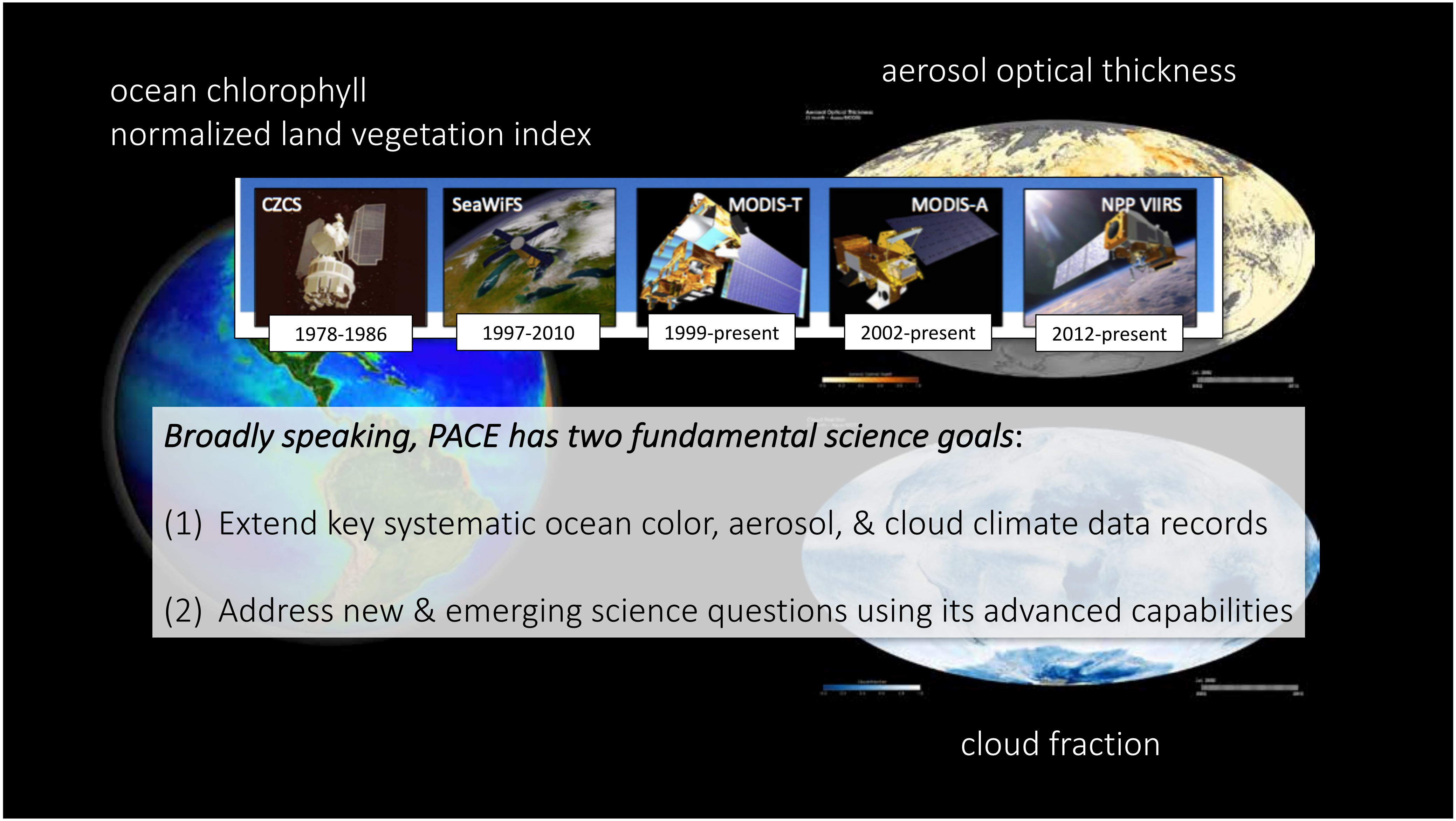
The Plankton, Aerosol, Cloud, ocean Ecosytem (PACE) mission: Status, science, advances

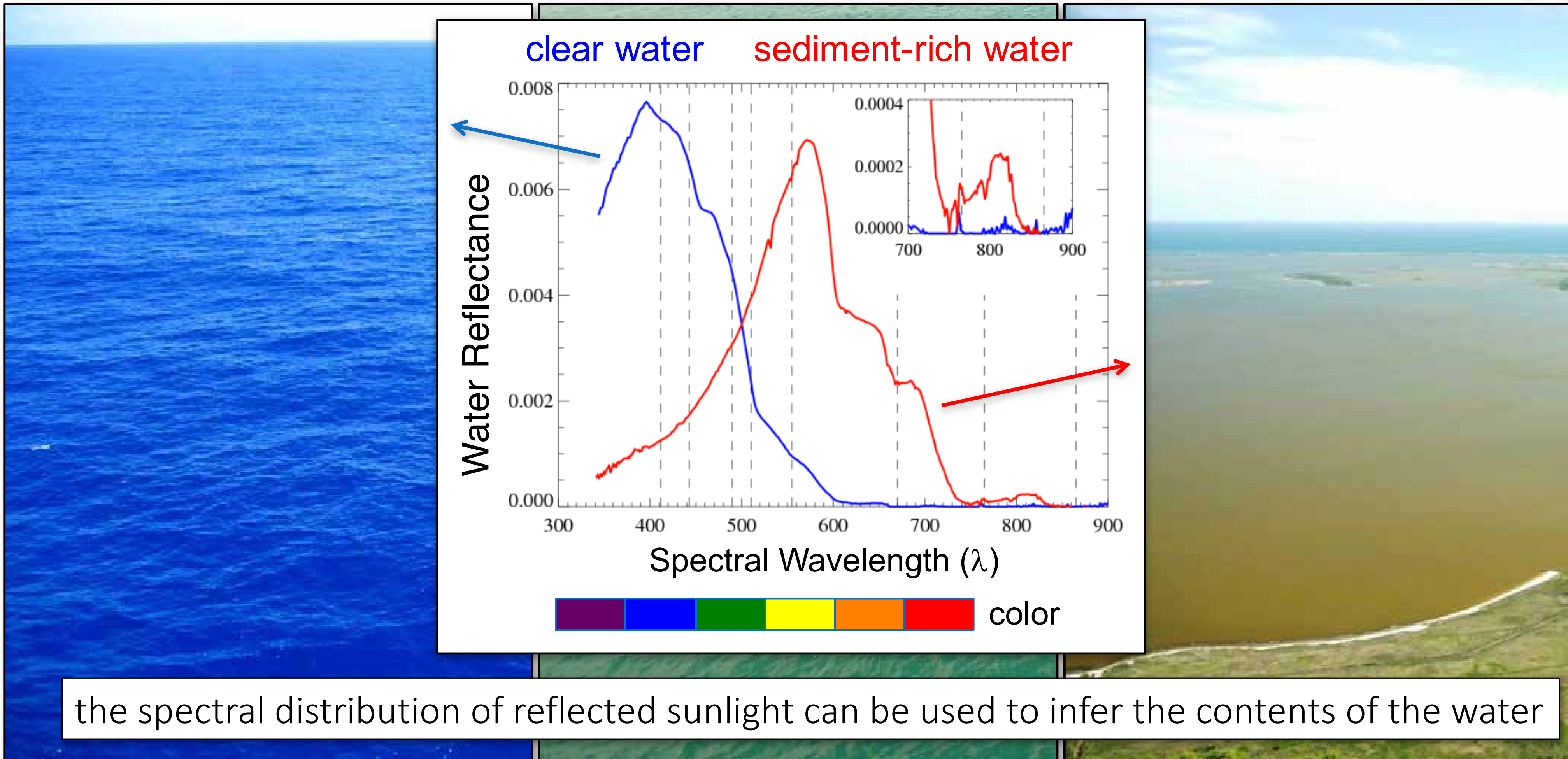
Jeremy Werdell

PACE Project Scientist, NASA Goddard Space Flight Center

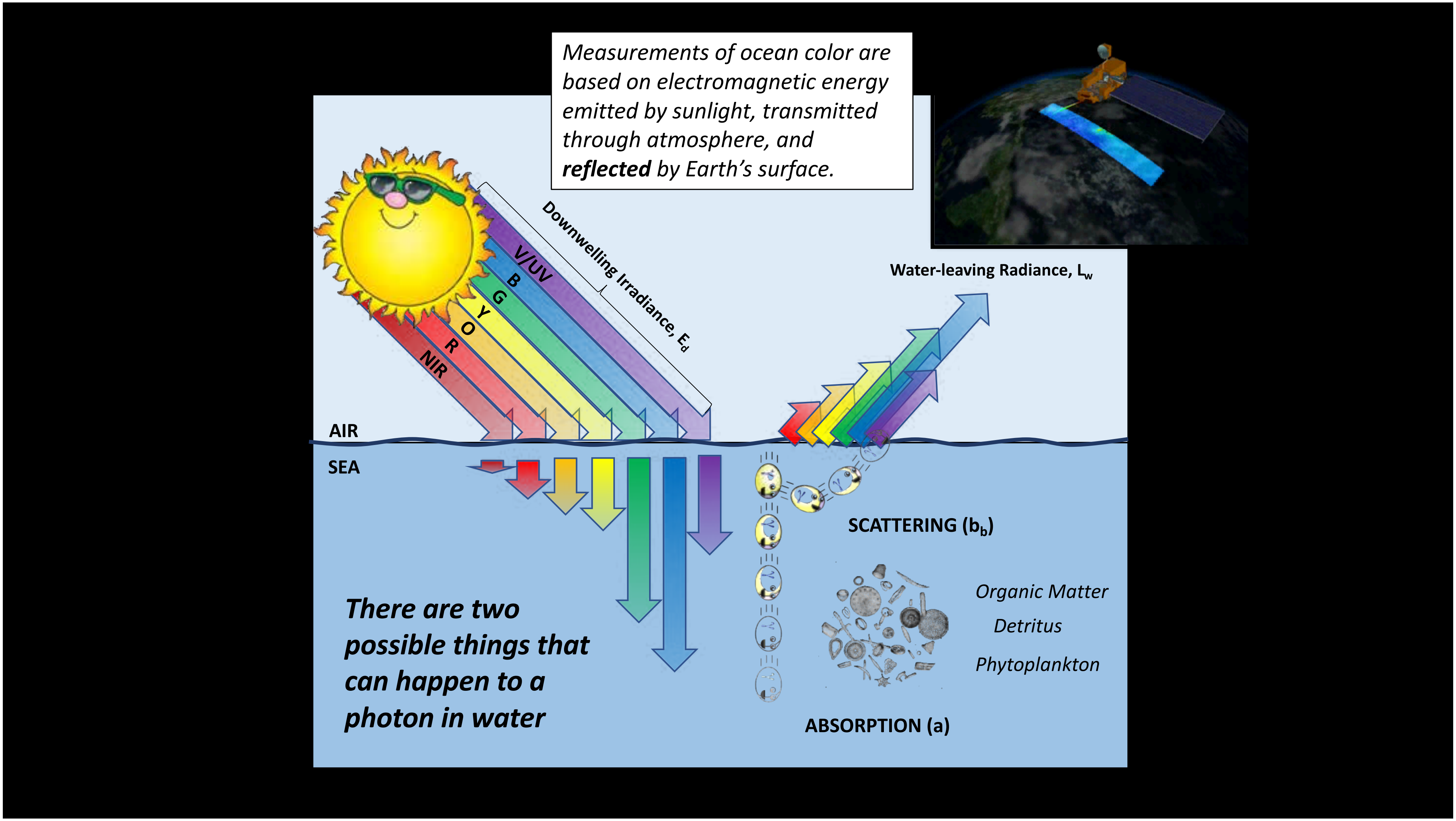
21 March 2018 @ the Sun-Climate Symposium


ocean chlorophyll
normalized land vegetation index
aerosol optical thickness
CZCS
1978-1986
SeaWiFS
1997-2010
MODIS-T
1999-present
MODIS-A
2002-present
NPP VIIRS
2012-present
Broadly speaking, PACE has two fundamental science goals:
(1) Extend key systematic ocean color, aerosol, & cloud climate data records
(2) Address new & emerging science questions using its advanced capabilities
cloud fraction

What is “ocean color”?



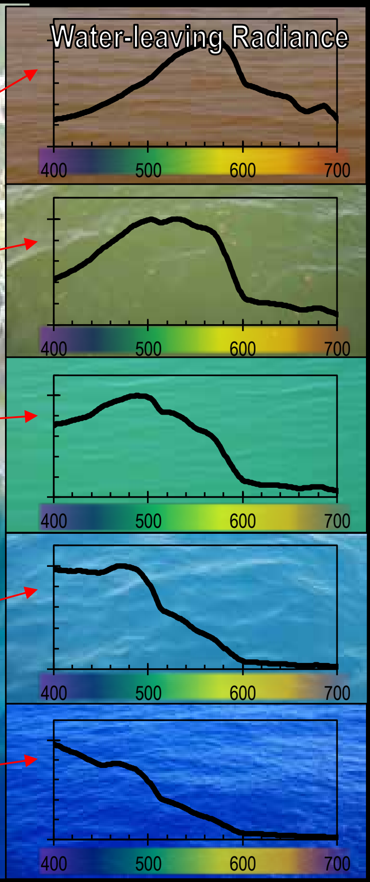
the spectral distribution of reflected sunlight can be used to infer the contents of the water


Measurements of ocean color are based on electromagnetic energy emitted by sunlight, transmitted through atmosphere, and **reflected** by Earth's surface.
Downwelling Irradiance, E_d
V/UV
B
G
Y
O
R
NIR
Water-leaving Radiance, L_w
AIR
SEA
SCATTERING (b_b)
Organic Matter
Detritus
Phytoplankton
ABSORPTION (a)
There are two possible things that can happen to a photon in water

What causes variation in the color of the ocean?

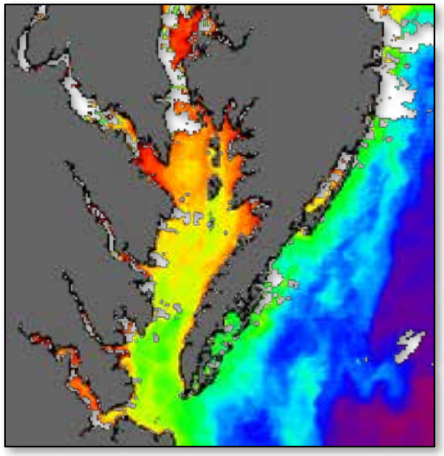
The color of the ocean is a function of light that is absorbed or scattered as a result of constituents in the water.

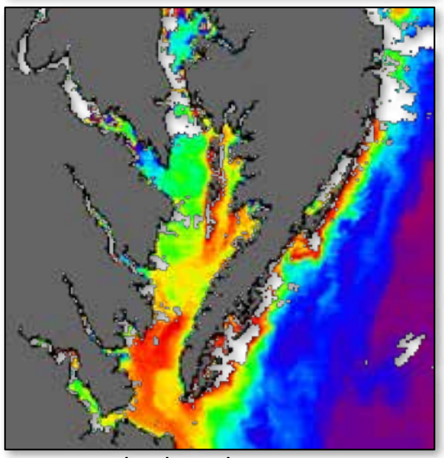
- *Phytoplankton and pigments*
- *Dissolved organic matter*
- *Detritus (fecal pellets, dead cells)*
- *Inorganic particles (sediment)*
- *Water absorption*



Ocean color data products

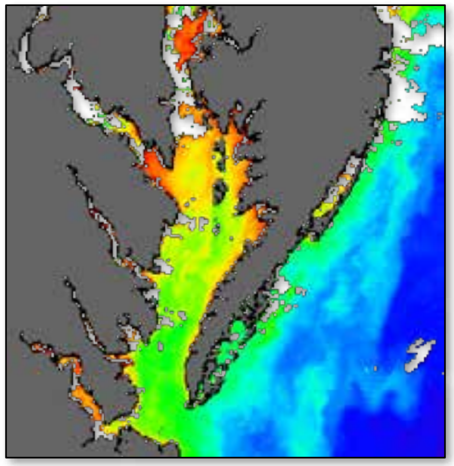
chlorophyll-a (*algal biomass*)



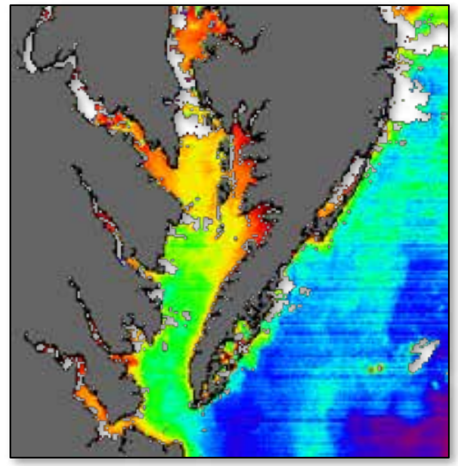


particle backscattering (*sediment load*)

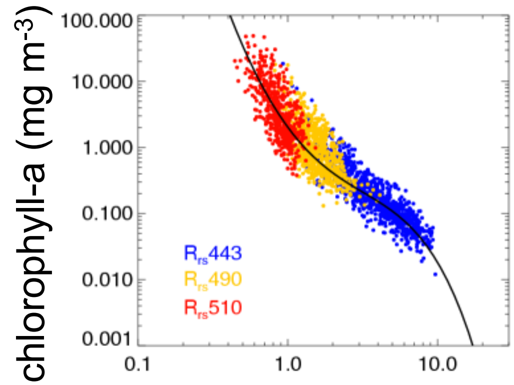
diffuse light attenuation (*water clarity, turbidity*)



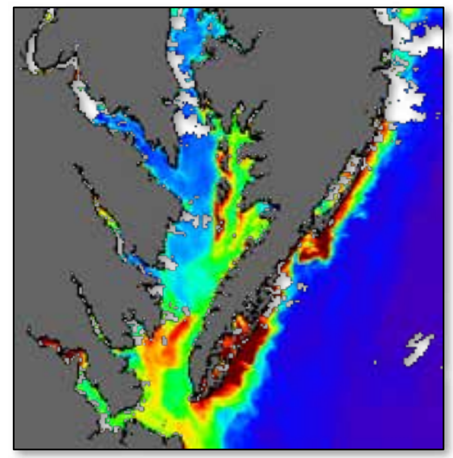
dissolved organic matter absorption (*runoff*)



and, many others, including:
phytoplankton community composition (*including HABs*)
particle size distributions (*water composition*)
particulate (in)organic carbon (*productivity*)
euphotic depth (*visibility, water clarity*)
water temperature (MODIS, VIIRS)



ratio of blue:green radiances



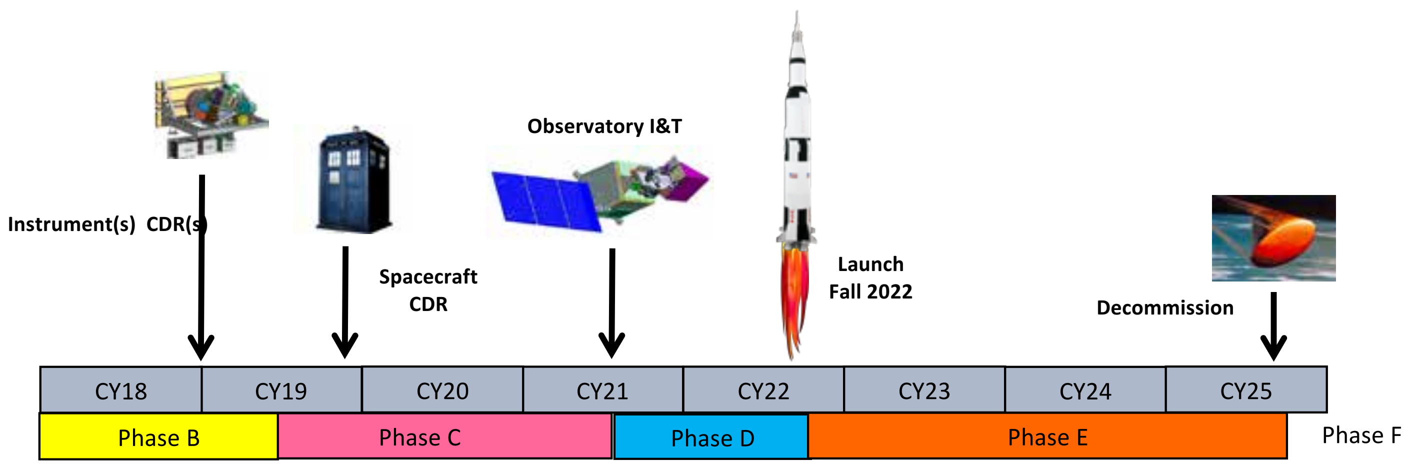
red light reflectance (*sediment load*)

jeremy.werdell@nasa.gov

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
Science Team	2019-2022 + 2023-2025 (ROSES)
Cal/Val Team	2018/19-2021 + 2022-2025 (ROSES)



jeremy.werdell@nasa.gov

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

Phase B – preliminary design & technology completion

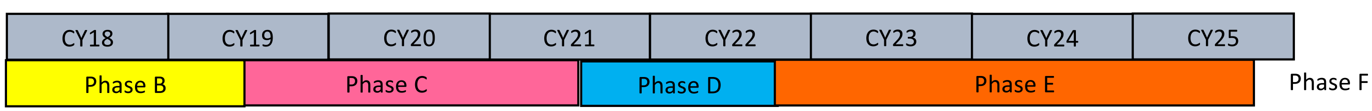
- July 2017 – Q2 2019
- All mission elements must pass Preliminary Design Reviews (PDR)
- Preceded by series of sub-element Engineering Peer Reviews (EPRs)

- 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

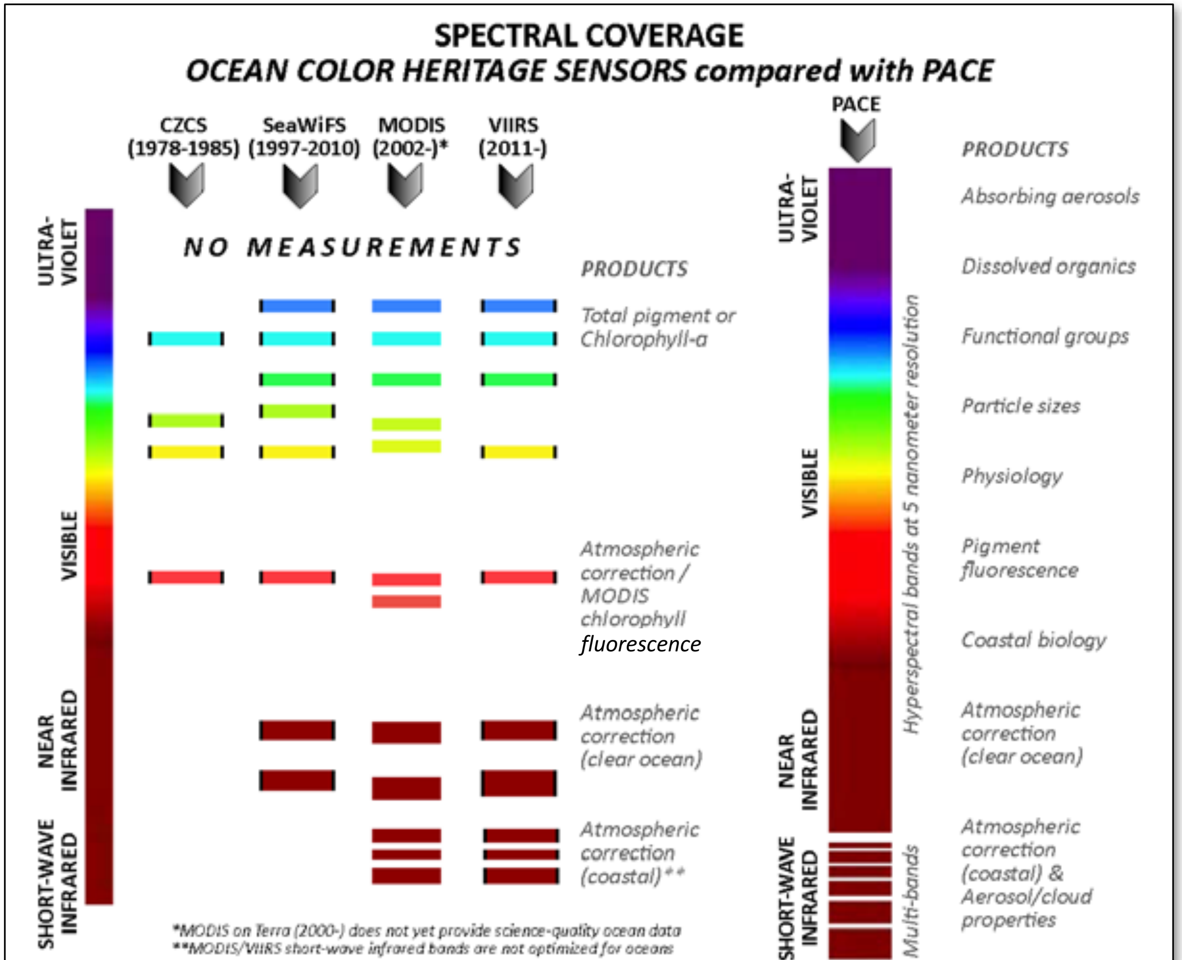
Phase D – system assembly, integration & testing, & launch

Phase E – science operations



jeremy.werdell@nasa.gov

Moving from multi-spectral radiometry to spectroscopy



Example diatom

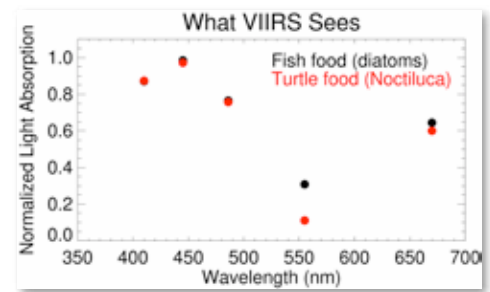
Linda Armbrecht, abc.com.au

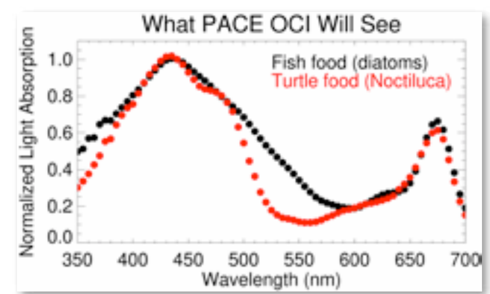
Example Noctiluca

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

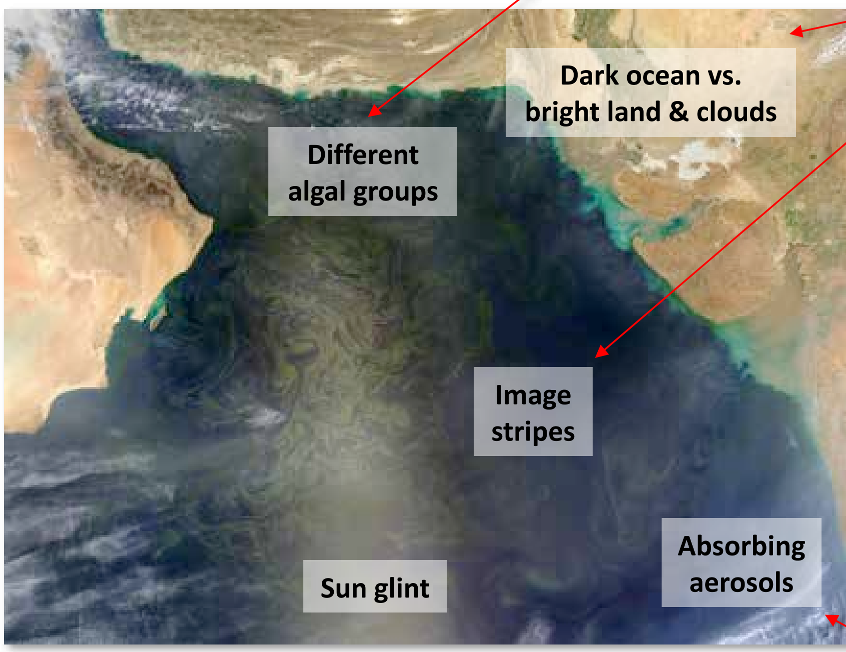
GSD of 1 ± 0.1 km² at nadir

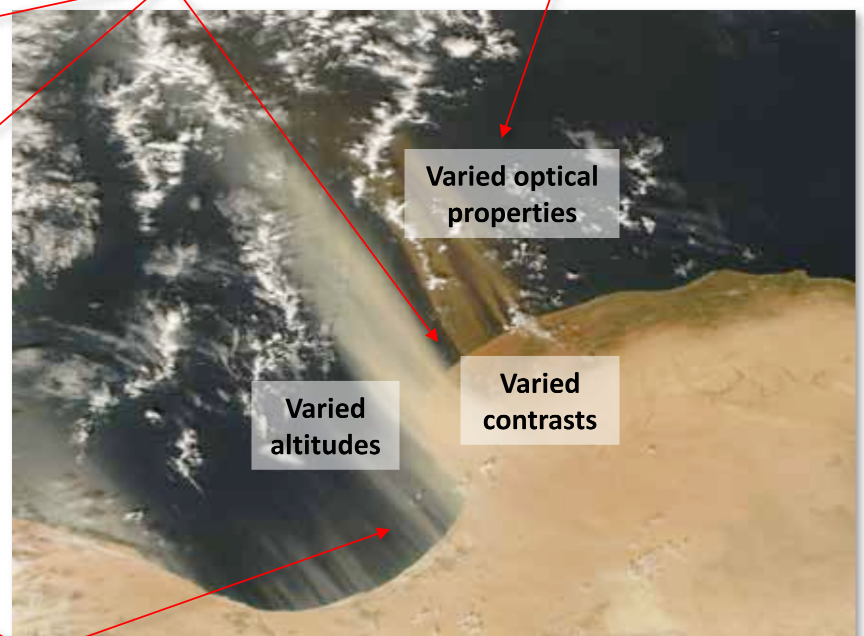
Spectral range from 350-865 @ 5 nm

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

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

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**

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

jeremy.werdell@nasa.gov

Advanced & evaluation science data products

Required data products & additional expected data products:

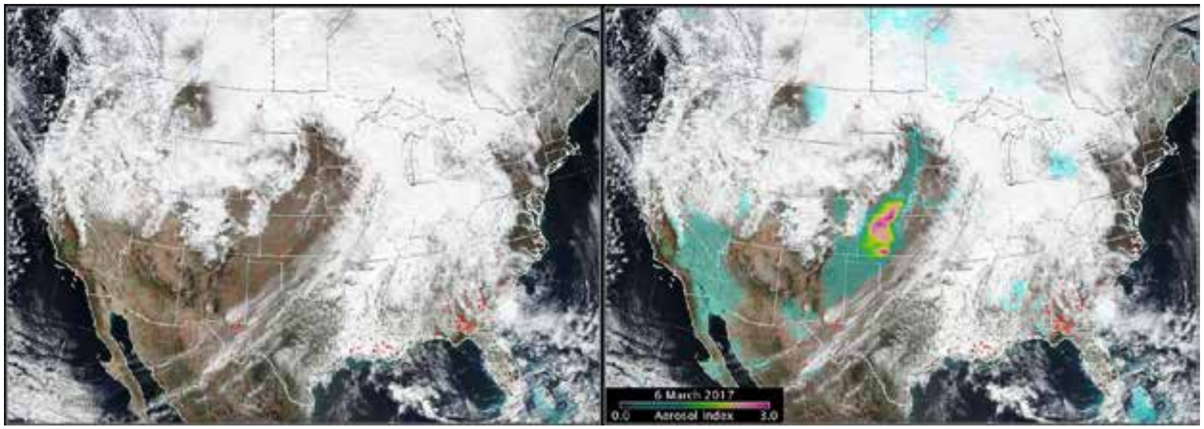
Incomplete list of advanced (~baseline) products

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

OCI atmospheric improvements over heritage



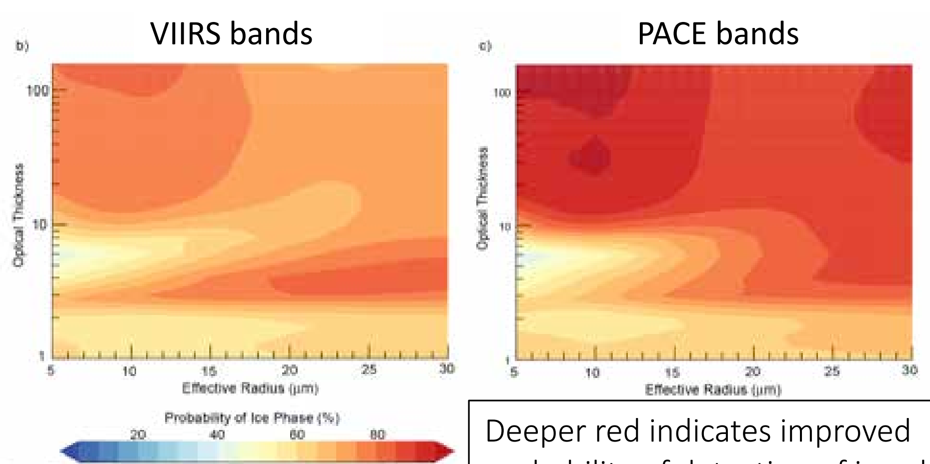
VIIRS RGB + OMPS Aerosol Index

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

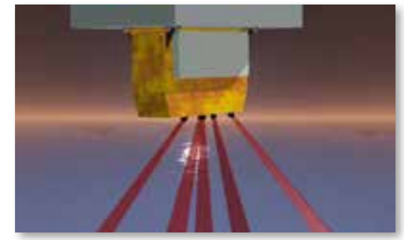
AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres
RESEARCH ARTICLE
10.1002/2017JD026493

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

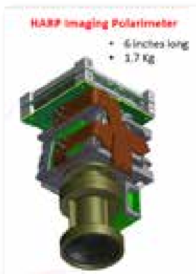


Spectro-Polarimeter for Planetary Exploration (SPEXone)

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.

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.


PACE

Applications Plan

Ver. 1.0

October 2017

Edited by:

Maria Tzortziou [1], Ali Omar [2], Woody Turner [3], Jeremy Werdell [4], Antonio Mannino [4], and Annette de Charon [5]

[1] NASA HQs PACE Deputy Program Applications Lead - Oceans, [2] NASA HQs PACE Deputy Program Applications Lead - Atmosphere, [3] NASA HQs PACE Program Applications Lead, [4] NASA PACE Project Scientist, [5] NASA PACE Deputy Project Scientist - Oceans, [5] PACE Project Communications Team.

jeremy.werdell@nasa.gov

Take home messages

PACE is unlike any other ocean color mission planned in the 2020's by any agency; it fills a substantial void:

	Spatial	Spectral *	Temporal	Detectors
VIIRS	750 m global	7 bands from 412 – 865 nm 1.24, 1.61, 2.25 μm	2-day nadir view	multiple 16 – rotating telescope
OLCI / Sentinel-3	300 m global	21 programmable bands from 400 – 1020 nm	3-day nadir view	multiple pushbroom
OLI / Landsat-8/9 MSI / Sentinel-2	10 - 60 m coastal	5-9 bands from 443 – 865 nm 1.60, 2.20 μm	16-day nadir view	multiple pushbroom
PACE	*1000 m* *global*	***>114*** *bands from* ***320*** *– 885 nm* *1.04, 1.25, 1.61, 2.13, 2.26 μm*	*2-day* ***±20° tilt***	***single*** ***1*** *– rotating telescope*

* only bands used for ocean color shown

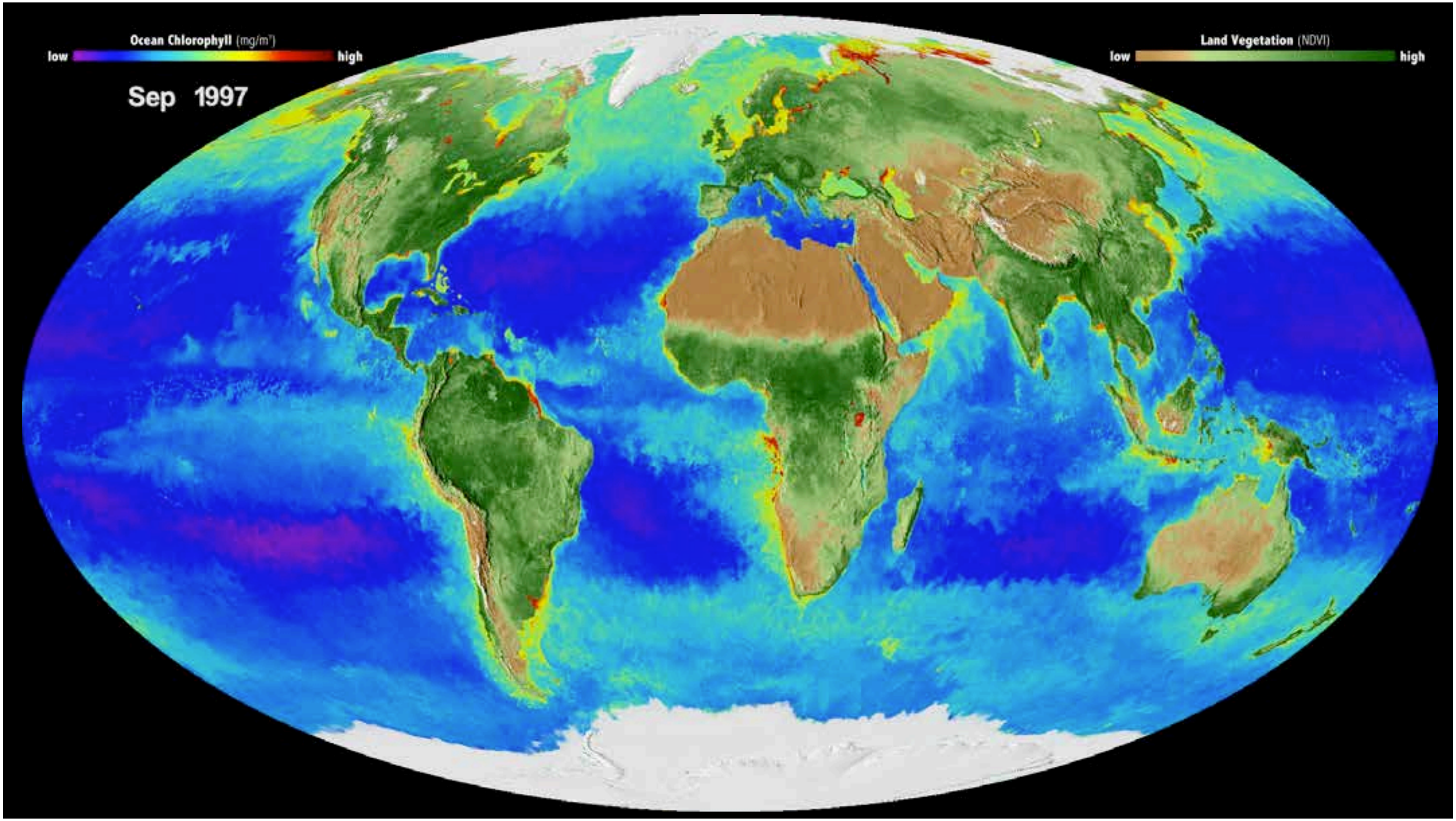
The ocean color instrument concept provides a leap forward in capabilities for the ocean color community; by itself, it will provide a wealth of information not currently available or planned to become available

Polarimetry provides a leap forward in capabilities for the atmospheric community – it also provides a benefit to the ocean color community, making the combination of instruments a major contribution to science

jeremy.werdell@nasa.gov

Learn more about PACE

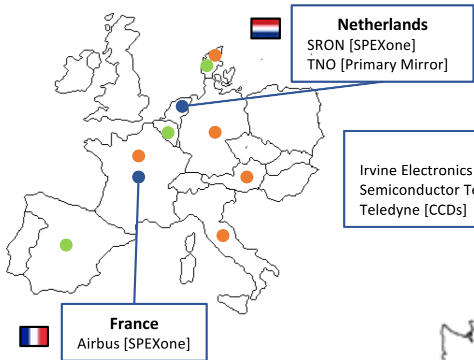
https://pace.gsfc.nasa.gov
@NASAOcean (Twitter)
@NASA.Ocean (Facebook)
Technical Memo. series

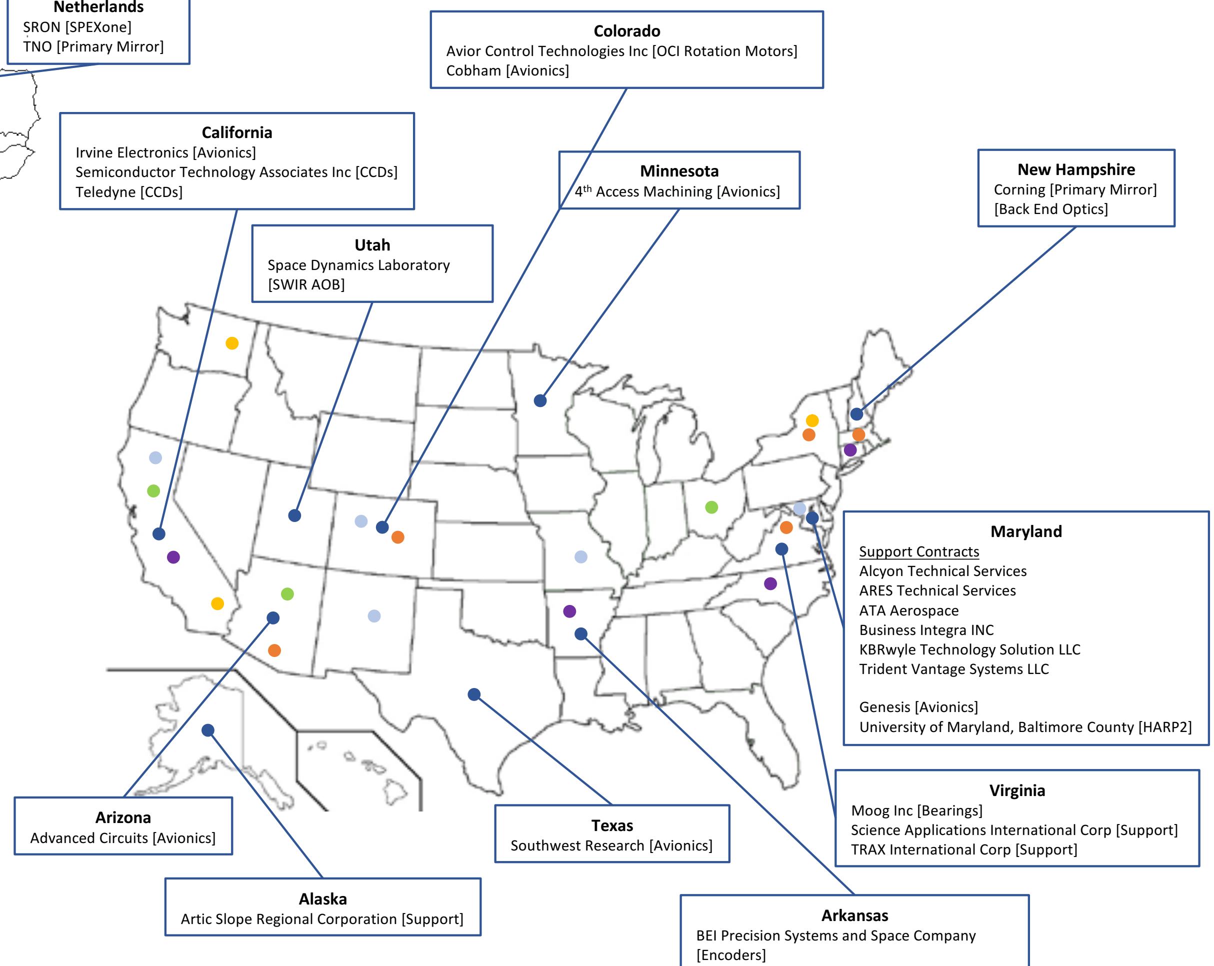


Ocean Chlorophyll (mg/m³)
low
high
Sep 1997
Land Vegetation (NDVI)
low
high


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

Who's working on PACE (as of early Feb 2018)?

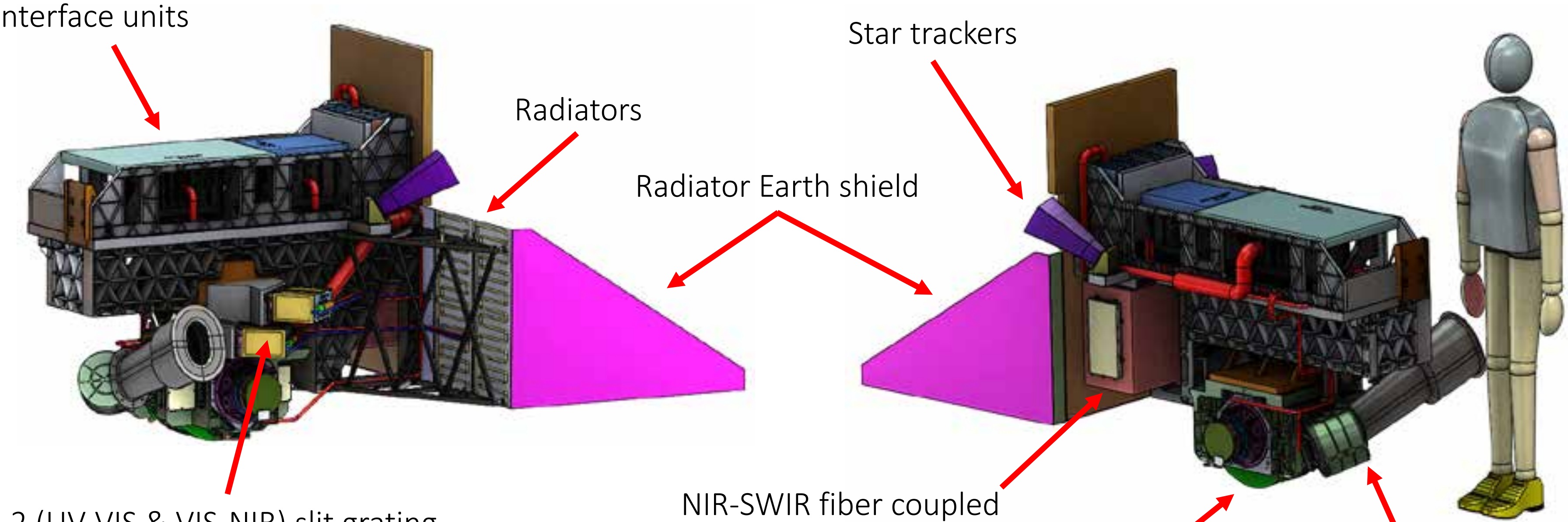




the first PACE science team (2014-2017)

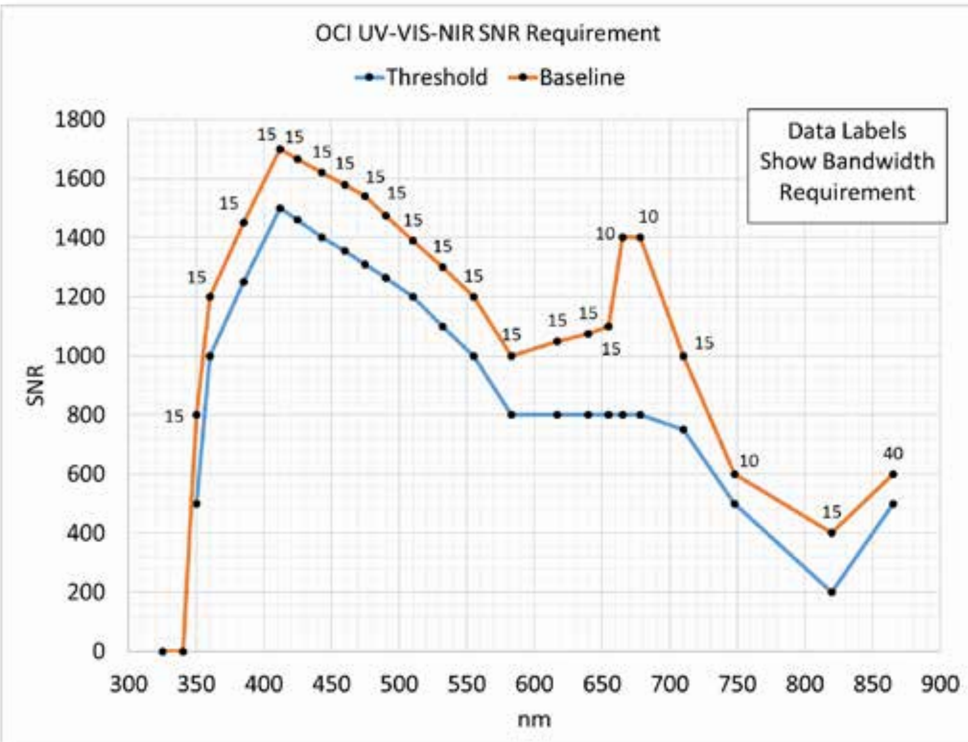
Ocean Color Instrument – physical assembly

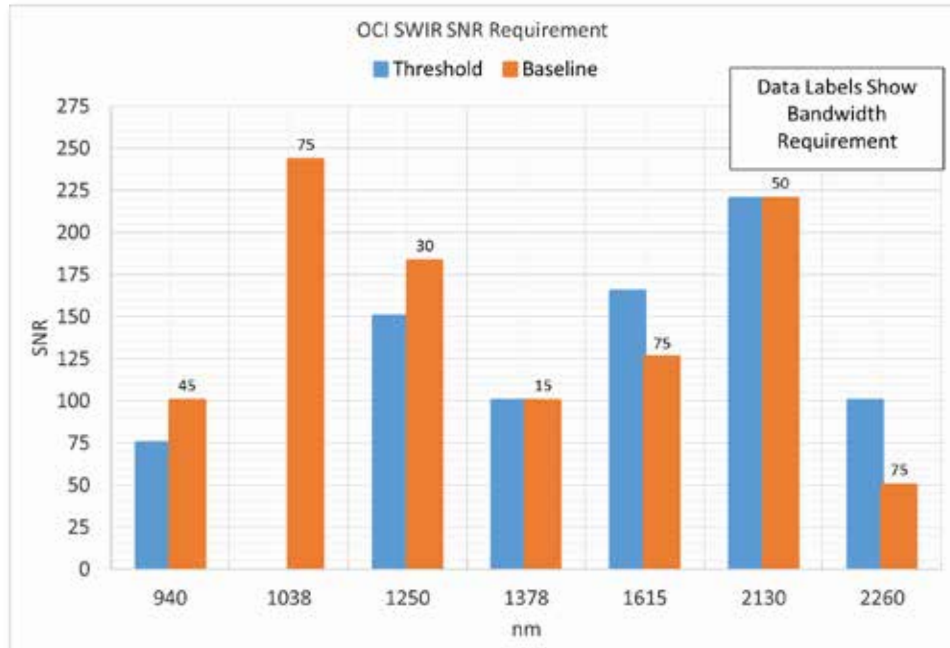
Concept follows the heritage of the SeaWiFS, MODIS, and VIIRS



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

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

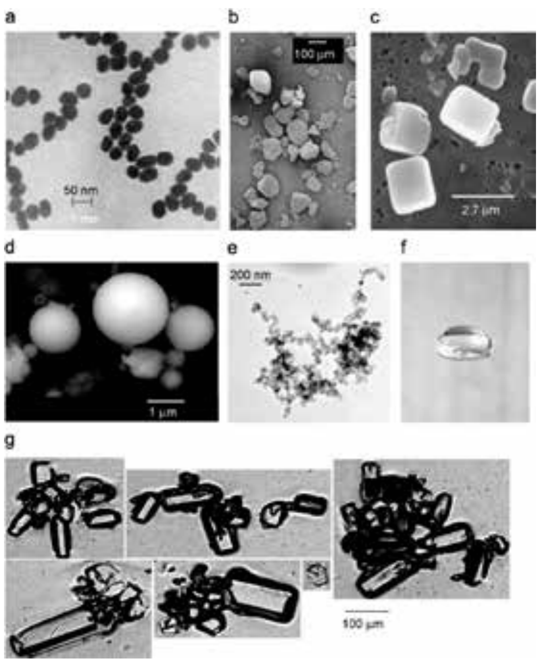




jeremy.werdell@nasa.gov

Multi-angle polarimeter(s) 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

- While the total intensity reflected by land surfaces has considerable spectral variation, polarized intensity does not. A wide spectral baseline is needed to perform accurate aerosol retrievals over land.
- UV to characterize aerosol absorption would compliment OCI's UV sensitivity.

Swath width

- A broad, OCI-matching swath is needed to provide atmospheric correction for the entirety of the OCI observation.

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

- Roughly 5 angles needed for accurate aerosol retrievals
- Characterization of ice cloud crystal shape (Aspect Ratio - AR) and roughness requires ~10 angles. Determination of liquid cloud droplet size requires 40-60 view angles.

Looking forward: noteworthy mentions

Budget Status: FY18 and beyond (as of early Feb 2018)

- "The President's 2018 Budget requests $19.1 billion for NASA, a 0.8 percent decrease from the 2017 annualized CR level…for ESD: $1.8B, down $102M, or ca 5% cut from 2017 annualized CR level."
- FY18 President's Budget identified termination of five missions: OCO-3, DISCOVR, PACE, CLARREO Pathfinder, RBI, NASA's Office of Education, and a reduction to ESD research (first step in budget process)

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

- Free download: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm
- 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."

jeremy.werdell@nasa.gov

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

Pre-launch Science Teams

- FY15 – 17: ROSES 2013 A.25
  - Achieved consensus and develops community-endorsed paths forward for IOPs and Atmospheric Correction
- 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

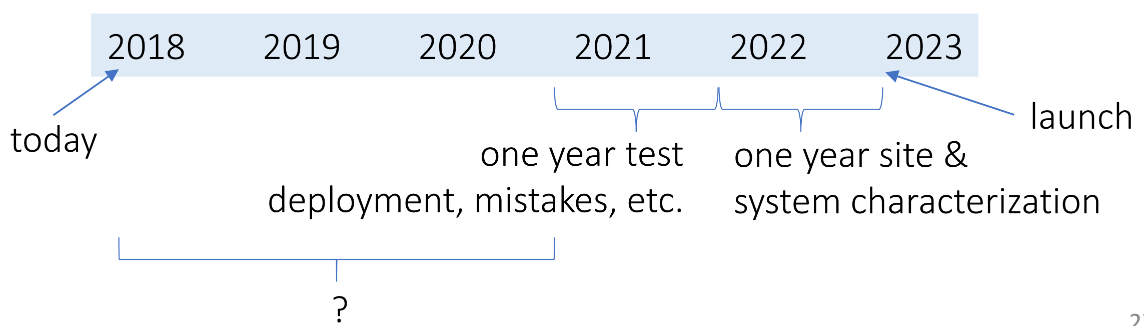
- Competed through ROSES 2025
- After launch, joint funding between EOS project, R&A, and PACE mission budget, exploring additional funding from Applied Sciences
- Mission contributions (many TBDs)
- Continue during mission extensions

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



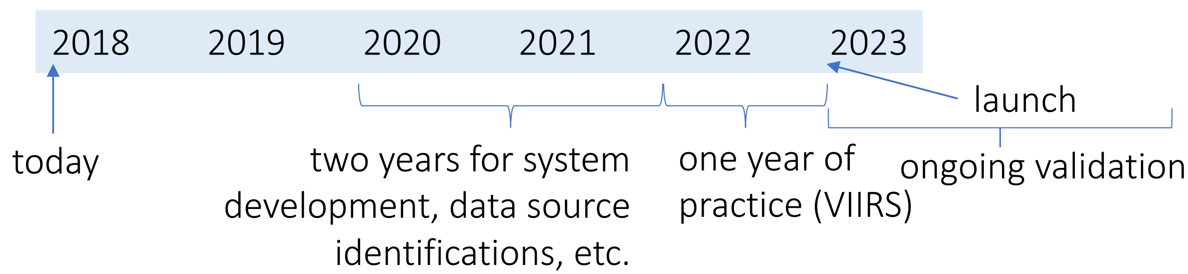
Looking forward: a validation program

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)