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

Jeremy Werdell
PACE Project Scientist, NASA Goddard Space Flight Center
21 March 2018 @ the Sun-Climate Symposium
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
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.

There are two possible things that can happen to a photon in water:

- **Absorption** (a)
- **Scattering** (b)

These processes affect the water-leaving radiance, $L_w$, which is a measure of the light that reaches the surface of the ocean after interacting with the water column.
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)
- Diffuse light attenuation (water clarity, turbidity)
- Dissolved organic matter absorption (runoff)
- Particle backscattering (sediment load)
- Red light reflectance (sediment load)
- Ratio of blue:green radiances

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)
### Key Mission Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission management</td>
<td>NASA Goddard SFC</td>
</tr>
<tr>
<td>Ocean Color Instrument</td>
<td>NASA Goddard SFC</td>
</tr>
<tr>
<td>HARP2 polarimeter</td>
<td>U. Maryland Baltimore County</td>
</tr>
<tr>
<td>SPEXone polarimeter</td>
<td>SRON (Netherlands)</td>
</tr>
<tr>
<td>Spacecraft/Mission Ops</td>
<td>NASA Goddard SFC</td>
</tr>
<tr>
<td>Science data processing</td>
<td>Ocean Biology Processing Group</td>
</tr>
<tr>
<td>Competed science teams</td>
<td>NASA Earth Sciences Division</td>
</tr>
</tbody>
</table>

### Key Mission Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Directed, DTC, $805M</td>
</tr>
<tr>
<td>Life</td>
<td>3-yr, Class C, 10-yr fuel</td>
</tr>
<tr>
<td>Orbit</td>
<td>676.5 km, Sun sync, 1-pm MLT AN</td>
</tr>
<tr>
<td>Coverage (OCI)</td>
<td>2-day global</td>
</tr>
<tr>
<td>RF Communication</td>
<td>Ka direct to ground, 600Mbps</td>
</tr>
<tr>
<td>Science Team</td>
<td>2019-2022 + 2023-2025 (ROSES)</td>
</tr>
<tr>
<td>Cal/Val Team</td>
<td>2018/19-2021 + 2022-2025 (ROSES)</td>
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</table>

- **Launch Fall 2022**
- **Decommission**

**2018 Sun-Climate Symposium**

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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)

**Phase C** – final design & fabrication

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

**Phase E** – science operations

<table>
<thead>
<tr>
<th>CY18</th>
<th>CY19</th>
<th>CY20</th>
<th>CY21</th>
<th>CY22</th>
<th>CY23</th>
<th>CY24</th>
<th>CY25</th>
</tr>
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<tbody>
<tr>
<td>Phase B</td>
<td>Phase C</td>
<td>Phase D</td>
<td>Phase E</td>
<td>Phase F</td>
<td></td>
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<td></td>
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2018 Sun-Climate Symposium

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Moving from multi-spectral radiometry to spectroscopy

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

Extend key systematic ocean biological, ecological, & biogeochemical climate data records, as well as cloud & aerosol climate data records.

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

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

Instrument performance requirements

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

Spectral range goal of 320-865 @ 5 nm

Tilt $\pm 20^\circ$
**Required science data products (OCI)**

**Required data products & additional expected data products:**

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<th>Level 1 required (~threshold) products</th>
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<td>Water-leaving reflectance</td>
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</tr>
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<td>Liquid / ice cloud optical thickness</td>
</tr>
<tr>
<td>Liquid / ice cloud effective radius</td>
</tr>
<tr>
<td>Cloud layer detection (τ &lt; 0.3)</td>
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<tr>
<td>Cloud top pressure (τ &gt; 3)</td>
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<tr>
<td>Shortwave radiation effect</td>
</tr>
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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:

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

Incomplete list of advanced (~baseline) products

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

Higher spatial resolution than many heritage products

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

Two 2-μm bands improve retrievals of cloud thermodynamic phase

Deeper red indicates improved probability of detection of ice phase
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

Hyper Angular Rainbow Polarimeter (HARP-2)
Contribution from University of Maryland Baltimore County
POC: Vanderlei Martins

<table>
<thead>
<tr>
<th>Instrument</th>
<th>SPEXone</th>
<th>HARP-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range (resolution)</td>
<td>385-770 nm (hyperspectral 2 nm)</td>
<td>440, 550, 670 nm (10) + 870 nm (40 nm)</td>
</tr>
<tr>
<td># viewing angles</td>
<td>5 (-52°, -20°, 0°, 20°, 52°)</td>
<td>20 for 440, 550, 870 nm + 60 for 670 nm (114°)</td>
</tr>
<tr>
<td>Swath width</td>
<td>9° (100 km)</td>
<td>94° (1550 km)</td>
</tr>
<tr>
<td>Ground sample distance</td>
<td>2.5 km²</td>
<td>3 km²</td>
</tr>
<tr>
<td>Heritage</td>
<td>AirSPEX</td>
<td>AirHARP, cubesat HARP for ISS</td>
</tr>
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Spectral range (resolution)

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Ground sample distance

2.5 km²

3 km²

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

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Applications Activity</th>
</tr>
</thead>
</table>
| 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. |
Take home messages

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

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

* 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
Learn more about PACE

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

Plankton, Aerosol, Cloud, ocean Ecosystem
Who’s working on PACE (as of early Feb 2018)?

- **France**
  - Airbus [SPEXone]

- **Netherlands**
  - SRON [SPEXone]
  - TNO [Primary Mirror]

- **Alaska**
  - Artic Slope Regional Corporation [Support]

- **California**
  - Irvine Electronics [Avionics]
  - Semiconductor Technology Associates Inc [CCDs]
  - Teledyne [CCDs]

- **Colorado**
  - Avior Control Technologies Inc [OCI Rotation Motors]
  - Cobham [Avionics]

- **Utah**
  - Space Dynamics Laboratory [SWIR AOB]

- **Minnesota**
  - 4th Access Machining [Avionics]

- **New Hampshire**
  - Corning [Primary Mirror]
    - [Back End Optics]

- **Maryland**
  - Support Contracts
    - Aeryon Technical Services
    - ARES Technical Services
    - ATA Aerospace
    - Business Integra INC
    - KBRayle Technology Solution LLC
    - Trident Vantage Systems LLC
    - Genesis [Avionics]
    - University of Maryland, Baltimore County [HARP2]

- **Virginia**
  - Moog Inc [Bearings]
  - Science Applications International Corp [Support]
  - TRAX International Corp [Support]

- **Arkansas**
  - BEI Precision Systems and Space Company [Encoders]

- **Arizona**
  - Advanced Circuits [Avionics]

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- **Alaska**
  - Artic Slope Regional Corporation [Support]

- **Texas**
  - Southwest Research [Avionics]

- **Utah**
  - Space Dynamics Laboratory [SWIR AOB]

- **New Hampshire**
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Ocean Color Instrument – physical assembly

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

- 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
- Cross-track rotating telescope with ± 56.5° field of regard
- Solar calibration assembly

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

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

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.”
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
  - 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

2018 2019 2020 2021 2022 2023

launch

today

one year test deployment, mistakes, etc.

one year site & system characterization

?
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

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