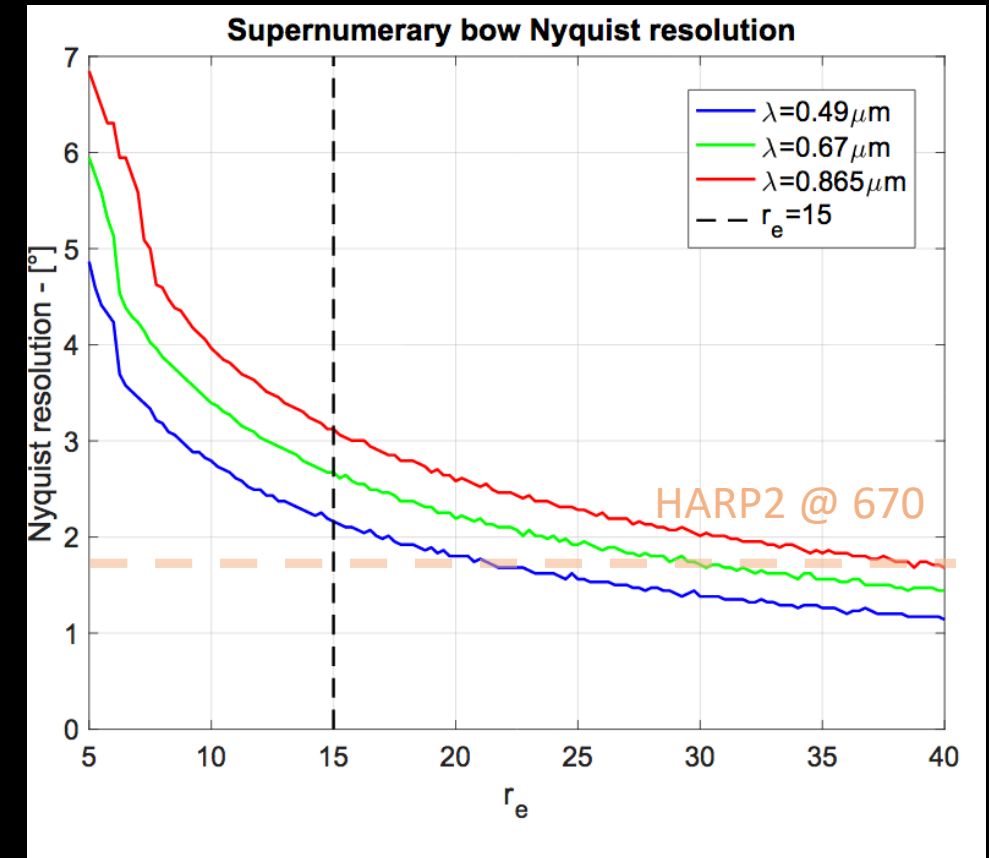


Droplet size distribution retrievals

Miller et al., AMT, 2018



Sufficient angular resolution is important to infer droplet size distributions



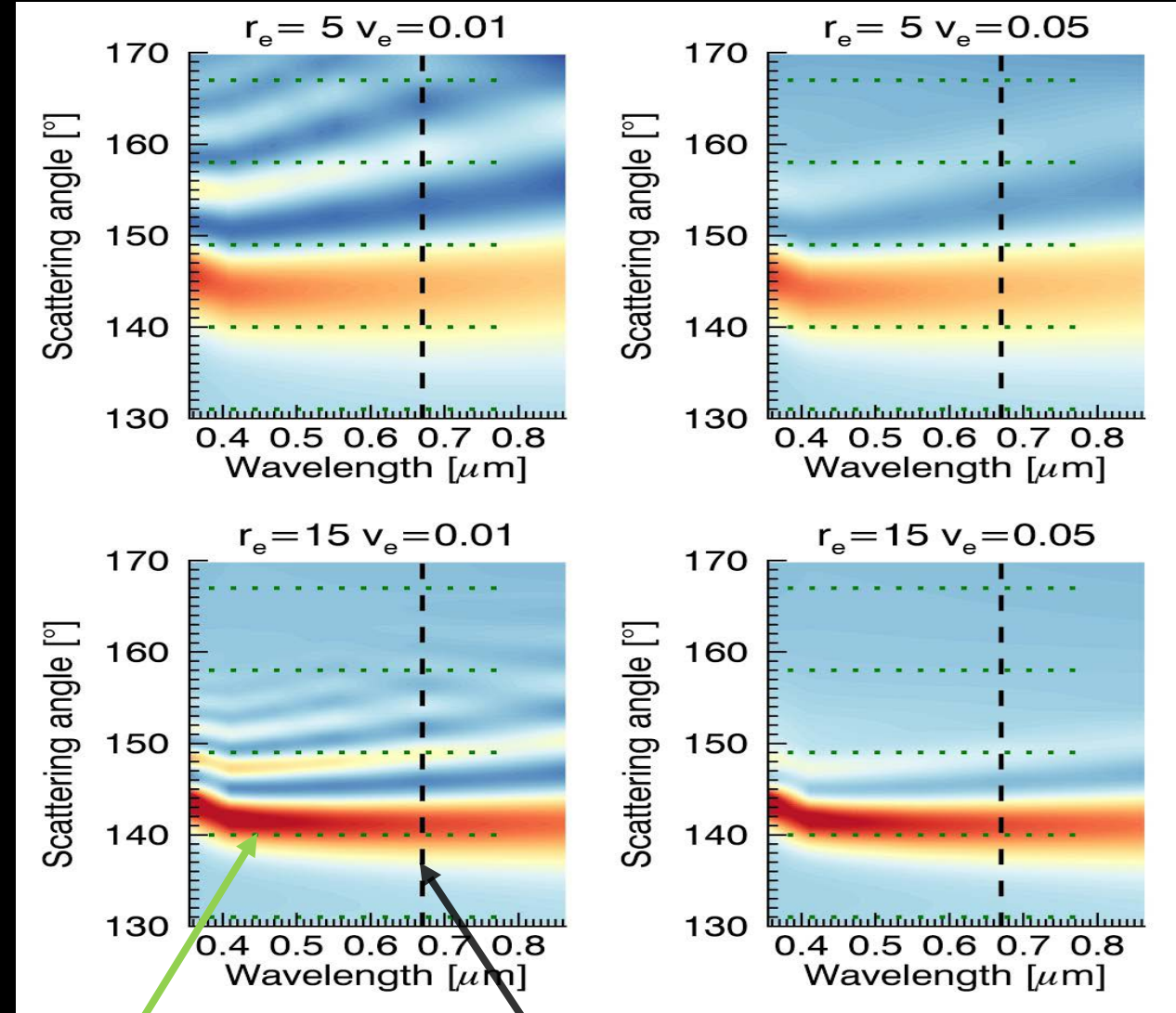
HARP-2's resolution of $\sim 2^{\circ}$ allows distinction of drop sizes up to effective radius of ~ 25 micron

SPeXone resolution of $10^{\circ} +$ is not sufficient

Droplet size distribution retrievals

Using SPEXone

- Varying refractive index and size parameter with wavelength also results in *spectral* variation of rainbow structure



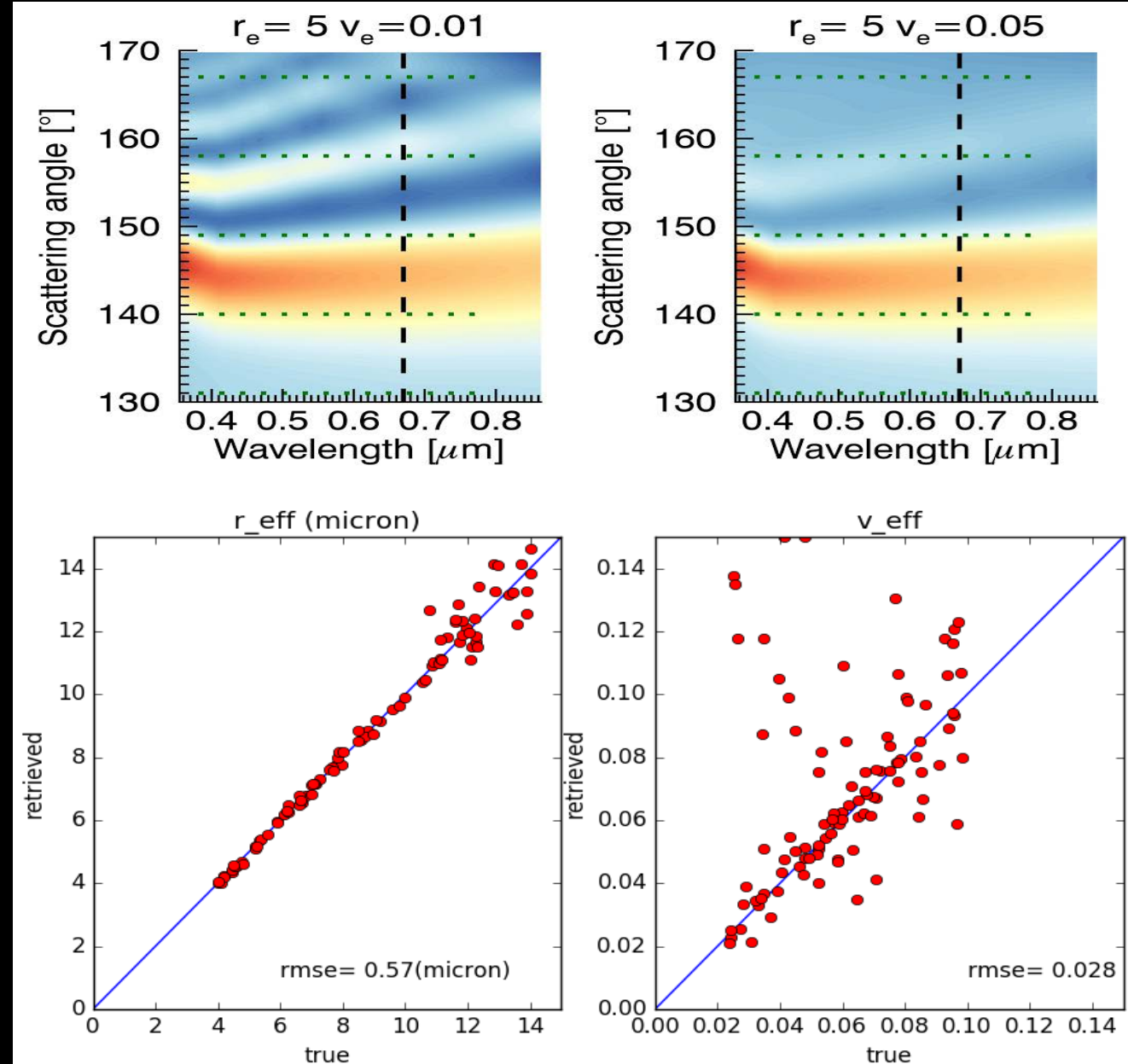
Spectral sampling
by SPEXone

Angular sampling
by HARP-2

Droplet size distribution retrievals

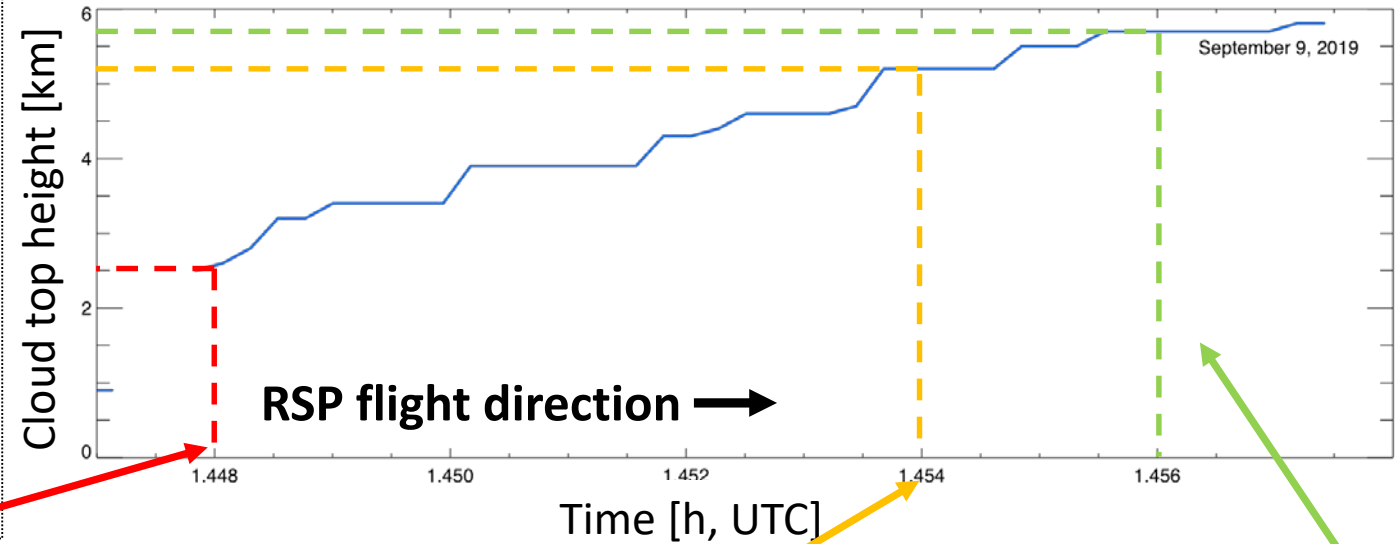
Using SPEXone

- Varying refractive index and size parameter with wavelength also results in *spectral* variation of rainbow structure
- Preliminary results on simulated SPEX measurements using adapted aerosol retrievals code from Hasekamp et al. are promising

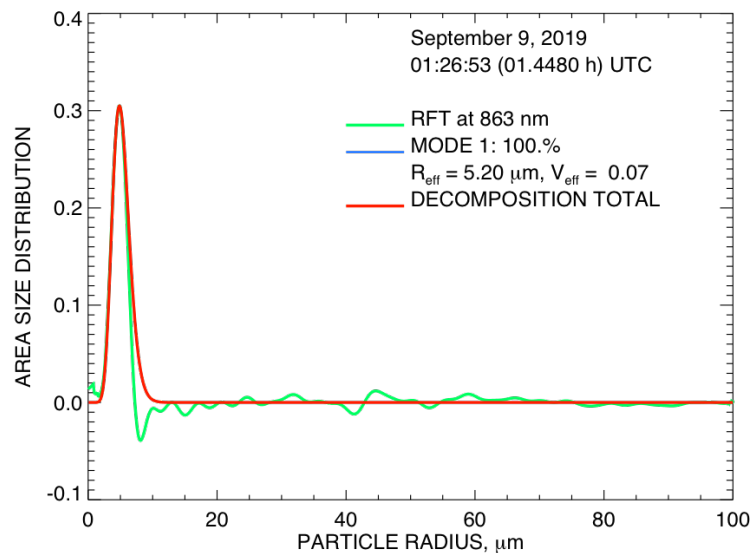


Rainbow Fourier Transform DSD retrievals

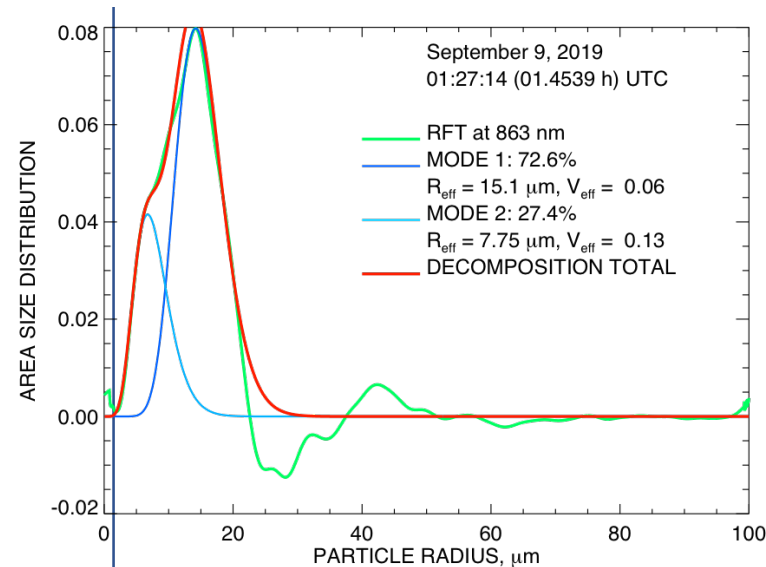
- Deconvolution of rainbow structures to infer non-parametric size distribution (Alexandrov et al., JQSRT 2012)
- HARP's 2° resolution sufficient
- RSP example of convective tower obs. shown



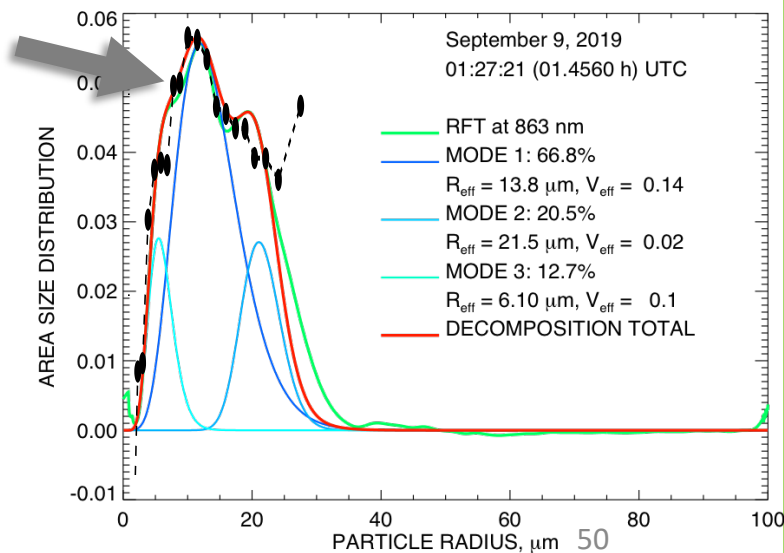
Mono-modal DSD at 2.5 km height



bi-modal DSD at 5.2 km height



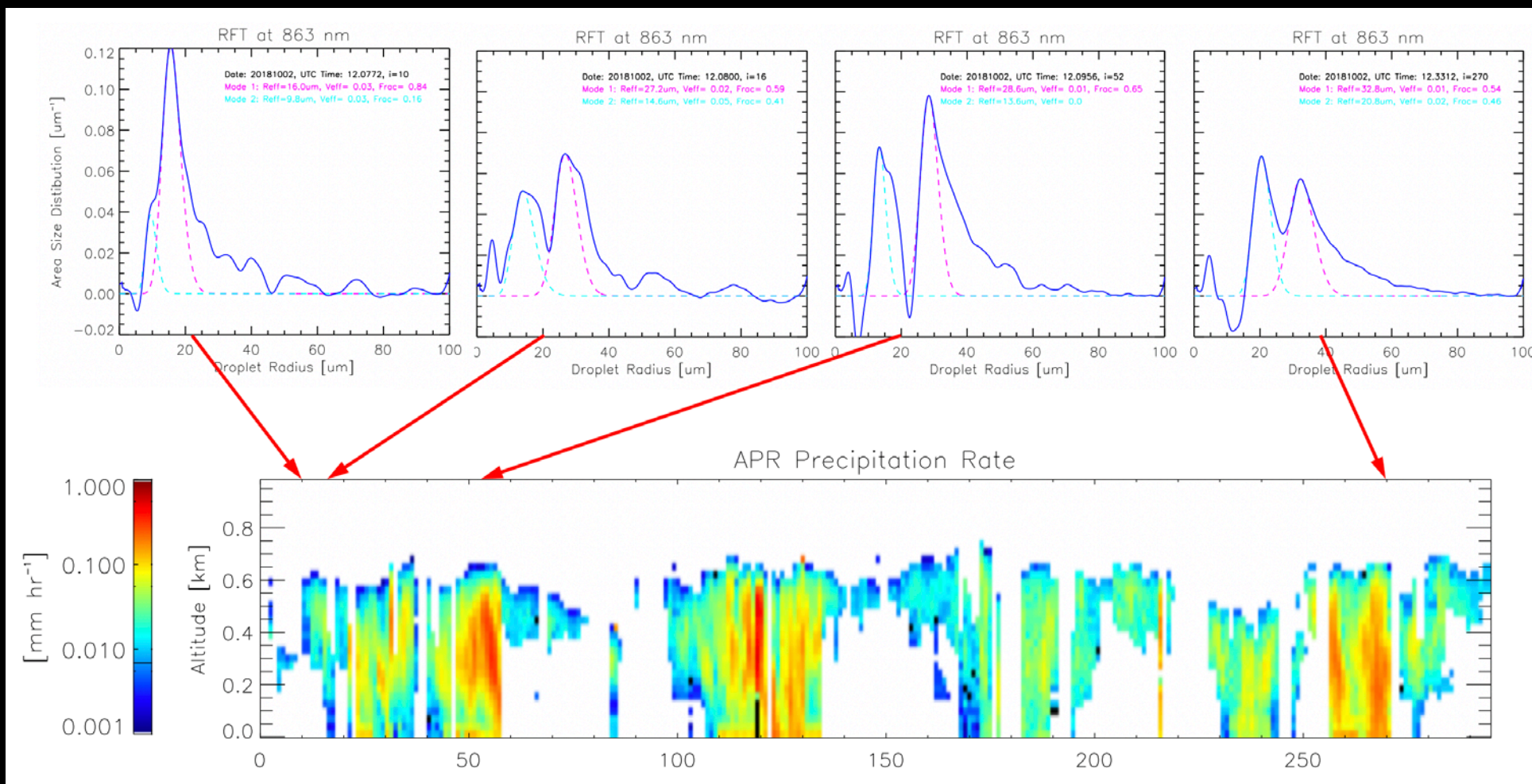
tri-modal DSD at 5.7 km height



Rainbow Fourier Transform DSD retrievals

Thursday: Poster Session 2; An investigation of a cloud droplet size distributions , Ken Sinclair, Columbia/GISS

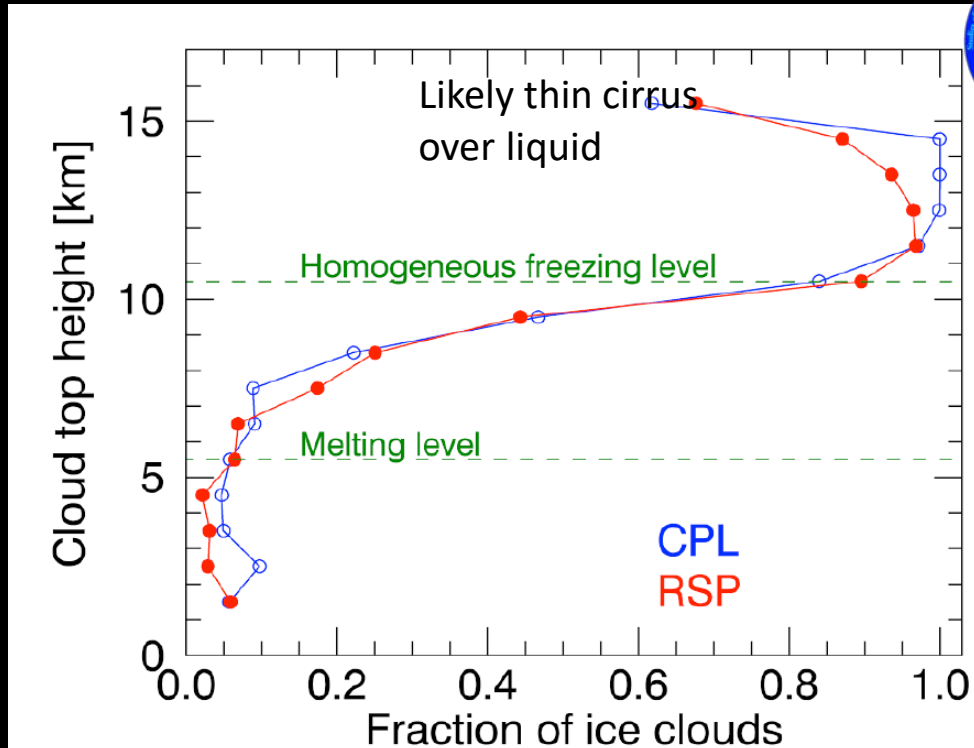
- Comparison of RFT retrievals to drizzle retrievals from APR3
- Initial results show the RFT technique has skill at detecting precipitation



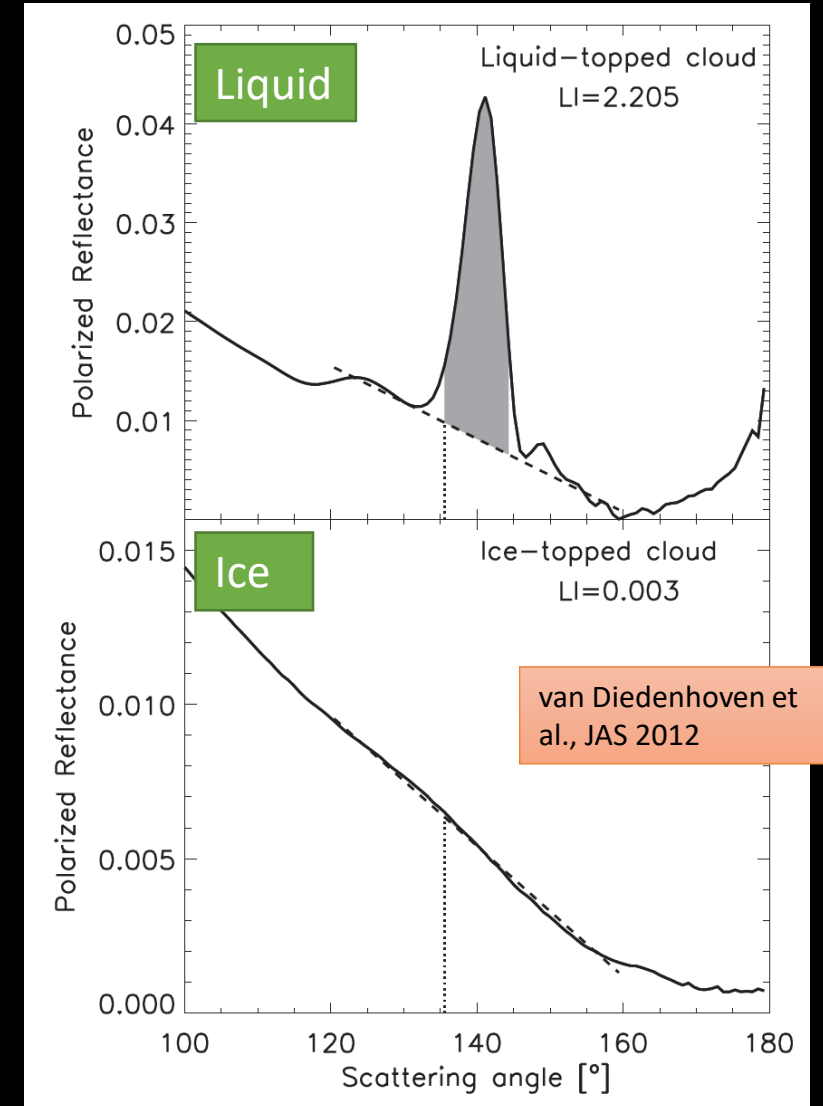
Detection of liquid at cloud top

Liquid-topped clouds have strong polarized rainbow feature, while ice-topped clouds are featureless

- References: (Goloub et al. 2000; Riedi et al. 2010; van Diedenhoven et al., JAS 2012)
- HARP resolution will allow pixel level phase detection



SEAC⁴RS RSP measurement showing good agreement with CPL lidar



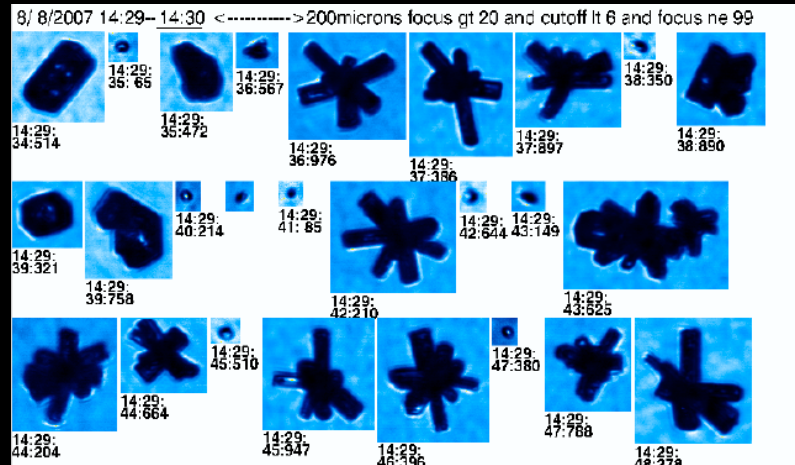
Ice crystal shape and asymmetry parameter

Thursday 10:05 – 10:20 Global statistics of cloud top ice microphysical and optical properties, Bastiaan van Dierenhoven, Columbia Univ. and NASA/GISS, USA

van Dierenhoven et al., AMT 2012

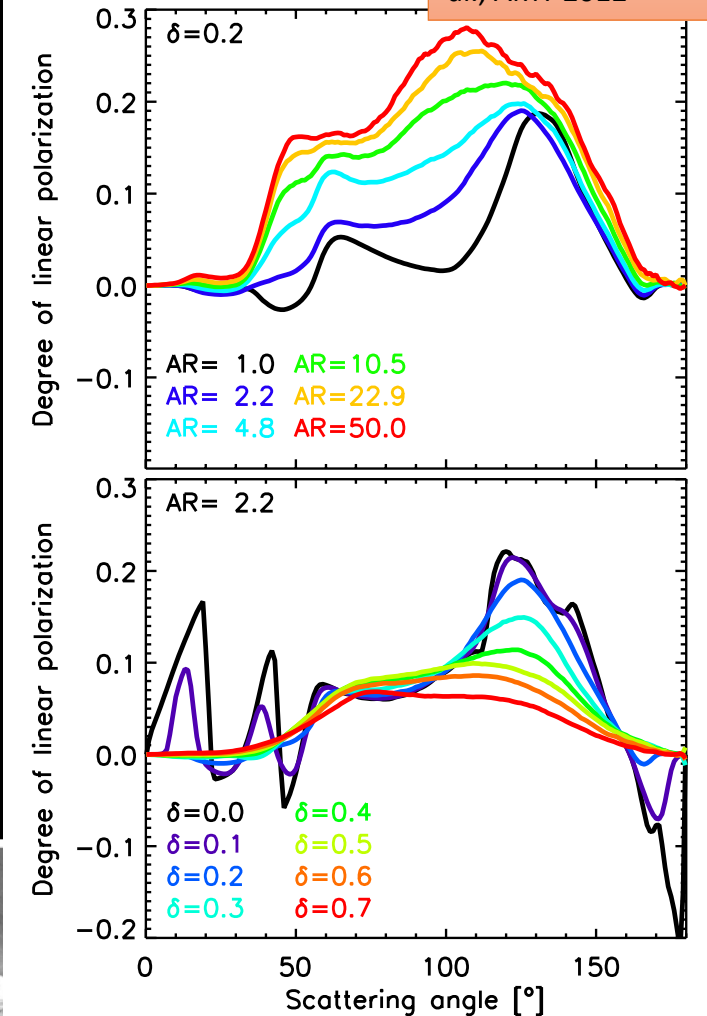
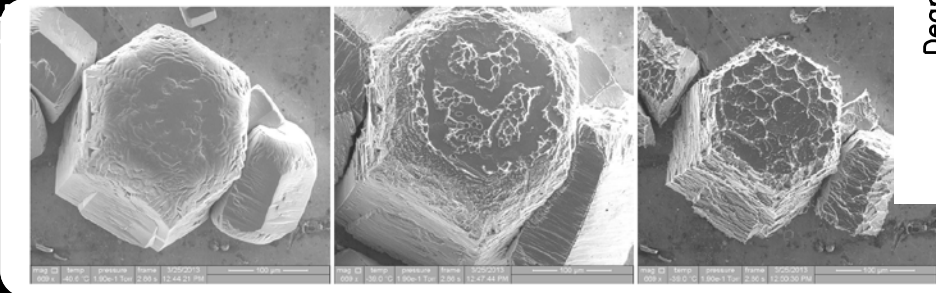
ice shape, *not size!*

- Ice scattering properties depend on (in order of importance):
 1. Aspect ratio of crystal components
 2. Level of distortion/roughness
 3. General shape (a.k.a. habit)
- Practical algorithm:**
 - Use simple hexagonal plates & columns
 - Vary aspect ratios and distortion to match measured and simulated polarized reflectances at 125-150°



In situ images of complex ice crystals

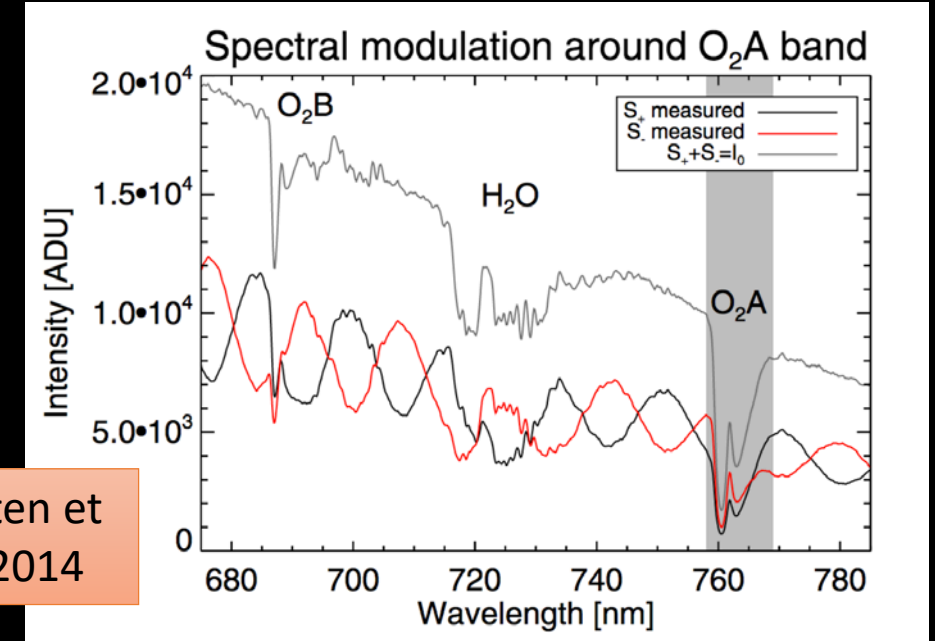
electron microscope images of roughness on ice crystals (Magee et al.)



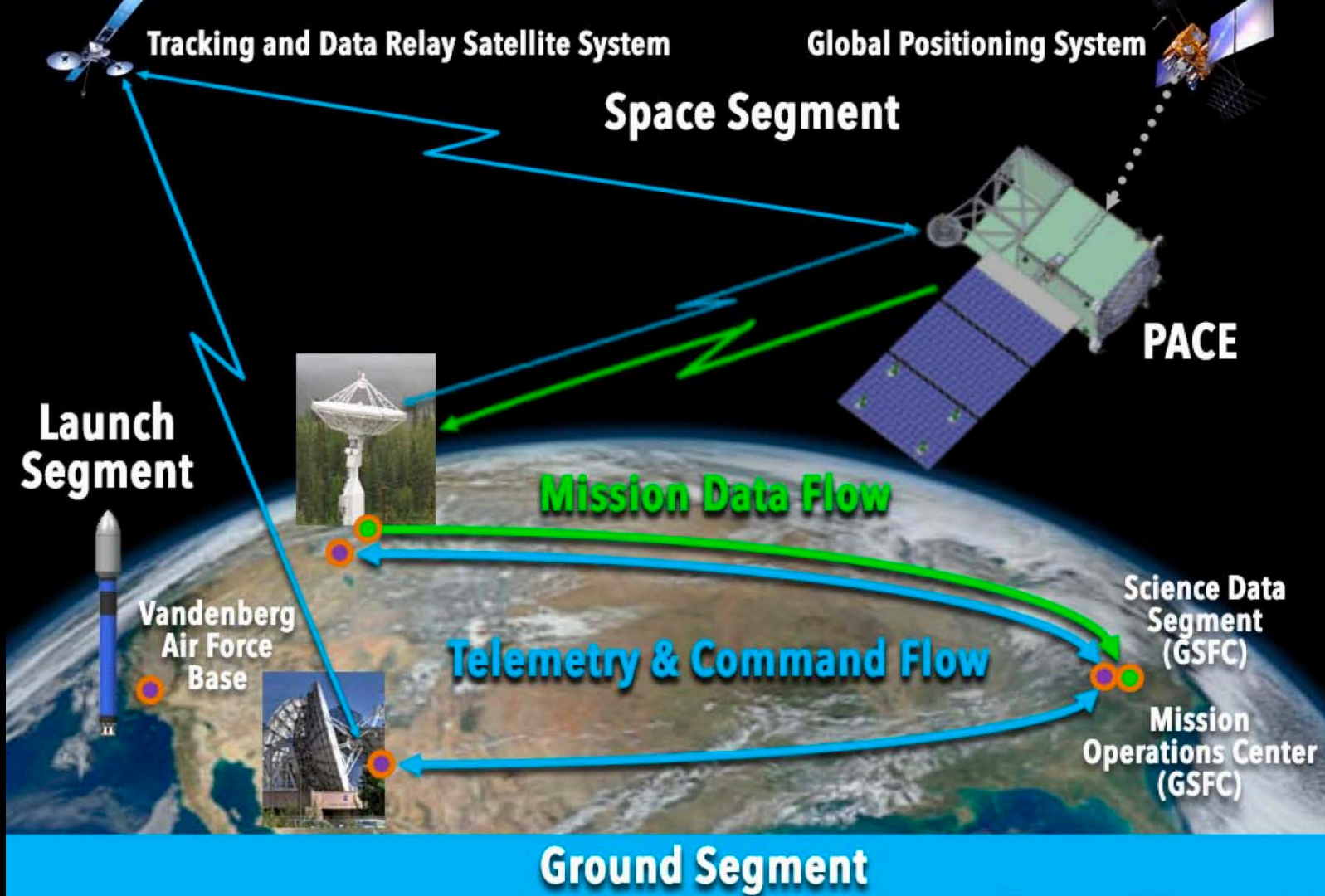
Multi-angle polarimetry in the O₂ A-band

Sinclair et al.,
RSE, 2019

van Harten et
al., AO, 2014



- Polarimetric measurements can be sampled at same spectral resolution as total reflectances (van Harten et al., AO, 2014)
- O₂ A band depth
 - total reflectance depends on height + thickness + optical thickness (Sanghavi et al., AMT 2015)
 - polarized reflectance depends on height only!
- Cloud droplet number concentrations without adiabatic assumptions



Mission Characteristics

Orbit

- 675.5 km altitude
- Polar, ascending orbit
- Sun synchronous
- 98° inclination
- 13:00 local Equatorial crossing

Communications

- Ka direct to ground
- 600 Mbps data transfer

Cost, Schedule, Lifespan

- \$805M Design-to-Cost
- Category 2, Class C
- Fall 2022 launch
- 3-year design life
- 10-years of fuel



Alaska US

Fairbanks



Chile

Punta Arenas



Norway

Svalbard



New Mexico US

White Sands
Alternate T&C



Maryland US

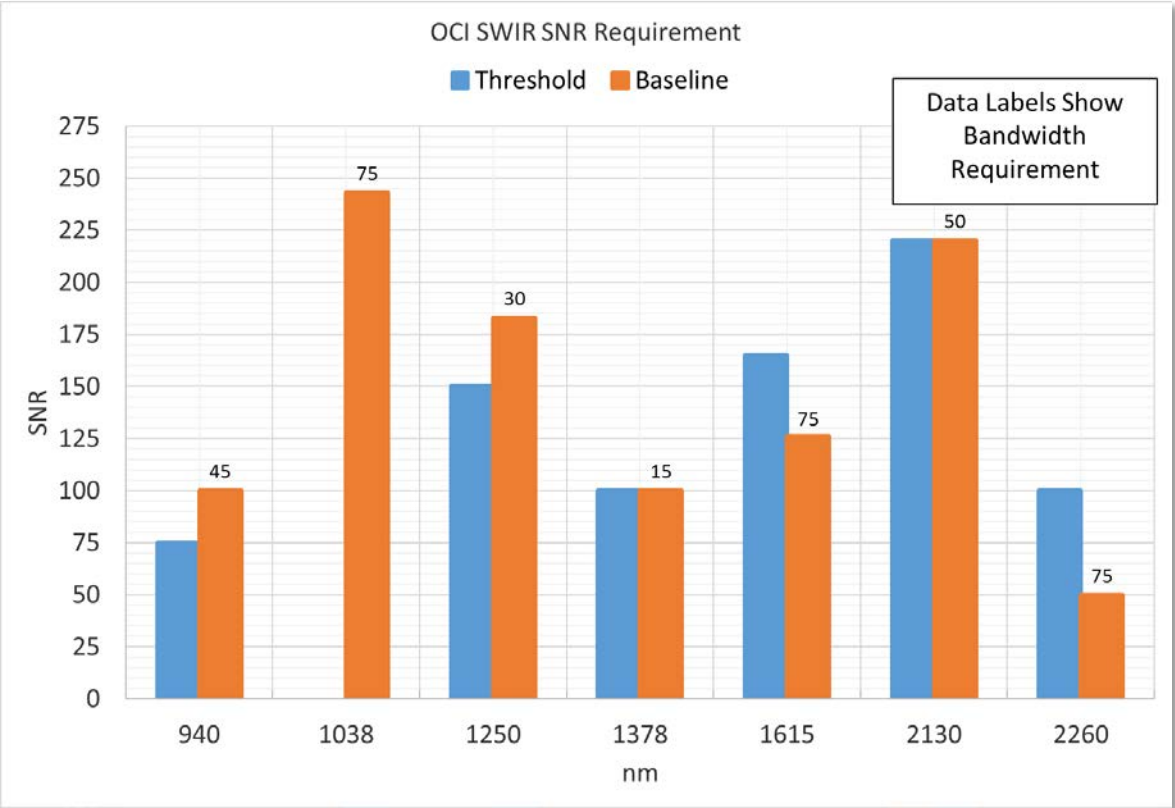
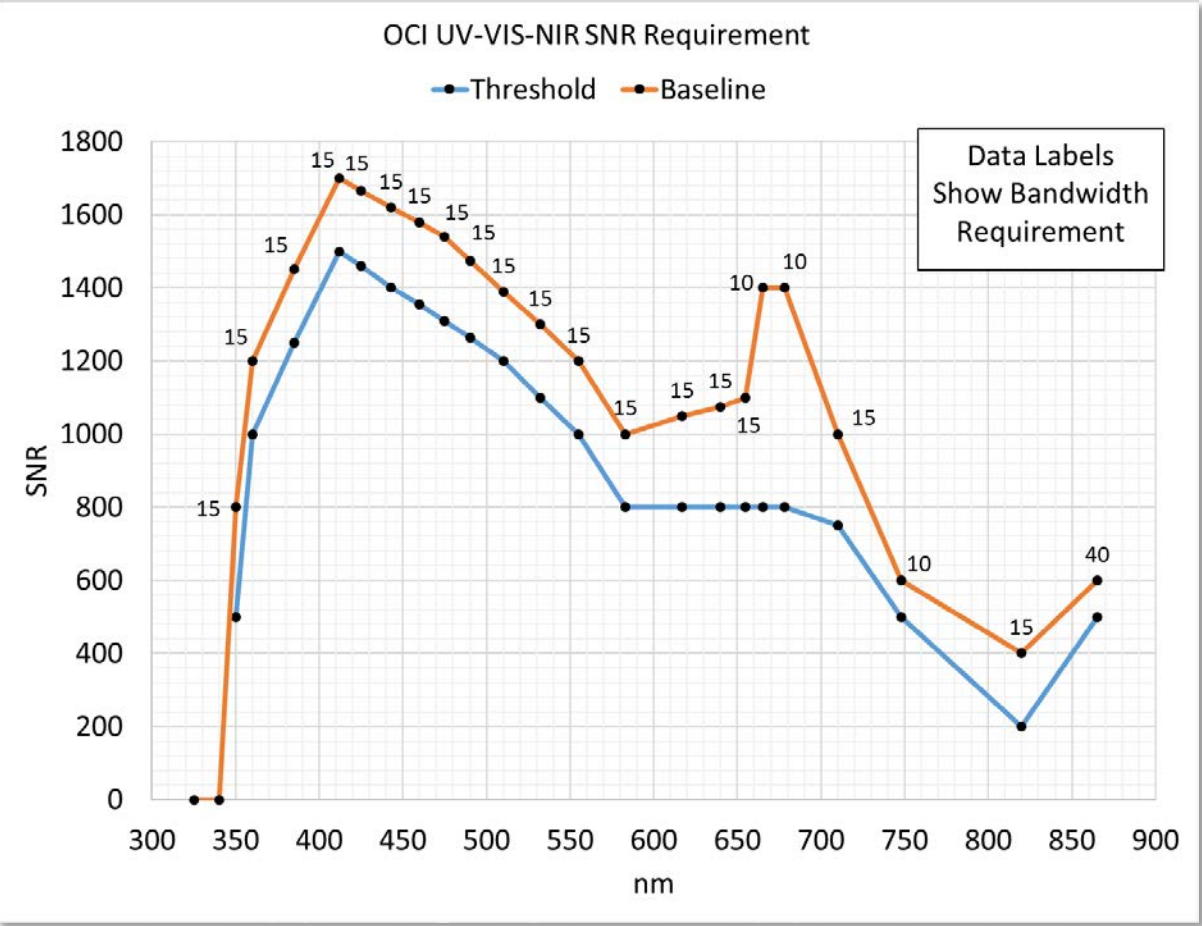
Goddard Space Flight Center
(GSFC)



Primary Telemetry & Command (T&C)
and Science Data Ground Stations

Mission Operations Center & Science Data Segment

Ocean Color Instrument (OCI) – signal-to-noise (SNR)



Required science data products (OCI)

Required data products & additional expected data products:

Level 1 required (~threshold) products

Water-leaving reflectance	Aerosol optical thickness
Chlorophyll-a	Aerosol fine mode fraction
Phytoplankton absorption	Liquid / ice cloud optical thickness
NAP+CDOM absorption	Liquid / ice cloud effective radius
Particulate backscattering	Cloud layer detection ($\tau < 0.3$)
Diffuse attenuation	Cloud top pressure ($\tau > 3$)
Fluorescence line height	Shortwave radiation effect

Building capabilities to produce this full suite of OCI products from proxy data using preliminary/heritage algorithms by the end of 2018

Advanced & evaluation science data products

Required data products & additional expected data products:

Incomplete list of advanced (~baseline) products

Carbon stocks & fluxes	Liquid / ice cloud water path
Phytoplankton pigments	Polarimeter-specific products
Phytoplankton physiology	Applied sciences-specific products
Community structure (PFTs)	Land data products (TBD)
Productivity	Your very favorite data product that
PAR, light attenuation, water quality	I forgot to list (<i>so plz don't ask</i>)

General expectations for future PACE science teams:

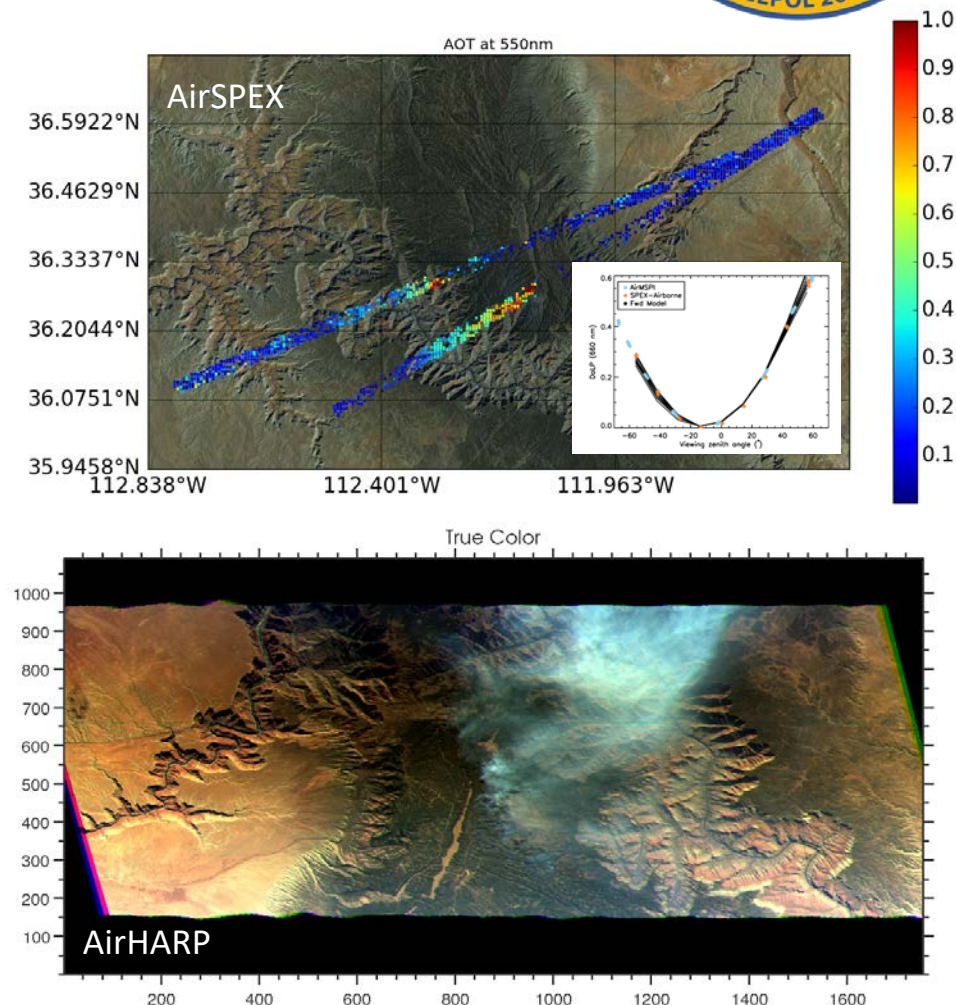
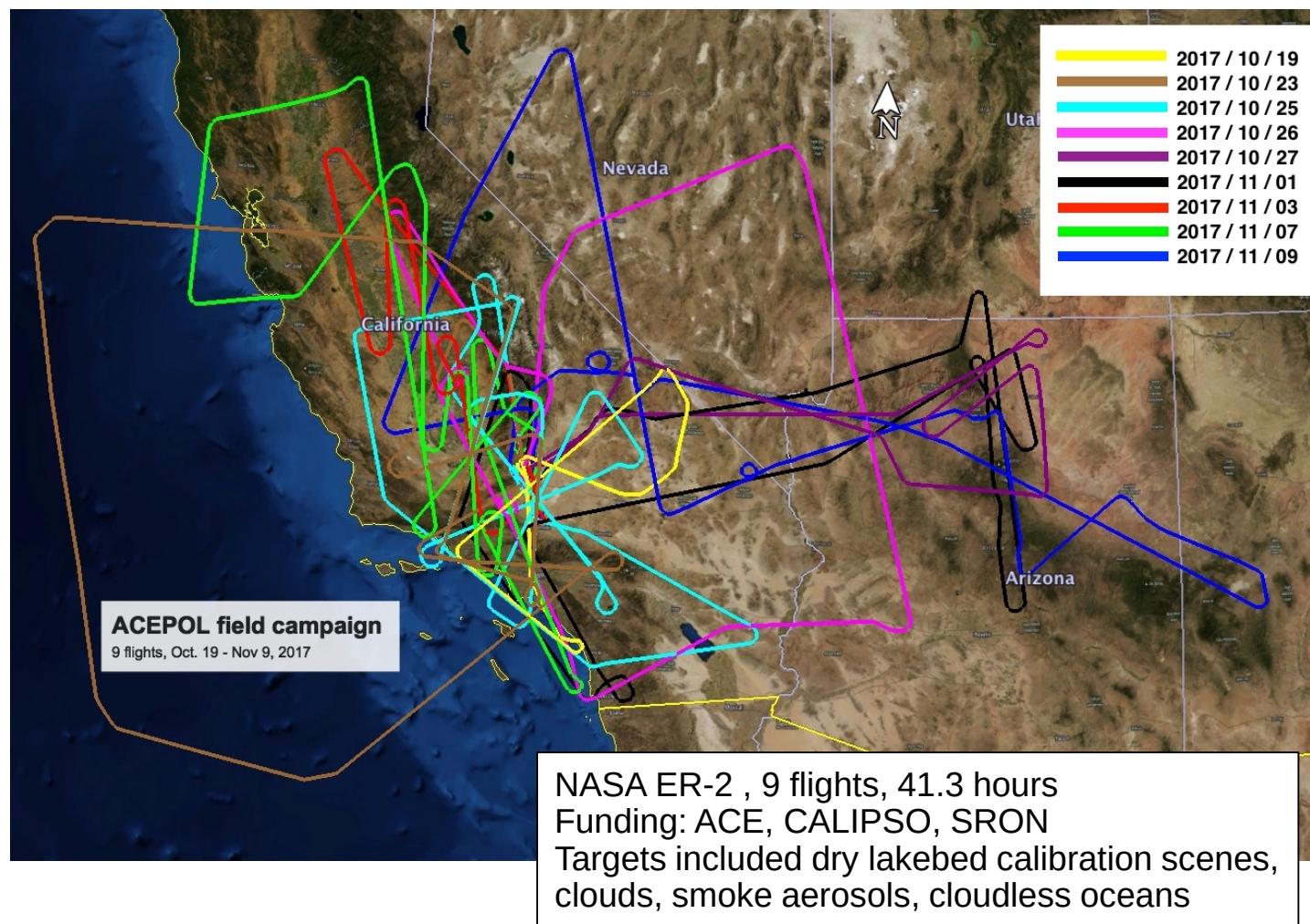
- *Novel* methods for required products (exploit spectral capabilities)
- Methods for advanced products + scientific applications

ACEPOL: airborne polarimeter prototypes flew together

Airborne versions both flew as part of the Aerosol Characterization from Polarimeter and Lidar (ACEPOL) field campaign, Oct-Nov 2017 (alongside other polarimeters and lidars).

Polarimeters: AirMSPI, AirHARP, RSP, AirSPEX

Lidars: CPL, HSRL-2

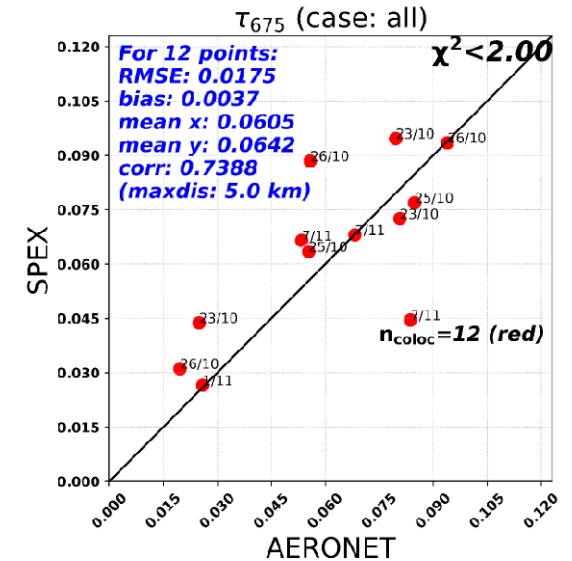
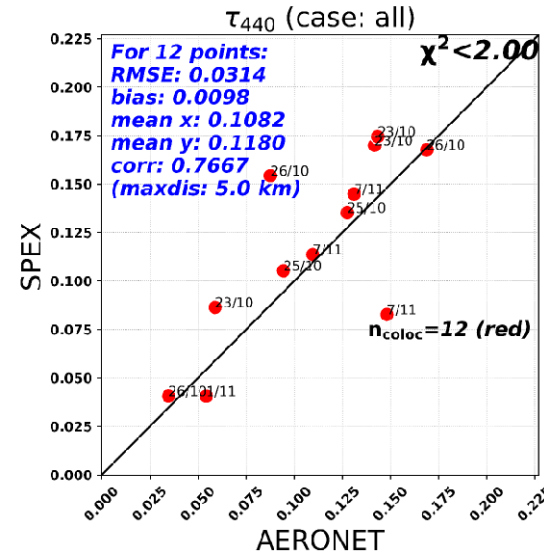
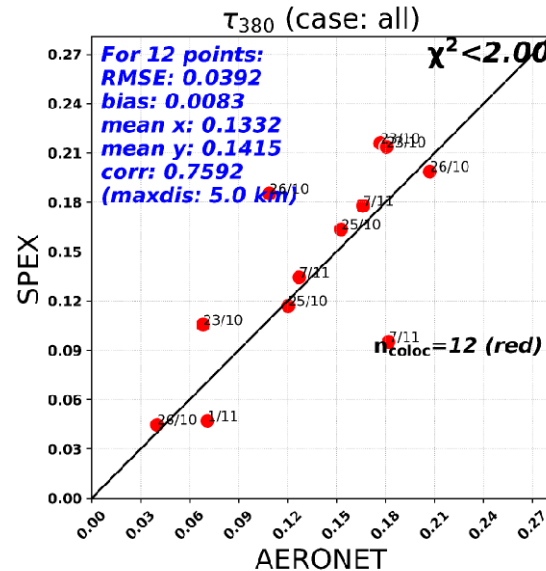


How will PACE polarimeters perform?

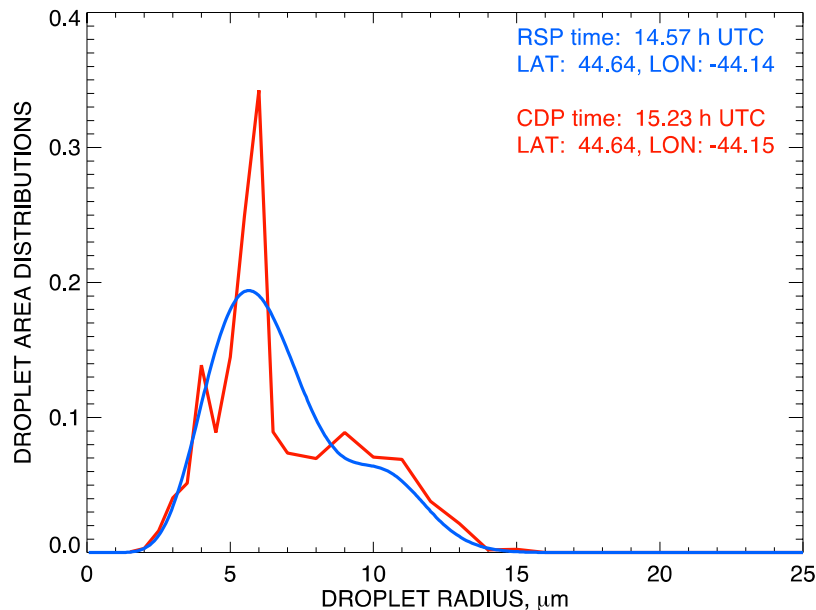
SPEXone:

Example aerosol retrievals from SPEXAirborne during ACEPOL

Hasekamp et al. AGU 2018



HARP2: Examples of what a hyperangular capability provides

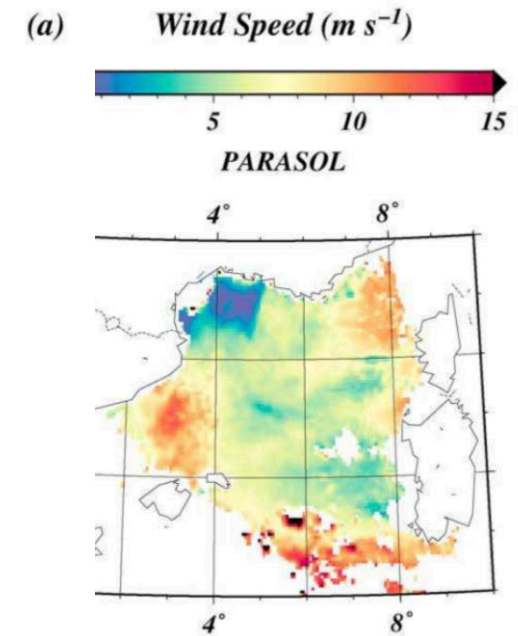
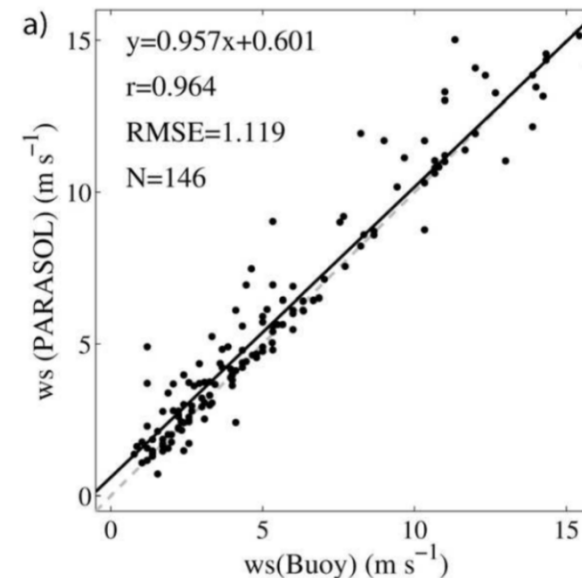


Droplet size distributions

Alexandrov et al. 2018

Wind speeds

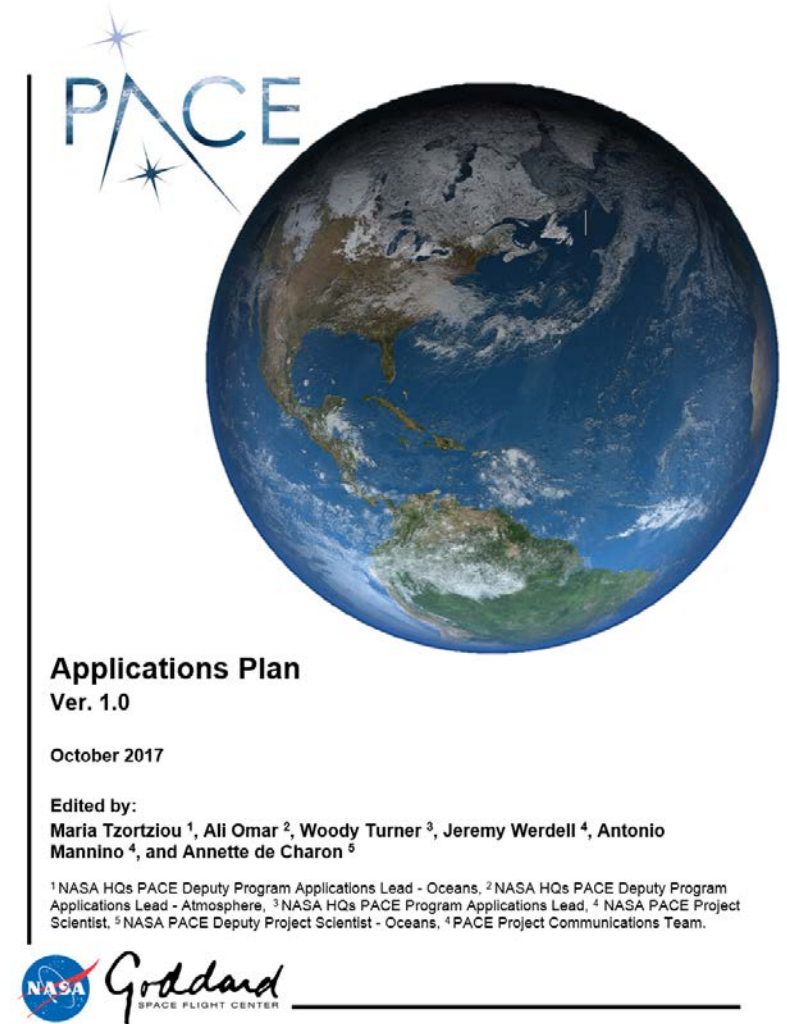
Harmel and Chami 2012



Looking forward: applied sciences

New agency directive on Applied Sciences within missions

Mission Phase	Applications Activity
Pre-phase A	- Assessment of the community of practice. - Description of potential applications from the PACE data using the requirements established by the Science Definition Team (SDT).
Phase A	- Applications website establishment. - Database of user community individuals begins. - Applications Plan written and posted to website. - Applications white papers developed and posted to the website. - Applications Traceability Matrices developed and posted to the website. - Applications Working Group established.
Phase B	- Workshop conducted with targeted science communities to communicate key model, observation and Applied Sciences opportunities and requirements. - Newsletters, articles, posters, and other communications developed to expand the community of potential. - Early Adopters Program established.
Phase C/D	- Annual workshop focused on results from Early Adopters. - Description of validation datasets to the community of practice. - Conference presentations and papers; newsletters and journal articles on user interaction to expand the community of potential. - Data workshops, short courses, focus sessions, tutorials. - Interaction with NASA HQ Applied Sciences to prepare funding opportunities.
Phase E	- Documenting decision support provided by mission data. - Newsletter, journal articles, conference presentations of applications of data. - Community interaction and support of data reprocessing and improvement. Calibration/validation of data quality, format, issues. - Conduct Impact Workshop to assess success of Applications implementation. - Conduct a Quantitative PACE Data Societal Benefit Value Assessment. - Information for Senior Review Submissions.



Extend key systematic **ocean** biological, ecological, & biogeochemical climate data records and **cloud & aerosol climate data records**

Make **new global measurements of ocean color** that are essential for understanding the global carbon cycle & ocean ecosystem responses to a changing climate

Collect **global observations of aerosol & cloud properties**, focusing on reducing the largest uncertainties in climate & radiative forcing models of the Earth system

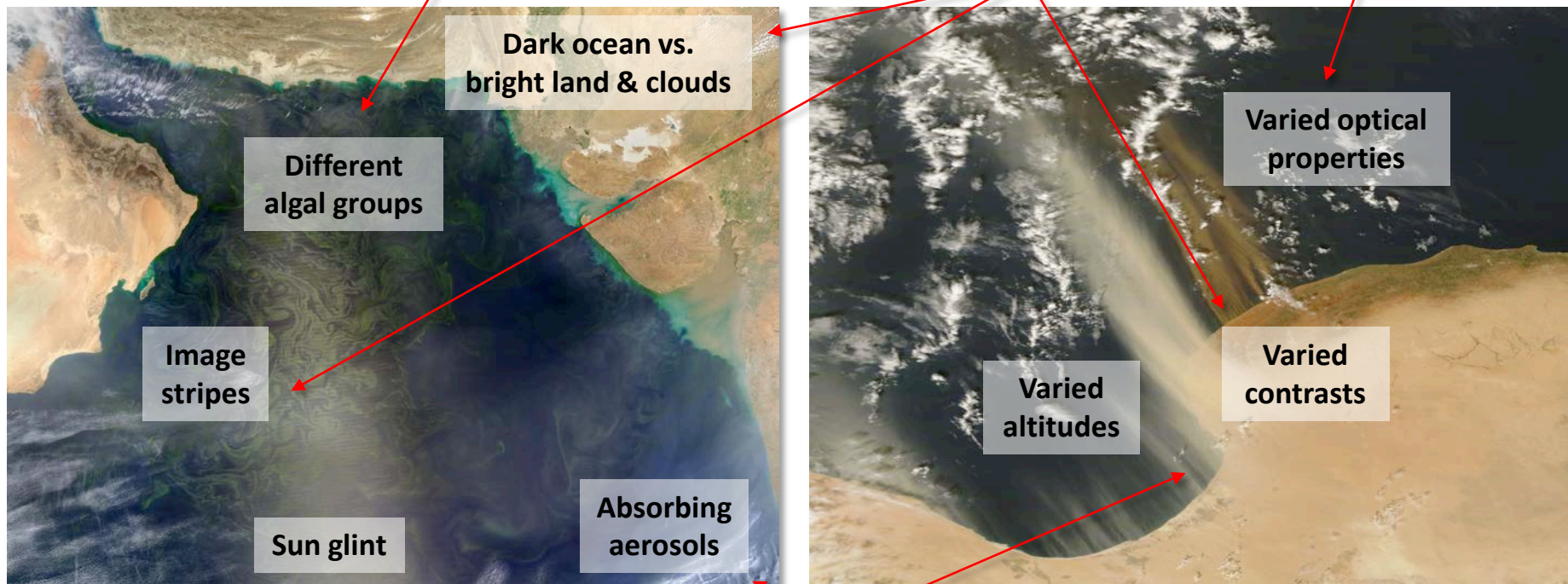
GSD of $1 \pm 0.1 \text{ km}^2$ at nadir

Twice-monthly lunar calibration & onboard solar calibration (daily, monthly, dim)

Spectral range from 350-865 @ 5 nm

940, 1038, 1250, 1378, 1615, 2130, 2260 nm

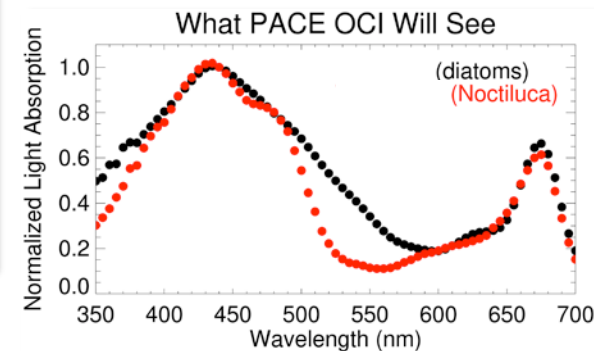
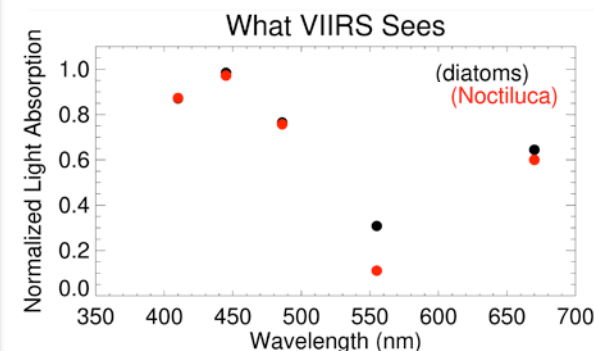
Instrument performance requirements



Tilt $\pm 20^\circ$

*Spectral range goal of **320**-865 @ 5 nm*

Challenge addressed:
signals from the ocean are small & differentiating between constituents requires additional information relative to what we have today



Improve our understanding of how **aerosols influence ocean ecosystems & biogeochemical cycles** and how **ocean biological & photochemical processes** affect the atmosphere

Extend key systematic **ocean** biological, ecological, & biogeochemical climate data records and **cloud & aerosol climate data records**

Make **new global measurements of ocean color** that are essential for understanding the global carbon cycle & ocean ecosystem responses to a changing climate

Collect **global observations of aerosol & cloud properties**, focusing on reducing the largest uncertainties in climate & radiative forcing models of the Earth system

Challenge addressed:
aerosol, cloud, climate interactions are complicated and difficult to observe

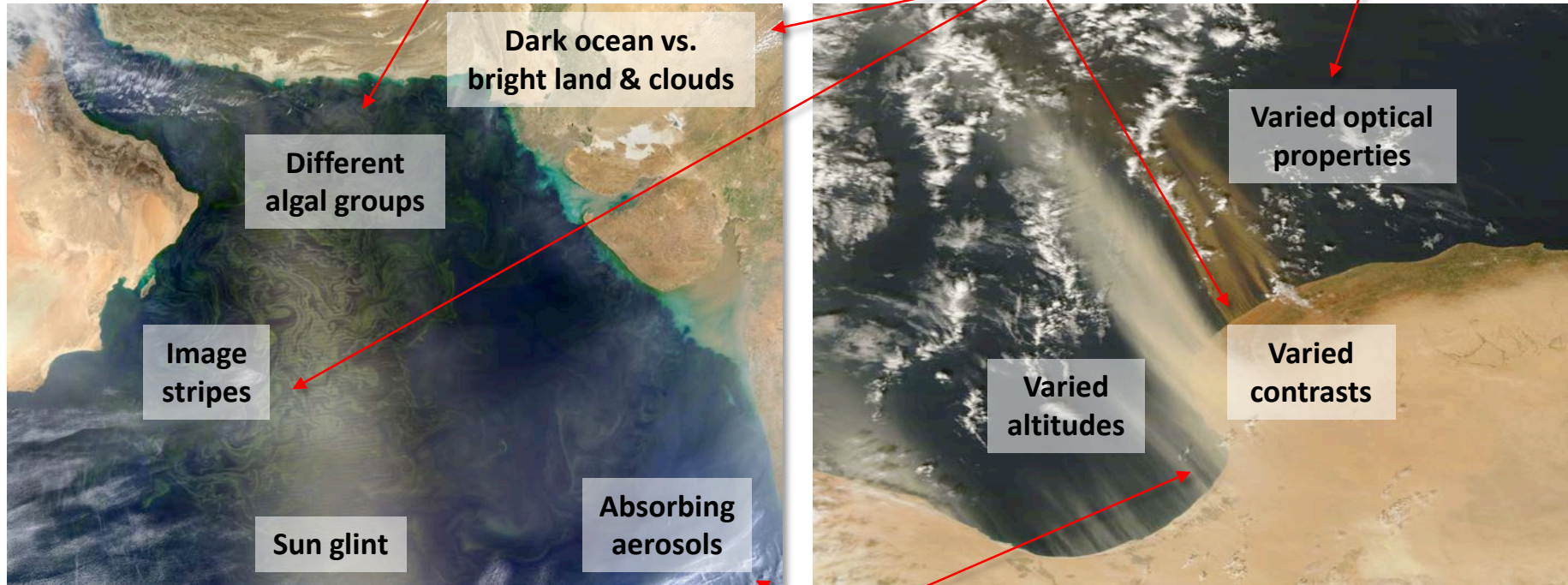
GSD of $1 \pm 0.1 \text{ km}^2$ at nadir

Twice-monthly lunar calibration & onboard solar calibration (daily, monthly, dim)

Spectral range from 350-865 @ 5 nm

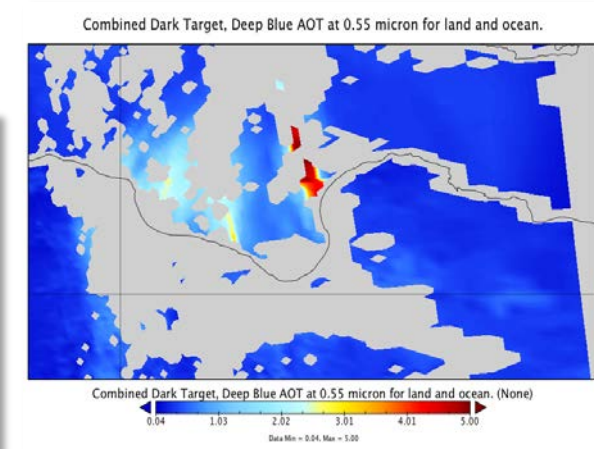
940, 1038, 1250, 1378, 1615, 2130, 2260 nm

Instrument performance requirements



Tilt $\pm 20^\circ$

*Spectral range goal of **320**-865 @ 5 nm*



PACE will have:

- an OCI with UV bands to 350 nm (320 nm goal) & two 2 μm bands
- **multi-angle polarimetry**
- (no thermal bands)

Improve our understanding of how **aerosols influence ocean ecosystems & biogeochemical cycles** and how **ocean biological & photochemical processes** affect the atmosphere

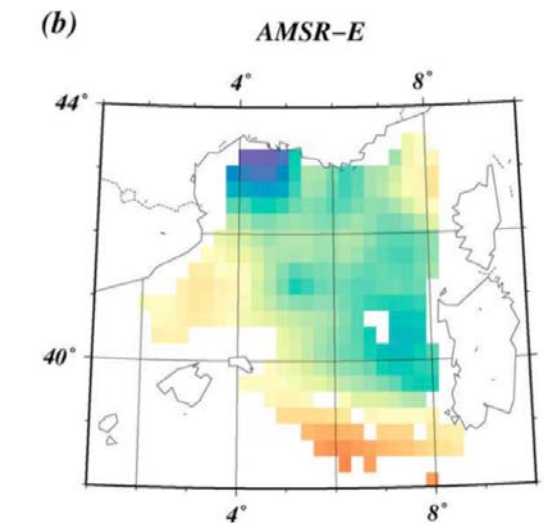
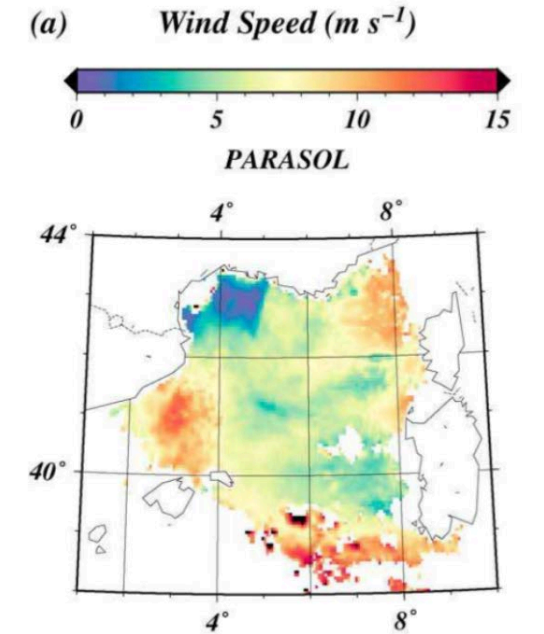
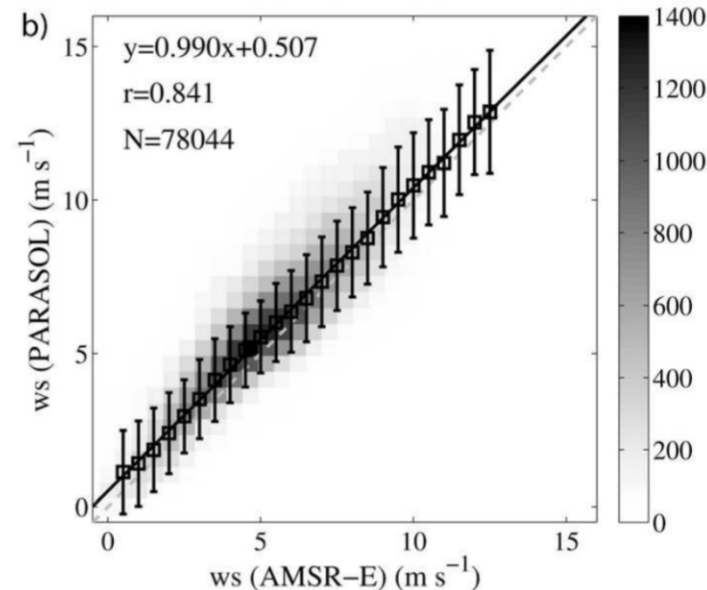
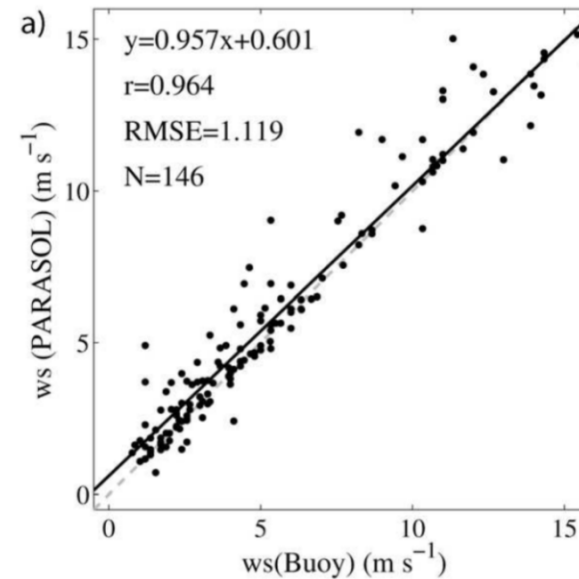
PACE Polarimeters characteristics

	Thresholds	SPEXone (SRON, Airbus)	HARP2 (UMBC)
Polarimetric analysis method	no req't.	Spectral Modulation Full Linear (Stokes I, Q and U)	Amplitude Split with Philips Prisms 0°, 45°, 90°
DoLP accuracy	<0.01 in aerosol, cloud, atmos. correction	0.002 (goal)	<0.01 * likely < 0.005 but it will depend on vicarious calibration efforts
Radiance accuracy	5% aerosols, clouds, atmos. correction	2%	est. 3% from ground cal
Spectral Range	four in 400-1600 nm, 2200 nm desired	385-770 nm, spectrometer	440, 550, 670, 870 nm
Spectral Resolution	no threshold req't.	2 nm	10nm / 40 nm for 870
#Viewing angles	4 aerosols 5-6 cloud 4 atmos. correction	5 (-52°, -20°, 0°, 20°, 52°)	20 for 440, 550, 870 nm; 60 for 670 nm * limited by data rate
Along track viewing angle range	±50° view angle range from nadir	103.2°	114°
Swath	±15° aerosol, cloud ±25° atmos. correction	~9°(100km)	94° (1550 km) <i>(compare to 113° for OCI)</i>
GSD	5km ² aerosol, cloud, atmos. correction	2.5 km ²	2.5km ² * this is an estimate as the GSD can vary with binning approach
Prior History	n/a	1) AirSPEX	1) cubesat HARP for ISS 2) AirHARP

Wind speed & ocean currents

- Hyperangular polarimetric observations offer a new capability to accurately retrieve sea states and wind speeds.
- Vector wind speed will be retrieved at higher spatial resolution than from microwave radiometers

Harmel and Chami , 2012



Overview of data products

Standard OCI ocean data products

Spectral water-leaving reflectances
Chlorophyll-a
Inherent optical properties (a's & b's)
Photosynthetically available radiation
Diffuse attenuation coefficient
Particulate Organic Carbon
Particulate Inorganic Carbon
Fluorescence Line Height

OCI atmospheric data products

Spectral aerosol optical depth
Cloud layer detection
Cloud top pressure
Liquid & ice cloud optical depth
Liquid & ice cloud effective radius
Shortwave radiation effect

What sets PACE apart?

OCI capabilities & performance relative to heritage

Inclusion of 2 multi-angle polarimeters

Phytoplankton community structure
Phytoplankton physiology parameters
Photosynthetic pigments
Primary/community production
Dissolved Organic Carbon
Particle abundances
Particle size distributions
Carbon fluxes & export
Seafloor characterization

Advanced OCI data products

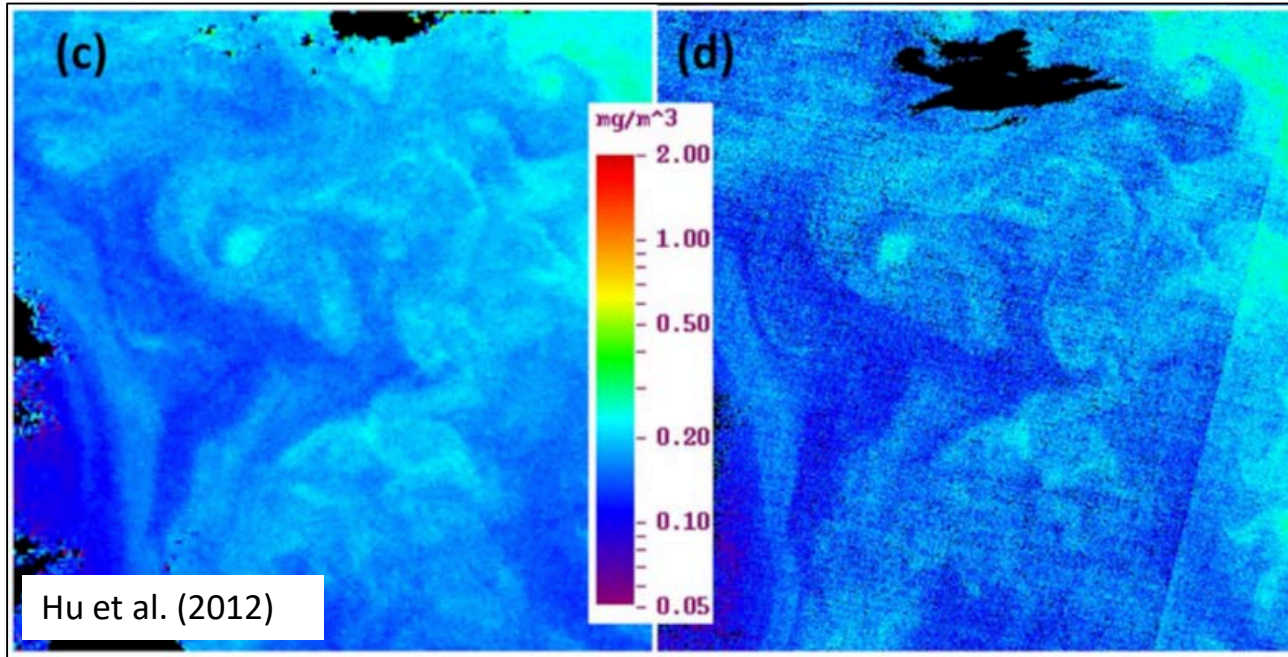
Aerosol particle size distributions
Aerosol refractive index
Aerosol single scattering albedo
Aerosol shape & non-spherical fraction
Aerosol layer height
Cloud liquid particle size distributions
Cloud ice particle shape & roughness
Cloud top & base height

Polarimeter data products beyond OCI

Image artifacts & instrument design

SeaWiFS (rotating telescope)
1 science detector

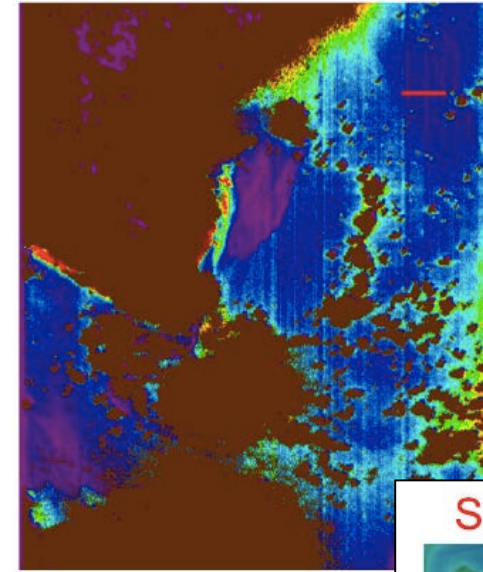
MERIS (pushbroom)
multiple science detectors



often larger science pixels
(1 km)

often smaller science pixels
(30-300 m)

HICO TOA 444 nm



All multiple detector
instruments show
stripes in ocean color
imagery (more
detectors to calibrate)

SNPP VIIRS chlorophyll

