The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission and its polarimeters: an overview

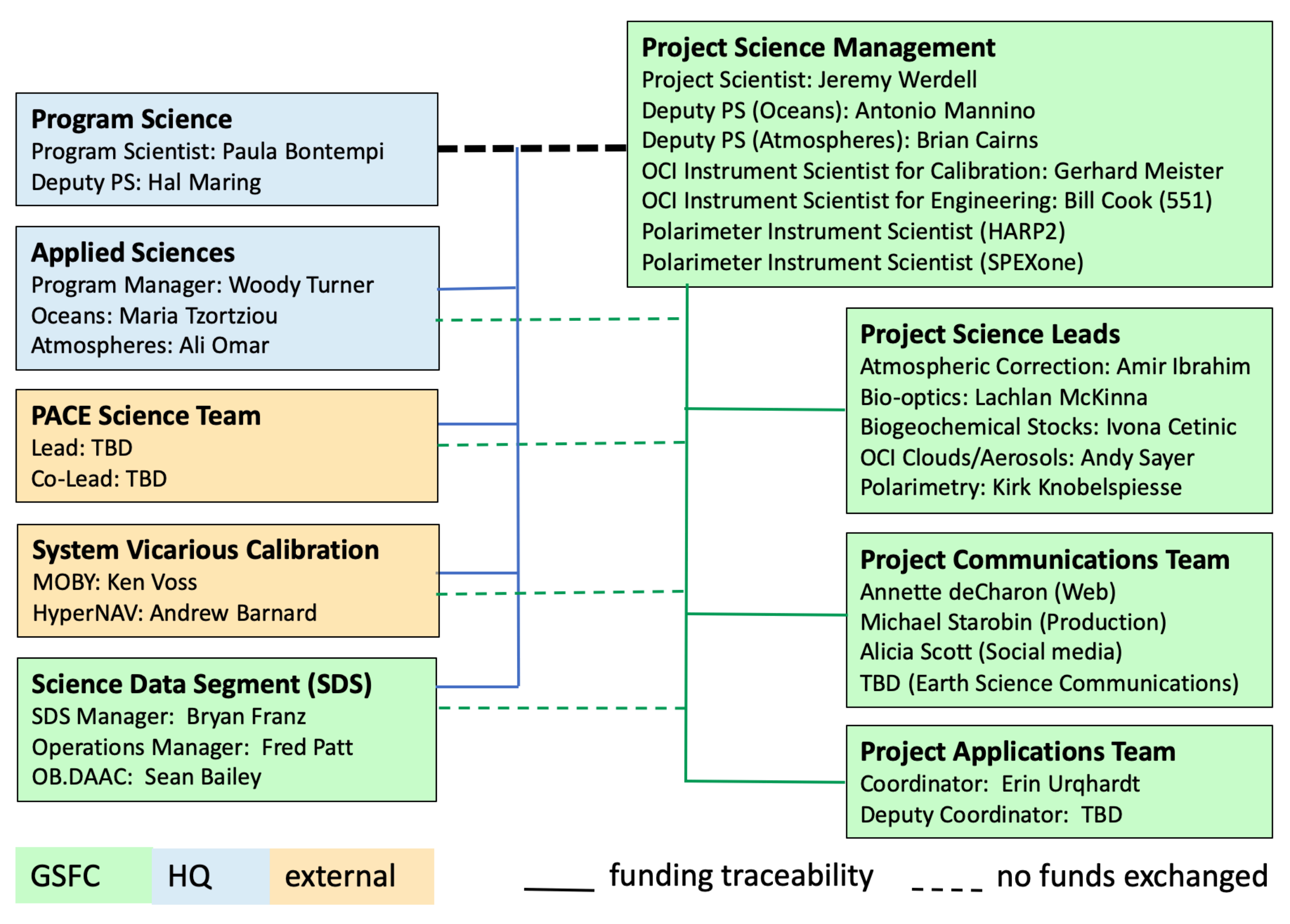
Brian Cairns

PACE

5 November 2019

Plankton, Aerosol, Cloud, ocean Ecosystem

science update – mission organization



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
- Nov-Dec 2019: Science Team award (TBR)
- 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 – news

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

science update – definitions

Threshold: required for mission success; owned by HQ

- OCI is threshold
- atmosphere performance of 940, 1250, 1378, 1615, 2130, 2260 nm

Baseline: mission design target; still successful if not achieved; owned by Project

- Project schedule & budget tuned to baseline
- the polarimeters are baseline
- ocean performance of 1250, 1615, and 2260 + 1038 nm
- processing of polarimetry to Level-1C

Goal: anything above and beyond baseline

- OCI measurements from 320-350 nm
- production of Level-2/3 polarimetric, applications, land products

science update– required & desired products

Table 1. Required science data products and their allowable uncertainties. Each uncertainty is defined as the maximum of the absolute and relative values when both are provided and for level-2 satellite data processing (geophysical values in the original satellite coordinate system). The water-leaving reflectance requirements are defined for ≥50% of the observable deep ocean (depth ≥ 1,000 m). The other requirements are defined for ≥65% of the observable atmosphere.

Data product	Uncertainty
Water-leaving reflectances from 350 to 400 nm	0.0057 or 20%
Water-leaving reflectances from 400 to 600 nm	0.0020 or 5%
Water-leaving reflectances from 600 to 710 nm	0.0007 or 10%
Total aerosol optical depth at 380 nm	0.06 or 40%
Total aerosol optical depth at 440, 500, 550, and 675 nm over land	0.06 or 20%
Total aerosol optical depth at 440, 500, 550, and 675 nm over oceans	0.04 or 15%
Fine mode fraction of aerosol optical depth over oceans at 550 nm	±25%
Cloud-layer detection for optical depth < 0.3	40%
Cloud-top pressure of opaque (optical depth > 3) clouds	60 hPa
Optical thickness of liquid clouds	25%
Optical thickness of ice clouds	35%
Effective radius of liquid clouds	25%
Effective radius of ice clouds	35%

plus, production of …
marine inherent optical properties
chlorophyll + pigment concentrations
fluorescence line height
water path of liquid/ice clouds
shortwave radiation effect

… from OCI alone

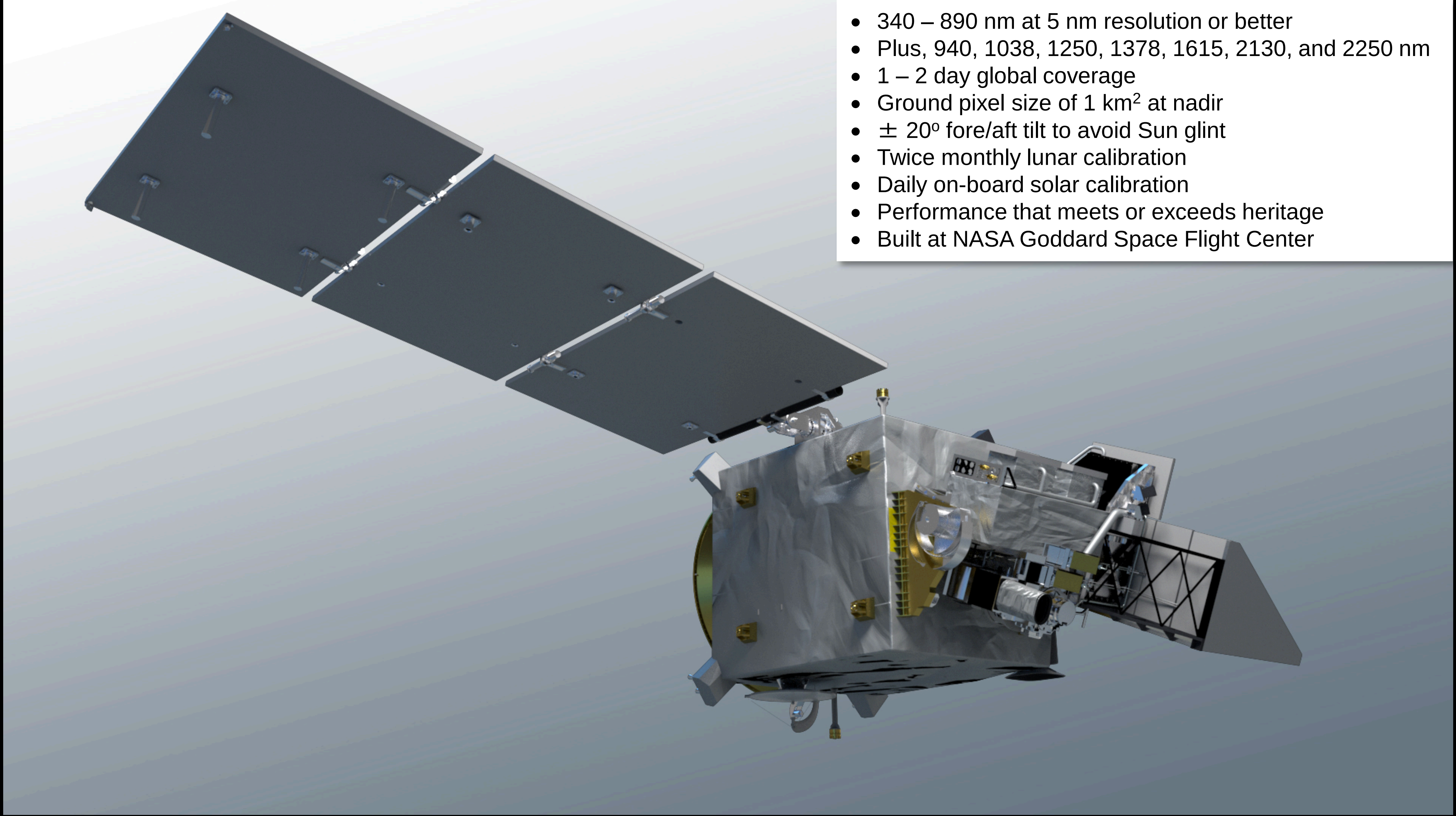
Project plan is to produce far more (baseline/goal) science data products, including from polarimetry and combined OCI/polarimetry

PACE mission

Key characteristics of the PACE observatory include:

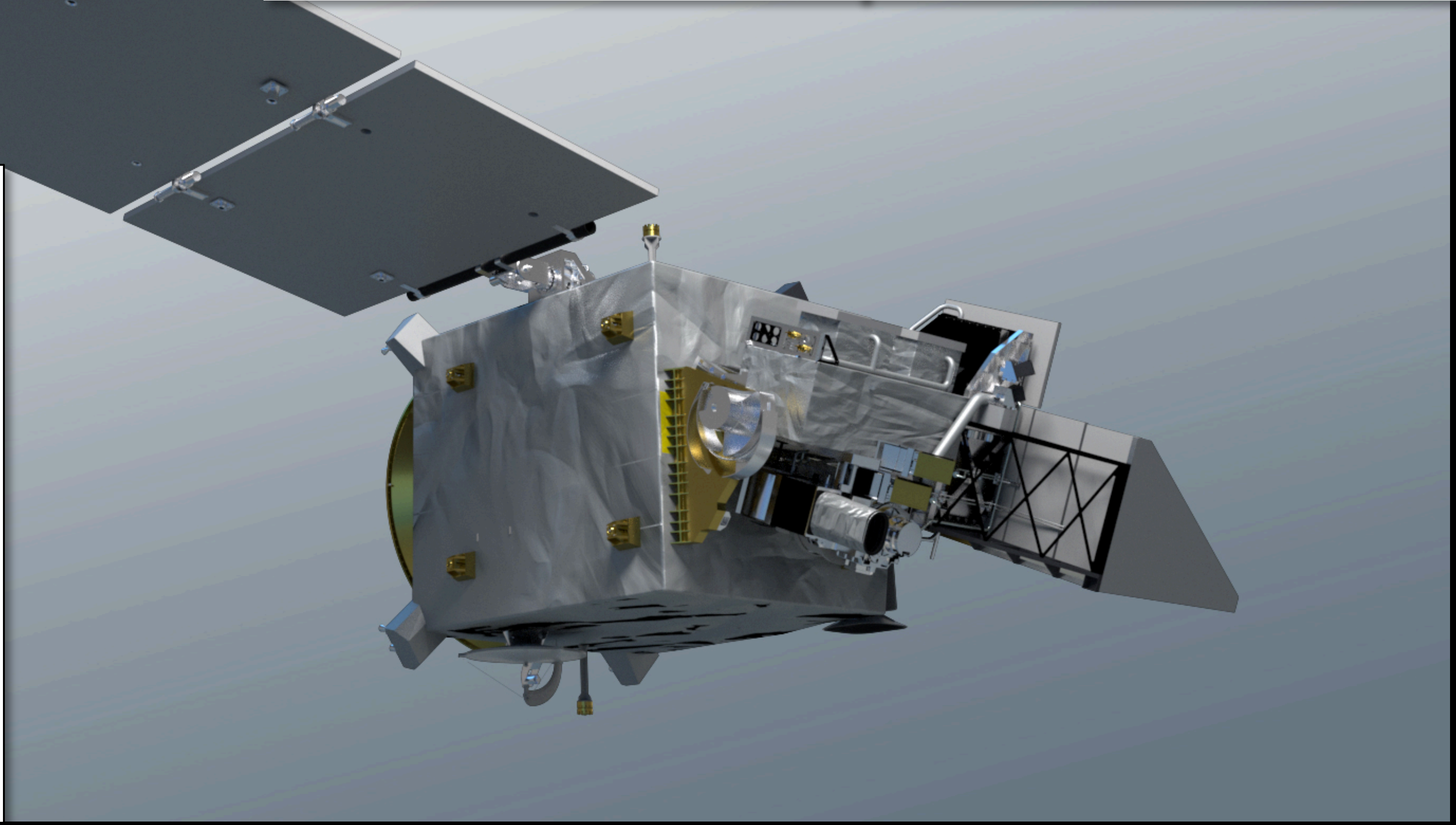
- The Ocean Color Instrument (OCI), built at GSFC
- The Hyper Angular Rainbow Polarimeter (HARP-2), contributed by the Earth and Space Institute at the University of Maryland Baltimore County
- The Spectro-polarimeter for Planetary Exploration (SPEXone), contributed by a Netherlands-based consortium consisting of the Netherlands Institute for Space Research (SRON) and Airbus Defence and Space Netherlands
- 676.5 km altitude and 13:00 local Equatorial crossing time
- Sun synchronous, polar, ascending orbit with 98º inclination
- Fall 2022 launch, three-year design

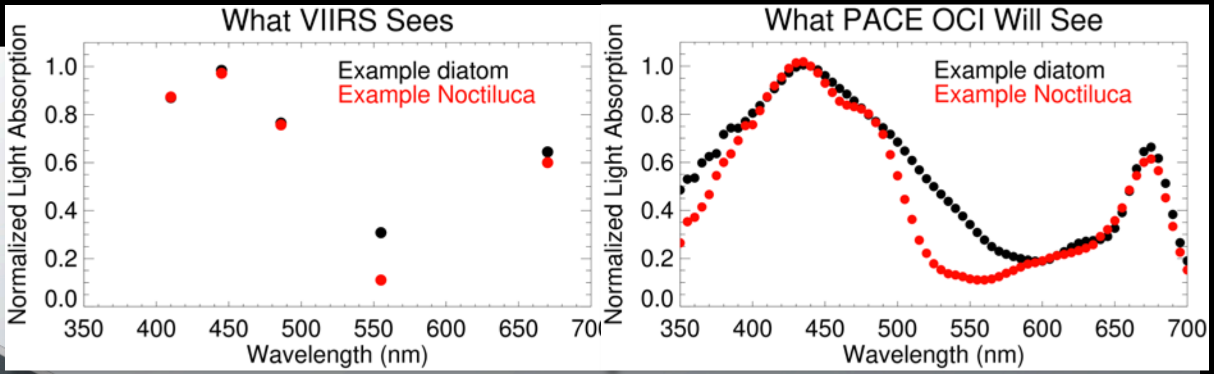
Ocean Color Instrument

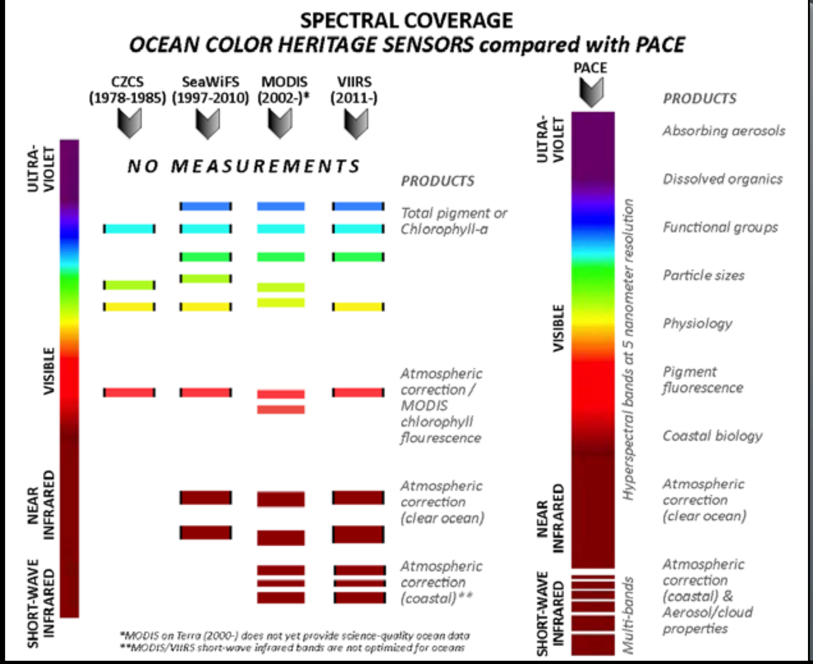


- 340 – 890 nm at 5 nm resolution or better
- Plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- 1 – 2 day global coverage
- Ground pixel size of 1 km^2 at nadir
- ± 20^o fore/aft tilt to avoid Sun glint
- Twice monthly lunar calibration
- Daily on-board solar calibration
- Performance that meets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

Ocean Color Instrument







Polarimetry on PACE: Two cubesat-sized *contributed* instruments

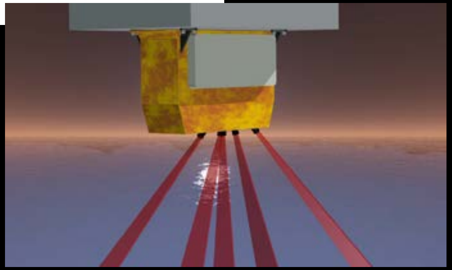
Spectro-Polarimeter for Planetary Exploration (SPEXone)

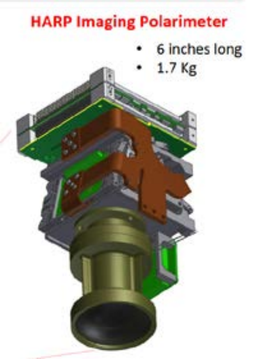
Optimized for aerosol measurements

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

POC: Otto Hasekamp

Hyperspectral (UV) + narrow swath + high accuracy





Hyper Angular Rainbow Polarimeter (HARP-2)

Optimized for cloud measurements

Contribution from University of Maryland Baltimore County

POC: Vanderlei Martins

Hyperangular + wide swath

	SPEXone	HARP-2
Spectral range (resolution)	385-770 nm (continuous @ 5 nm)	440, 550, 670 nm (10) + 870 nm (40 nm)
Polarized bands	385-770 nm (continuous @ 15-45 nm)	All
Polarimetric accuracy (DoLP)	0.002	< 0.01
# viewing angles	5 (-57°, -20°, 0°, 20°, 57°)	10 for 440, 550, 870 nm + 60 for 670 nm (114°)
Swath width	9° (106 km at nadir); 30+ day global cov.	94° (1556 km at nadir); 2 day global coverage
Ground sample distance	2.5 km^2	3.0 km^2
Heritage	AirSPEX, SPEX/ASPIM	AirHARP, cubesat HARP for ISS

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Key characteristics of PACE

	OCI	HARP-2	SPEXone
UV-NIR range [bandwidth]	Continuous from 345-890* nm in 5 nm steps [5]	440, 550, 670 [10] nm and 870 [40] nm	Continuous from 385-770 nm in 2-4 nm steps
SWIR range [bandwidth]	940 [45], 1038 [75], 1250 [30], 1378 [15], 1615 [75], 2130 [50], and 2260 [75] nm	None	None
Polarized bands	None	All	Continuous from 385-770 nm in 15 to 45 nm steps
Number of viewing angles [degrees]	Fore-aft instrument tilt of ±20^o to avoid Sun glint	10 for 440, 550, 870 nm; 60 for 670 nm [spaced over 114^o]	5 [-57^o, -20^o, 0^o, 20^o, 57^o]
Swath width	±56.5^o [2663 km at 20^o tilt]	±47^o [1556 km at nadir]	±4^o [100 km at nadir]
Global coverage	1-2$^+$ days	2 days	~1 month
Ground pixel	1 km at nadir	3 km	2.5 km
Heritage	N/A	AirHARP, cubesat	AirSPEX
Institution	GSFC	UMBC	SRON

* The mission carries a goal of extending the shortest wavelength to 320 nm.

+ 2-day coverage when limited to solar and sensor viewing angles of 75^o and 60^o, respectively

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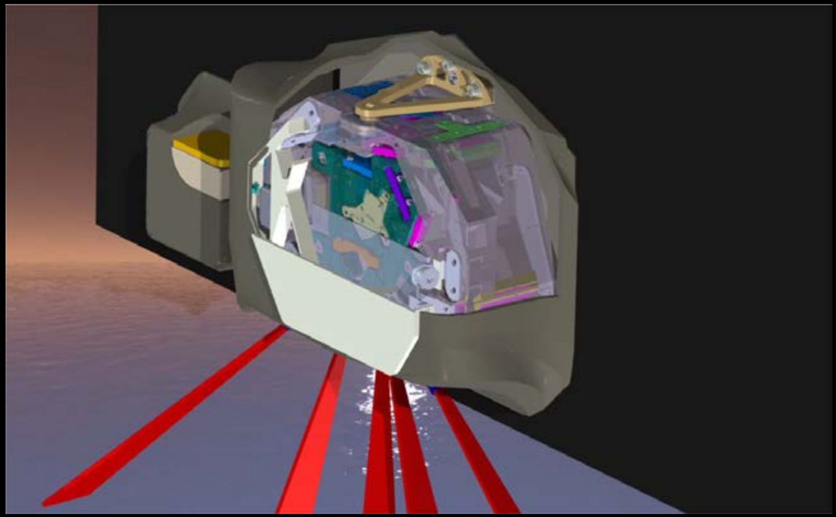
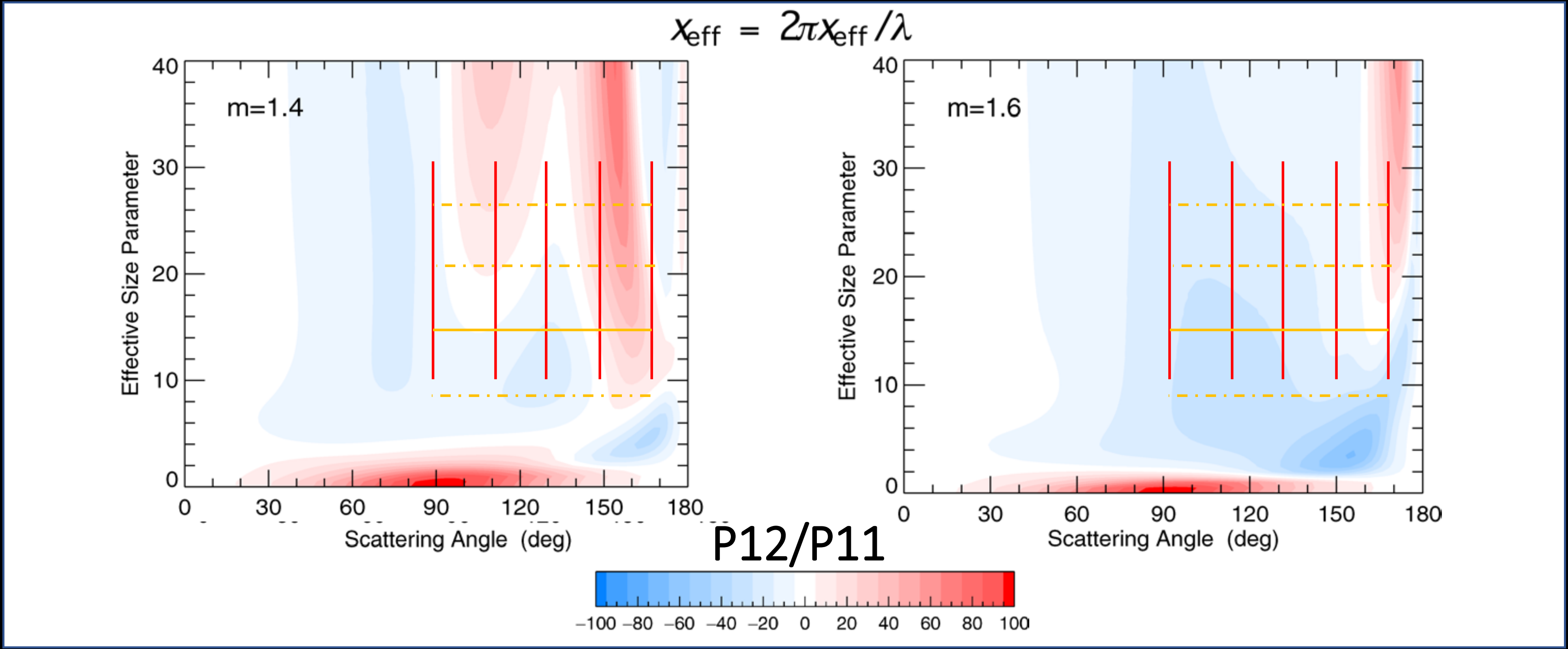
PACE pixel-level polarimetric aerosol products

- Aerosol microphysical retrievals
  - Over ocean, land, clouds (and snow?)
- Aerosol layer height
  - Blue/UV polarized observations (both) and O_2 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



SPEXone and HARP2 observations



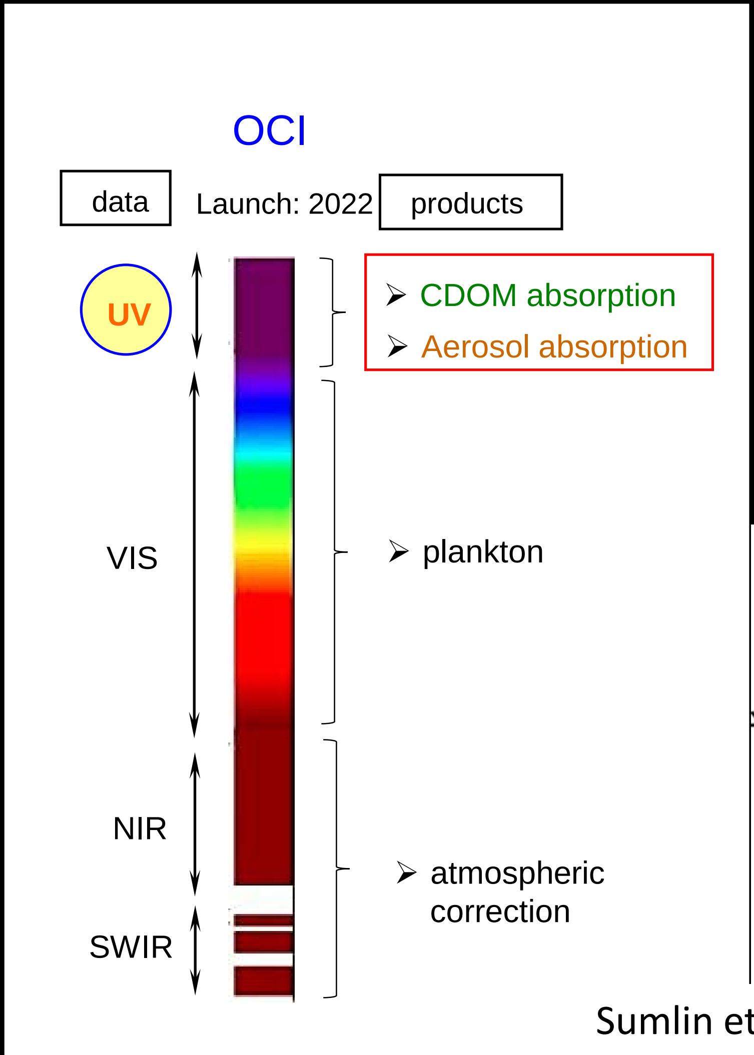
The hyperspectral observations of SPEXone and the hyperangular/higher angular sampling of HARP2 are complementary in identifying aerosol refractive index and size

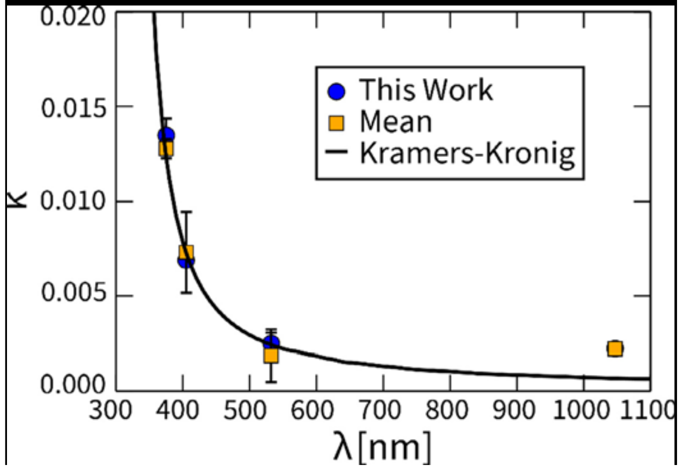
Talks today before and after this one on detailed aerosol retrieval algorithms and Wednesday specifically on SPEX and HARP aerosol retrievals.

PACE pixel-level polarimetric aerosol products

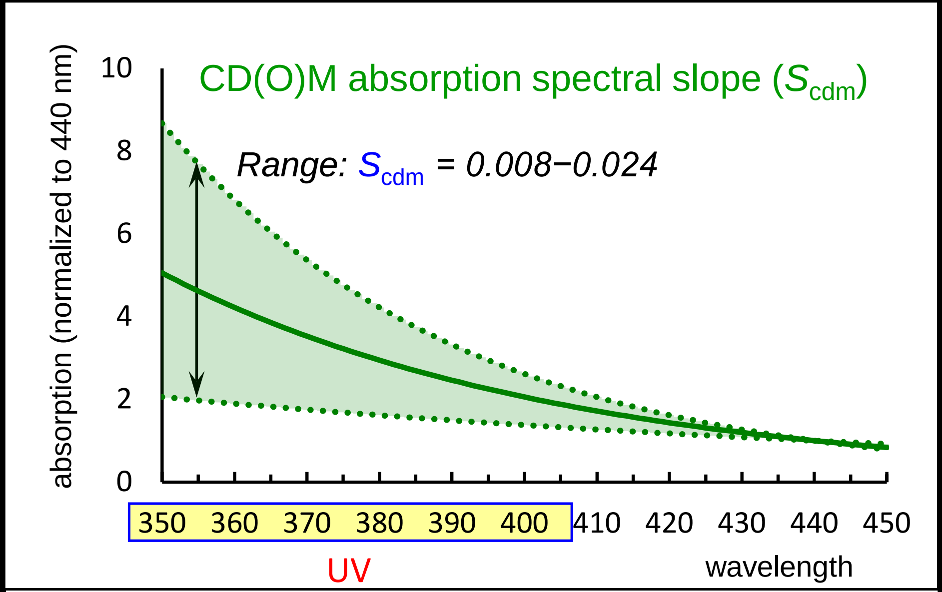
Wednesday 12:00 – 12:15; Spaceborne polarimetry …in the UV-A spectrum; Jacek Chowdhary, NASA GISS, USA

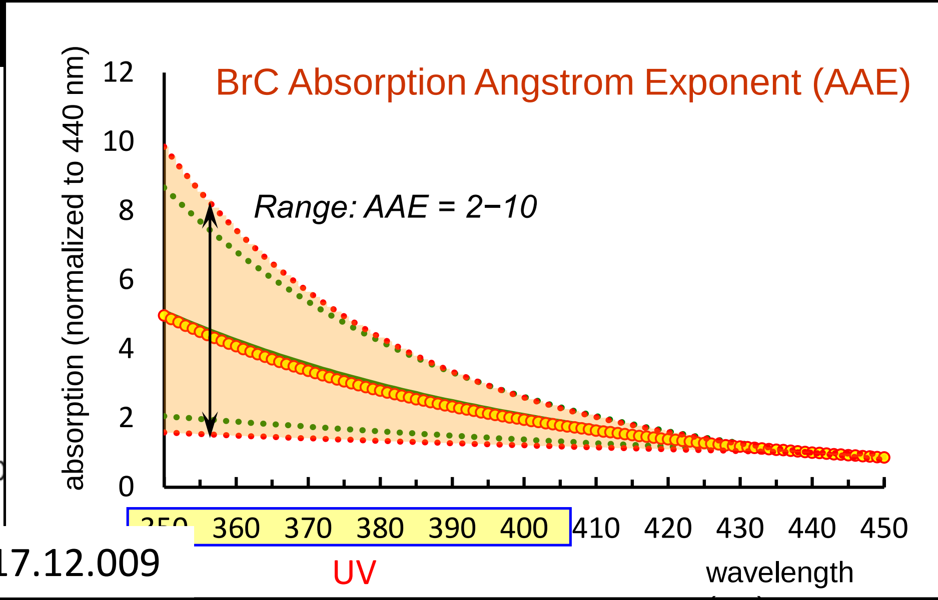
- Separation of brown and black carbon into different products, differentiations of BrC/CDOM





Sumlin et al. https://doi.org/10.1016/j.jqsrt.2017.12.009

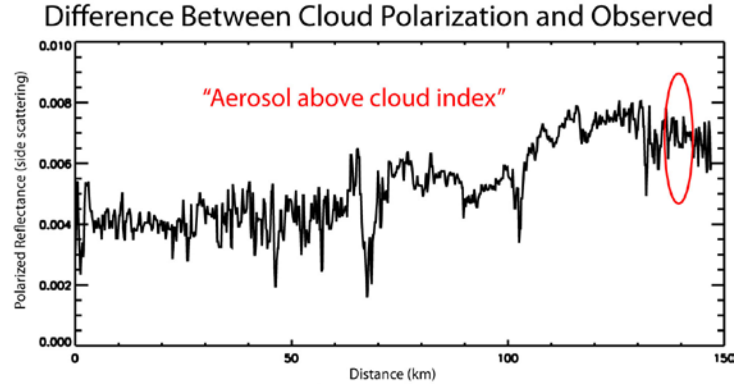


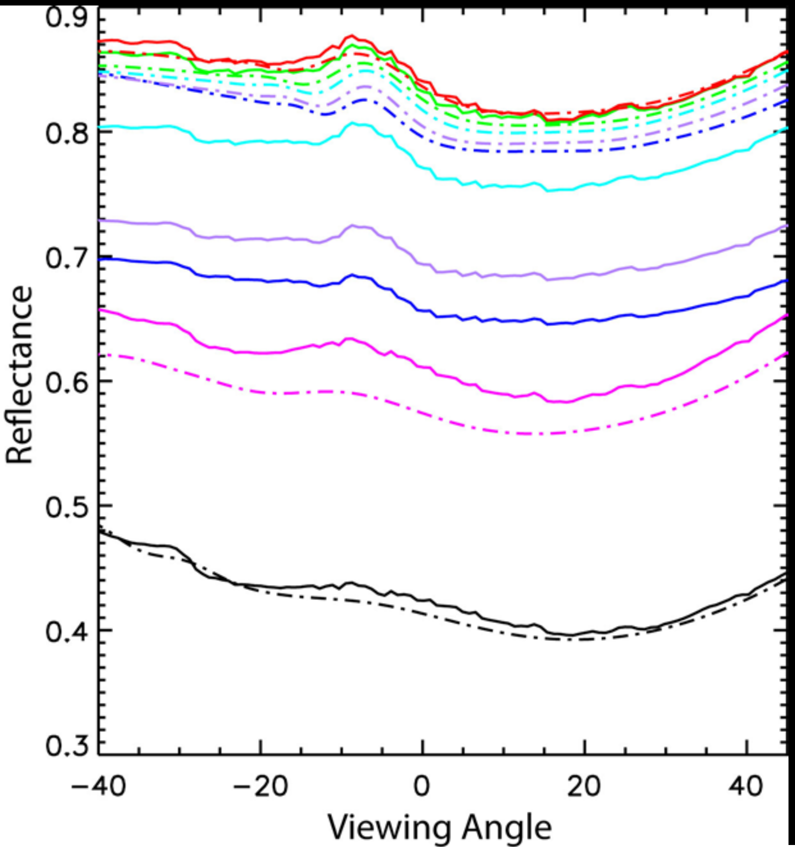


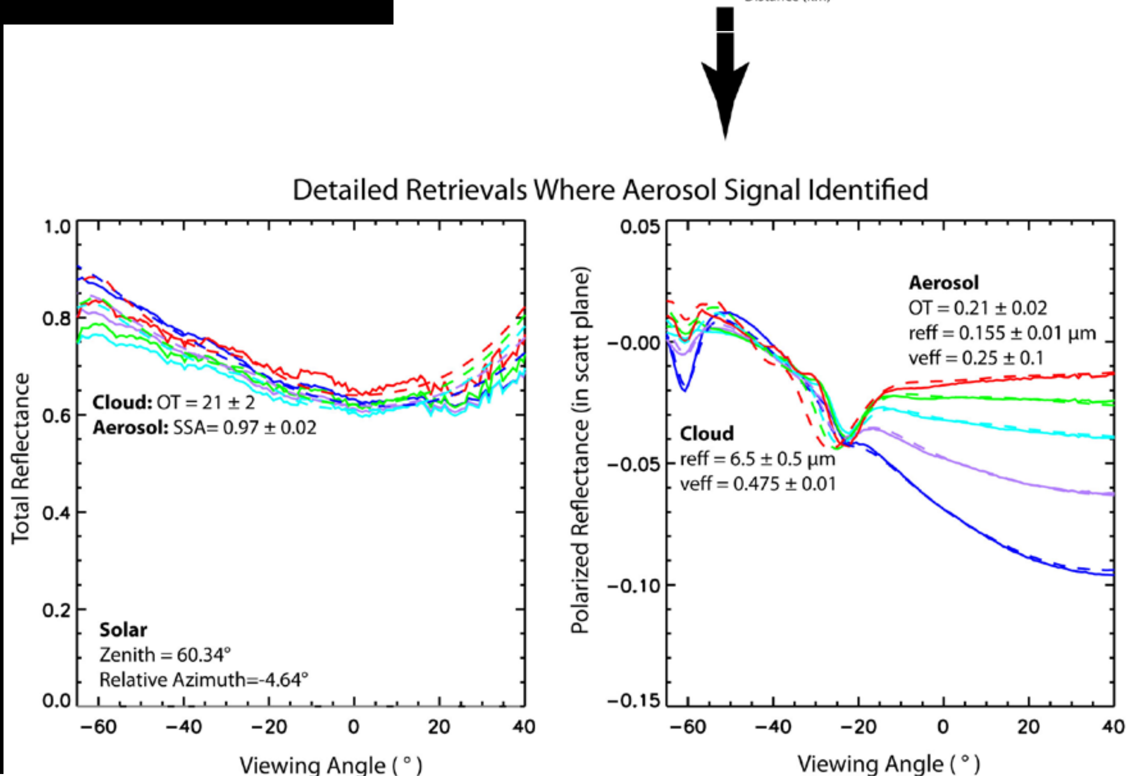
PACE pixel-level polarimetric aerosol products

Earlier; 5 Retrieval of aerosol properties above clouds from satellites: an overview Fabien Waquet, Lille Univ, France

- Aerosol above clouds, polarization and UV – SWIR
  - Cloud bow at pixel level (HARP2)
  - UV radiance (OCI) and multi-angle polarization (SPEXone)
  - O_2 A- B- band for vertical profile (OCI & SPEXone)
  - SWIR bands for additional droplet size constraints





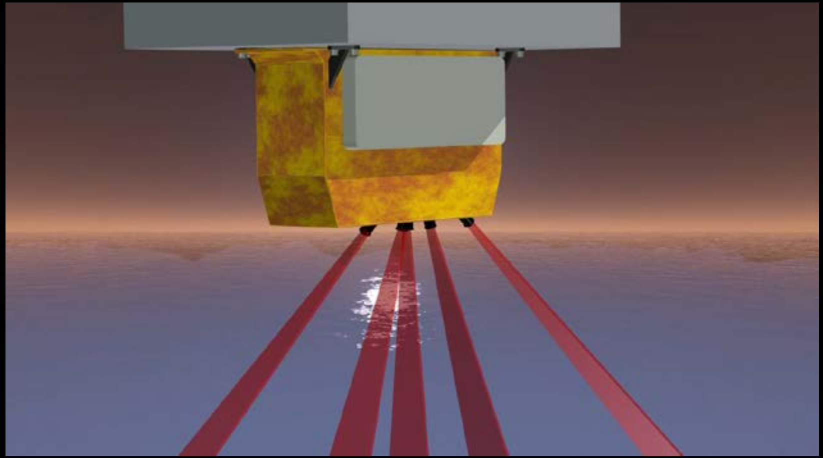


Spectropolarimeter for Planetary Exploration (SPEXone)

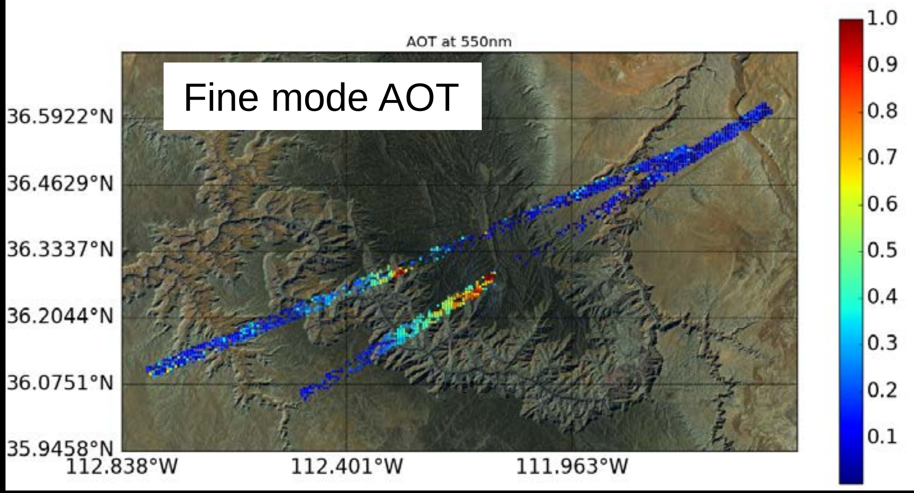
Wednesday: 10:40– 10:55 Aerosol retrievals from the ACEPOL campaign Guangliang Fu, SRON, The Netherlands

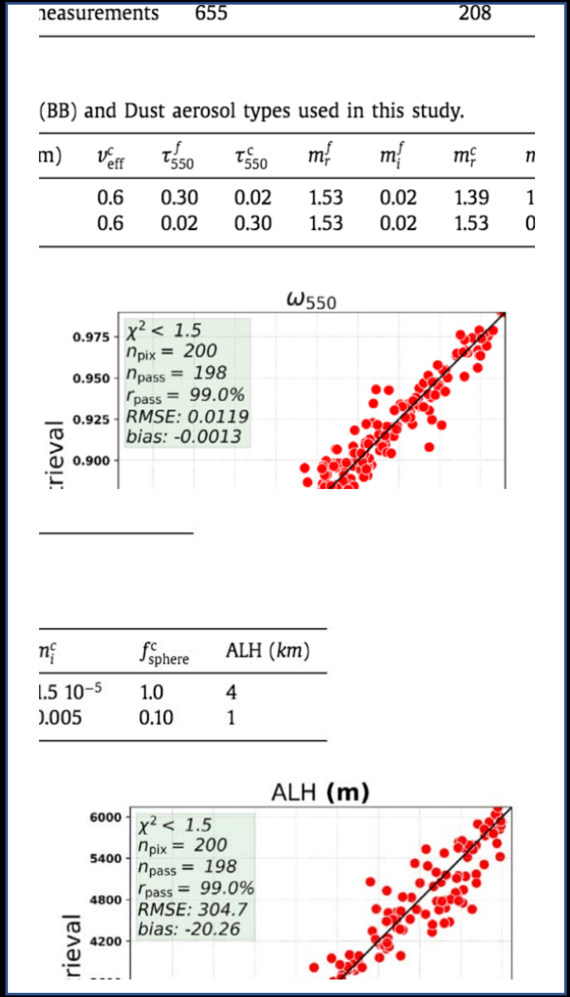
Provided by: SRON (Management, Science, Calibration), Airbus (Engineering), TNO (optics), using earlier optical designs. **100% contribution from Netherlands**

Heritage: SPEX airborne flew in Oct/Nov 2017 ACEPOL campaign in Palmdale, CA on ER-2 (alongside AirHARP, RSP, AirMSPI, CPL and HSRL2). L2 algorithms delivered to NASA and in test at GSFC.



SPEXone, 5 view angles, hyperspectral measurements from UV to NIR for detailed aerosol retrievals.



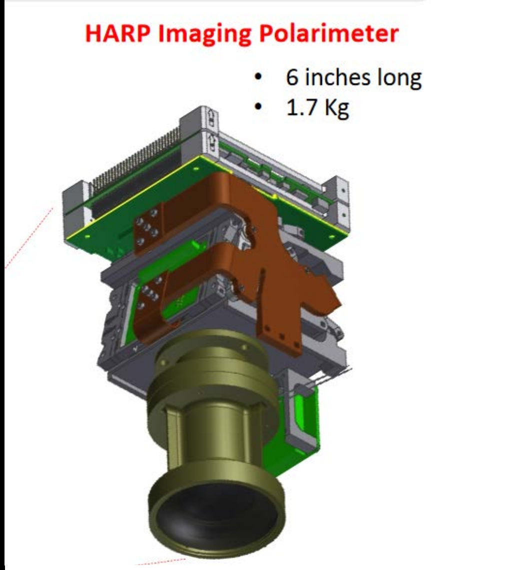


Hyper Angular Rainbow Polarimeter (HARP2)

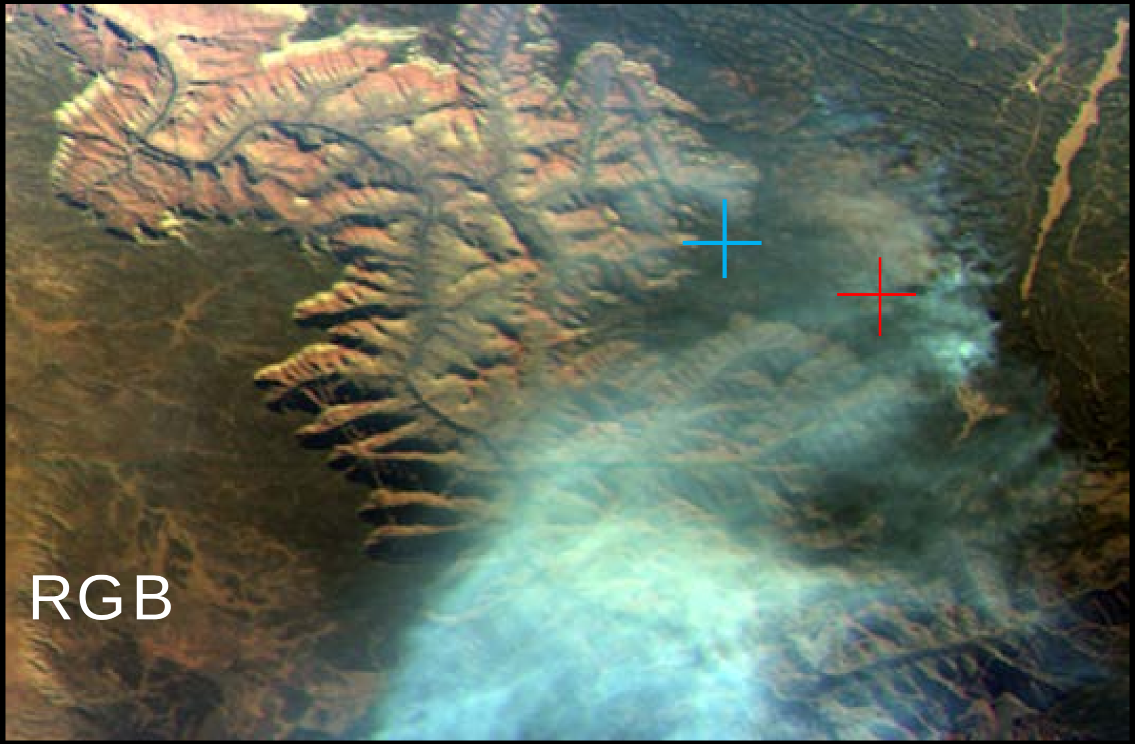
Wednesday: 10:25– 10:40 Retrieval of aerosol properties from (AirHARP), Anin Puthukkudy, UMBC, USA

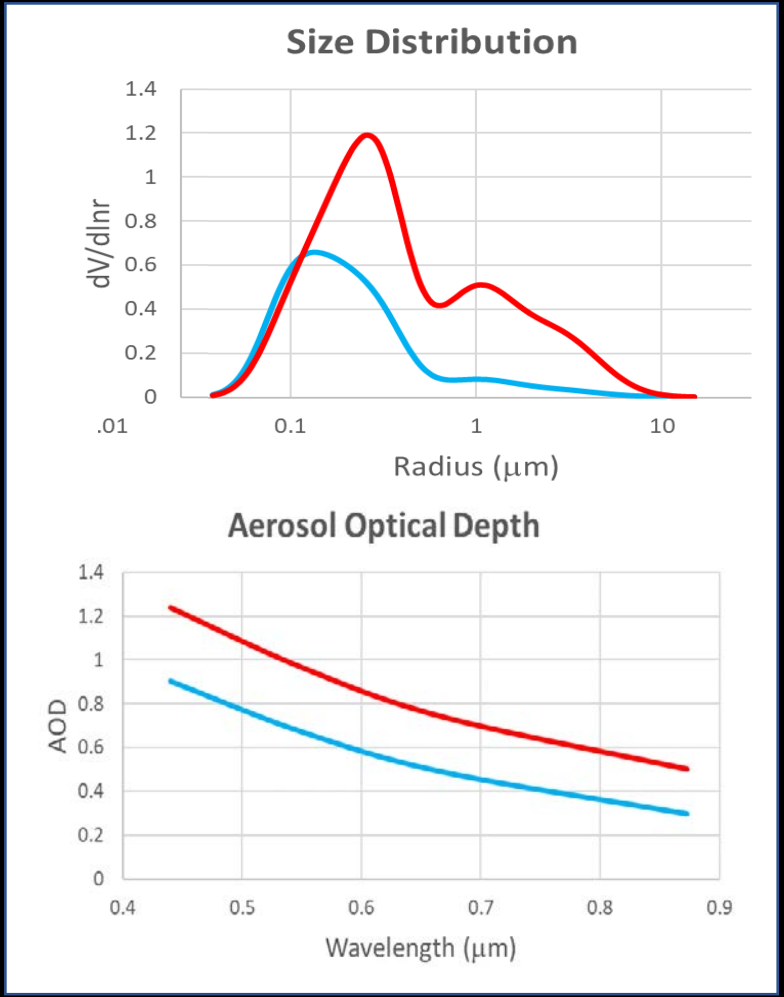
Provided by: PI Vanderlei Martins with a team at UMBC. Originally developed as a cubesat instrument. HARP2 for PACE has some improvements over the cubesat version for polarimetric calibration.

Heritage: AirHARP flew in Oct/Nov 2017 ACEPOL campaign in Palmdale, CA on ER-2 (alongside SPEXairborne, RSP, AirMSPI, CPL and HSRL2).



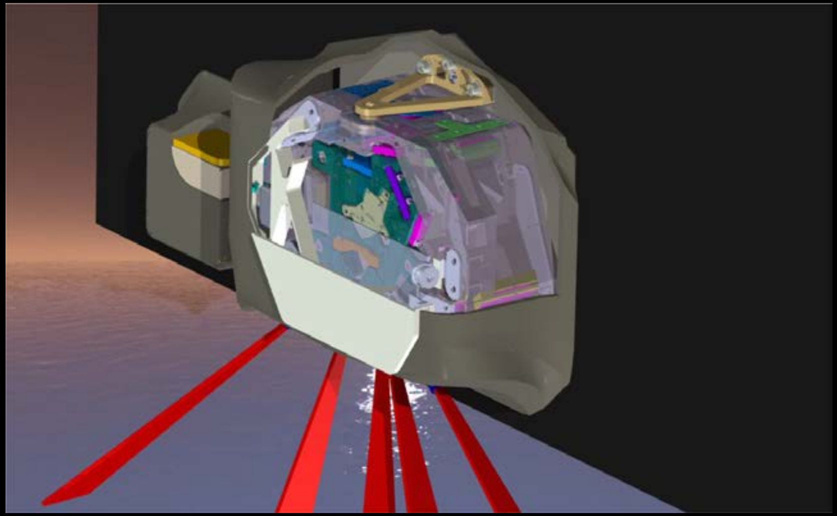
4 spectral bands, includes hyperangular capability in one spectral band for cloud bow size distribution retrievals





PACE pixel-level polarimetric cloud products

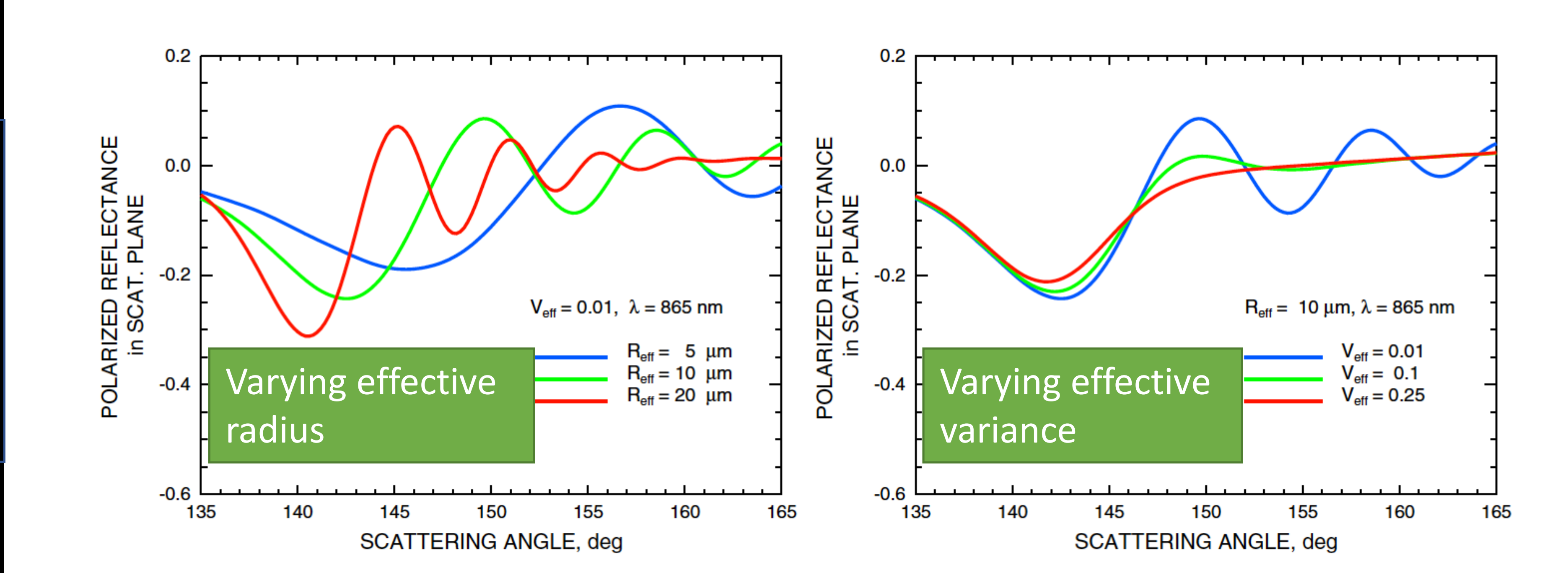
- Droplet size distributions at cloud tops
  - Accurate in ‘challenging’ conditions: broken, mixed phase, low optical depth, snow, ….
- Robust cloud-top phase detection
  - Detection of cloud is ‘unambiguous’ indication of liquid at tops
- Ice shape and scattering properties collocated with OCI retrievals
  - 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



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

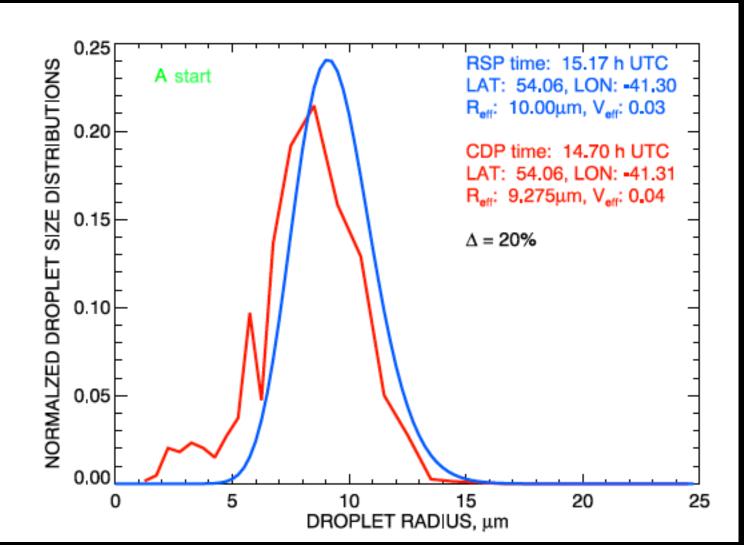
$$R_Q(\lambda,\Theta) = A(\lambda)\, P_{12}^{Mie}(\lambda,\ \Theta, r_e, v_e) + B(\lambda)\, cos^2\Theta\ + C(\lambda)$$

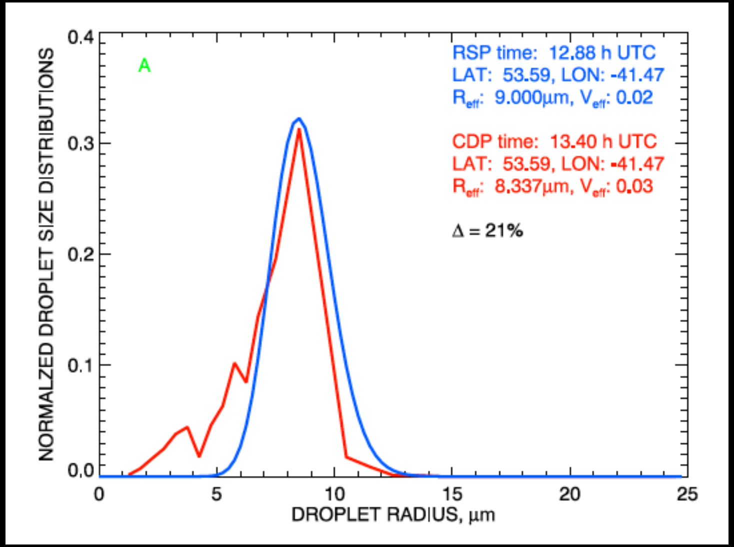
A, B, C are fit parameters accounting for optical thickness, multiple scattering, 3D effects, calibration, Rayleigh, ice, aerosols

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

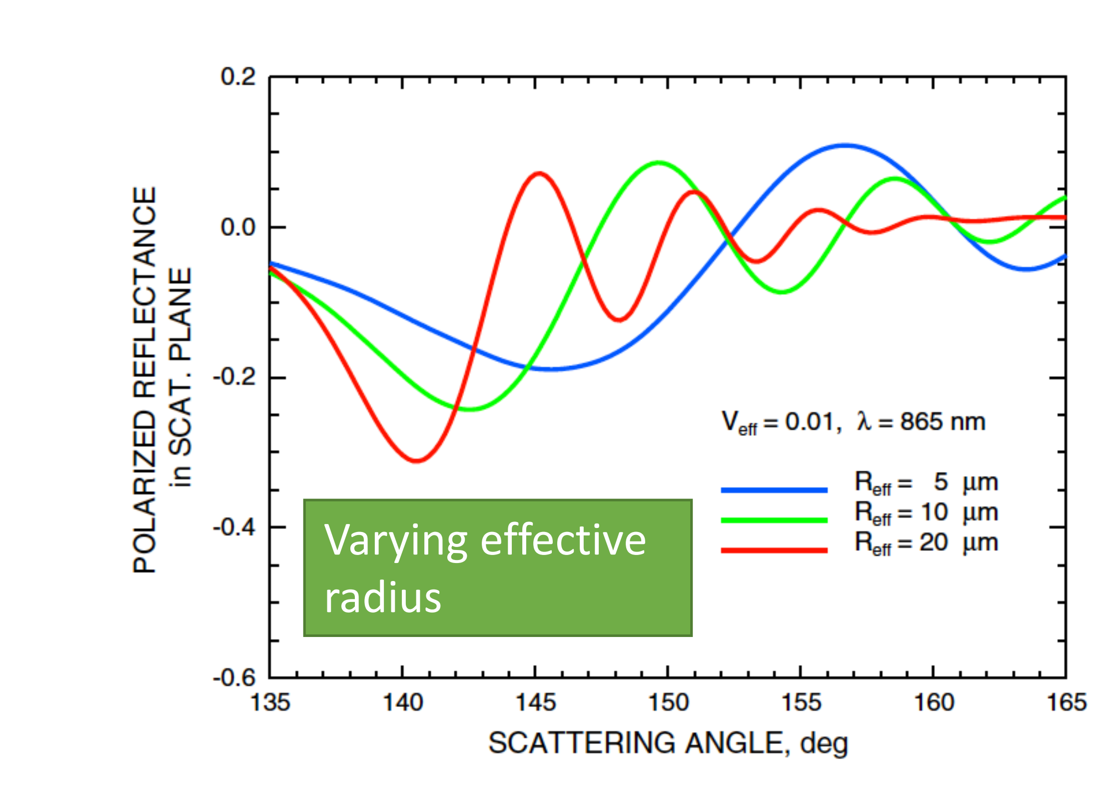


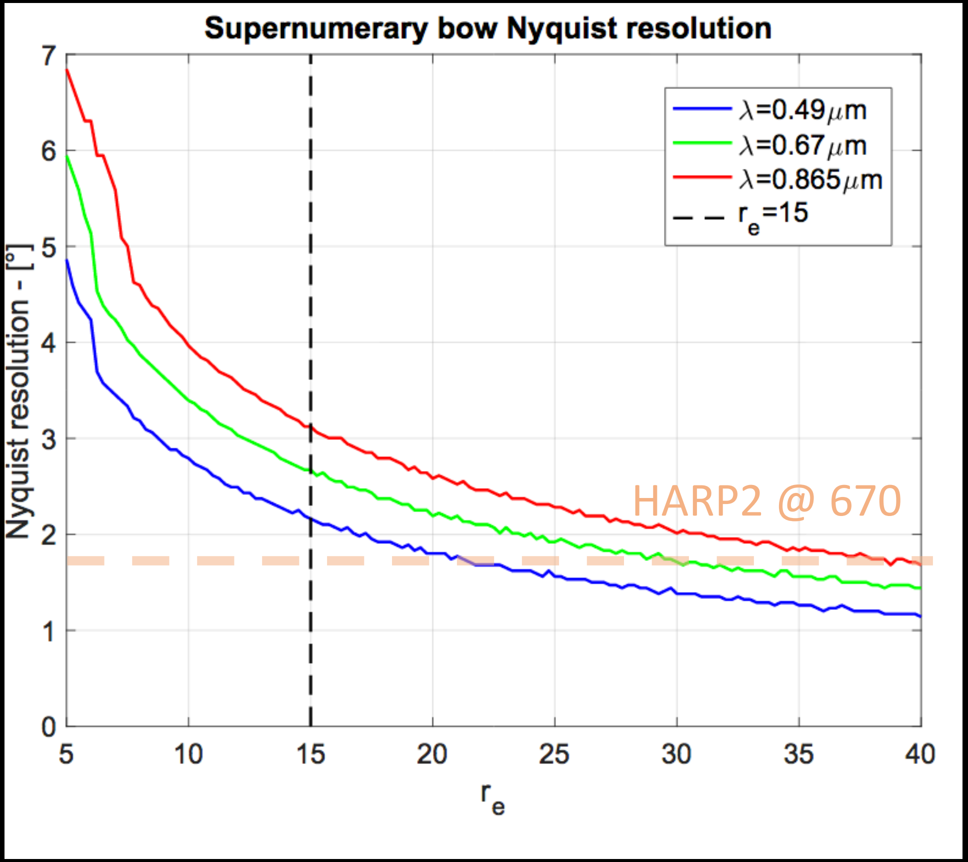


Alexandrov et al. 2018

Droplet size distribution retrievals

Miller et al., AMT, 2018





Sufficient angular resolution is important to infer droplet size distributions

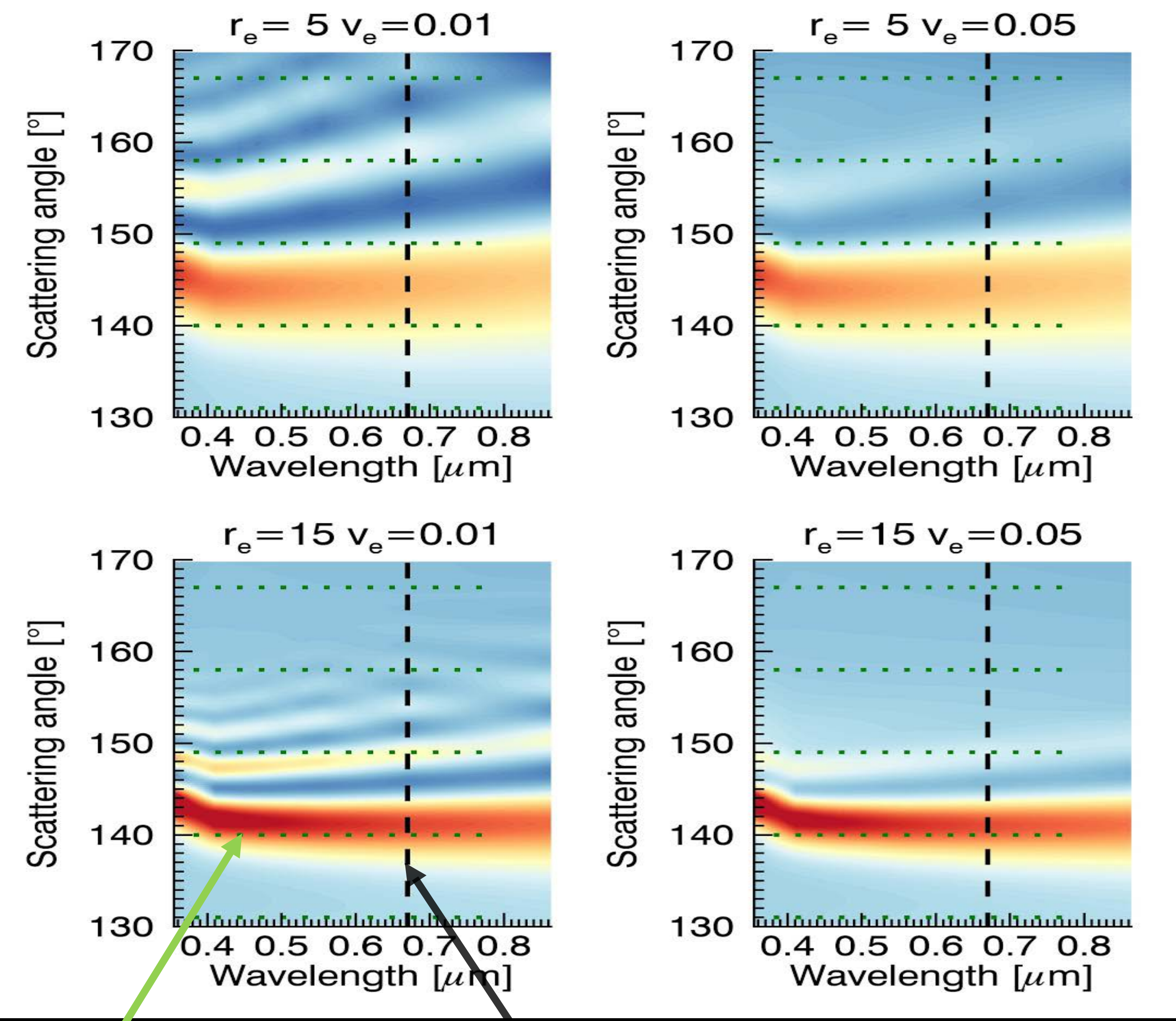
HARP-2's resolution of ~2^{o} allows distinction of drop sizes up to effective radius of ~25 micron

SPEXone resolution of 10^{o} + 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



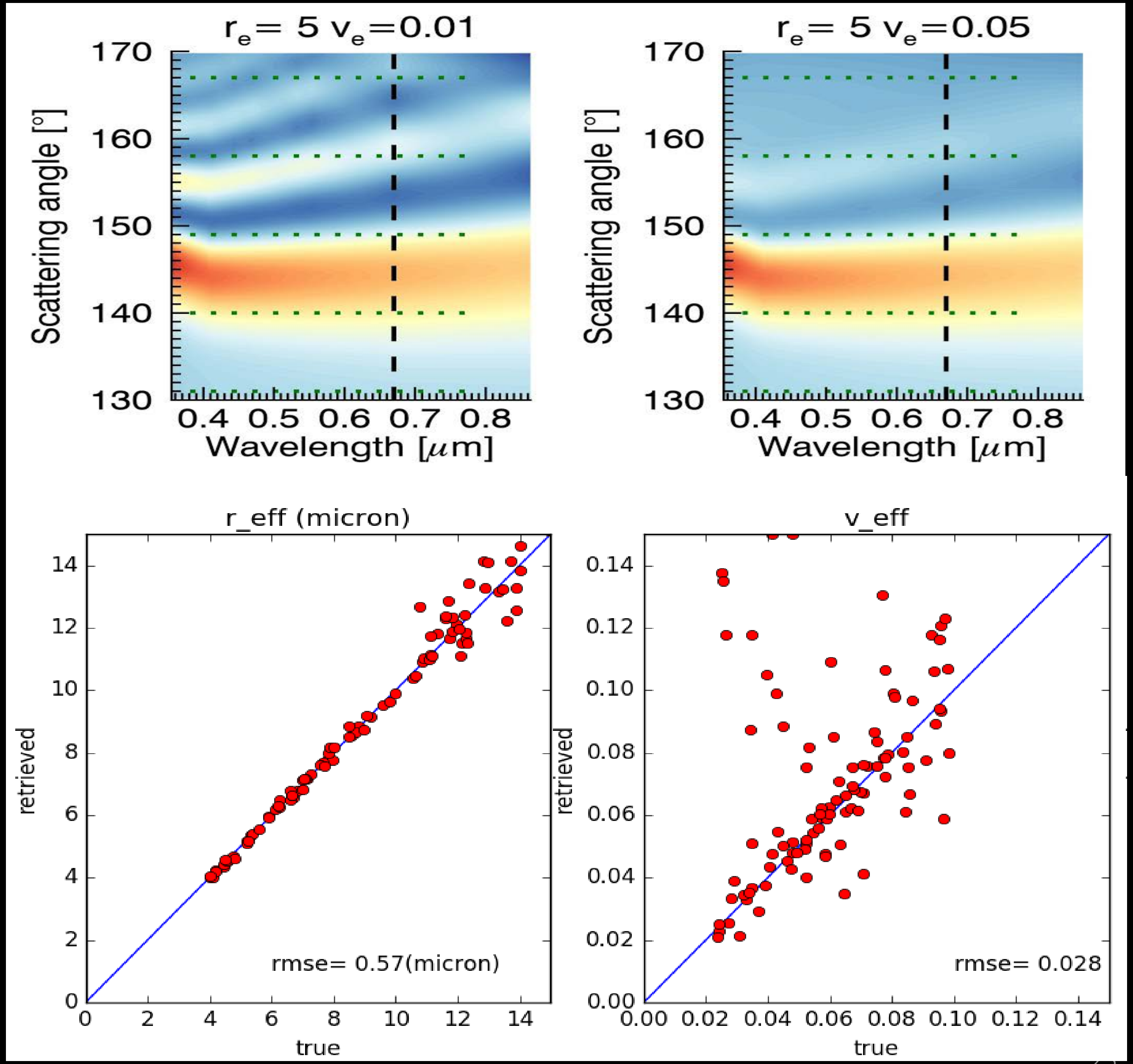
Spectral sampling by SPEXone

Angular sampling by HARP-2

Droplet size distribution retrievals

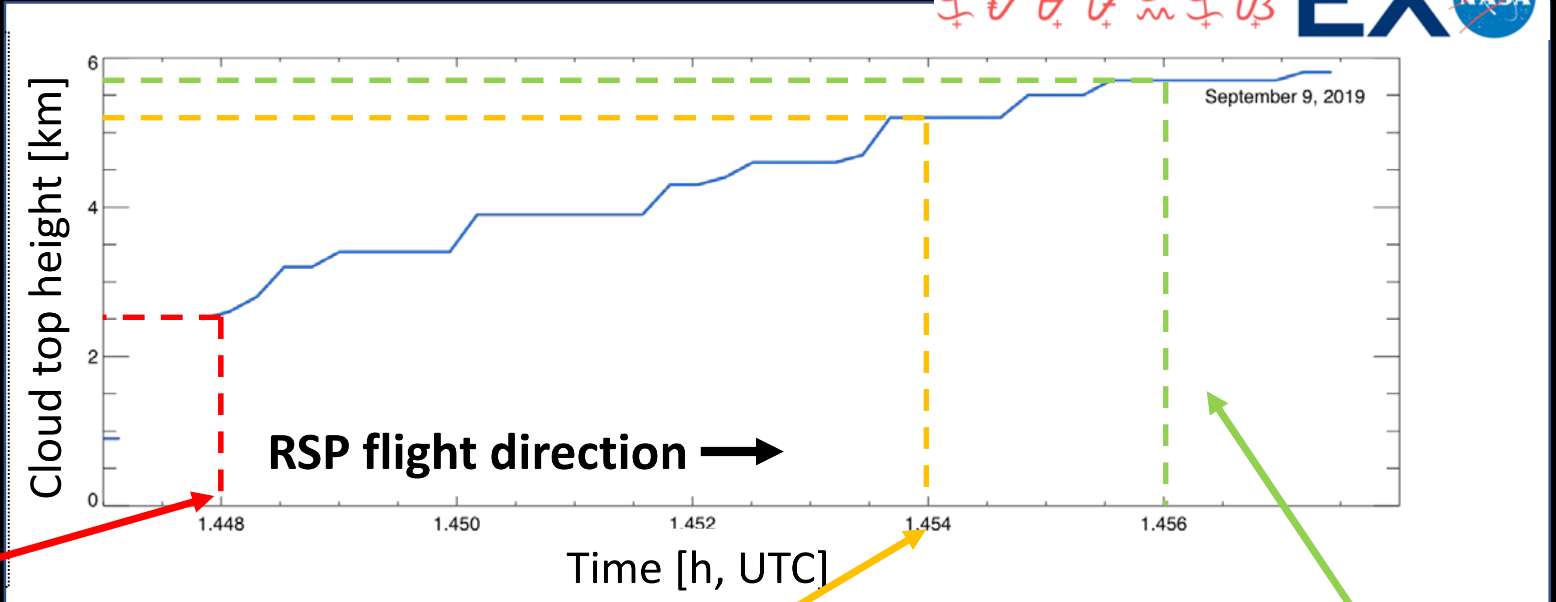
Using SPEXone

- 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

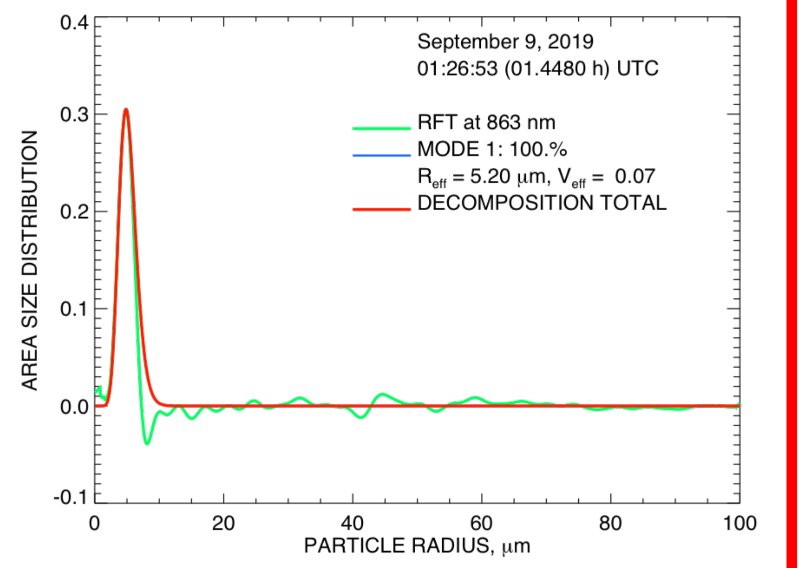


Rainbow Fourier Transform DSD retrievals

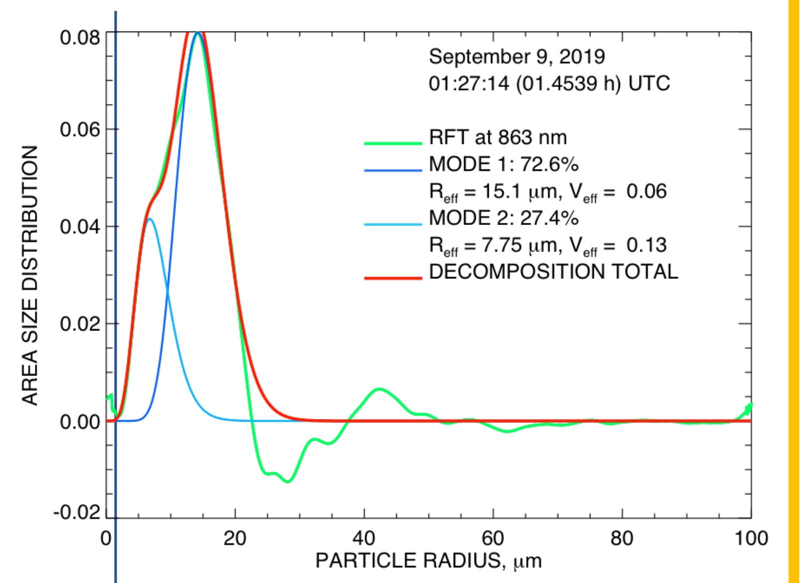
- Deconvolution of rainbow structures to infer non-parametric size distribution
  (Alexandrov et al., JQSRT 2012)
- HARP's 2° resolution sufficient
- RSP example of convective tower obs. shown



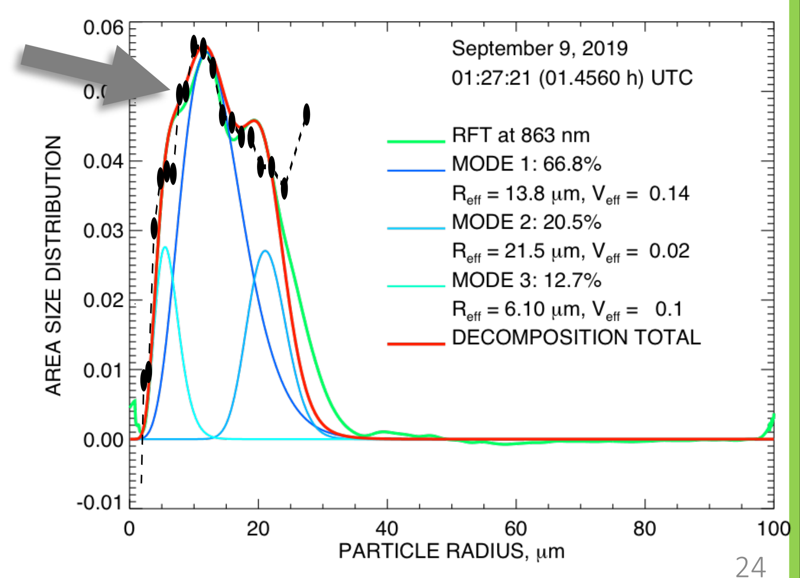
Mono-modal DSD at 2.5 km height



bi-modal DSD at 5.2 km height



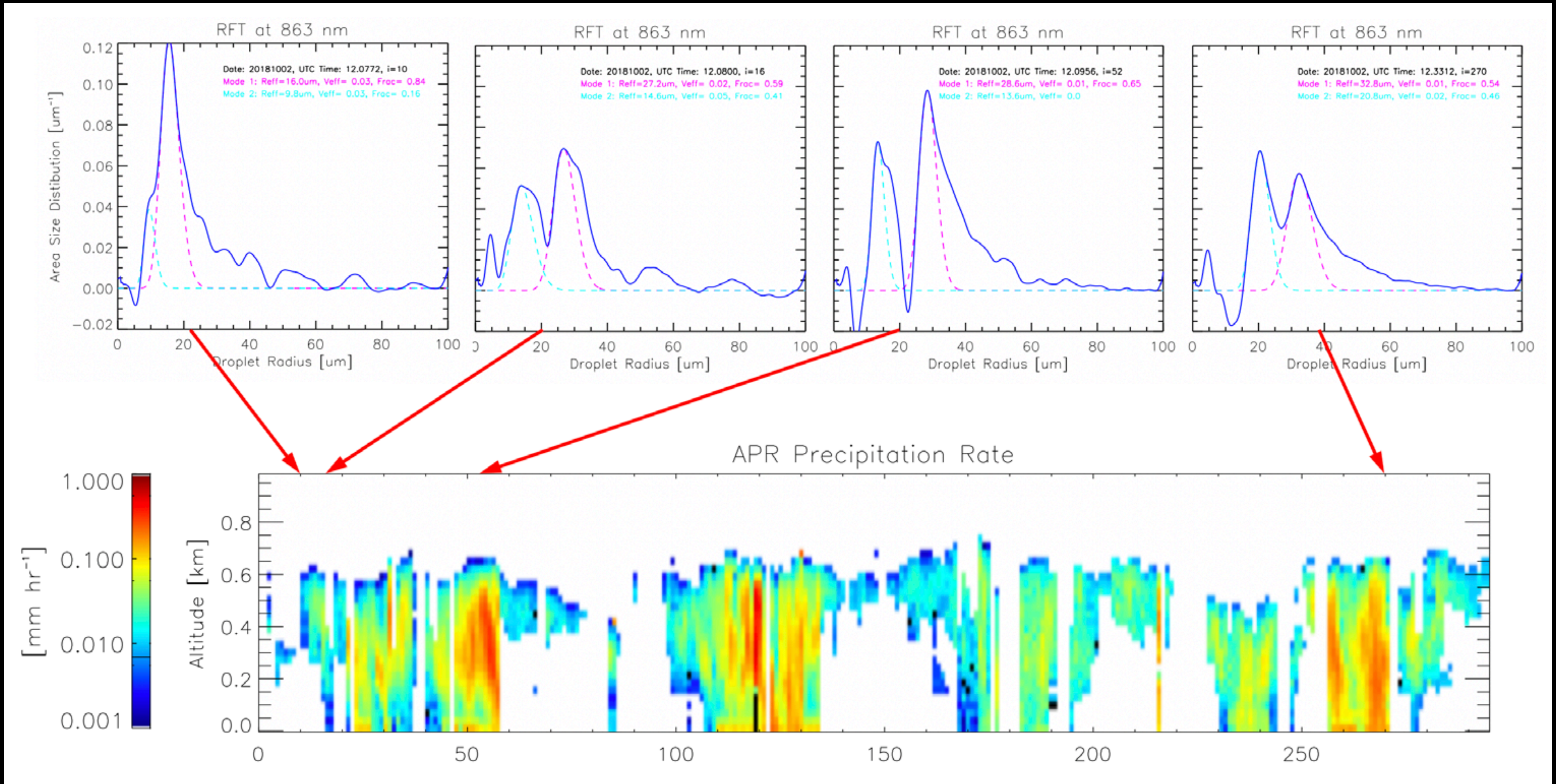
tri-modal DSD at 5.7 km height



Rainbow Fourier Transform DSD retrievals

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

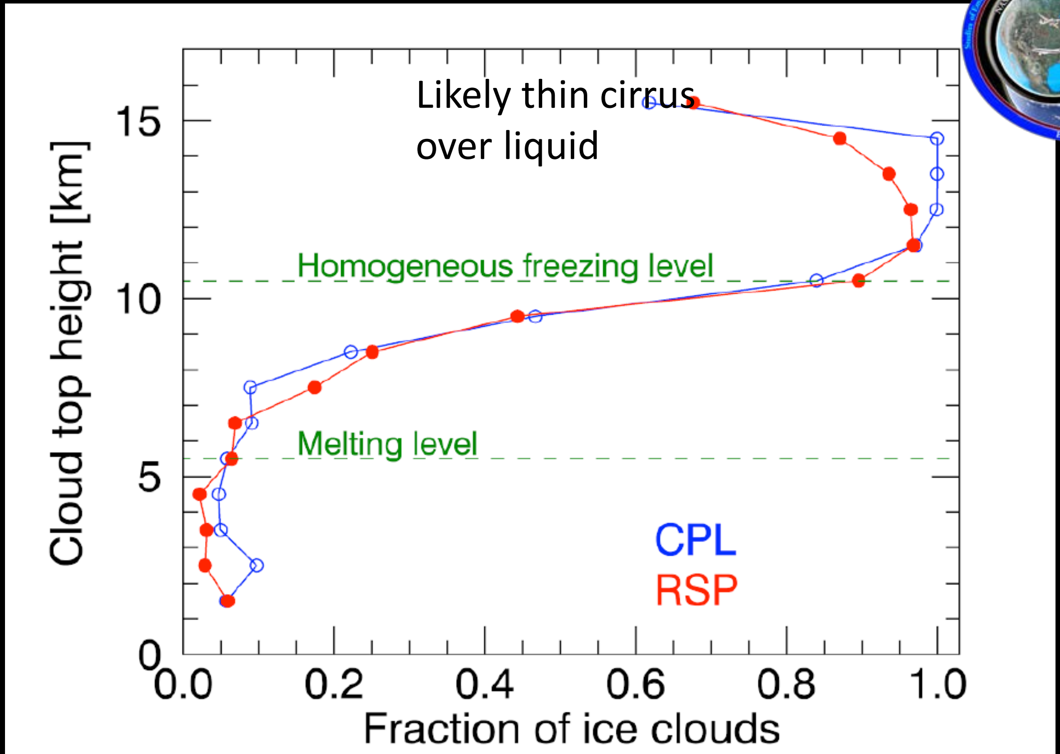
- Comparison of RFT retrievals to drizzle retrievals from APR3
- Initial results show the RFT technique has skill at detecting precipitation



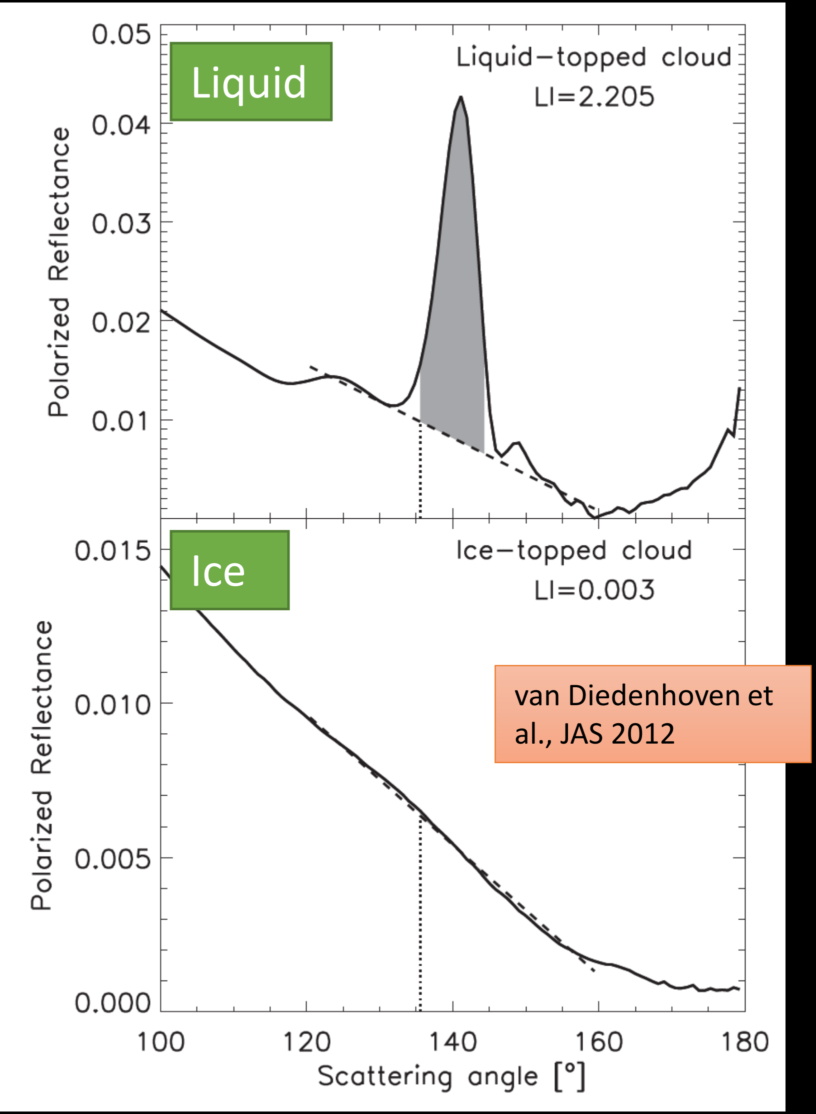
Detection of liquid at cloud top

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



SEAC^{4}RS RSP measurement showing good agreement with CPL lidar



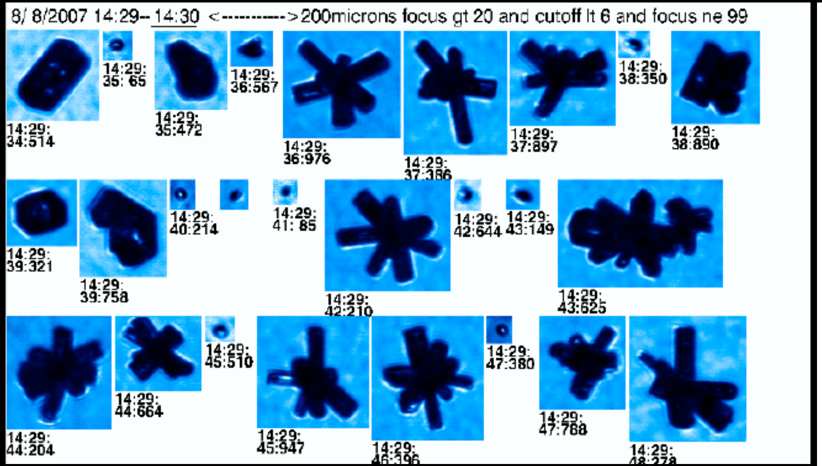
Ice crystal shape and asymmetry parameter

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

van Diedenhoven et. al., AMT 2012

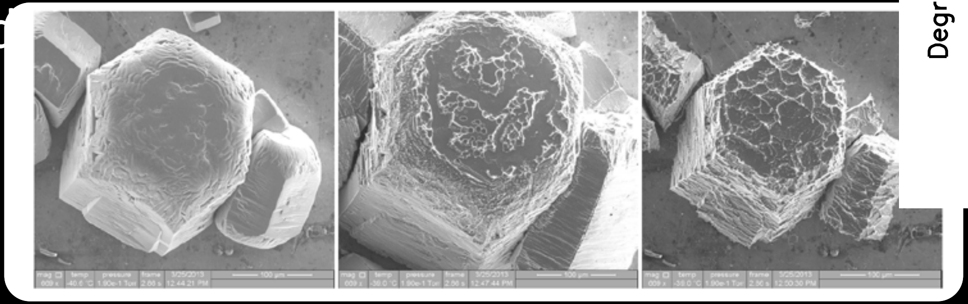
ice shape, *not size!*

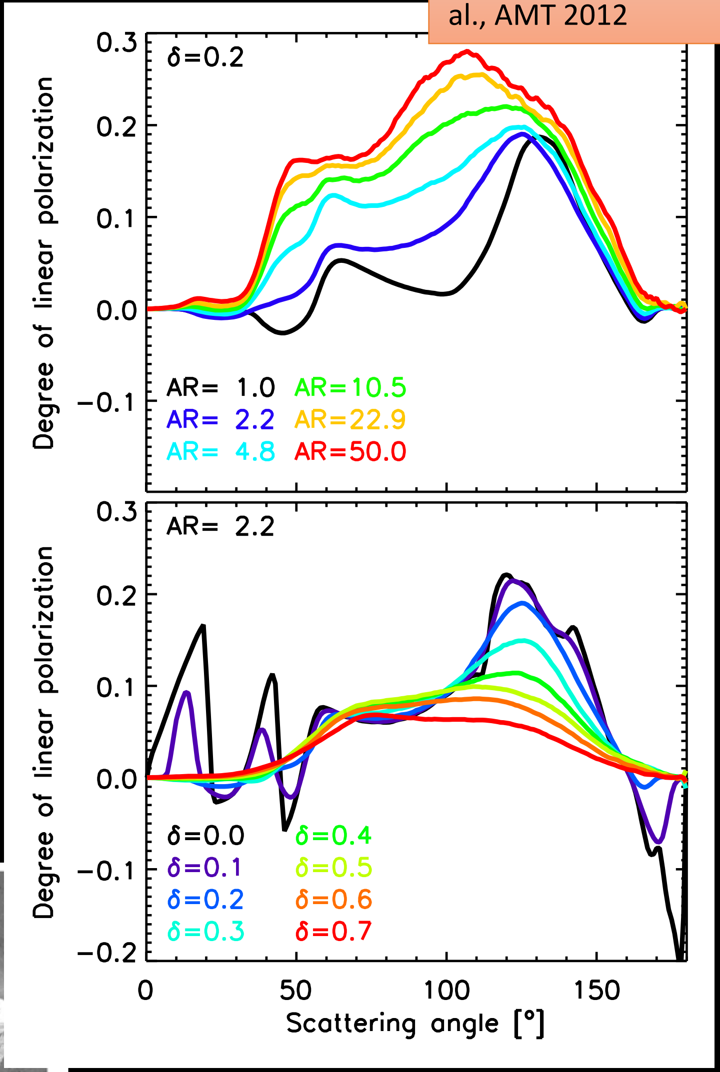
- Ice scattering properties depend on (in order of importance):
  1. Aspect ratio of crystal components
  2. Level of distortion/roughness
  3. General shape (a.k.a. habit)
- **Practical algorithm**:
  - Use simple hexagonal plates & columns
  - Vary aspect ratios and distortion to match measured and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



In situ images of complex ice crystals

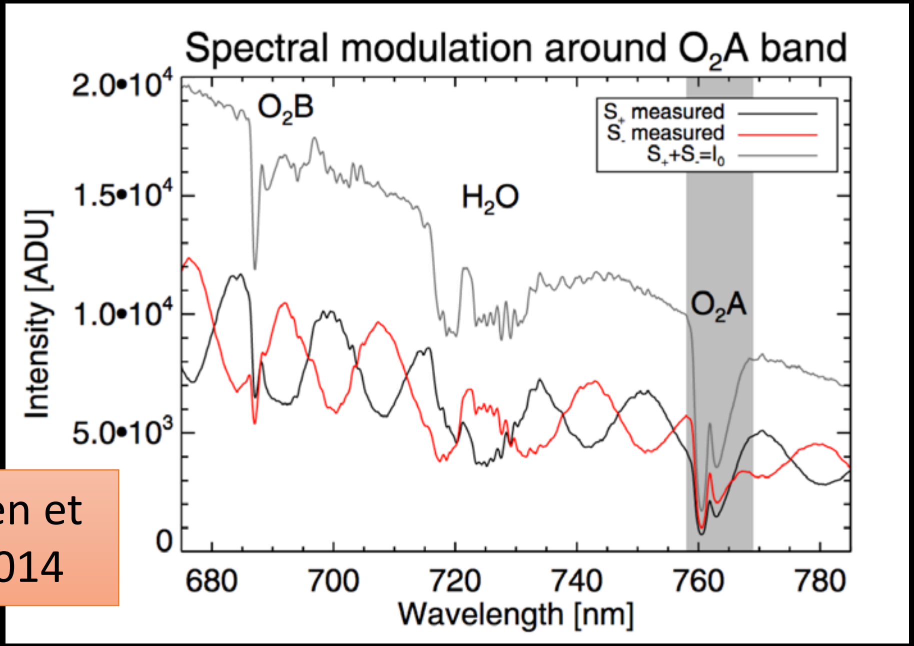
electron microscope images of roughness on ice crystals (Magee et al.)





Multi-angle polarimetry in the O_2 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)
- O_2 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

PACE mission

Key characteristics of the PACE observatory :

- The Ocean Color Instrument (OCI), single view hyperspectra,l 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 98º inclination
- Fall 2022 launch, three-year design

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