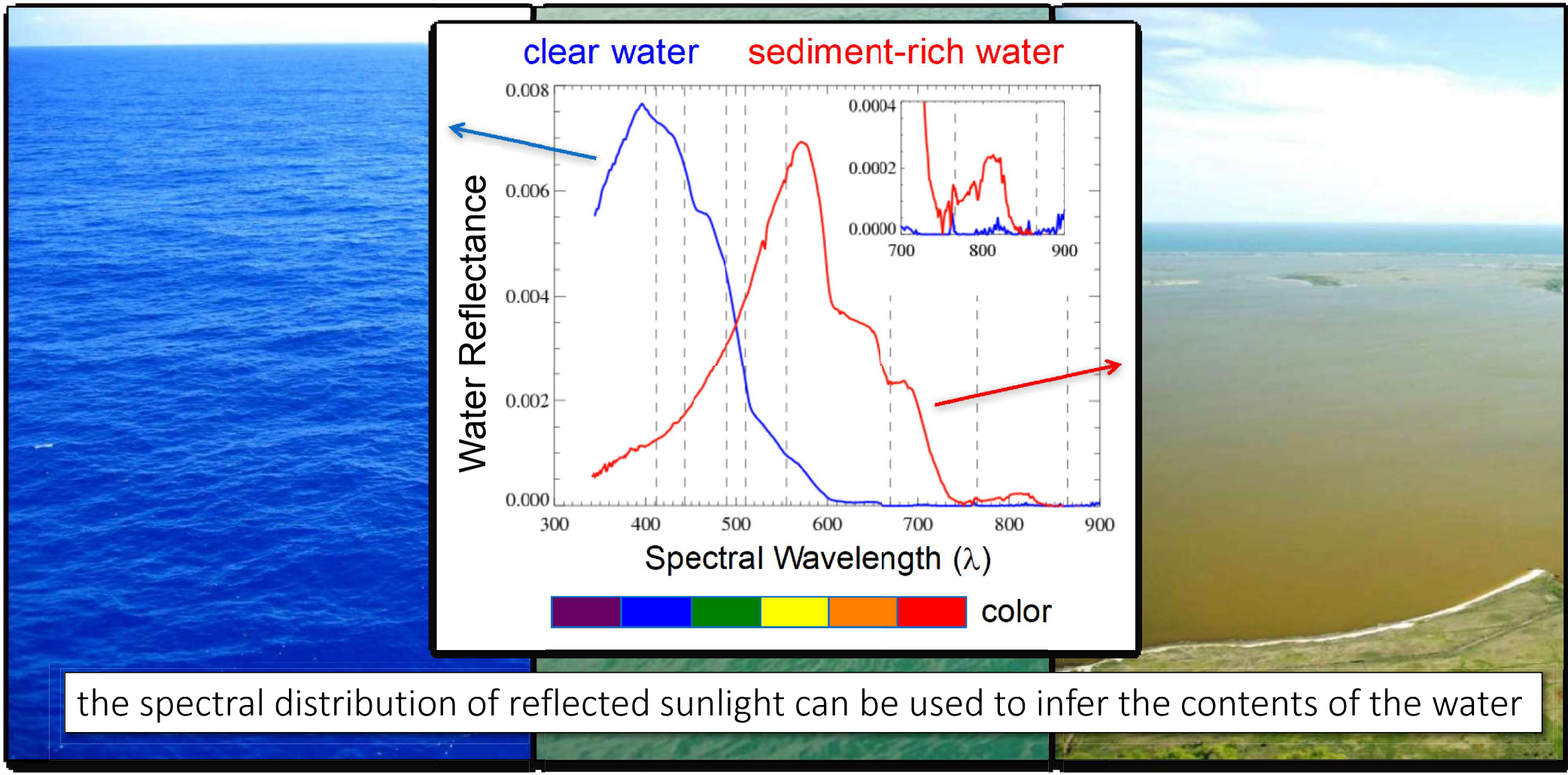
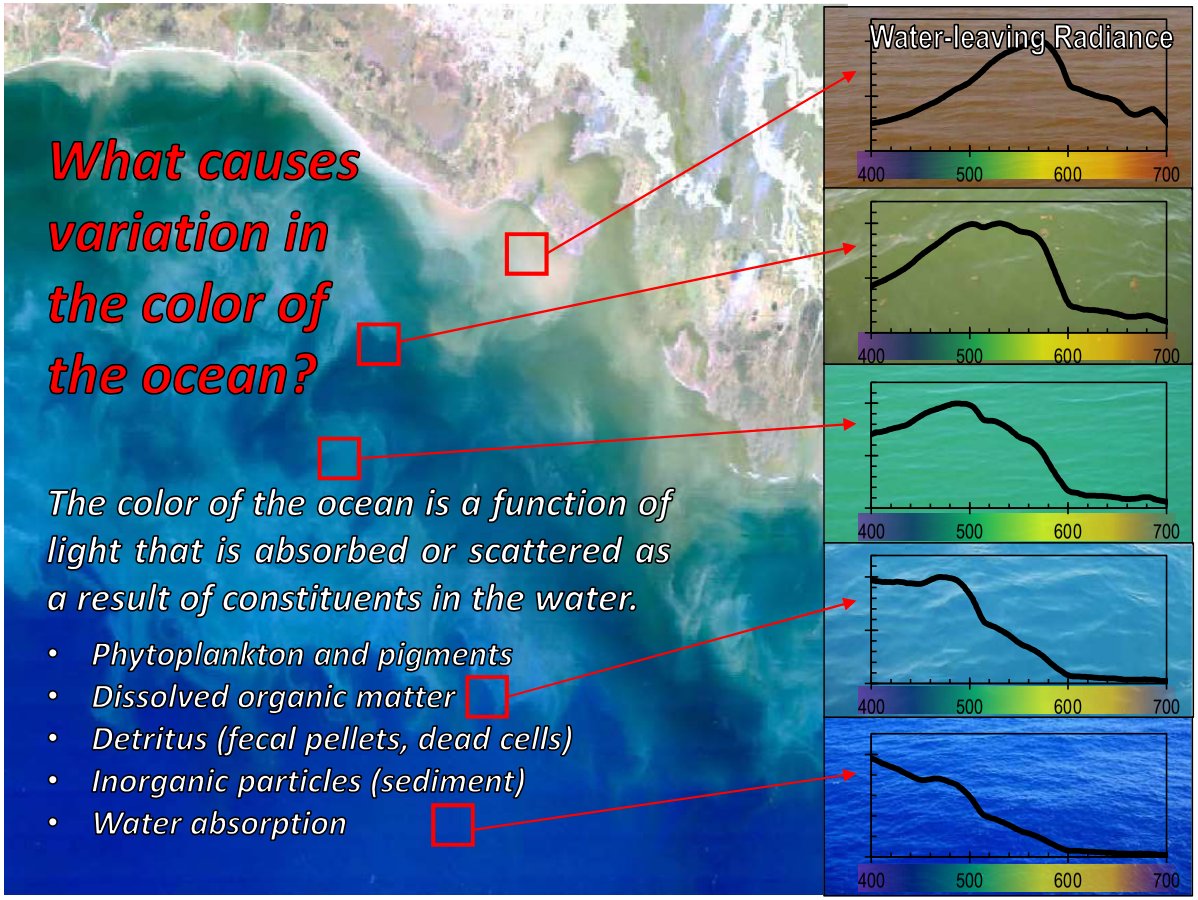
What is “ocean color”?

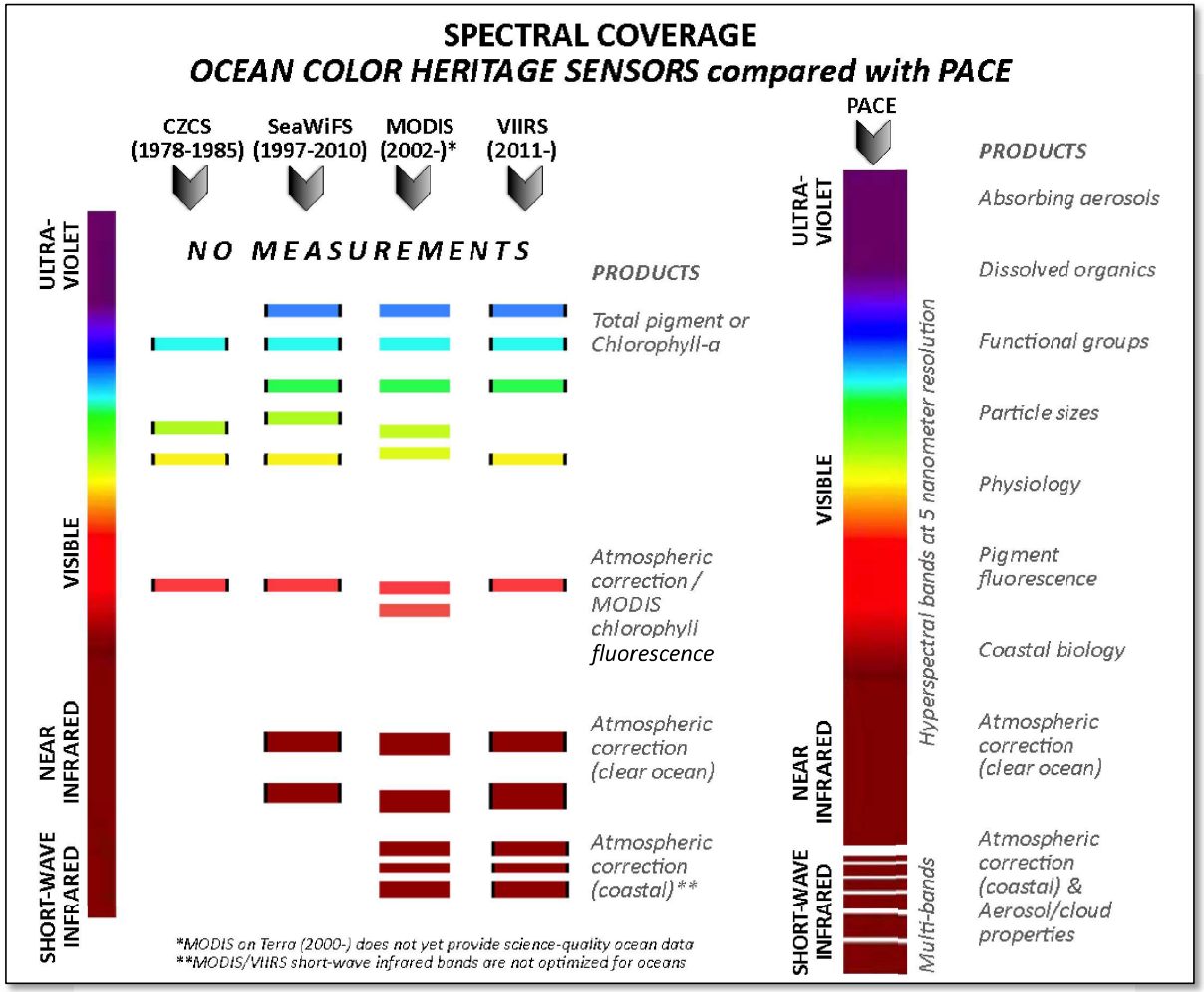


the spectral distribution of reflected sunlight can be used to infer the contents of the water

What is “ocean color”?



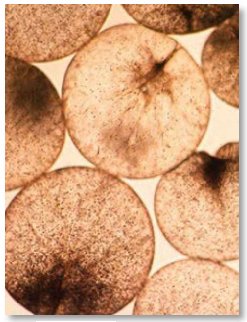
Moving from multi-spectral radiometry to spectroscopy



Example diatom

Linda Armbrecht, abc.com.au

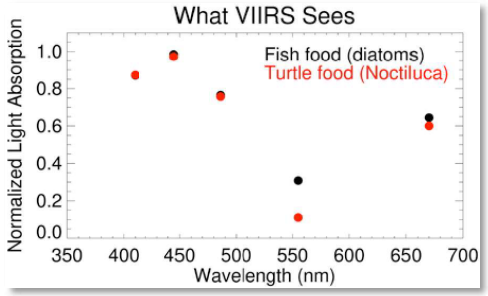
Example Noctiluca

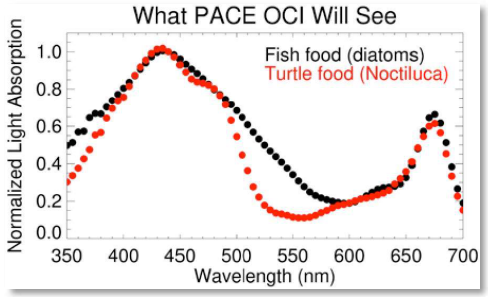


1 mm

Joaquim Goes, LDEO

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





Extend key systematic **ocean** biological, ecological, & biogeochemical climate data records, as well as **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

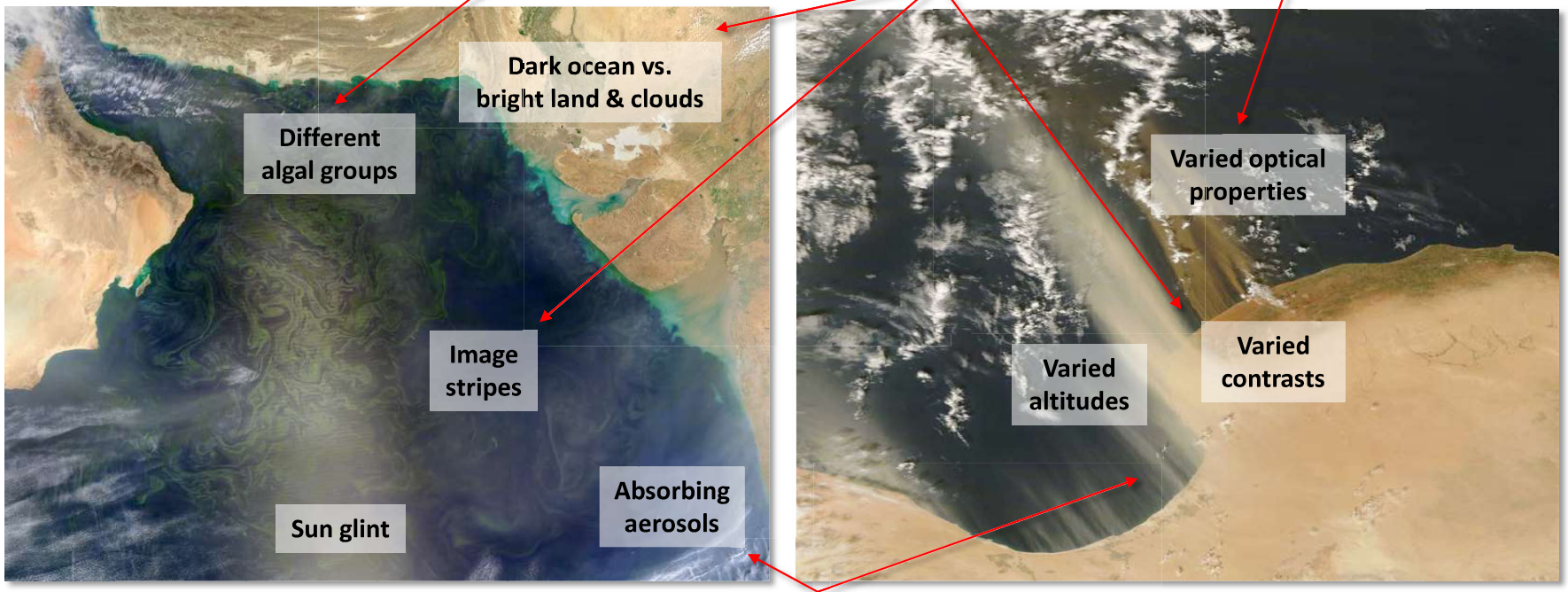
GSD of 1 ± 0.1 km² at nadir

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 ± 20°

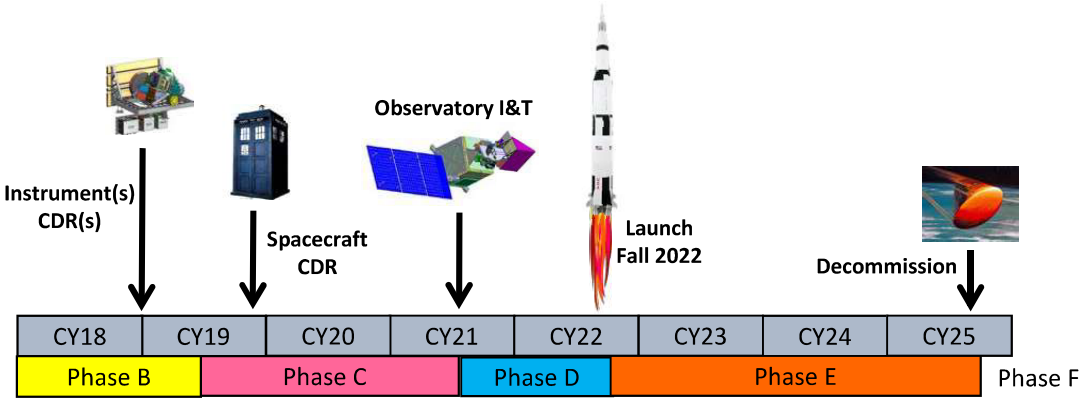
Spectral range goal of 320-865 @ 5 nm

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

Mission characteristics

Key Mission Elements

Mission management	NASA Goddard SFC
Ocean Color Instrument	NASA Goddard SFC
HARP2 polarimeter	U. Maryland Baltimore County
SPEXone polarimeter	SRON (Netherlands)
Spacecraft/Mission Ops	NASA Goddard SFC
Science data processing	Ocean Biology Processing Group
Competed science teams	NASA Earth Sciences Division



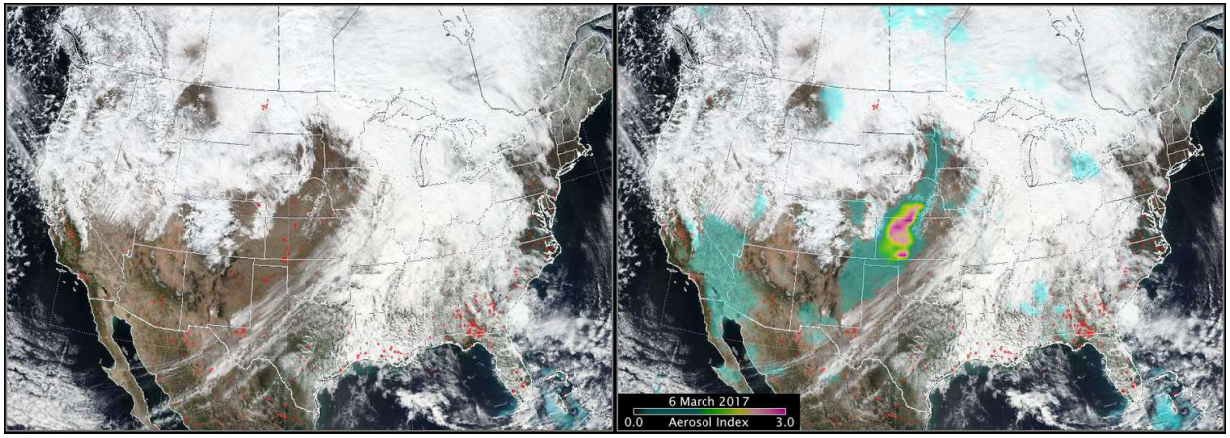
Key Mission Features

Cost	Directed, DTC, $805M
Life	3-yr, Class C, 10-yr fuel
Orbit	676.5 km, Sun sync, 1-pm MLT AN
Coverage (OCI)	2-day global
RF Communication	Ka direct to ground, 600Mbps

Key Mission Science Requirements

Ground sample distance of 1 ± 0.1 km^2 at nadir
Sun glint mitigation (OCI tilt ± 20°)
OCI spectral range from (320) 350-865 nm @ 5 nm resolution
OCI with 940, 1038, 1250, 1378, 1615, 2130, 2260 nm bands
Twice-monthly lunar calibration
Onboard solar calibration (daily, monthly, dim)
A vicarious calibration system
Core data products, uncertainties, & a validation program

OCI atmospheric improvements over heritage

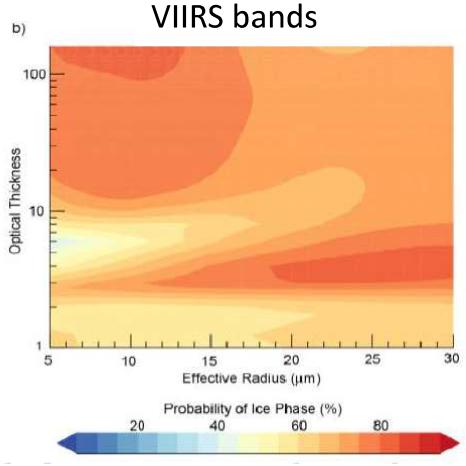


VIIRS RGB + OMPS Aerosol Index

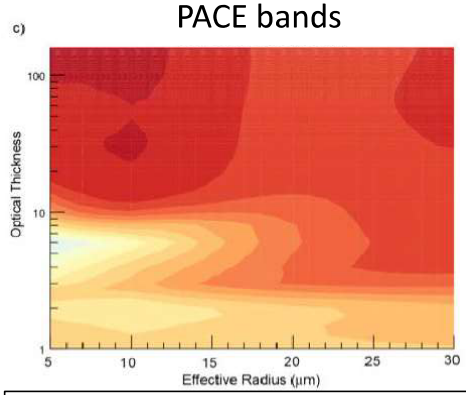
Higher spatial resolution than many heritage products

UV + oxygen-A bands to estimate concentrations & absorption magnitudes, not just an index

VIIRS bands



PACE bands



Deeper red indicates improved probability of detection of ice phase

Two 2-μm bands improve retrievals of cloud thermodynamic phase

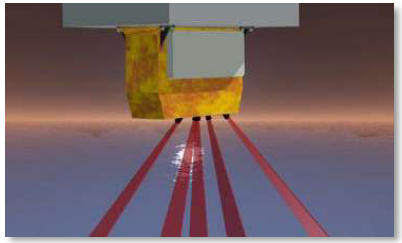
AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres
RESEARCH ARTICLE
10.1002/2017JD026493

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

O. M. Coddington[1], T. Vukicevic[2], K. S. Schmidt[1,3], and S. Platnick[4]

Polarimetry on PACE

Two cubesat-sized *contributed* instruments

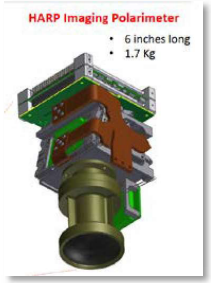


Spectro-Polarimeter for Planetary Exploration (SPEXone)

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

POC: Otto Hasekamp

Hyperspectral (UV) + narrow swath



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)
# 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	3 km^2
Heritage	AirSPEX	AirHARP, cubesat HARP for ISS

OCI-polarimetry synergy

Spectro-Polarimeter for Planetary Exploration (SPEXone)

- Excellent for aerosol characterization
- Addresses aerosol climate objectives beyond those required of OCI

Hyper Angular Rainbow Polarimeter (HARP-2)

- Excellent for cloud droplet size and ice particle shape/roughness retrievals
- Provides cloud capabilities beyond those required of OCI
- Wide swath ~matches OCI, offering potentially improved atmospheric correction

OCI + SPEXone + HARP-2

- Hyperspectral + hyperangular + highly accurate radiometric & polarimetric observations = far greater information content than any current instrument suite for ocean color, aerosol, & cloud observations
- New data products: ocean color from multi-angle polarimetry, wind speed, etc.

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 (*so plz don't ask*)

General expectations for future PACE science teams:

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

Looking forward: noteworthy mentions

Budget Status: FY18 and FY19 (as of March 2018)

- The FY18 Omnibus signed on 23 March 2018 funds the continued development of the PACE mission at $147M (FY18 PresBud proposed termination of development activities for PACE, CLARREO-PF, OCO-3 and RBI)
- FY19 President's Budget continues to propose termination of DSCOVR EO instruments EPIC, NISTAR; as well as OCO-3; PACE; CLARREO-PF; RBI, and points to implementing the Program of Record in the 2017 Decadal Survey

2017-2027 Decadal Survey for Earth Science and Applications from Space

- Free download: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm
- Briefing slides available, as is webinar
- Program of Record – "The series of existing or previously planned observations, which should be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record flight missions from FY18-FY27 be capped at $3.6B."

Looking Forward: PACE Science Team pre-launch & post-launch schedule

Pre-launch Science Teams

- FY15 – 17: ROSES 2013 A.25 – written and competed before PACE was a real mission
  - Achieve consensus and develop community-endorsed paths forward for IOPs and Atmospheric Correction
  - Dr. Emmanuel Boss (UMaine) and Dr. Lorraine Remer (UMBC) – Science Team Leaders
  - Accomplishments include:
    - Werdell, P. J., et al. (2018), An overview of approaches and challenges for retrieving marine inherent optical properties from ocean color remote sensing, Prog. Oceanogr., 160 (2018) 180-212, https://doi.org/10.1016/j.pocean.2018.01.001.
    - Boss, E., and L. A. Remer (2018), A novel approach to a satellite mission's science team, Eos, 99, https://doi.org/10.1029/2018EO092639. Published 2.12.2018
    - Polarimetry in the PACE mission (Remer et al.) white paper
    - Research Topic in Frontiers in Earth Science – "From the Satellite to the Earth's Surface: Studies Relevant to NASA's Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) Mission" /https://www.frontiersin.org/research-topics; Co-Editors David Antoine and Oleg Dubovik. Due date for submission is October 2018.
    - Atmospheric correction and many other technical memoranda
- FY19 – 22: ROSES 2019 (4 years)
  - Allow lead time for scientific algorithm development & applications development prior to launch
  - Initiates interface between instrument developers and OBPG; OBPG/OB DAAC and algorithm developers; possible LaRC DAAC for polarimetry (not yet decided)
- FY23 – 25: ROSES 2022 (3 years)
  - Pre-launch algorithms and post-launch competed science/applications for ocean color instrument's aerosol, cloud, ocean science, plus aerosol and clouds from polarimeters

Post-launch Competed Science - options

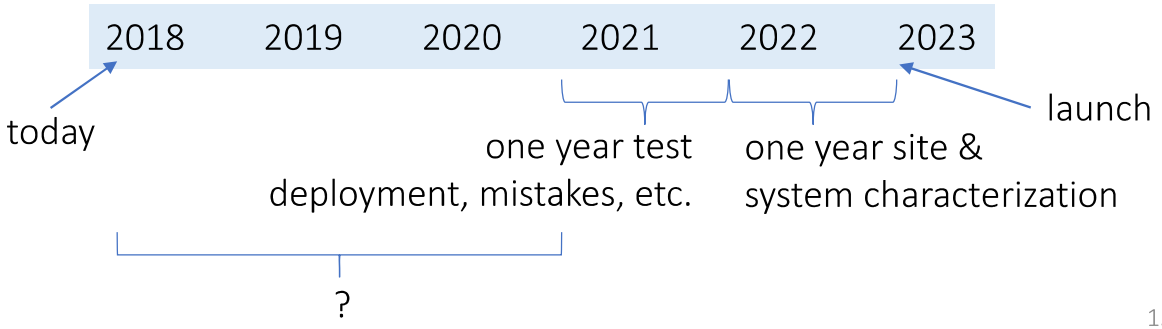
- Competed through ROSES 2025
- After launch, joint funding between EOS project and R&A, possible additional funding from Applied Sciences
- Mission contributions (many TBDs) + continuation during any mission extensions

Looking forward: vicarious calibration

ROSES 2014 A.3 OBB (FY15-17) - written and competed before PACE was a real mission

- Issued under OBB, managed jointly between OBB and ESTO
- Allowed lead time for concepts to mature prior to launch + Identified technical development needs/risks for the approaches selected
- Three projects funded that are completing analysis and testing of hardware:
  - Hyperspectral radiometric device for accurate measurements of water leaving radiance from autonomous platforms for satellite vicarious calibrations - PI – Andrew Barnard, SeaBird Scientific
  - Hybrid-spectral Alternative for Remote Profiling of Optical Observations for NASA Satellites (HARPOONS) - PI – Carlos DelCastillo, NASA GSFC
  - Developing a MOBY-NET instrument, suitable for a federation network for Vicarious Calibration of Ocean Color Satellites Perform cal/val during mission operations - PI – Ken Voss, University of Miami
- **ROSES 2018 or 2019 - Select best approach and hardware (pre-launch) or further risk reduction on instrumentation, if needed, for vicarious calibration of ocean color data products.**

options: systems in development, expected external assets (e.g., MOBY, BOUSSOLE), FRM4SOC, other in situ sources, models



Looking forward: applied sciences

New ESD 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.

Learn more about PACE

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


Thank you.
Questions?
PACE
Plankton, Aerosol, Cloud, ocean Ecosystem

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

Phase B – preliminary design & technology completion

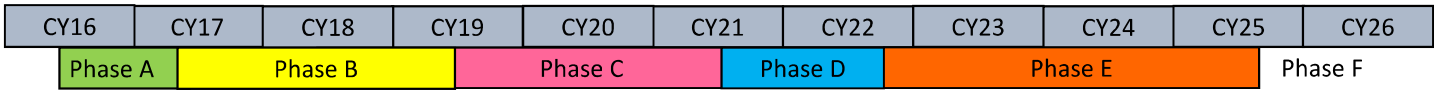
- July 2017 – Q2 2019
- All mission elements must pass Preliminary Design Reviews (PDR)
- Preceded by series of sub-element Engineering Peer Reviews (EPRs)
- Mission PDR
- KDP-C

- 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.)

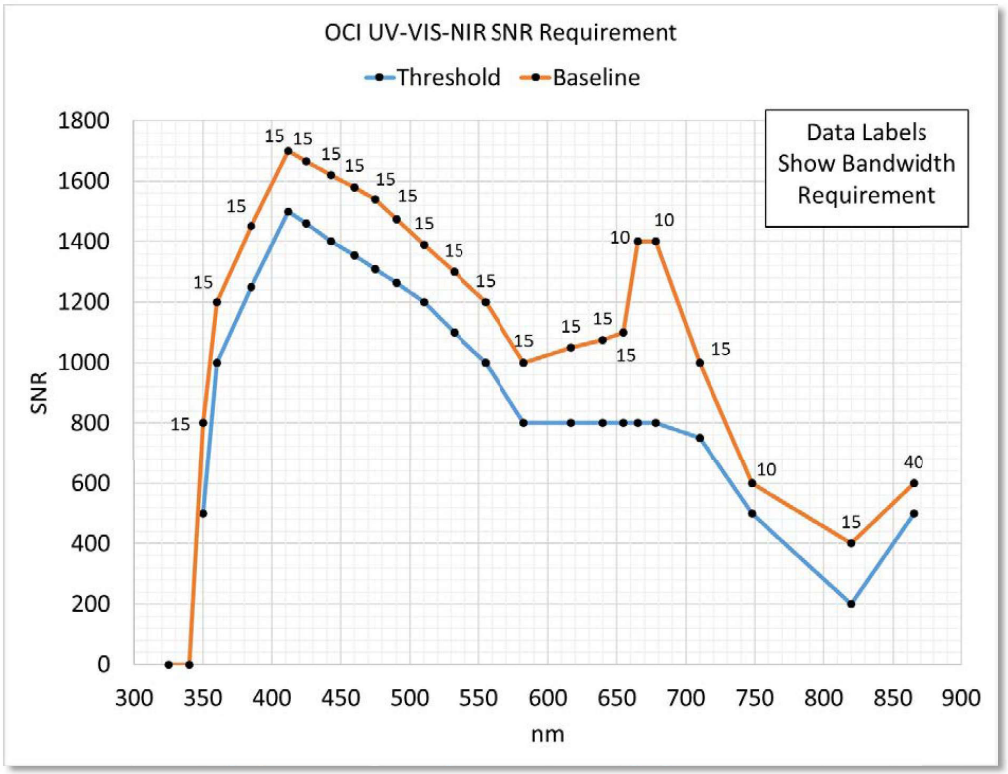
Phase C – final design & fabrication

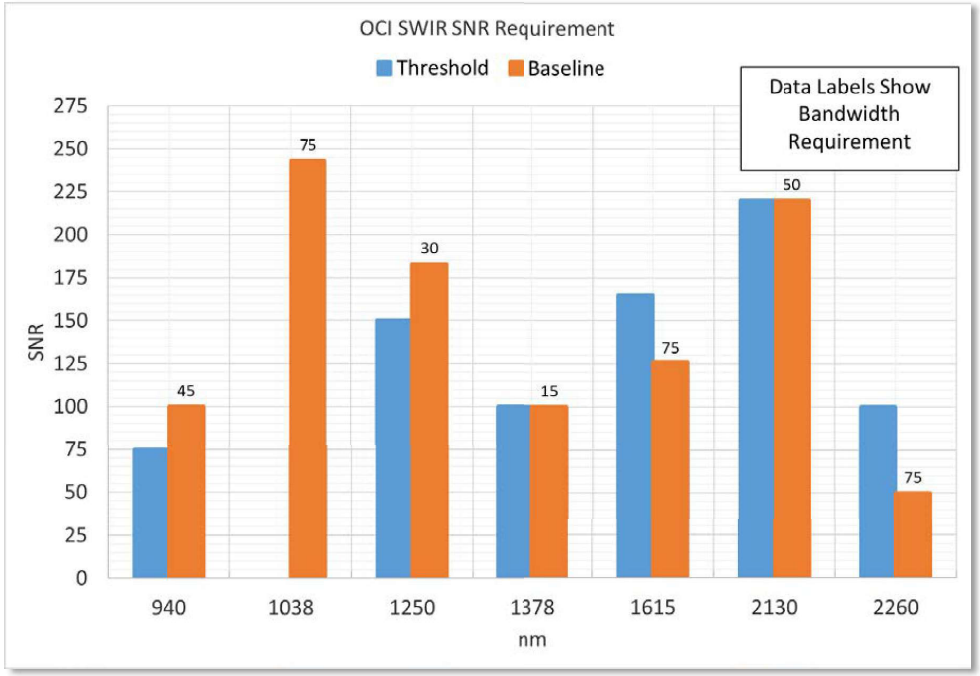
Phase D – system assembly, integration & testing, & launch

Phase E – science operations



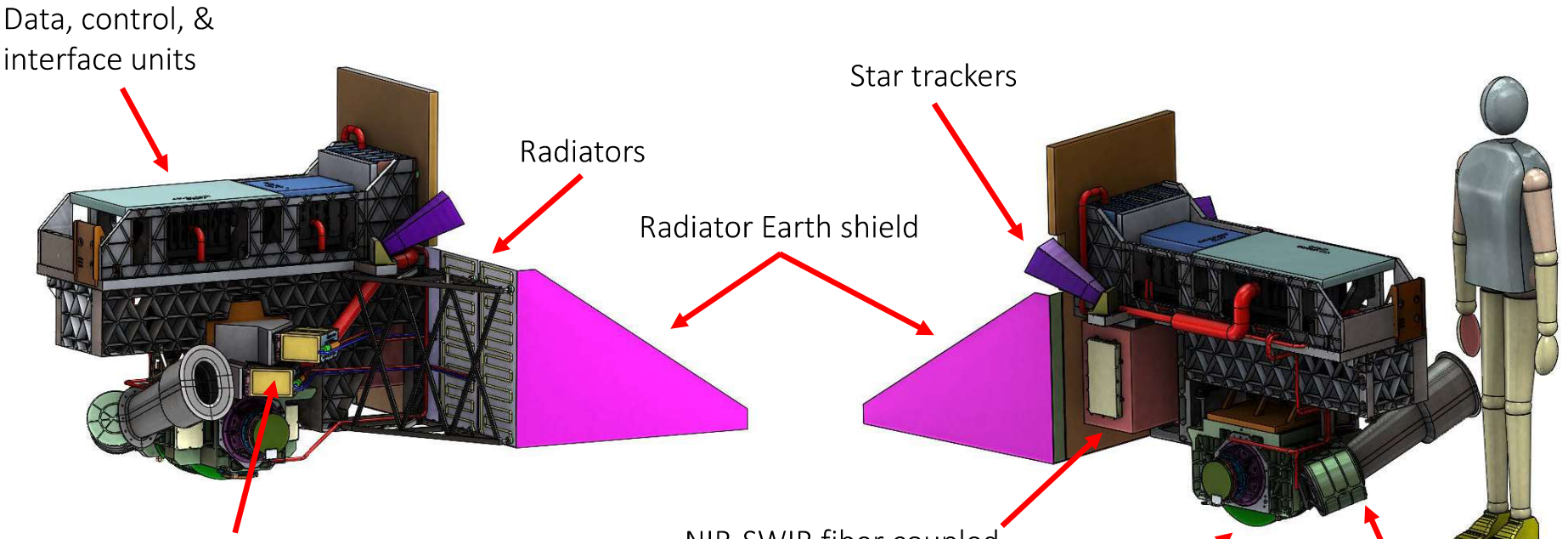
Ocean Color Instrument (OCI) – signal-to-noise (SNR)





Ocean Color Instrument – physical assembly

Concept follows the heritage of the SeaWiFS, MODIS, and VIIRS



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

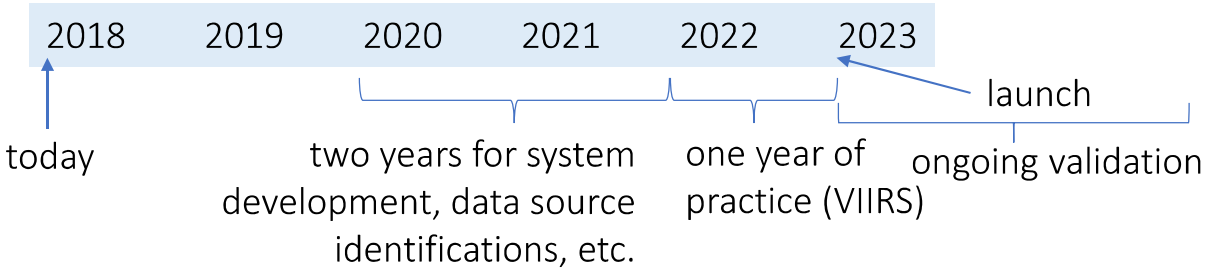
Looking forward: a validation program

FY19 – 21: ROSES 2018 or 2019 (3-4 years)

- Selects best approach and hardware (pre-launch) or further risk reduction on instrumentation, if needed, for validation of all data products (aerosol, cloud, ocean color) – *in situ;* Calibration/validation of polarimetry data products (TBD)

FY22 – 25: ROSES 2021 or 2022 (4 years)

- Perform cal/val during mission ops; Includes airborne and *in situ* measurements; Continue every year during mission extension(s)
- International community (EUMETSAT, ESA, and the Copernicus Program) are investing in Fiducial Reference Measurements for Sentinel and coordination is critical

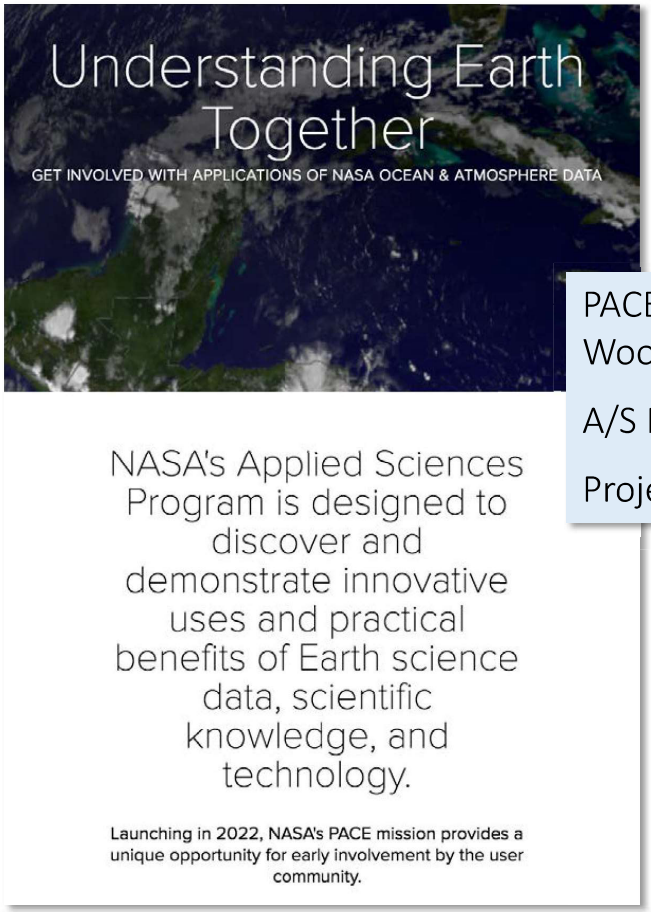


Level 1 required (~threshold) products

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

Uncertainty requirements accompany all L1 req'd data products (i.e., we need quantitative validation of all of these products)

Looking forward: applied sciences

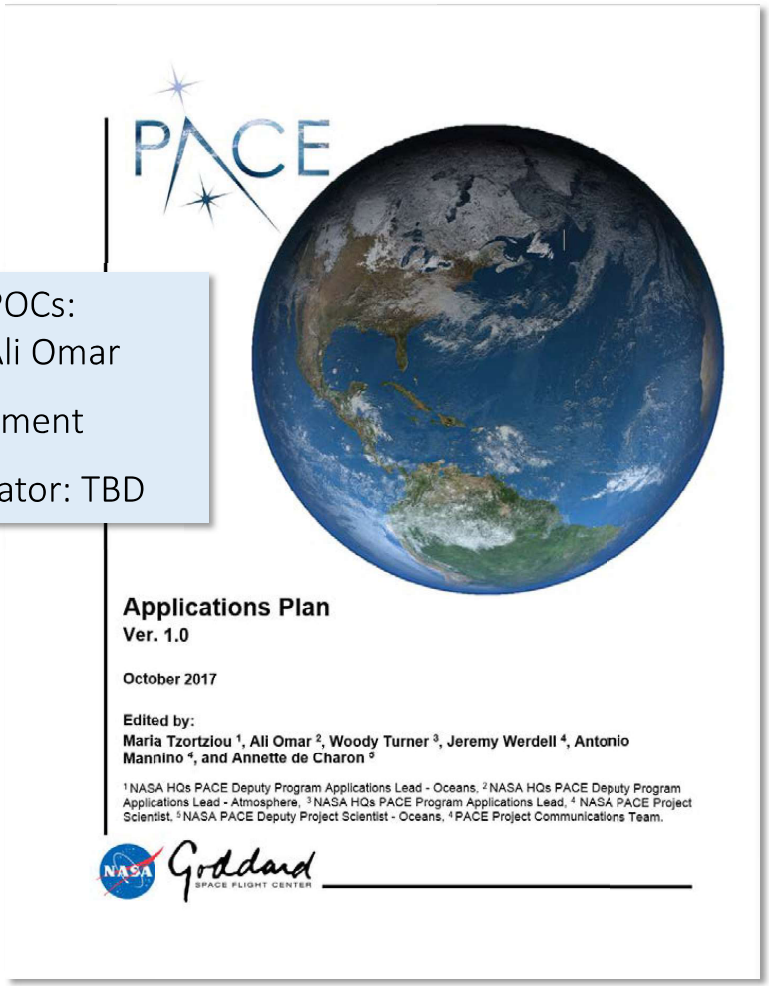


Consider joining the PACE Early Adopter Program!

PACE Applied Sciences program POCs:
Woody Turner, Maria Tzortziou, Ali Omar

A/S Program currently in development

Project Applied Sciences Coordinator: TBD



Take home messages

- **Possibilities for next competed science team**
  - new approaches for existing data products (e.g., OCI spectral range!)
  - advanced & merged data products & science and interdisciplinary science
- **Vicarious calibration system**
  - System(s) in field 2+ years prior to launch
  - Calibration needs for cloud & aerosol communities?
  - OSSEs or needs for site(s) characterization?
- **Field data - Validation**
  - What do we need (field campaigns, communities, instruments, timing)?
    How do we ensure collection & availability of resources such as ships/aircraft?
  - Existing resources, docs, & partners of which to be aware?
- **Algorithms**
  - Heritage approaches being identified & implemented
  - Open process for new products & methods/approaches for existing products