The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: An emerging era of global, hyperspectral Earth system remote sensing[†]

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ABSTRACT

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission represents NASA's next investment in satellite ocean color and the study of Earth's ocean-atmosphere system, enabling new insights into oceanographic and atmospheric responses to Earth's changing climate. PACE objectives include extending systematic cloud, aerosol, ocean biological and biogeochemical data records, making essential ocean color measurements to further understand marine carbon cycles and ecosystem responses to a changing climate, as well as improving knowledge of how aerosols influence ocean ecosystems and, conversely, how ocean ecosystems and photochemical processes affect the atmosphere. PACE objectives also encompass management of fisheries, large freshwater bodies, and water quality and reducing uncertainties in climate and radiative forcing models of the Earth system. PACE observations will also provide information on radiative properties of land surfaces and characterization of the vegetation and soils that dominate their reflectance. The primary PACE instrument – the Ocean Color Instrument (OCI) – is a hyperspectral imaging radiometer that spans the ultraviolet to shortwave infrared, with a ground sample distance of 1-km at nadir. This includes continuous collection of spectra from 340 nm to 890 nm in 5 nm steps. The PACE payload is complemented by two multi-angle polarimeters with spectral ranges that span the visible to near-infrared region. Scheduled for launch in late 2022-to-early 2023, the PACE observatory will enable significant advances in the study of Earth's biogeochemistry, carbon cycle, clouds, hydrosols, and aerosols in the ocean-atmosphere system. We present a brief overview of the PACE mission, followed by a discussion of the capabilities and design concept of OCI.

Keywords: hyperspectral radiometer, ocean color, aerosol, cloud, passive remote sensing

1. INTRODUCTION

The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission will extend the high quality ocean biological and ecological, ocean biogeochemical, cloud, and aerosol particle data records begun by NASA in the 1990s, building on the heritage of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; 1997-2010), the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra (1999-present) and Aqua (2002-present), and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard Suomi NPP (2012-present) and NOAA-20 (2016-present) [1]. New discoveries in Earth's living ocean will be revealed with PACE's advanced hyperspectral radiometer, such as the diversity of organisms fueling marine food webs and how aquatic ecosystems respond to environmental change. PACE will also observe our atmosphere to study clouds, tiny airborne particles known as aerosols, and the interactions between the two. Looking at the ocean, clouds, and aerosols together will improve our knowledge of the roles each plays in our changing planet. Other applications of PACE science data records – from identifying the extent and duration of aquatic harmful algal blooms to

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improving our understanding of air quality – will result in direct economic, recreational, and societal benefits. Ultimately, by extending and expanding NASA's long record of satellite observations of our living planet, the PACE mission will take Earth's pulse in new ways for the coming decade.

The PACE observatory (Figure 1) is planned for launch in late 2022 to early 2023 into an ascending, Sun-synchronous polar orbit at 676.5 km, with an inclination of 98º and a 13:00 local ascending node crossing time. Its observatory will consist of three instruments, the Ocean Color Instrument (OCI) and two small multi-angle polarimeters, the Hyper-Angular Rainbow Polarimeter instrument (HARP2; [2]) and the Spectropolarimeter for Planetary EXploration one (SPEXone; [3]). OCI is the primary instrument on the observatory and is being developed at NASA Goddard Space Flight Center (GSFC). It is a hyperspectral scanning radiometer designed to measure spectral radiances from the ultraviolet (UV) to shortwave infrared (SWIR). HARP2 is a wide-swath, four wavelength (visible (VIS) to near-infrared (NIR)), hyperangular photopolarimeter being developed at the University of Maryland Baltimore County Earth and Space Institute. SPEXone is a narrow-swath, hyperspectral (VIS to NIR), five angle photopolarimeter being developed by a Dutch consortium consisting of SRON Netherlands Institute for Space Research and Airbus Defence and Space Netherlands. OCI will produce a large suite of geophysical products from its UV-SWIR radiometry including, but not limited to, spectral aquatic inherent optical properties (e.g., absorption and scattering coefficients of seawater and its particulate and dissolved constituents), phytoplankton pigment concentrations, metrics related to phytoplankton physiology and carbon stocks, indices of absorbing aerosols, water paths for liquid and ice clouds, and data products to support terrestrial and applications studies (see, e.g., [4, 5]). The multi-angle polarimeters on the observatory will enable production of additional data products not possible with OCI alone, such as aerosol and hydrosol refractive indices and cloud bows, that further facilitate coupled ocean-atmosphere-land retrievals [6].

Here, we present key characteristics and several novel aspects of the OCI preliminary design concept. The latter serves as the motivation for this paper and includes the optical system, the focal plane assemblies, and the thermal system. While this by no means provides an exhaustive description of the OCI preliminary design concept, it serves to provide a high level snapshot of critical, in-development aspects of the instrument system. As of this writing, OCI has passed its preliminary design review (March 2018), with limited and comprehensive engineering test unit performance tests planned for Fall 2019 and a critical design review scheduled for December 2019.

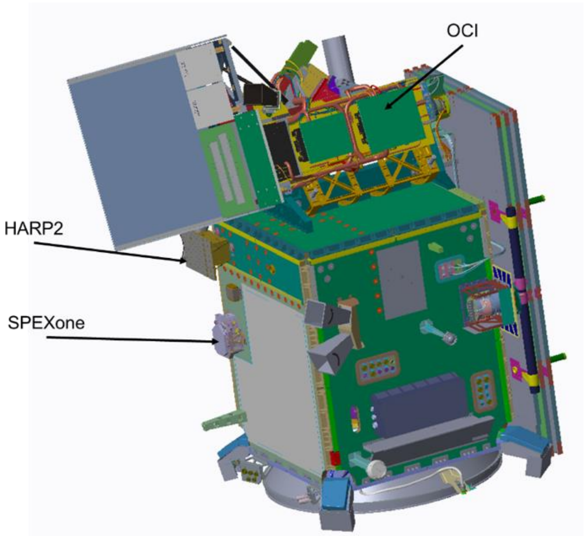

Figure 1. The PACE observatory.

2. THE PACE OCEAN COLOR INSTRUMENT

2.1 Key characteristics

Ocean color data record development ultimately drives the design of OCI. OCI is a 260 kg, 280 W hyperspectral scanning radiometer that combines design aspects from SeaWiFS, MODIS, and VIIRS. It consists of two slit grating, hyperspectral spectrographs that continuously span the ultraviolet to orange and orange to near infrared spectral regions. Additional fiber coupled band detectors will collect measurements at seven discrete shortwave infrared (SWIR) bands, six of which are at similar wavelengths to those on MODIS and VIIRS. Like SeaWiFS, OCI will perform a tilt maneuver every orbit at approximately the subsolar point to avoid Sun glint reflected off the ocean looking 20° north (fore) in the northern hemisphere and 20° south (aft) in the southern hemisphere, which maximizes the number of ocean science pixels retrieved. Tilting OCI allows capture of ocean science pixels that would otherwise be unusable because of Sun glint contamination. The OCI telescope will scan from west to east at a rotation rate of 5.77 Hz, acquiring Earth view data at ~1 km^2 at nadir and an angular range of ±56.5°, which results in a ground swath width of 2663 km. At its sun-synchronous 676.5 km ascending node orbit with a 13:00 local equator crossing time, OCI realizes 1-day global coverage at all sensor zenith angles and 2-day global coverage at sensor zenith angles up to 60°.

Sources of typical instrument uncertainties (e.g., sensitivity to polarization, stray light, and temperature) are addressed through design choices and a prelaunch test efforts, based largely on lessons learned from SeaWiFS, MODIS, and VIIRS heritage [7]. Variations in the radiometric sensitivity of each wavelength over time will be monitored by solar diffuser measurements for short-term instrument gain adjustments and by lunar measurements for adjustments over long time periods (>2 years). The solar diffuser calibration assembly consists of three diffusers: two bright solar diffusers and one dim solar diffuser. One bright quasi-volume diffuser (QVD) will be exposed each day. The other bright diffusor is identical to the daily bright diffusor, but will only be exposed to solar irradiance monthly, such that its reflectance will degrade significantly less than the daily target. The measurements of the monthly target will be used to correct the reflectance degradation of the daily target. Lunar irradiance will be measured at ±7° moon phase angle (resulting in two measurements each month). The measured radiances from the Moon will be combined to yield the lunar irradiance, corrected for the oversampling rate, and compared to the lunar irradiance provided by the U.S. Geological Survey Robotic Lunar Observatory (ROLO) model [8]. If over long periods of time (>2 years), a trend can be detected in the ratios of the ROLO lunar irradiances and the OCI lunar irradiances, this lunar calibration will be used in addition to the solar calibrations to adjust any temporal degradation in OCI [9]. The dim solar diffuser has a substantially lower reflectance (~2%) relative to the two others. Using this dim diffusor, a special charge accumulation mode of the OCI Charge Coupled Devices (CCDs) will be used to verify the linearity of the OCI readout electronics and track changes in linearity over time.

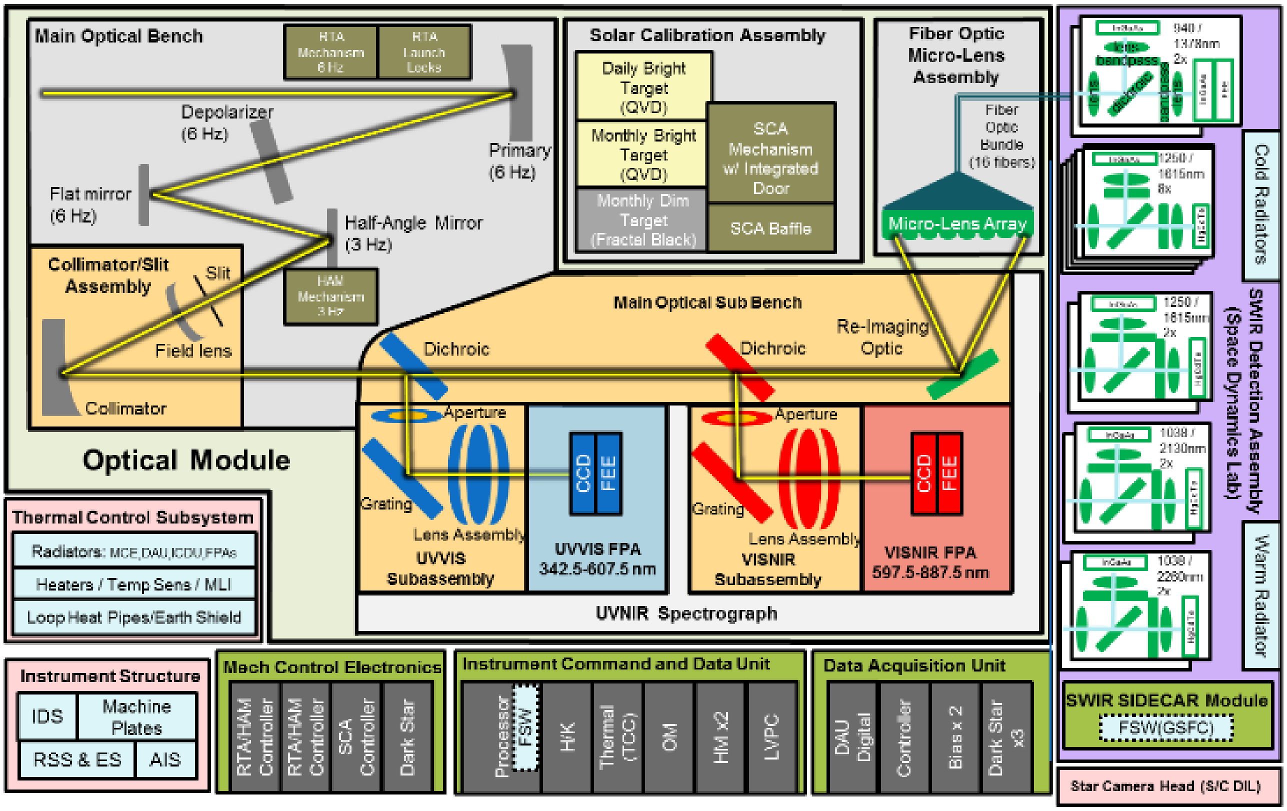

Figure 2. A two-dimensional overview of the OCI optical path and its key instrument components.

2.2 Optical system

Similar to SeaWiFS, the OCI fore optical system (main optical bench; MOB) is comprised of a rotating telescope, a half-angle mirror (HAM), and a depolarizer (Figure 2). As light enters the aperture of the telescope, it first passes through stray light baffles and the aperture stop before hitting the first powered optic in the system, an off-axis parabolic primary mirror. The primary mirror focuses the light onto a slit later in the system. The second major optical element in the telescope portion is a double-wedge polarization scrambler. The purpose of the scrambler is to reduce the sensitivity of OCI to polarization. The scrambler consists of two wedged birefringent pieces of magnesium fluoride (MgF_2) with their crystal axes oriented at 45° to each other. The third optical element is a simple fold mirror. To reduce the diameter of the rotating telescope, and keep the bulk of the optical system behind the entrance of the telescope, a fold in the telescope was necessary. The fold mirror directs light from the rotating telescope towards the HAM, which is positioned on the center of rotation of the telescope. This way, the position of the spot on the HAM does not change, only the incident angle. The HAM rotates in the same direction as the telescope, but at half the speed. This counter-rotates the beam and maintains the focus of the primary on a stationary slit. Because it rotates at half-speed, both sides of the HAM are reflective. Alternate scans of the telescope use alternating sides of the HAM.

The first stationary optical component in the system is a slit defining the field of view. The spectrograph half of the OCI optical system begins at this internal slit and includes three channels imaging unique wavelength regions. The slit is sized to provide a 16 km x 1 km instantaneous field of view and is blackened with carbon nanotubes. The blackening was primarily necessary to reduce stray light from back-reflections in the back-end of the system. A field lens sits directly behind the slit. As a weak negative singlet, its purpose is to push the pupil of the telescope system out to the gratings so that the field and spectral pupils share the same location. Next, a second off-axis parabolic mirror re-collimates the light and passes it to the dichroics and gratings. Collimating the light allows for better packaging, and also reduces the angular range of incident light at the dichroics and gratings.

Table 1. SWIR band centers (with tolerances), full-width half maxes (FWHM), and full-width at one percent (FW1P) signal.

Band Center (nm)	FWHM (nm)	FW1P (nm)
940 ± 4	45 ± 4	FWHM * 2
1038 ± 2	75 ± 4	FWHM * 2
1250 ± 4 (standard gain)	30 ± 4	FWHM * 2
1250 ± 4 (high gain)	30 ± 4	FWHM * 2
1378 ± 2	15 ± 2	FWHM * 2
1615 ± 10 (standard gain)	75 ± 10	FWHM * 2
1615 ± 10 (high gain)	75 ± 10	FWHM * 2
2130 ± 5	50 ± 5	FWHM * 2
2260 ± 10	50 ± 5	FWHM * 2

2.3 Focal plane assemblies

Collimated light gets separated between the three focal plane assemblies (FPAs). The ultraviolet to visible (UV-VIS) FPA captures light between 342–607 nm, the visible to near infrared (VIS-NIR) FPA captures light between 597–887 nm, and the SWIR FPA captures light in bands between 940–2260 nm. The first dichroic reflects the lower visible wavelengths onto a CCD in the UV-VIS FPA, and the second reflects the longer visible wavelengths onto a CCD in the VIS-NIR FPA. The remaining light passes through both dichroics and is imaged by the SWIR FPA. Gratings in the UV-VIS and VIS-NIR FPAs provide spectral dispersion. The UV-VIS and VIS-NIR CCDs are 128 pixels (cross-track) x 512 pixels (along-track/spectral) with 26 µm pixels. In the cross-track, the 16 km slit dimension is imaged on the 128 pixels enabling each 1 km ground scene to be imaged onto 8 physical pixels on the CCD. In the along-track, the spectral and spatial information is convolved such that each physical pixel contains the spatial information of a 1 km ground scene and a spectral bandwidth of 5 nm at a center wavelength. Both CCDs provide time delay integration (TDI) of the input spectral image, in which the charge transfer and readout of the CCD is synchronized with the rotating telescope. The rotating telescope allows the same science pixel to be imaged on the detector 16 times (recall the 16 km cross-track slit dimension). The CCD detector uses TDI to collect and transfer the charge from pixel to pixel of the same 1 km ground scene at the same rate as the rotating telescope. This occurs in analog charge space to avoid noise introduced by reading, amplifying, and digitizing the signal. This also allows the detection system to view the same ground scene for an extended time and build up enough signal to meet the signal-to-noise ratio (SNR) while eliminating image striping due to detector pixel gain offsets. A key advantage of the single pixel, along track rotating telescope and TDI architecture is the ‘virtual single pixel’, in which each 1 km hyperspectral science band is the sum of all CCD pixels. The UV-VIS and VIS-NIR CCDs are identical except for their antireflection coatings and the distribution of output sensitivities.

Light in the SWIR detection assembly (SDA) passes through both dichroics and is focused by another off-axis parabolic mirror. The mirror images the slit onto a micro-lens array (MLA), which is a 16 x 1 array of lenslets (designed to match the 1 km x 16 km slit). Each lenslet represents a single 1 km ground spot diameter (GSD). The MLA captures and directs the light from each GSD into one of 16 identical subassemblies. Each subassembly contains a collimator, dichroic, band pass filter, focusing lens, and focal plane. Each dichroic lets light >1.4 µm pass and reflects the shorter wavelengths. The band pass filter is designed for the spectral response of each band (Table 1). The fibers bring the light to the SWIR detection system, where the emitted light is again split and reimaged onto 2 SWIR detectors each, giving 32 total SWIR focal planes, comprised of either a single InGaAs or HgCdTe photodiode. Bands 0.940, 1.038, 1.250, and 1.378 µm use an InGaAs diode and bands 1.615, 2.130, and 2.260 µm use an HgCdTe diode. Each diode is passively cooled to -65ºC to reduce dark current contribution to noise while each front-end electronics assembly and optical housing is passively cooled to -25ºC. The SDA has an integrated 16-bit SIDECAR ASIC to digitize all 32 focal planes. Each focal plane readout and digitization is synchronized with the rotating telescope. To increase SNR, the SDA has duplicate channels in adjacent fiber inputs, subsequent readouts of adjacent channels are added via digital TDI.

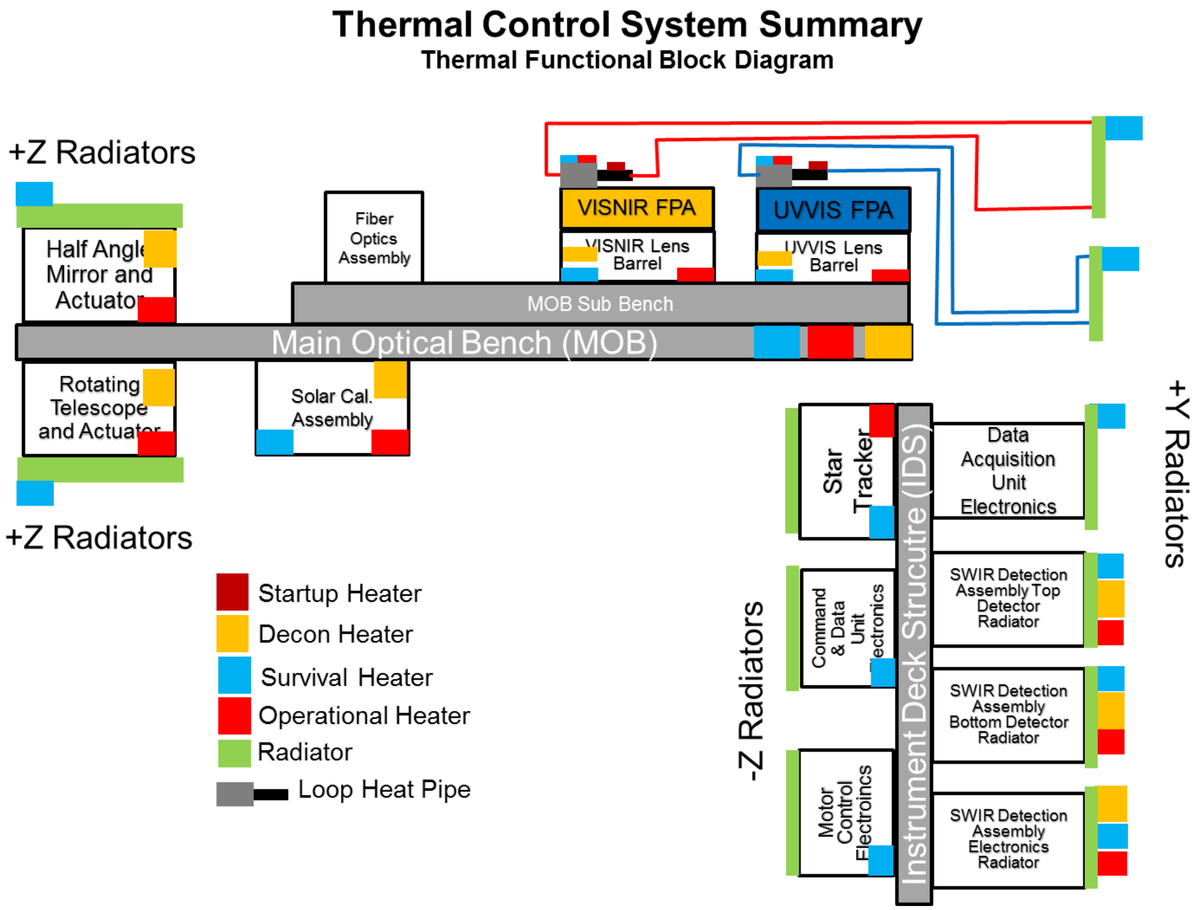

Figure 3. Thermal control system block diagram.

2.4 Thermal system

The OCI thermal control system is comprised of both two phase and passive cooling devices to maintain temperatures within the requirements of the instrument (Figure 3). The two-phase system is comprised of a loop heat pipe (LHP) that directly maintains the stability (±0.5°C) and temperature (-25°C) of the UV-VIS and VIS-NIR CCDs. The LHP has an evaporator mounted directly to each FPA that transfers heat out to radiators located >0.5 meters away that view a constant cold sink environment. Within the UV-VIS and VIS-NIR assemblies are pyrolytic graphite thermal straps that transfer the electronics and detector heat to the LHP evaporator. The radiators maintain temperatures through the use of an Earth shade that blocks ~80% of Earth's infrared and albedo energy from directly hitting them. The OCI electronics boxes that require thermal stability, namely its data acquisition unit (DAU), are mounted to provide a constant deep space view with the least amount of environmental influence. The mechanism control electronics (MCE) and instrument command and data unit (ICDU) both have radiators that view the Sun for part of OCI's orbit and deep space for the rest. This is acceptable as there are no stability requirements on these two boxes. The mechanism radiators, which are required in order to reject the frictional heat being generated by the motors, are curved and mounted on the +Z deck of the spacecraft (with -Z indicating a nadir, Earth view during standard science operations). For all cases, the radiators were sized for a hot scenario (e.g., maximum power dissipation, environmental heating, and spacecraft interface temperature). For all cases, the operational and survival heaters were sized for a cold scenario (e.g., minimum power dissipation, environmental heating, and spacecraft interface temperature).

3. CONCLUDING THOUGHTS

The Plankton, Aerosol, Cloud, ocean Ecosystem mission concept encompasses the scientific needs of the ocean color, aerosol, and cloud communities and, importantly, envisions synergistic opportunities between and across these science communities. This is only possible with the successful realization of an advanced hyperspectral scanning radiometer such as OCI. In its lifecycle of development, OCI currently falls in between its preliminary (March 2018) and critical (nominally December 2019) design reviews, and has yet to complete a rigorous, full engineering test unit performance evaluation. Despite the final instrument concept and performance remaining to-be-determined, we felt it prudent to share this high level content and discuss several critical high level aspects of its design. To that end, we presented current high level descriptions of the OCI optical system, focal plane assemblies, and thermal system. Routine updates to OCI and its observatory can be found online at https://pace.gsfc.nasa.gov.

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