Life after launch: A snapshot of the first 6 months of NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission

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ABSTRACT

The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission launched from Kennedy Space Center in the early morning of February 8, 2024. Just 63 days later, data from NASA's newest Earth-observing satellite became available to the public. These data will extend and improve upon NASA's 20+ years of global satellite observation of our living oceans, atmospheric aerosols, and cloud and initiate an advanced set of climate-relevant data records. Ultimately, PACE is the first mission to provide daily, global measurements that will enable prediction of the "boom-bust" cycle of fisheries, the appearance of harmful algae, and other factors that affect commercial and recreational industries. PACE also observes clouds and tiny airborne particles known as aerosols that influence air quality and absorb and reflect sunlight, thus warming and cooling the atmosphere. In the months since launch and initial data release, the PACE Project pursued instrument temporal and system vicarious calibrations, executed cross-instrument comparisons, conducted performance assessments, explored synergies with other missions, and released advanced science data products. In parallel, the PACE Validation Science Team left for the field and the Post-launch Airborne eXperiment (PACE-PAX) prepared for its mission. And, most importantly, preliminary science results were realized. Here, we present a snapshot of these activities and their impacts and outcomes, encompassing the first half year of the PACE mission.

Keywords: PACE, OCI, HARP2, SPEXone, ocean color, atmospheric aerosols, clouds, remote sensing

1. INTRODUCTION

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, launched on 8 February 2024, will extend the continuous high-quality ocean color, atmospheric aerosol, and cloud data records begun by NASA in the late 1990s, building on the heritage of the Coastal Zone Color Scanner (CZCS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR), and Visible Infrared Imaging Radiometer Suite (VIIRS) [1]. PACE's global hyperspectral imaging radiometer design concept will enable new discoveries in Earth's living ocean, such as the diversity of organisms fueling marine food webs and how aquatic ecosystems respond to environmental change. Its full instrument payload also observes Earth's atmosphere to study clouds, airborne aerosol particles, and the interactions between the two [2, 3]. Looking at the ocean, clouds, and aerosols together improves our knowledge of the roles each plays in our evolving planet. Other applications of PACE science data records – from identifying the frequency, extent, and duration of aquatic harmful algal blooms to improving our understanding of air quality to providing a pathfinder for hyperspectral terrestrial applications – will result in direct economic, recreational, and societal benefits [4, 5]. Ultimately, by extending and expanding NASA's long record of global Earth satellite observations, the PACE mission will monitor our home planet in new and advanced ways in the coming decade.

In the first six months since launch (the time of this writing), the PACE Project completed in-orbit commissioning, released radiometric and heritage ocean color science data publicly, pursued instrument on-orbit calibrations, executed cross-instrument comparisons, conducted preliminary performance assessments, released advanced science data products, and reprocessed the full mission time-series. In parallel, a third PACE Science and Applications Team (SAT3) assembled, the PACE Validation Science Team (PVST; https://pace.oceansciences.org/pvstdoi.htm) left for the field and the Post-launch Airborne eXperiment (PACE-PAX, [6]) prepared for deployment. Here, we provide a brief overview of the PACE mission its data products, and the timeline from launch to time-of-writing, followed by a more in-depth presentation of PACE Project activities and their impacts and outcomes. In doing so, we provide a snapshot of activities conducted in the first half year of the PACE mission, complete with celebration of successes and identification of ongoing and anticipated issues.

2. MISSION OVERVIEW AND STATUS

The PACE satellite observatory consists of three instruments, a hyperspectral imaging radiometer and two multiangle polarimeters (Table 1). The primary instrument was developed at NASA Goddard Space Flight Center and is an advanced radiometer known as the Ocean Color Instrument (OCI) to measure the "colors" of the ocean, land, and atmosphere. Whereas heritage instruments such as SeaWiFS, MODIS, and VIIRS observe roughly six visible wavelengths from blue to red, OCI collects a continuum of colors that span the visible rainbow from the ultraviolet to near infrared and beyond. In doing so, OCI is the first of its kind to collect such "hyper"spectral radiometry on daily global scales, which will allow unique and highly advanced continuous identification of aquatic phytoplankton communities, as well as atmospheric aerosol, cloud, and terrestrial data products. The general OCI design concept is described in [1, 7], with pre-launch testing and early on-orbit calibration results presented in [8-13].

The two PACE polarimeters include the Spectro-polarimeter for Planetary Exploration (SPEXone; [14]), developed by a Netherlands-based consortium consisting of the Space Research Organization of the Netherlands (SRON) and Airbus Defence and Space Netherlands, and the Hyper Angular Rainbow Polarimeter (HARP2; [15]), developed by the Earth and Space Institute at the University of Maryland Baltimore County. These two multi-angle instruments complement each other, with SPEXone providing narrow-swath hyperspectral polarimetric retrievals at five view angles and HARP2 providing wide-swath multispectral polarimetric angles at 10 view angles in the blue, green, and near infrared, and at 60 view angles in the red. In sum, these instruments present an unprecedented opportunity to enhance our understanding and representation of atmospheric and surface conditions [3] and bridge future multi-angle, multi-spectral polarimetric observations, such as the European Space Agency (ESA) Multi-viewing Multi-channel Multi-polarisation Imager (3MI) on board the MetOp-SG satellites. Early on-orbit results for SPEXone and HARP2 are found in [16, 17] and [18, 19].

Table 1. PACE instrument characteristics. Spectral resolution is defined as full-width half-maximum (FWHM).

	OCI	**SPEXone**	**HARP2**
Spectral range	320-895 nm @ 5 nm FWHM in 1.25-2.5 nm steps	385-770 nm @ 2 nm FWHM in 1 nm steps	440, 550, 670 @ 10 nm, 870 nm @ 40 nm
Polarization	None	Same spectral range. 50 bands in 5-15 nm steps	All bands
Viewing angles	20° fore/aft tilt to mitigate Sun glint	5 view angles (-50°, -20°, 0°, 20°, 50°)	60 view angles for 670 nm, 10 for the rest
Global coverage	1-2 day global coverage	30+ day global coverage	2 day global coverage
Footprint & swath	1.2 km at 20°; 2663 km swath at 20° tilt	2.5 / 5.0 km (sampling / resolution); 100 km swath	3 km at nadir; 1556 km swath at nadir

The PACE observatory follows an ascending, Sun-synchronous polar orbit at 676.5 km, with an inclination of 98° and a 13:00 local Equatorial crossing time. The altitude and crossing time will be maintained to within ±1.5 km and ±10 min, respectively, over PACE's three-year design life (noting that it contains ten+ years of propellant). NASA Goddard Space Flight Center manages the mission, with all science data processing performed by the PACE Science Data Segment, which resides in the Ocean Ecology Laboratory (https://oceancolor.gsfc.nasa.gov). Data latency averages 3-6 hours from collection to distribution of radiometric and geophysical products at Levels-1 and -2 (those in the satellite coordinate system). Geophysical data are also distributed at Level-3 (global spatial and temporal composites). Additional details related to the observatory can be found in [1, 20] and on the PACE Web site (https://pace.gsfc.nasa.gov). Furthermore, a growing series of NASA Technical Memoranda exist to describe all aspects of the mission, from the original Science Definition Team Report [21] to a history of mission formulation to studies that informed the instrument and observatory design concepts to PACE applications and validation plans (https://pace.oceansciences.org/documents.htm?id=memo).

The PACE Web site provides an exhaustive list of geophysical data products available from or to be produced by PACE (https://pace.oceansciences.org/data_table.htm). Broadly speaking, PACE science data records include (or will include) calibrated radiometry and polarimetry, ocean properties from OCI, atmospheric properties from OCI, land data products from OCI, aerosol and ocean properties from HARP2, aerosol and land surface properties from HARP2, cloud properties from HARP2, ocean surface properties from HARP2, aerosol and ocean properties from SPEXone, aerosol and land surface properties from SPEXone, and aerosol and ocean properties from OCI + HARP2 + SPEXone. Figures 1 and 2 provide a graphical representation of PACE science products. Methods for accessing PACE data and a description of data processing levels and disposition can be found at https://pace.oceansciences.org/access_pace_data.htm (Figure 3).

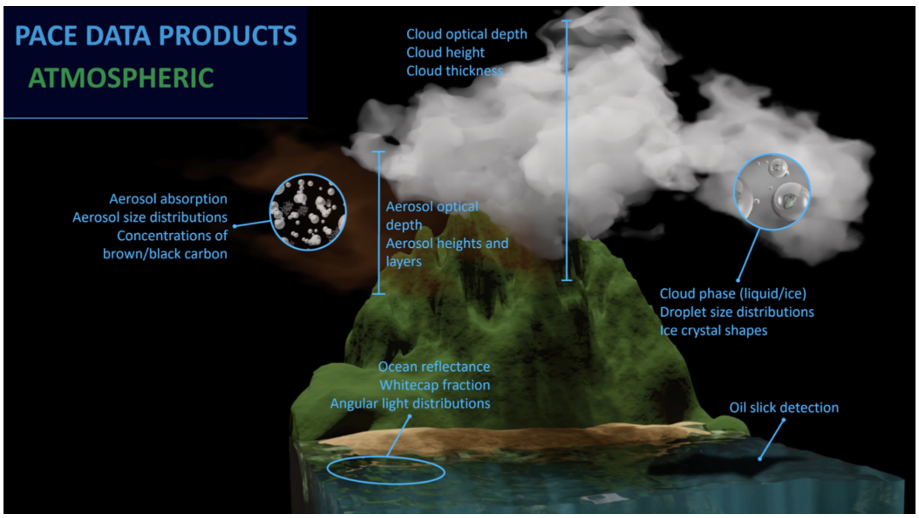

Figure 1. PACE atmospheric and ocean surface data products

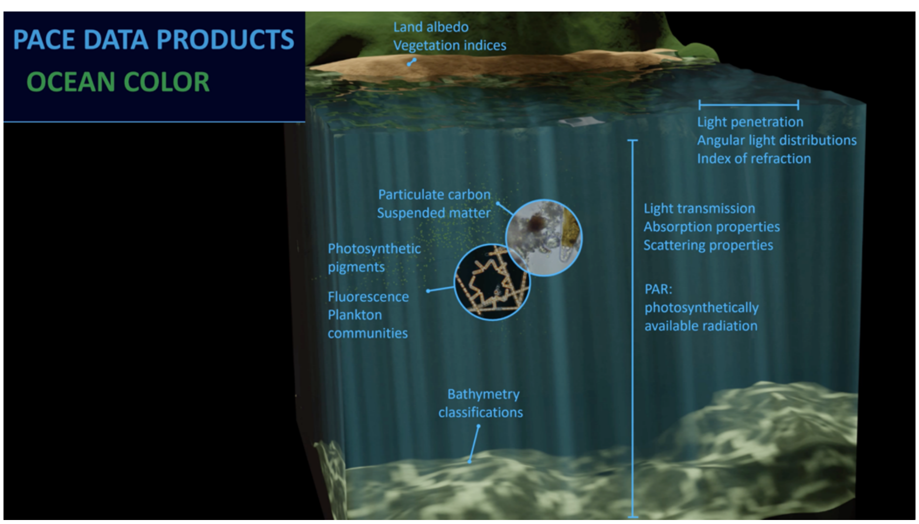

Figure 2. PACE ocean and land surface data products.

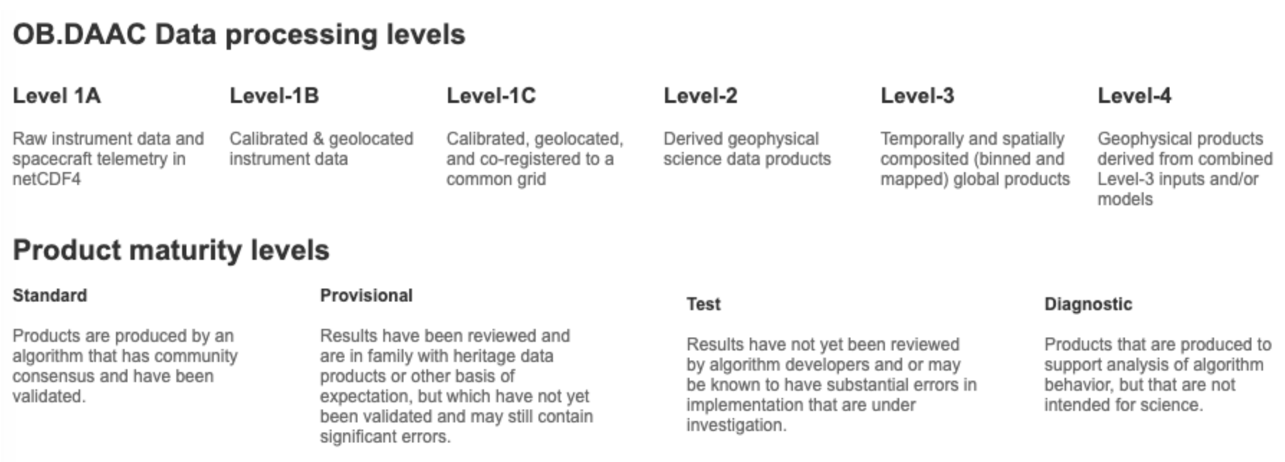

Figure 3. Ocean Biology Distributed Active Archive Center (OB.DAAC) data processing levels and definitions of NASA science data product maturity levels.

Finally, the mission supported three community-driven efforts to pursue instrument performance assessments and OCI system vicarious calibration [22] in the months preceding and following launch. First, the PVST began field data collection in the April-May timeframe. This competitively selected cohort, consisting of 24 teams, is tasked with collection and provision of "ground truth" measurements from all over the world to support performance assessment of PACE science data products from all three instruments. This four-year program comprises one aspect of the PACE Science Data Product Validation Plan (https://pace.oceansciences.org/docs/PACE_Validation_Plan_14July2020.pdf) and will proceed in two staggered, overlapping three-year phases. The first (years 1-3) focuses on validation of mission-required, heritage products, inclusive of ocean color remote-sensing reflectances, spectral aerosol optical depths, and core cloud optical properties. The second (years 2-4) will focus on assessment and supporting data compilation in support of advanced products, such as metrices of phytoplankton community composition and aerosol and cloud microphysical properties derived from polarimetry. A description of PVST teams and their data are available at https://pace.oceansciences.org/pvstdoi.htm. Second, PACE-PAX will commence aircraft and ship operations in late August 2024, just after time-of-writing [6]. PACE-PAX provides a second component of the Validation Plan that specifically addresses validation of new atmospheric data products. Because these products are often the result of multi-parameter retrieval algorithms, focused and extensive measurements will be made as part of a dedicated field campaign using a robust suite of instruments deployed on aircraft, which will fly in coordination with ground and ocean-based observations and the PACE satellite overpass. PACE-PAX will deploy from three sites in California, USA, spanning the month of September 2024. Additional resources, including the PACE-PAX Validation Traceability Matrix, are available at https://pace.oceansciences.org/campaigns.htm. And, third, two system vicarious calibration instrument teams continue to support post-launch, on-orbit calibration efforts, with plans to extend one or both through prime 3-year mission life. The HyperNAV radiometric float system [23, 24] deployed at four sites within a March to July timeframe, the data from which will likely provide the first OCI systematic vicarious calibration. The MarONet multi-arm, tethered mooring system, a follow on to the Marine Optical BuoY (MOBY; [25]; https://mlml.sjsu.edu/moby/) is en route to Perth, Australia and is expected to provide a second system vicarious calibration source in late 2024. Data collected under all three programs are publicly available via the NASA Ocean Biology Distributed Active Archive System (OB.DAAC; https://oceancolor.gsfc.nasa.gov/).

3. INSTRUMENT STATUS

A 60-day in-orbit commission (IOC) period immediately followed launch on 8 February 2024. This effort included: powering the spacecraft, communications and navigation systems, and instruments; deployment of the solar panels; final verification and adjustment of all spacecraft and instrument systems; fine-tuning of the orbit; and evaluation of instrument data collection processes. At the conclusion of the PACE Post-launch Acceptance Review on 9 April 2024, IOC officially concluded, with nominal observatory operations commencing on 10 April 2024. The following day, just 63 days after launch, PACE first light imagery became publicly available (https://www.nasa.gov/earth/nasas-pace-data-on-ocean-atmosphere-climate-now-available/). The science data (Version 1) that accompanied this release included provisional

Level-1 radiometry from all three instruments, plus provisional heritage Level-2 and -3 ocean color products from OCI (https://oceancolor.gsfc.nasa.gov/data/reprocessing/V1.0/pace-oci/). The first full mission reprocessing (Version 2) occurred in early July 2024 and served to incorporate improved calibration knowledge from on-orbit measurements collected by the three PACE instruments, as well as to release several additional atmospheric and terrestrial test product suites (https://oceancolor.gsfc.nasa.gov/data/reprocessing/V2.0/pace-oci/).

By nearly all metrics when considering its very recent launch, PACE already provides useful and seemingly high-quality data. However, issues remain that should be noted before using data from any of its instruments. The broad categories currently under investigation include geolocation and radiometric performances. Additionally, several on-orbit calibrations have yet to be applied or need refinement, and instrument-to-instrument intercomparisons are only beginning. Overall, there are particular bands, influenced by instrument or atmospheric characteristics, that we recommend avoiding at the moment (Figure 4). The remainder of this section provides highlights about each instruments' status and known performance and issues, as well as planned upcoming activities.

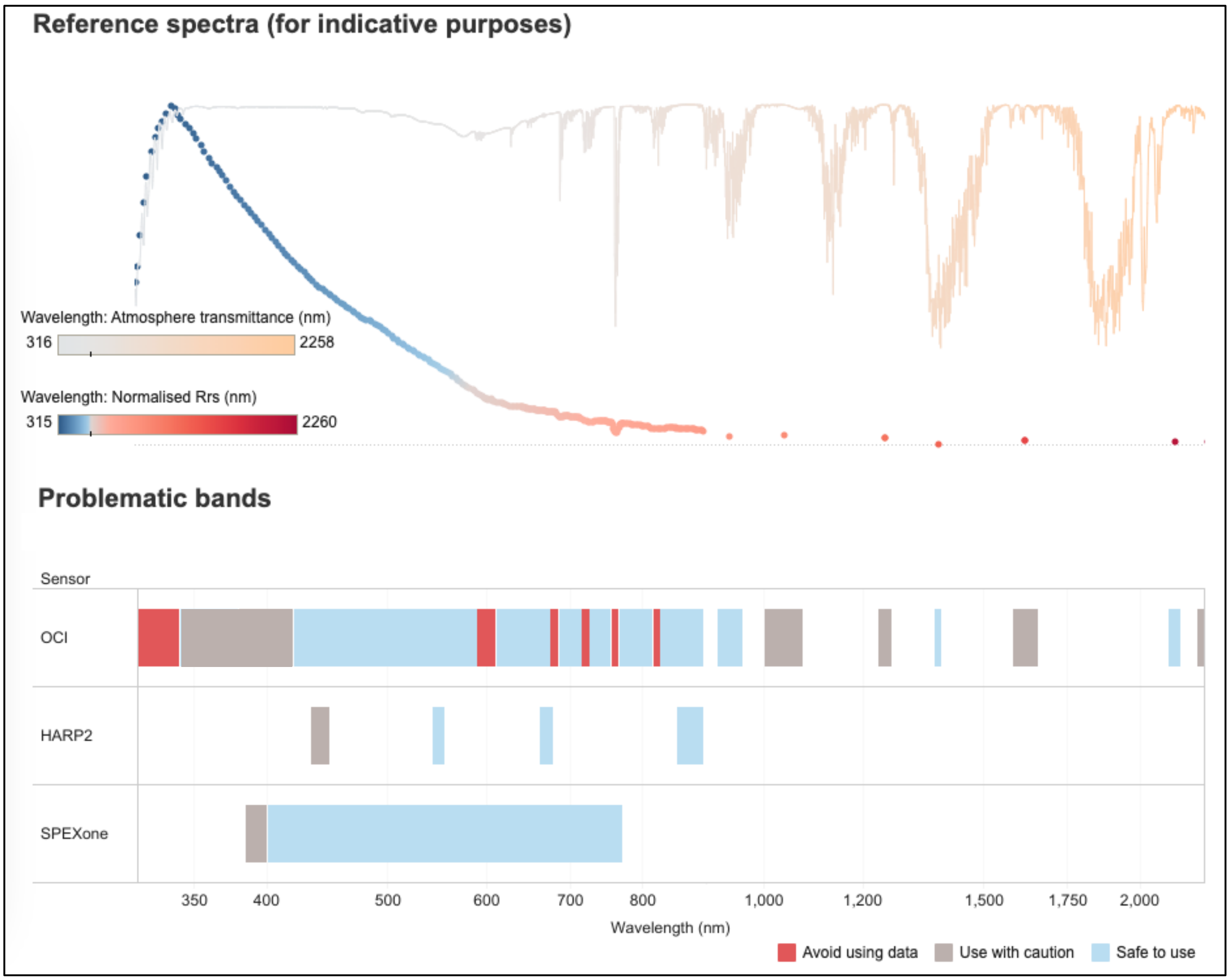

Figure 4. Graphical description of problematic PACE wavelengths that we recommend avoiding at Level-2 (e.g., Rrs(λ) or in approaches that use Rrs(λ) as input).

3.1 OCI

OCI continues to operate nominally. Its Version 2 data release makes first use of on-orbit data collected during solar calibration exercises. Specifically, the absolute calibration coefficients were revised by combining on-orbit solar diffuser measurements and prelaunch Goddard Laser for Absolute Measurement of Radiance (GLAMR; [26]) measurements. This involved adjusting the solar diffuser-based calibration coefficients below 900 nm to agree with the longer-range spectral trends of the GLAMR coefficients, which eliminated noise that manifested in mirror side ratios and adjacent spectral channels. Currently, calibration coefficients of the shortwave infrared (SWIR) channels remain purely based on solar diffuser measurements, because a hysteresis correction has not yet been applied to the prelaunch data. Additional post-launch working included improving geolocation accuracy, which is now well within 1 pixel at all scan angles [13]. Known issues at the time-of-writing include:

- System vicarious calibration has not yet been applied.
- The optical design of the OCI SWIR detector assembly (SDA) causes the bands to view different locations along-scan at a given time, and the data are packetized by time. The bands are pixel-shifted into alignment with the hyperspectral bands. This results in fill pixels at the start or end of the scan, depending on the required pixel shift. The worst case is the 2260 nm band that has 13 fill pixels at the start of the scan (Figure 5).
- Data below 340 nm have not been characterized prelaunch as completely and accurately as the data above 340 nm. The data below 340 nm are only released to facilitate assessment and potential refinement of radiometric accuracy and should not be considered as science quality (Figure 4).
- Data in the transition region between the red and blue focal planes, between 590 and 610 nm, show significant discontinuity. The discrepancy varies with mirror side and possibly with scan angle. Measurements in this range have much higher uncertainty and should not be used for science algorithms (Figure 4).
- Some SWIR bands show significant signs of apparent band-to-band registration issues, especially bands 1038 nm, 1250 nm Standard Gain, and 1615 nm Standard Gain.
- The temporal gain trend of the calibration in Version 2 is derived from measurements of the daily solar diffuser (SD) measurements, assuming that the SD reflectance is stable. In a future update, the monthly solar diffuser measurements will be used to reduce the impact of changes in solar diffuser reflectance on the trend in measured top-of-atmosphere radiances. The impact will likely be small above 450 nm (less than 0.2%), but larger at shorter wavelengths.
- Occasional noise spikes are seen in OCI dark data, especially in and around the Southern Atlantic Anomaly. These spikes corrupt the background subtraction for a complete scan line, leading to striping in the L1B data. The algorithm to calculate the background subtraction in the L1B code will be improved to remove these noise spikes in Version 3 reprocessing. It is likely that similar noise spikes are present in individual pixels of the earth view data as well. Handling earth view noise spikes will be a longer-term effort.
- Further improvements in geolocation accuracy are on-going. It has been determined that the PACE spacecraft on-board ephemerous data currently used for geolocation of OCI produces uncertainties of order 150 meters. This will be resolved in Version 3 reprocessing through use of definitive ephemerous data derived in ground-based post-processing of the GPS data.

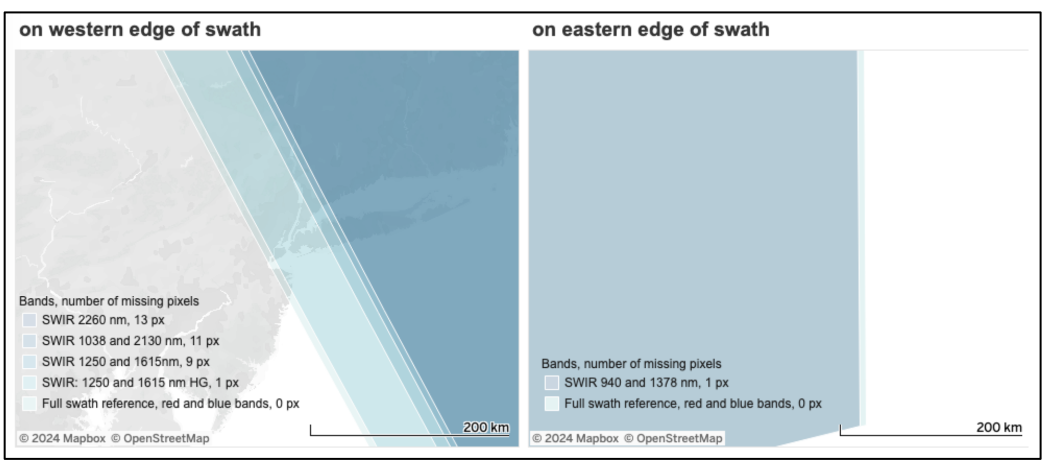

Figure 5. Graphical depiction of missing SWIR pixels on either edge of the swath.

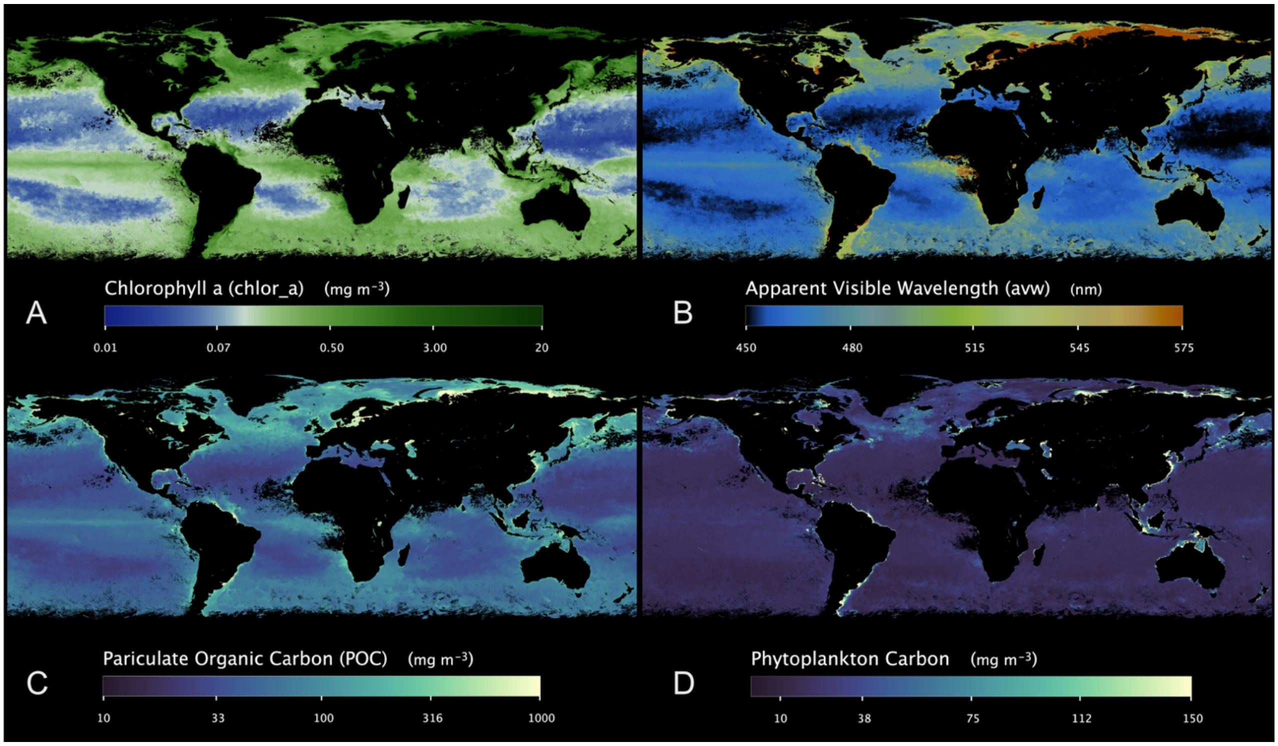

Figure 6: Initial results from OCI's chlorophyll a (chlor_a; A), Apparent Visible Wavelength (avw; B), Particulate Organic Carbon (POC; C), and Phytoplankton Carbon (carbon, phyto; D) data products. Each panel is a monthly composite of the respective geophysical quantity from July 2024 from the ocean surface.

Level-1(A-C) radiometry from OCI are available publicly, as well as several Level-2 and -3 provisional heritage ocean color products and Level-3 test cloud and terrestrial products. OCI aerosol products are expected to become available within the coming months. Level-2 and -3 data are organized into product suites, with each suite in one file per granule. Each suite and commentary on known issues is provided below, noting that all geophysical products are subject to the radiometric performance of OCI. Note that uncertainties for selected products are only provided at Level-2.

- The ocean apparent optical properties suite (OC_AOP): spectral remote sensing reflectances (Rrs(λ); sr^{-1}) and uncertainties (Provisional), apparent visible wavelength (Provisional), aerosol optical thickness (Diagnostic), and aerosol angstrom exponent (Diagnostic) (Figure 6). Known issues:
    - As noted above, no vicarious calibration has yet been applied. It is expected that a vicarious calibration will be applied in Version 3 reprocessing to further reduce bias in the retrievals relative to ground truth.
    - Limited validation of Rrs(λ) retrievals has been performed (Figure 7; see caption for details). Results show good agreement (to first order) with ground truth and with Rrs(λ) retrievals from heritage multispectral satellite missions (e.g., VIIRS), but more sampling is needed to fully assess data quality.
    - Performance of Rrs(λ) retrieval in the ultraviolet (below 400 nm) has not yet been meaningfully reviewed and is likely to contain significant biases and erroneous variability.
    - Corrections for absorbing gases have been applied, but refinement is on-going. Rrs(λ) variability, especially in the red, is likely to contain residual artifacts from water vapor and oxygen absorption near 680, 720, 760, and 820 nm.

- As noted above, there is a discontinuity in the observed radiances at the transition between the blue and red focal planes. This results in an artifact in Rrs(λ) in the 590-610 nm region. Science algorithms should avoid use of data in this region.
- The current processing extends to higher view zenith angles than the heritage sensors. The atmospheric correction becomes increasingly difficult at these extreme geometries, and erroneously elevated reflectance has been observed in red wavelengths near scan edge. These data are flagged at Level-2 and masked at Level-3.
- Chlorophyll fluorescence line height (FLH) will be included in a future release.
- The aerosol properties represent the atmospheric correction outputs for the ocean color atmospherically corrected retrievals, and not the atmospheres discipline algorithms.

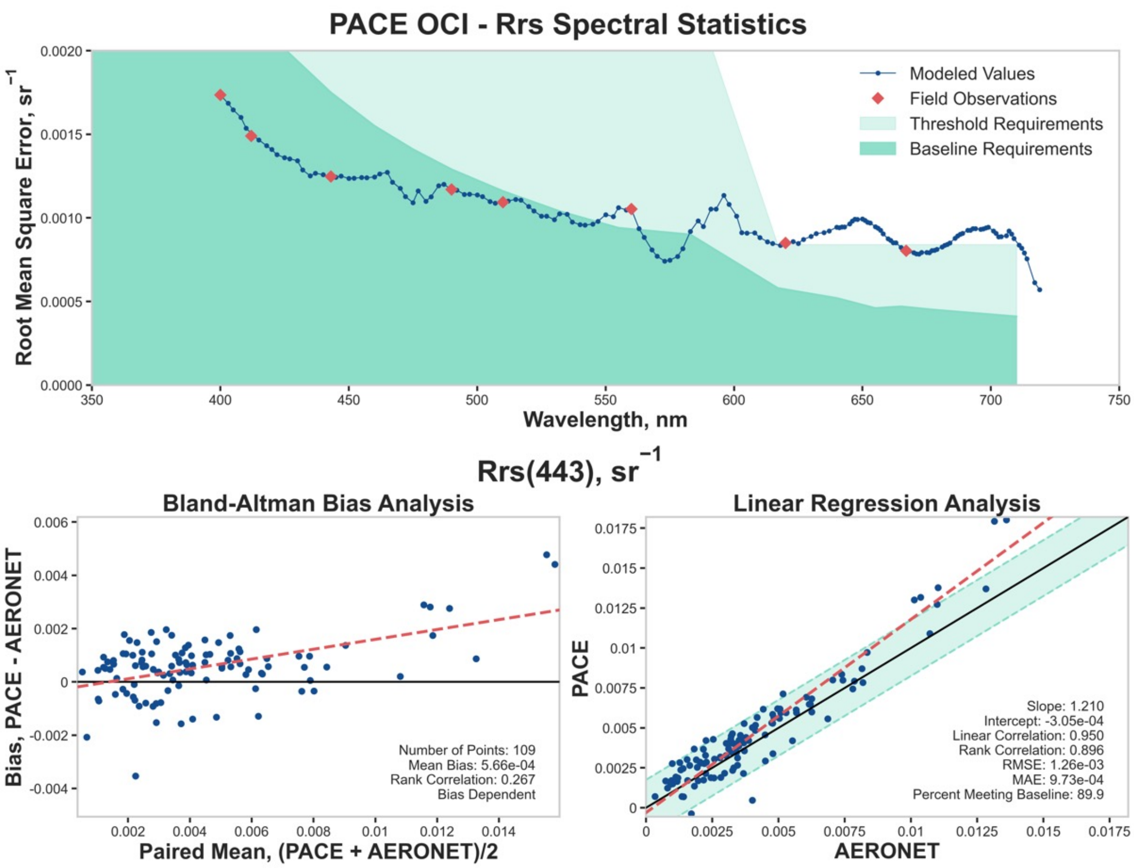

Figure 7. Initial assessment of Rrs(λ) using in situ measurements from the Ocean Color extension of the AErosol RObotic NETwork (AERONET-OC), which have been calibrated and quality controlled according to methods detailed in [27]. Data processing involves matching satellite and in situ data based on temporal and spatial proximity. Matched pairs are filtered following criteria from [28] and associated validation protocols (https://seabass.gsfc.nasa.gov/wiki/validation_description) from the NASA SeaWiFS Bio-optical Archive and Storage System (SeaBASS; [29]). To date, there are over 100 matchups from eight globally distributed AERONET-OC sites representing a range of oligotrophic to eutrophic oceanic conditions. The average, spectral root mean square errors between OCI and multispectral field observations as well as against modelled hyperspectral field observations are shown in comparison with the threshold and baseline mission uncertainty requirements (top). Across the spectrum, 83-90% of Rrs(λ)meet or improve upon baseline requirements. Summary statistics for bias analysis (lower left) and linear regression analysis (lower right) are shown for remote-sensing reflectance at 443 nm (Rrs(443)).

- The ocean inherent optical properties suite (OC_IOP): spectral total absorption and backscattering coefficients and uncertainties (Provisional), spectral component absorption and backscattering coefficients (Provisional), and spectral diffuse attenuation coefficients (Provisional). Known issues:
    - Products are derived from Rrs(λ). See OC_AOP known issues and Figure 4.
    - Algorithm failure and artifacts have been noted in highly productive and near-shore waters.
- The ocean biogeochemical properties suite (OC_BGC): phytoplankton chlorophyll-a and uncertainties (Provisional), phytoplankton carbon and uncertainties (Test), and particulate organic carbon (Test) (Figure 6). Known issues:
    - Products are derived from Rrs(λ). See OC_AOP known issues.
- The ocean photosynthetically available radiation (PAR) suite: daily and instantaneous planar and scalar PAR, both above and below the ocean surface (Test). Known issues:
    - None.

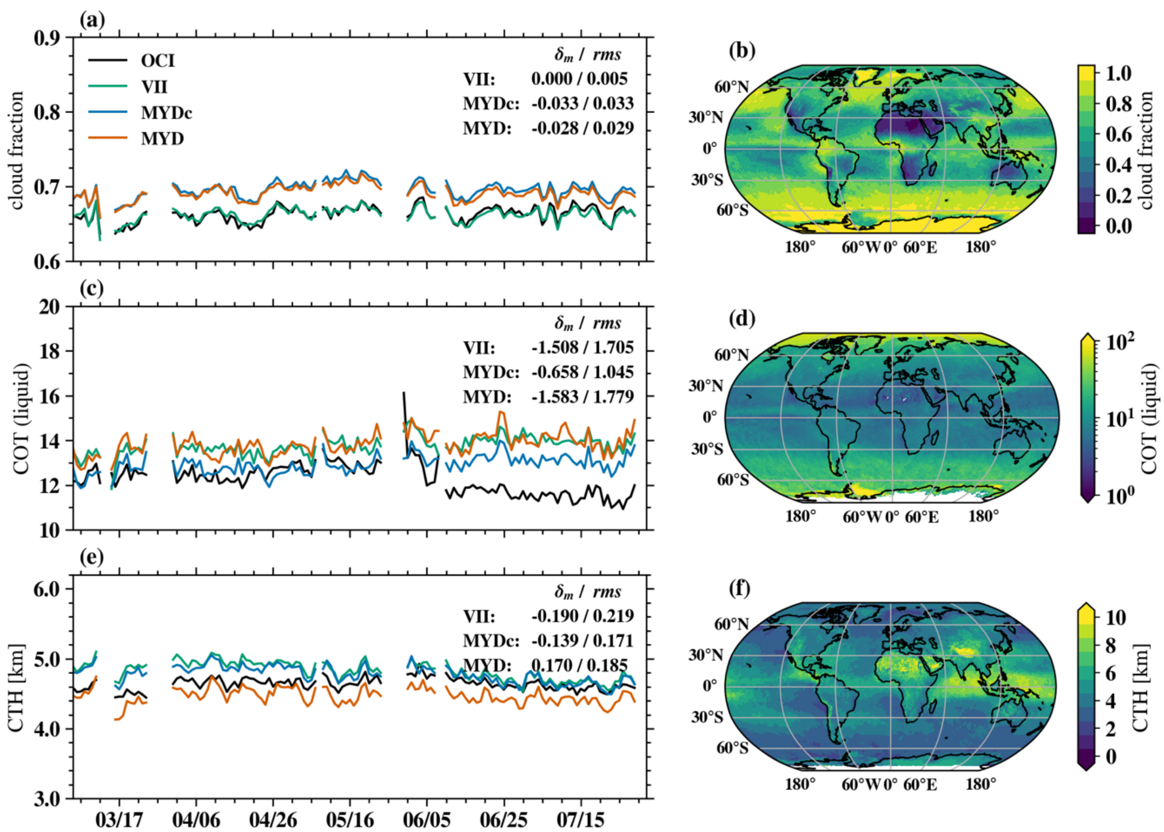

Figure 8. Examples of OCI cloud products. Panels (a), (c), (e) show time series of globally averaged cloud fraction, liquid cloud optical thickness (COT), and cloud top height (CTH), respectively, from the start of operations (March 5 2024) until end of July 2024. Also shown are equivalent time series from MODIS standard (MYD) and MODIS and VIIRS "continuity" (MYDc, VII) cloud products, along with statistics showing offset and root mean square difference. Panels (b), (d), (f) show mapped mean values of those OCI cloud properties on a 1-degree grid. Grid cells without data are shown in white.

- A cloud mask suite (CLDMASK): cloud mask and cloud-adjacent mask (both Test). Known issues:
    - The current implementation of the MERRA2 [30] snow/sea ice mask can cause blockiness around coasts where the land is snow-covered. This will be fixed in a forthcoming reprocessing.

- A cloud optical properties and altitude suite (CLD): cloud top pressure, cloud top temperature, cloud top height, cloud effective radius, cloud optical thickness, cloud water path, and cloud phase (all Test) (Figure 8). Known issues:
    - Inherits the blockiness from the CLDMASK product.
- A surface reflectance suite (SFREFL): spectral terrestrial and aquatic surface reflectances (Test) (Figure 9). Known issues:
    - Data are limited to 50 spectral wavelengths between 339 and 2260 nm.
    - Aerosol contributions are not removed.
    - Residual artifacts in the spectral vicinity of strong atmospheric gas absorption (e.g., water vapor and oxygen) are expected.
    - Data are cloud masked using the cloud and cloud-adjacent CLDMASK product, which will mask extra pixels in the vicinity of clouds and bright targets.

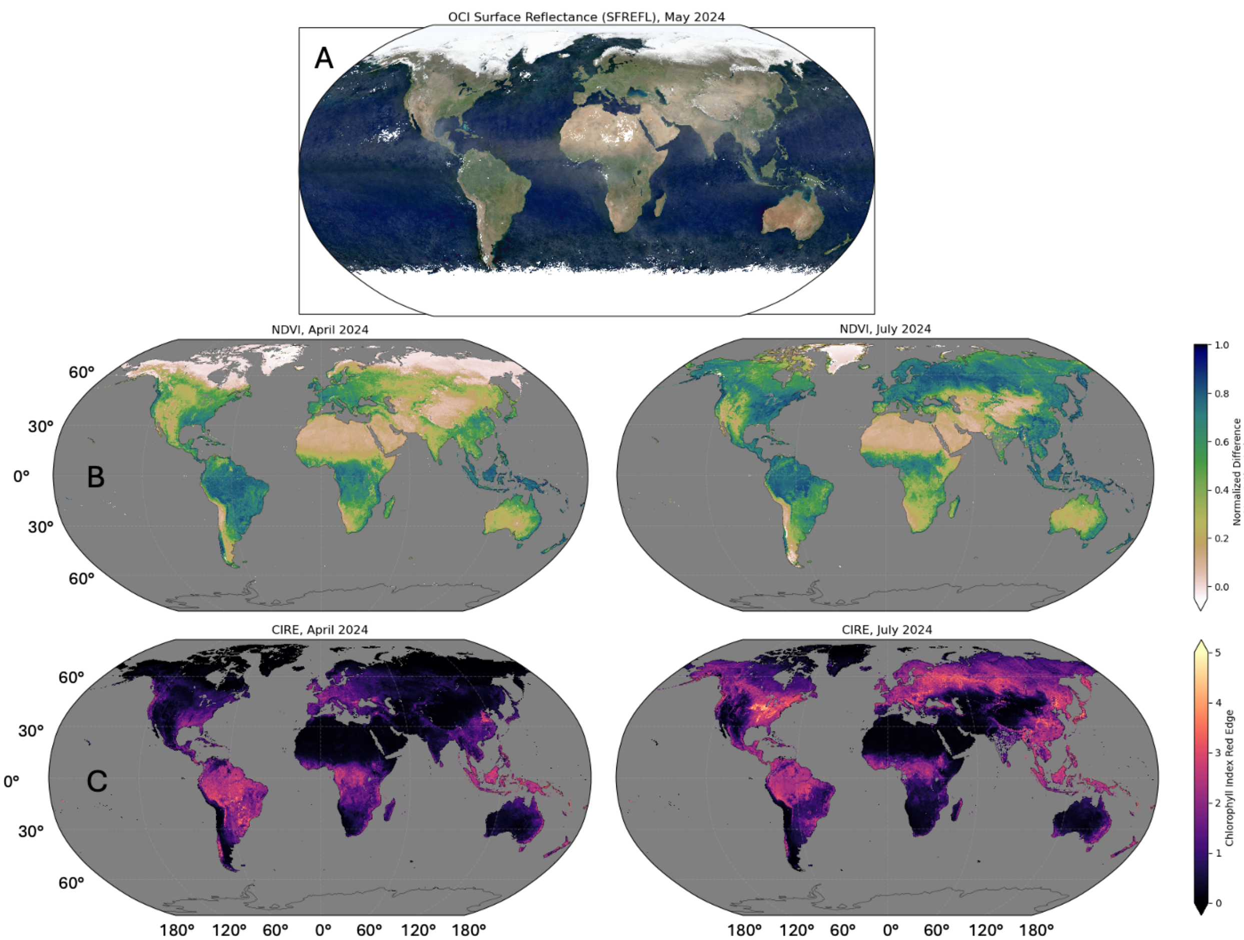

Figure 9: Initial results from OCI's surface reflectance (SFREFL; A) and vegetation index (LAND; B,C) products. Each panel is a monthly composite of the respective geophysical quantity. (A) is an RGB depiction of the Earth where the red, green, and blue channels represent measurements at 645 nm, 555 nm, and 470 nm, respectively. (B) shows global trends of NDVI from April to July, showing the transition of seasons across the globe. (C) shows global trends of the hyperspectral Chlorophyll Index Red Edge over the same interval, providing information on specific chlorophyll pigment dynamics through time.

- A land surface indices suite (LAND): enhanced vegetation index (EVI), normalized difference vegetation index (NDVI), normalized difference water index (NDWI), normalized difference infrared index (NDII), normalized difference snow index (NDSI), chlorophyll-carotenoid index (CCI), carotenoid content index (Car), chlorophyll index red edge (CIRE), photochemical reflectance index (PRI), and modified anthocyanin reflectance index (mARI) (all Test) (Figure 9). Known issues;
    - The normalized difference snow index does not currently incorporate a snow impossible mask.
    - Aerosol contributions are not currently removed from surface reflectance data, which may cause residual artifacts in vegetation index calculations.
    - The multi-band indices are calculated using aggregates of OCI spectral reflectances corresponding to relevant MODIS bandwidths.

3.2 SPEXone

SPEXone continues to operate nominally. During the commissioning phase a new detector setting was baselined that significantly reduces signal dependent biases at small signal levels. Further, post-launch work included improving geolocation and radiometric response accuracies (using the radiometric calibration performed at NASA Goddard Space Flight Center as a baseline), identifying and masking bad detector pixels, and reducing unphysical oscillations in the degree of linear polarization (DoLP; unitless) through application of a small shift to the detector image, and improving DoLP accuracies at the shortest wavelengths by applying new calibration data in that spectral range. Figure 10 presents examples of SPEXone spectra of radiance and DoLP for a cloud, ocean, and vegetation scene. A radiometric comparison between the SPEXone ±20° viewports with OCI shows agreement within 3% (2% for largest part of the spectral range) (Figure 11). Additional details on preliminary on-orbit SPEXone performance appear in [16, 17]. Future work focuses on in-flight monitoring activities using natural targets, as well as a more detailed comparison to OCI to quantify potential remaining signal dependent biases and stray light.

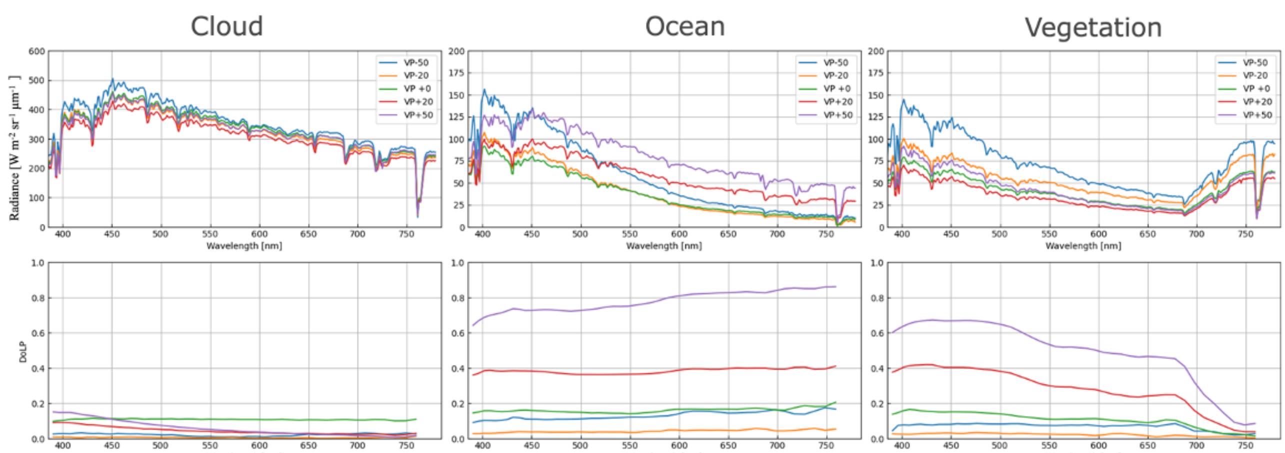

Figure 10: Example of SPEXone top-of-atmosphere measurements of radiance (top panels) and DoLP (bottom panels - unitless) for a cloud scene (left), a cloud-free ocean scene (middle), and a cloud-free vegetation scene (right). Different lines denote the 5 different viewports. For the cloud, we see only weak angle dependence of the radiance and low DoLP (except for cloud bow geometry). For ocean, we see strong wavelength dependence of radiance and very strong angular dependence for DoLP. Vegetation also shows strong wavelength dependence in both radiance and DoLP (with the typical increase towards the red), and a strong angular dependence in DoLP.

Level-1(A-C) radiometry from SPEXone are available publicly (at time of writing). These data are, naturally, subject to the radiometric calibration activities described above. The implementation and evaluation of downstream geophysical retrievals remains under internal evaluation. The RemoTAP aerosol retrieval algorithm [14] has been applied to globally derive aerosol optical properties, microphysical properties, and aerosol composition (volume fractions of dust, sea salt, aerosol water, sulphates/nitrates, black carbon, organic carbon). The retrievals show already good agreement with

AERONET for aerosol optical depth, Angstrom exponent, and single scattering albedo. After further algorithm optimization, we expect operational processing and public release of SPEXone aerosol data within the coming two months.

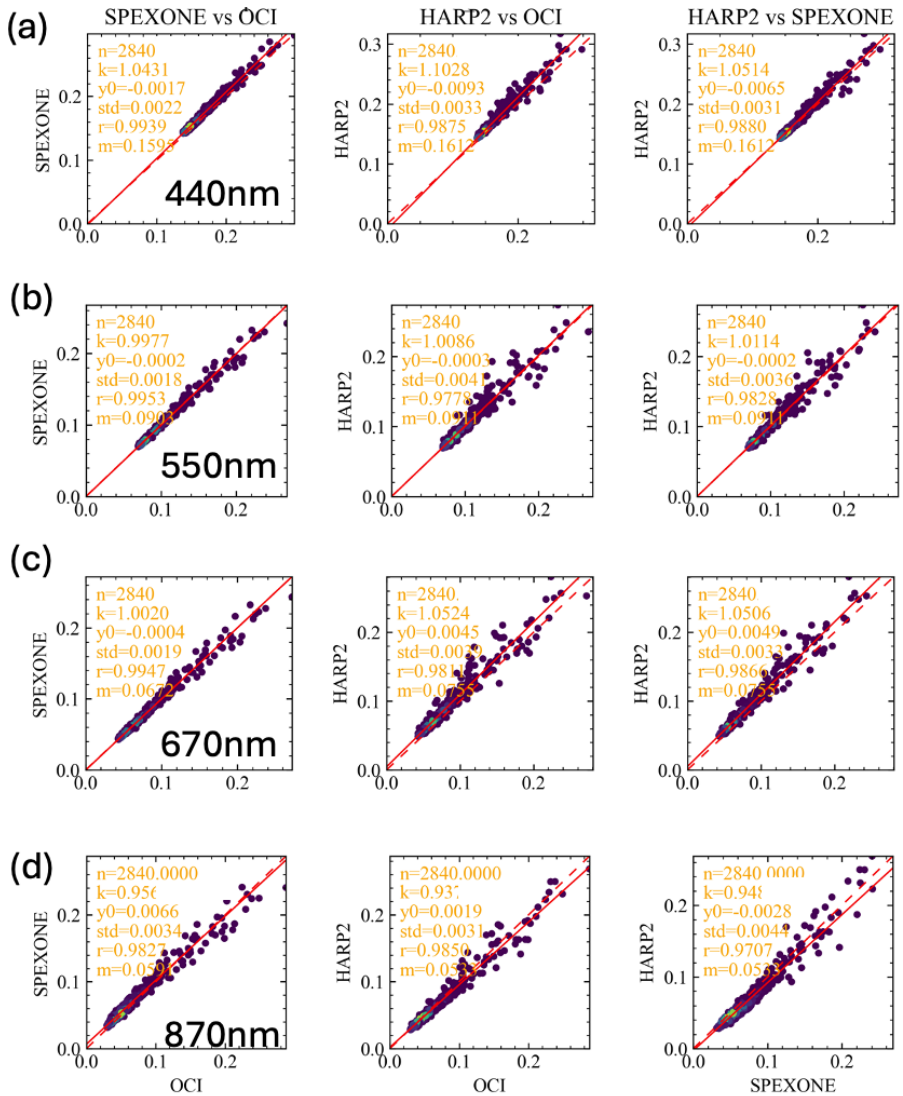

Figure 11. Intercomparison of OCI, HARP2 and SPEXone reflectances at collocated pixels and common spectral bands of 440, 550, 670, and 870 nm (780 nm is used for SPEXone). Differences between all three instruments are mostly within ±3%.

3.3 HARP2

HARP2 continues to operate nominally. Its Version 2 data release makes first use of on-orbit data collected during solar and lunar calibration exercises. These calibration data enabled correcting for elevated background that was observed in Version 1, refining field-of-view-dependent radiometric and polarimetric characterizations, and updating dark offsets. Version 2 results are now within ±3% in comparison with OCI (Figure 11). Additional post-launch work included improving detector alignment to reduce false polarization and improving geolocation accuracy using updated boresight offsets and an optical model that considers spectrally dependent magnification and distortion and improved multiview sampling. Additional details on preliminary on-orbit HARP2 performance appear in [18, 19]. Future work related to currently known issues includes:

- The polarimetric performance remains subject to additional comprehensive evaluation, particularly in the accuracy of DoLP and reference plane orientation. Additional corrections are currently being tested and will be applied to the upcoming Version 3 data processing.
- The blue band exhibits both positive and negative bias depended on the viewing angle and latitude when compared with SPEXone over multiple orbits spanning several days. The root cause of this issue has been traced back to a wavelength crosstalk artifact during ground calibration. A correction has been tested successfully and will be implemented in the Version 3 data processing.
- The geolocation performance and multiangle co-registration require additional refinements.
- Alignment related false polarization needs further evaluation and improvement

Level-1(A-C) radiometry from HARP2 are available publicly (at time of writing). As for SPEXone, these data are subject to the radiometric assessments described above. The implementation and evaluation of geophysical retrievals remains under internal evaluation. The FastMAPOL [31] and GRASP [32] aerosol retrieval algorithm(s) have been applied to derive aerosol optical properties and microphysical properties (Figure 12). After future algorithm optimization, we expect operational processing and public release of HARP2 aerosol data within the next few months.

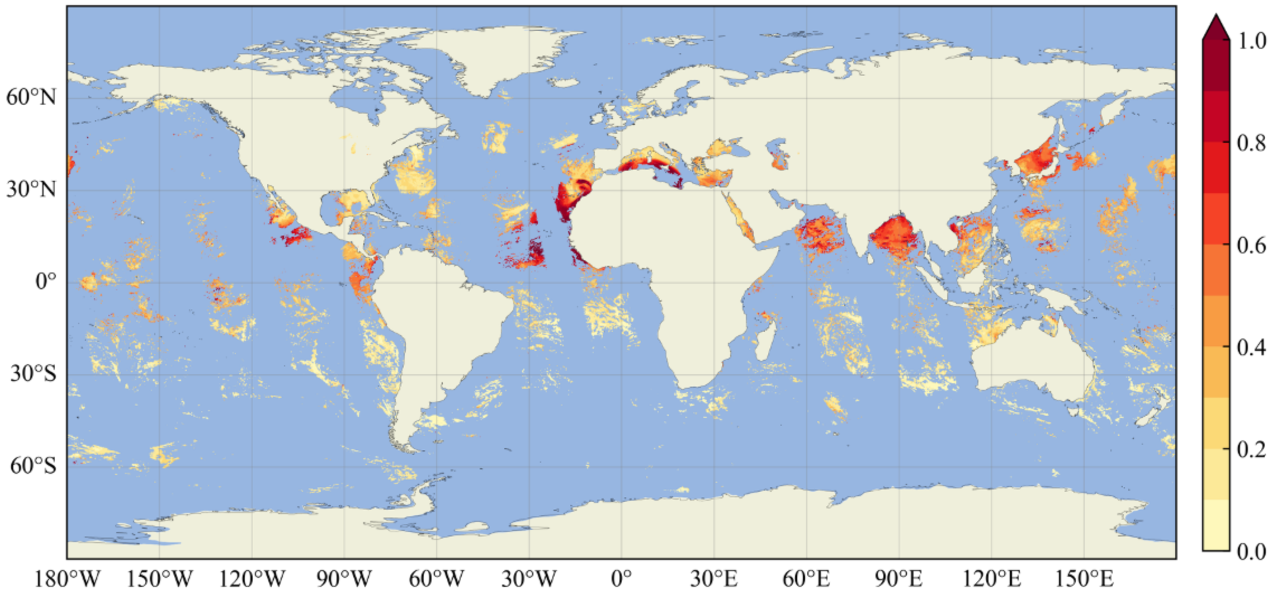

Figure 12. Preliminary HARP2 retrievals of aerosol optical depth at 550 nm (unitless)) on 14 April 2024 using FastMAPOL [31].

LOOKING FORWARD AND CONCLUDING THOUGHTS

Anticipated PACE Project activities for the coming 6-12 months (e.g., the late 2024-early 2025 timeframe) generally fall into three broad categories. First, radiometric performances for all three instruments will continue to be monitored, with on-orbit absolute and temporal calibrations updated when sufficiently robust. A mission long reprocessing will accompany each milestone calibration update. For OCI, the next reprocessing (Version 3; planned for late 2024) will also include its first system vicarious calibration. Second, implementation of new and advanced geophysical retrieval approaches will continue, with test products publicly released prior to or within in each mission reprocessing as appropriate. Nearest term, we expect to produce, for example: improved Rrs(λ) from OCI via improvements to atmospheric correction (e.g., updates to corrections for atmospheric gases) and vicarious calibration; new OCI products, such as metrices of phytoplankton community composition, indices of coastal and inland water quality, and atmospheric aerosol products; and new SPEXone and HARP2 retrievals of atmospheric aerosol and cloud microphysical properties. Note that, while formal science teams have long been included in the PACE ecosystem [33], community contribution of science algorithms is welcomed following the Science Data Product Selection Plan [34]. Third, performance assessments for and validation of derived products from all three instruments will be pursued. By design of these programs, we expect the data collected during PACE-PAX and by the PVST to enable robust evaluation of core PACE data products within one year of initial public release. All performance assessments will be shared online (https://pace.oceansciences.org/pace_data_matchups.htm).

Over two decades in the making, PACE now celebrates its first half year in orbit. The goal of this proceeding is to document well the state-of-the-art of this mission at this moment in time and provide the foundation for tracking the evolution of this groundbreaking mission over the coming decade. As suggested in [1], PACE is a mission of discovery within which the Earth science community will grow for years to come.

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