The PACE Ocean Color Instrument (OCI): From Concept to Commissioning

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***Abstract*— The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is a strategic climate continuity mission that was defined in the 2010 document *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for Climate-Centric Architecture for Earth Observations and Applications from Space* (referred to as the "Climate Initiative"). Launched on February 8, 2024, the PACE mission represents NASA's next investment in ocean biology, clouds, and aerosol data records [1]. PACE will extend the high quality ocean ecological, ocean biogeochemical, cloud, and aerosol particle data records begun by NASA in the 1990s, building on the exceptional heritages of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), and the Visible Infrared Imaging Radiometer Suite (VIIRS) [2].**

The PACE project office at NASA's GSFC was responsible for the satellite development, launch and operations. The NASA Headquarters PACE Program Science office is responsible for supporting the science data processing system and assembling competed community science teams, which includes field-based vicarious calibration and data product validation efforts to support the PACE Project Science team.

The mission launched into a Sun synchronous polar orbit at 676.5 km with an inclination of 98 degrees and a 1 pm local ascending node crossing time. The PACE observatory is comprised of three instruments, an Ocean Color Instrument (OCI) and two polarimeters, the Hyper-Angular Rainbow Polarimeter 2 (HARP2) and the Spectro-Polarimeter for Exploration (SPEXone). The OCI is the primary instrument on the observatory and was developed at Goddard Space Flight Center (GSFC). It is a hyperspectral scanning radiometer designed to measure spectral radiances from the ultraviolet to shortwave infrared (SWIR) to enable advanced ocean color and heritage cloud and atmospheric aerosol science [3-5].

NASA Headquarters directed the mission development to be guided by a Design-to-Cost (DTC) process. All elements of the mission, other than the cost, are in the DTC trade space. At the heart of the DTC process are the mission studies, performed across all the mission elements. The mission studies were used to define appropriate approaches within and across elements while maximizing science capabilities at a high cost confidence. Mission baseline requirements development is also embedded within the DTC process, as these requirements were not established at the onset of the mission concept development. Baseline mission requirements are a product of the mission studies and are defined by the project office as part of the DTC process.

At the time of this writing, OCI has been commissioned as part of the PACE observatory and has begun operational science data collection. This paper provides a look into the design-to-cost trade space and how it influenced the Ocean Color Instrument development and capabilities from concept to commissioning.

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1. INTRODUCTION: PROJECT MISSION BACKGROUND

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is a strategic climate continuity mission that was defined in the 2010 document *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for Climate-Centric Architecture for Earth Observations and Applications from Space* (referred to as the "Climate Initiative"). The Climate Initiative complements NASA's implementation of the National Research Council's Decadal Survey of Earth Science at NASA, NOAA, and USGS, entitled *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The PACE mission represents NASA's next investment in ocean biology, clouds, and aerosol data records [1].

PACE is extending the high quality ocean 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), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), and the Visible Infrared Imaging Radiometer Suite (VIIRS) [2]. The mission is capable of collecting radiometric and polarimetric measurements of the ocean and atmosphere, from which these biological, biogeochemical, and physical properties will be determined. PACE data products will not only add to existing critical climate and Earth system records, but also answer new and emerging advanced science questions related to Earth's changing climate.

PACE is classified as a Category 2 mission, per the criteria in NASA Procedural Requirement (NPR) 7120.5E, NASA Space Flight Program and Project Management Requirements. The mission classification is C according to NPR 8705.4B, Risk Classification for NASA Payloads.

The PACE observatory is comprised of three instruments, an Ocean Color Instrument (OCI) and two polarimeters, the Hyper-Angular Rainbow Polarimeter 2 (HARP2) and the Spectro-Polarimeter for Exploration (SPEXOne). The OCI is the primary instrument on the observatory, developed at Goddard Space Flight Center (GSFC). It is a hyper-spectral scanning (HSS) radiometer designed to measure spectral radiances from the ultraviolet (UV) over visible (VIS) and near-infrared (NIR) to shortwave infrared (SWIR) to enable advanced ocean color and heritage cloud and aerosol particle science [3-5].

The HARP2 and SPEXOne are secondary instruments on the PACE observatory, acquired outside of GSFC. The Hyper-Angular Rainbow Polarimeter instrument (HARP2) is a wide-swath, hyper-angular, multi-band imaging polarimeter. The SPEXOne is a narrow-swath, multi-angle, hyperspectral imaging polarimeter. Together they are capable of characterizing atmospheric aerosols for purposes of sensor atmospheric correction as well as atmospheric science.

The three-instrument PACE mission has the following multiple scientific goals:

- Extending key systematic ocean biological, ecological, and biogeochemical climate data records and cloud and aerosol climate data records;
- Making global measurements of ocean color data products that are essential for understanding the global carbon cycle and ocean ecosystem responses to a changing climate;
- Collecting global observations of aerosol and cloud properties, focusing on reducing the largest uncertainties in climate and radiative forcing models of the Earth system; and,
- Improving our understanding of how aerosols influence ocean ecosystems and biogeochemical cycles and how ocean biological and photochemical processes affect the atmosphere.

The GSFC PACE Project office oversaw the mission, including satellite bus development, launch vehicle acquisition and launch operations (in coordination with the NASA Launch Services Program), mission operations control center, on-orbit commissioning and operations plan, and implementation of science data processing. The NASA Headquarters Program Science authority separately administered the science data processing system and competed science teams, which includes field-based vicarious calibration and data product validation efforts to support the Project science team.

The PACE observatory launched on February 8, 2024 into a Sun synchronous polar orbit at 676.5 km with an inclination of 98 degrees and a 1 pm local ascending node crossing time. The spacecraft bus hosts the OCI, HARP2, and SPEXOne instruments as planned.

2. Formulation: Design-to-Cost Paradigm

NASA Headquarters directed the PACE mission development to be guided by a Design-to-Cost (DTC) process. All elements of the mission, other than the cost, are in the DTC trade space. At the heart of the DTC process are the mission studies, performed across all the mission elements. The mission studies were used to define appropriate approaches within and across elements while maximizing science capabilities at a high cost confidence. Mission baseline requirements development is also embedded within the DTC process, as these requirements were not established at the onset of the mission concept development. Baseline mission requirements were a product of the mission studies and defined by the project office as part of the DTC process, to be codified later in the project life cycle at KDP-C.

The Design-to-Cost paradigm as applied to PACE is founded on two principles: 1) Maximize capabilities above threshold requirements while remaining within cost constraints; 2) Start with threshold requirements and cost cap, then set baseline requirements; these are used to influence design. In essence, the architecture of the mission, and specifically the final OCI design was predicated on meeting threshold requirements plus margin. While at face value this may not seem like a novel decision, in actually, the flexibility afforded by not designing to baseline requirements per se was and is very powerful. Establishing threshold requirements and baseline goals was a game-changer for the success of PACE.

3. Development and Implementation: Design-to-Cost Application

The programmatic context for PACE began when the mission was directed to GSFC in December 2014. A subsequent kick-off meeting was held at NASA HQ in January 2015 where NASA HQ provided threshold requirements to the project (developed in conjunction with Project Science) that formed the design drivers for the mission. The project entered Pre-Phase A in January 2015. At this beginning phase of the mission, no agreed-to baseline requirements have been established (per DTC process). Only notional baseline capabilities have been established for the preferred mission concept and cost. The project then uses the DTC process to determine what set of baseline capabilities are achievable within the budget cost cap and at a 65% cost confidence. This process continued in Phase A and Phase B and to be codified at KDP-C.

Following the DTC process, shown in Fig. 1, initial trades were performed in Pre-Phase A, culminating in a recommended concept presented at the Concept Decision Point (CDP) meeting in October 2015. With stakeholder buy-in on the initial concept, the project proceeded to a Technical, Management, and Cost Review (TMC) held at GSFC in December 2015. Stemming from the success of the CDP and TMC in late 2015, in February 2016, the PACE Project received concurrence from the HQ Earth Science Division (ESD) to proceed to Mission Concept Review (MCR), including the current scope of the OCI. MCR was successfully held in March 2016, followed by KDP-A in June 2016. During pre-formulation, and continuing through formulation, the project worked closely with stakeholders to perform many trade studies. In the 17 months between kick-off and KDP-A, greater than 50 studies were performed.

There were significant Design-to-Cost decisions made during the initial phases of mission development. In some cases there was opportunity to add capability and in others capability was adjusted to balance performance requirements. At the mission level, two decisions for the spacecraft were to delay spacecraft start and shift momentum compensation capability to the bus. The delayed start for the spacecraft allowed for more development time of the Ocean Color Instrument as a risk mitigation to potential schedule delays and transferring momentum compensation to the bus reduced complexity from an already complex OCI tilting design. For polarimetry, the initial decision was to pursue a contributed instrument. In the end, the DTC trade space culminated with both a contributed SPEXOne instrument and a procured HARP2 instrument. Both complimentary and additive to the OCI capability.

There were significant DTC design decisions affecting the OCI architecture. Several added capability, such as: extending the instrument hyperspectral performance to the UV range (340nm); selecting/adding 2 additional SWIR

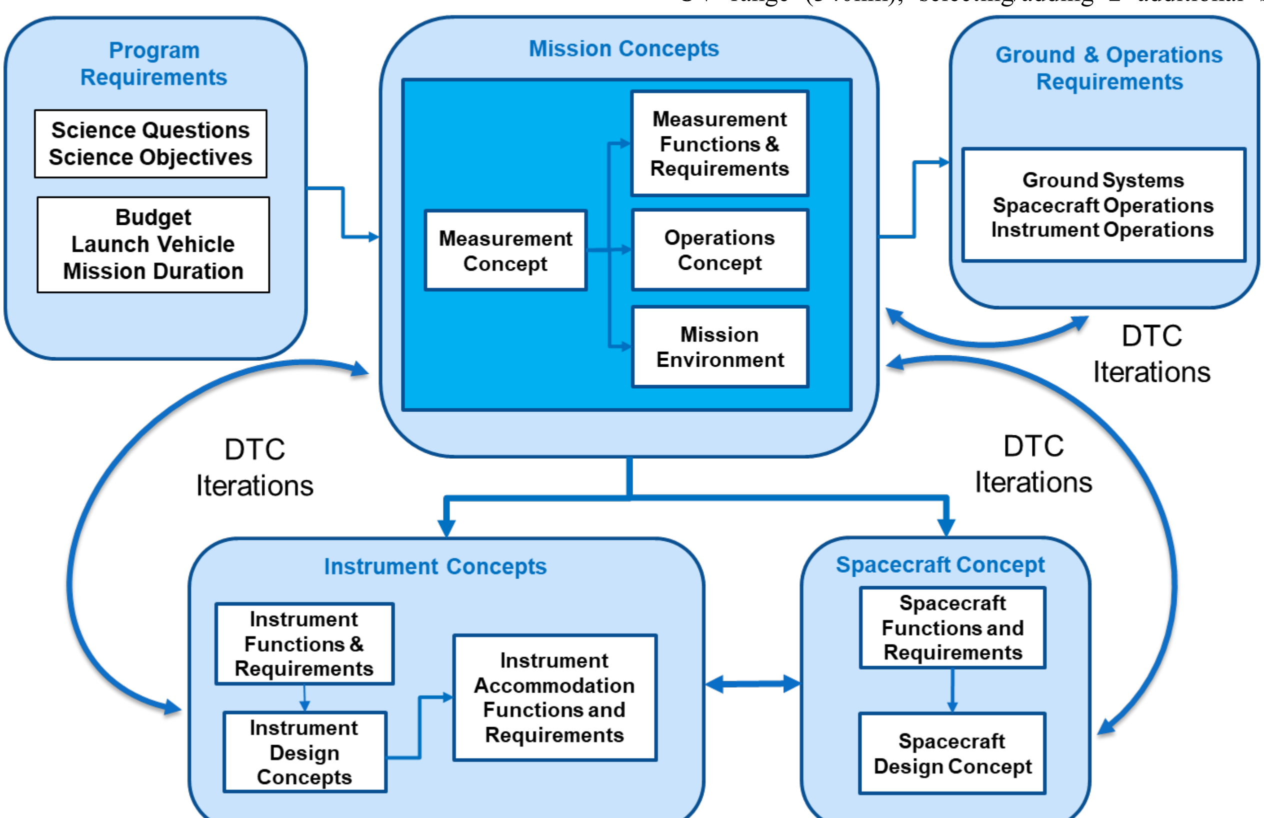


Figure 1. PACE Design-to-Cost is an Iterative Process from Science Objectives to Requirements and Concepts.

Bands (1250nm and 1615nm); and adding a solar diffuser for daily calibrations. Others included selecting the orbit, ground spatial distance (GSD) and signal-to-noise ratio (SNR) combination. The team defined threshold and baseline target SNR levels that linked directly to the number of SWIR channels. And, a fiber optics solution was selected for the SWIR band optical path through the telescope [4-5].

The OCI Team completed its Instrument System Requirements Review (SRR) in March 2017 and subsequent Phase A/B trades identified at SRR were completed in accordance with the DTC process. The OCI team completed its Instrument Preliminary Design Review (PDR) in May 2018, and Critical Design Review (CDR) in December 2019, following mission confirmation at KDP-C in August 2019. At the time of KDP-C, stakeholders agreed to defer final establishment of baseline requirements until OCI flight instrument testing was complete, prior to System Integration Review (SIR).

Following Mission CDR in February 2020, in March of 2020, due to the COVID-19 pandemic, the Project shutdown on-site operations at GSFC and experienced shutdowns and delays from external vendors across the United States and abroad. Operations returned to a relative pre-pandemic level of progress in September 2021. The instrument development entered Phase C during the pandemic, having transitioned from ETU System testing to Flight System integration, with the first subassembly arriving to system level I&T for next level of integration in February 2021. Flight System I&T began in August 2021.

From the hardware system-level development status point of view, OCI had successfully completed the Instrument System

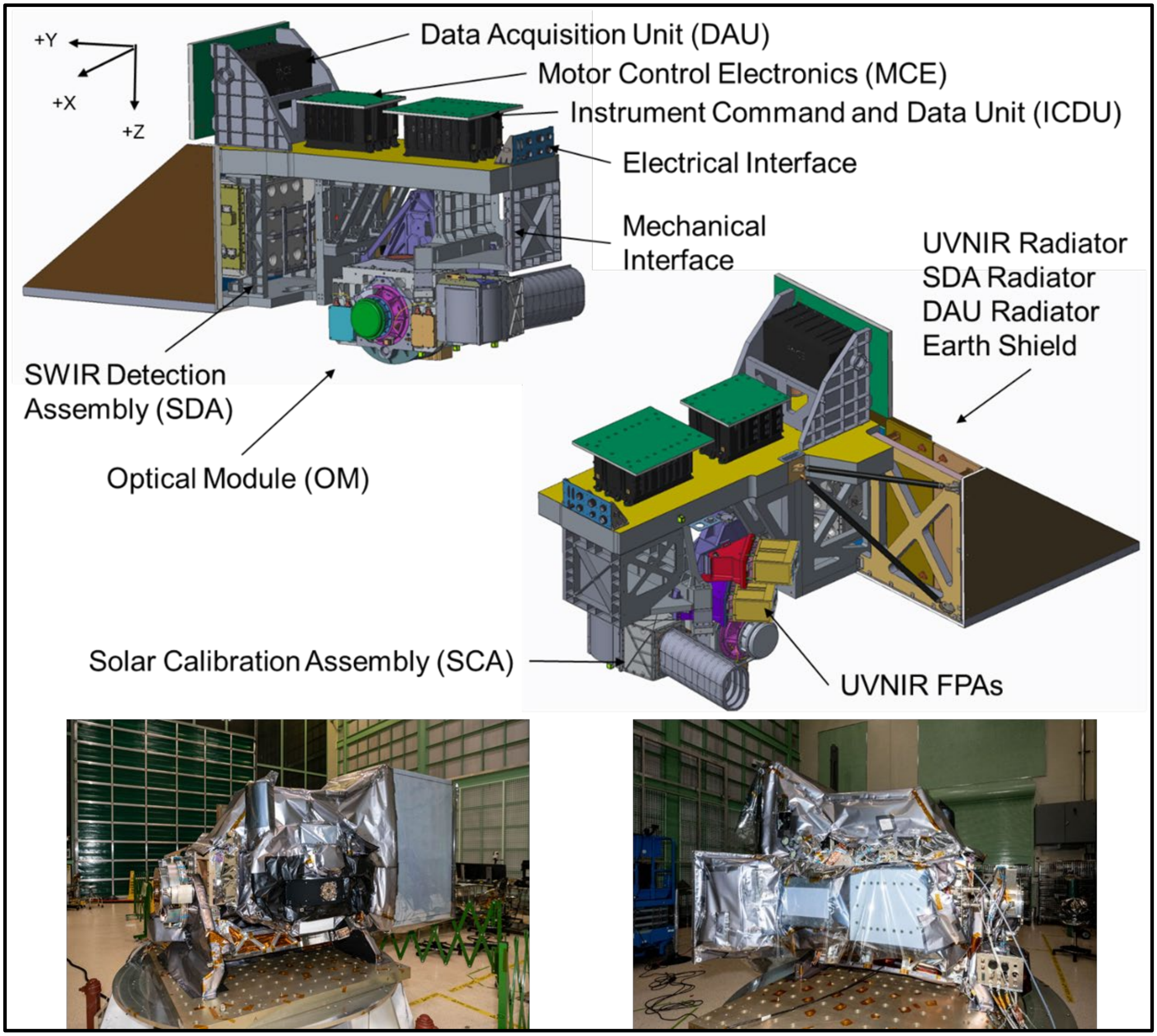


Figure 2. PACE Ocean Color Instrument Architecture.

Engineering Test Unit (ETU) I&T campaign and conducted an independent test data review with the Goddard Standing Review Team (GSRT) and the Agency Standing Review Board (SRB) for PACE. Test results demonstrated the OCI ETU System was meeting and, in some cases, exceeding system performance requirements. In addition, system level EMI/EMC testing was also conducted with very good results, indicating compliance with the EMI/EMC requirements. A KDP-C post-pandemic replan was completed in November 2021, which re-established the PACE launch readiness date and the remaining activities leading up to completion of the Observatory I&T and shipment to the launch site. Critical to maintaining planned spending profiles, planning and execution of test activities were constantly evaluated for necessity and efficiency. Aspects of testing were modified or eliminated based on a value-added mentality to keep in line with DTC principles. Incompressible test lists were used to compensate for unforeseen threats to cost and/or schedule and identify required activities versus "nice-to-haves".

Nearing the end of system integration, OCI conducted its Pre-Environmental review in April 2022. After mechanical and electrical environments testing, the thermal vacuum test and calibration campaign for OCI began in August 2022, for 62 days, as planned verifying excellent performance against requirements [5]. OCI, shown in Fig. 2, was ready for next level of integration in November 2022, was integrated with the Tilt Element, an additional Start Tracker and installed onto the PACE Spacecraft Bus to form the PACE Observatory.

PACE arrived at the launch site on November 14, 2023. Launch site processing commenced along with multiple readiness reviews, Red-tag/Green-tag item closeouts and dress rehearsals over the next two and a half months. The team experienced two launch delays on February 6 and 7 due to high winds, however, the third launch attempt on February 8, 2024 saw the PACE Observatory lifted to orbit on a SpaceX Falcon 9. The mission timeline is shown in Fig. 3. After approximately 9 years from kick-off, PACE was in orbit and it was nearly time for science collection to commence!

4. COMMISSIONING PHASE: DESIGN-TO-COST MINDSET

The entirety and content of the commissioning phase, although commencing much later than the DTC decision space that prescribed it, was conducted with the DTC mindset instilled. The team traded objectives throughout the mission architecture development to achieve an executable plan within constraints during the initial on-orbit phase of the mission. Throughout commissioning, unforeseen challenges arose that threatened the full completion of the plan. Objectives were reorganized and prioritized not to extend the total duration, and commensurately the cost. In the end, all planned commission objectives were met along with some opportunistic "nice-to-haves" that materialized along the way.

The PACE commissioning phase from launch to completion was 60 days including both spacecraft and instrument commissioning activities. The spacecraft commissioning phase involved activation of all spacecraft subsystems and several events to verify instrument pointing and maneuver

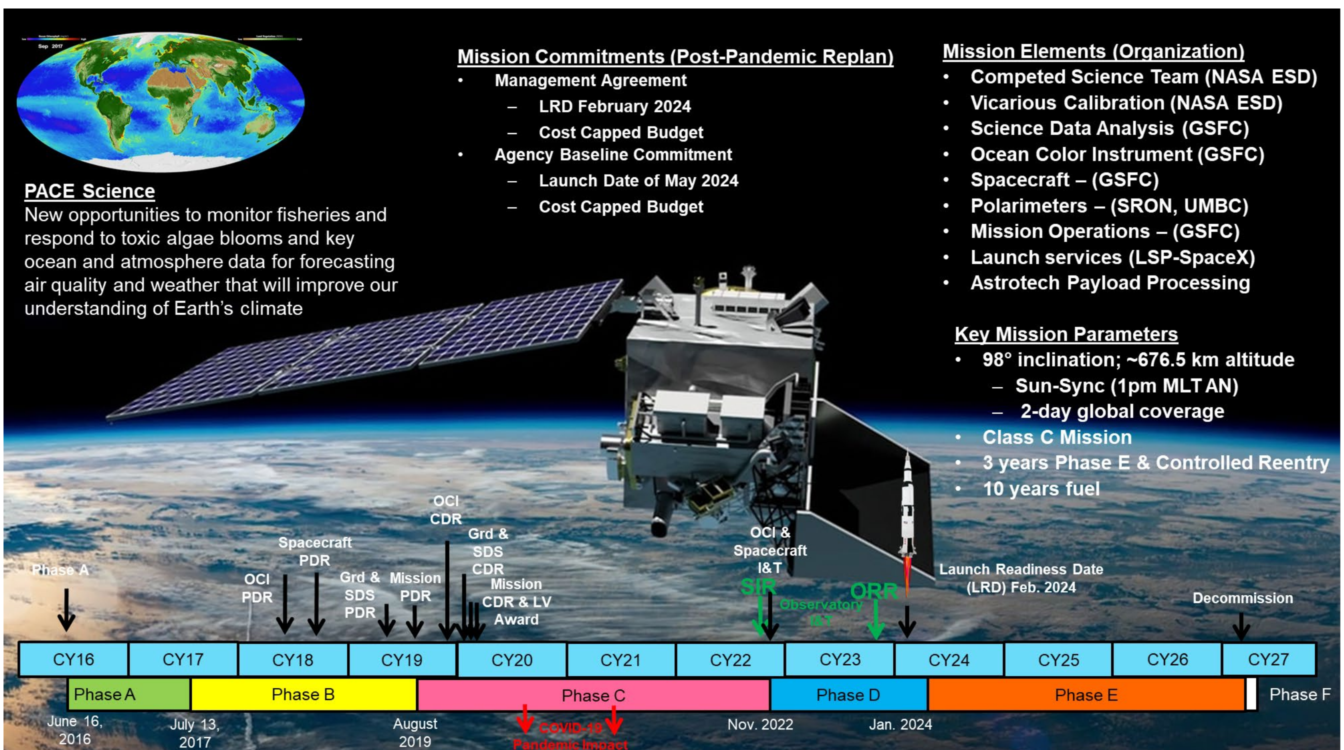


Figure 3. PACE Mission Timeline and Characteristics.

performance. These events included nadir pointing verification, Inertial Reference Unit (IRU) calibration slews, practice lunar and solar calibration spacecraft slews prior to OCI activation and mapping the OCI tilt system hard-stops. The tilt system is used to avoid sun-glint during OCI science data collection.

Once all spacecraft subsystems had been satisfactorily checked-out and calibration slew telemetry was approved by the science team, instrument commissioning began. This included activation of OCI, SPEXOne and HARP2. The OCI Instrument Command and Data Unit (ICDU) was already enabled soon after launch in order to maintain operation of the OCI heaters. The first instrument commissioning phase of OCI enabled all of the Mechanism Control Electronics (MCE) systems and verification that the solar calibration encoder system was reading appropriately. Next, the launch lock on the Rotating Telescope (RT) was successfully fired and the RT and Half Angle Mirror (HAM) were spun up and synchronized at their target spin rates of 5.7Hz and 2.9Hz.

Next for OCI, the Digital Acquisition Unit (DAU) was enabled. This box is the primary interface to the detector systems providing power, commanding and data handling. With the DAU enabled, next the UV-VIS and VIS-NIR Focal Plane Assemblies (FPAs) are powered on and brought to their target cold temperatures. This phase is risky and requires careful management of the Loop Heat Pipes (LHP) activation to avoid thermally stressing the detector systems. The SWIR Detection Assembly (SDA) was also enabled and brought to target cold temperatures. Once all detection systems were enabled, several internal diagnostic activities were successfully performed.

"First light" images of the Earth were first successfully obtained by OCI on February 24^{th}, 2024. Initial checks showed the imagery free of artifacts or other significant anomalies. Electrical noise measured during each dark scan of the spinning telescope met pre-launch expectations. Thermal drift over the course of each orbit was well within predictions. As commissioning continued, the tilt system was re-enabled to verify there were no issues tilting OCI with the telescope spinning. The solar calibration and lunar calibration maneuvers were also repeated with optical data obtained and analyzed by the OCI science team. The predicted and measured solar calibration irradiance spectra matched well [6].

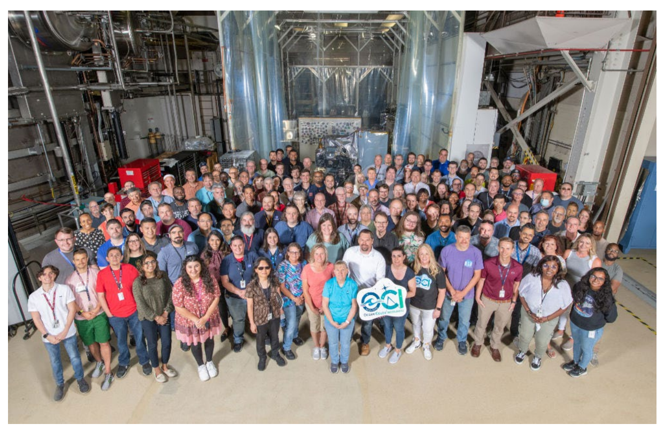
Several special tests were then conducted. These included a cruciform maneuver where the spacecraft was slewed in azimuth and elevation during solar calibration to verify there was no vignetting of the solar diffuser target and the solar incidence angle was as expected. Limited high-resolution data was obtained at 125 m cross-track resolution but narrower swath. The spacecraft was also slewed and imagery of the Earth limb was obtained to check for any stray light issues. With all data satisfactorily analyzed by the OCI science, project management, systems and sub-system leads, permission was granted to begin normal science operations in April 2024.

5. Final Thoughts: Design-to Cost Success

The PACE mission is a resounding success, technically, programmatically and scientifically. The Design-to-Cost approach enabled a programmatic and technical trade space that is typically not accessible under typical NASA project formulation. Early studies aimed at establishing mission architecture required more engineering design analysis and investigation, which drove earlier investment in proto-typing. These early investments paid forward in hardware development risk-reduction. Another notable aspect of the DTC process is the transference of requirements management at a higher level to the project. This enabled systems engineers and scientists to trade performance with design margin across a higher level of the system which opened trade space to balance over and underperforming areas of interest. In the early days of the project life, DTC itself was being defined among the stakeholders. As this definition matured, the mindset settled in with the project team and produced arguably one of the most complex and creative instrument architectures produced by NASA Goddard Space Flight Center. Now we are continuing the climate data record and looking forward to new applications and discoveries from the PACE platform!

Acknowledgements

The OCI Team for their many significant contributions to make PACE a successful mission.



The PACE and OCI Teams, SPEXOne and HARP2 partners, and industry contributors for their unwavering commitment to seeing the PACE mission through many external challenges; including multiple Government shutdowns, a Government furlough and the COVID-19 pandemic.

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REFERENCES

[1] Werdell, P. J., et. al., "The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: Status, science, advances." Bulletin of the American Meteorological Society, 100 (9): 1775–1794 (2019)

[2] C.R. McClain, et. al., “Genesis and Evolution of NASA’s Satellite Ocean Color Program,” Frontiers in Remote Sensing, Vol. 3, Article 938006, pp. 1-19, 2022.

[3] E.T. Gorman, et. al., "The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: an emerging era of global, hyperspectral Earth system remote sensing," Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111510G (10 October 2019)

[4] U. Gliese, et. al., “Optical and detector design of the Ocean Color Instrument for the NASA PACE mission,” Proc. IEEE IGARSS 2023, pp. 1337-1340, July 2023

[5] G. Meister, et. al., “The Ocean Color Instrument (OCI) on the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission: System Design and Prelaunch Radiometric Performance”, IEEE Trans. Geosci. Remote Sens., (2024), doi: 10.1109/TGRS.2024.3383812.

[6] G. Meister, et. al., “On-orbit OCI characterization measurements from the first six months of the PACE mission”, SPIE Sensors + Imaging 2024, Edinburgh, UK, Paper 13192-9.

BIOGRAPHIES

Robert Estep *received the Bachelor of Aerospace Engineering from the Georgia Institute of Technology, Atlanta, GA, and the Master of Business Administration from the University of Houston-Clear Lake, Houston, TX. He joined the National Aeronautics and Space Administration in 1997, where he has supported Agency activities in the Mission Operations Directorate at NASA's Johnson Space Center, the Balloon Program Office at NASA's Wallops Flight Facility, and managing flight instrument projects in the Engineering Technology Directorate and the Flight Projects Directorate at NASA's Goddard Space Flight Center (GSFC). He was the Instrument Manager for the JWST Micro-Shutter Subsystem that launched in 2022, the SMAP Radiometer which launched in 2015, and Project Manager of the Ocean Color Instrument (OCI) which launched aboard the PACE mission in 2024. Currently he is serving as the Deputy Associate Director of the Planetary Science Projects Division at GSFC.*

Joseph Knuble *received the B.S. degree in electrical and computer engineering from Worcester Polytechnic Institute, Worcester, MA, in 2002 and the M.S. degree in electrical and computer engineering from Johns Hopkins University, Baltimore, MD, in 2007. In 2002, he joined the Microwave Instrument Technology Branch (Code 555), at NASA's Goddard Space Flight Center where he designed active and passive microwave remote sensing instruments for 15 years. He was the Lead Engineer for the SMAP Radiometer Front-End which launched in 2015. In 2016, he joined the Ocean Color Instrument (OCI) instrument systems engineering team with a focus on calibration activities. In 2022, he became the Lead Instrument Systems Engineer for OCI which launched aboard the PACE mission in 2024. In 2023, he became the Principle Engineer for the Planetary Science Projects Division (Code 430) at GSFC.*

Ulrik Gliese *received the M.Sc.E.E and Ph.D. degrees from the Technical University of Denmark, Lyngby, in 1989 and 1992, respectively. Since 1992, he has led and performed R&D, covering a wide range of topics in the areas of microwave photonics, fiber-optic communication systems, wireless cellular communication networks, and space flight instruments including particle spectrometers, and optical imaging systems and spectrometers at the Technical University of Denmark, Corning, Corvis, Infinera, Naval Research Laboratory and NASA Goddard Space Flight Center (GSFC). From 2010-2015, he was the Chief Engineer leading the development of the 16 Dual-Electron Spectrometers on the NASA MMS 4-satellite constellation mission. Since 2015, he was Deputy Instrument Manager and Chief Engineer for the Ocean Color Instrument on the NASA PACE mission. He is currently Technology Development Manager at the Earth Science Technology Office at NASA.*

Leland Chemerys *received his bachelor's degree in Engineering Physics from Embry-Riddle Aeronautical University and his Masters in Systems Engineering from John's Hopkins University in 2004 and 2009, respectively. Since 2005 he has worked as a contractor for NASA Goddard Spaceflight Center through several engineering service providers supporting various missions including Hubble Space Telescope Service Mission 4, Joint Polar Satellite System, and Landsat Data Continuity Mission (Landsat 8). In September 2016, he joined the Ocean Color Instrument development team in its infancy and followed the mission through commissioning which completed in April of 2024.*