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The Ocean Radiometer for Carbon Assessment (ORCA):
Development History within an Advanced Ocean Mission Concept, Science Objectives, Design Rationale, and Sensor Prototype Description

Charles McClain, Michael Behrenfeld, Mark Wilson, Bryan Monosmith, Manuel Quijada, Gerhard Meister, Peter Shu, Leroy Sparr, Patrick Thompson, Ken Blumentstock, Alan Holmes, Brian Martin, and Fred Patt

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Preface: ORCA in the Context of an Emerging Advanced Ocean Mission

During 2000-2001, Chuck McClain and Mike Behrenfeld were involved in a study for NASA HQ to determine what a NASA carbon program would need to encompass in terms of satellite sensors, field studies, and modeling (McClain et al., 2002, Gervin et al., 2002). Chuck, along with Forrest Hall and Jan Gervin, was a lead on this study and one of our recommendations was an advanced ocean biology satellite sensor, to follow SeaWiFS and MODIS, that expanded upon heritage measurements by including UV bands for more accurate retrieval of colored dissolved organic matter (CDOM). During this time, Mike was also doing a parallel investigation on new lidar approaches for assessing phytoplankton carbon. In 2002 while returning from an annual NASA Carbon Program review at HQ (this may have been the first one), we began formulating a new ocean mission concept (potentially for proposal to an anticipated Earth System Science Pathfinder (ESSP) solicitation) that merged our ideas for an advanced ocean color sensor and an ocean lidar. This new mission was call the Physiology Lidar Multispectral Mission (PhyLM) and it focused on improving the characterization of ocean carbon stocks and flows through both a refined separation of optically active in-water constituents and improved atmospheric corrections. Over time, the PhyLM concept evolved considerably and has taken on a variety of mission names (OCEaNS, GOCECP, ACE), but the fundamental ideas developed between 2000 and 2002 have remained. Throughout this period, the Ocean Radiometer for Carbon Assessment (ORCA) has been the central ocean color sensor. Here, we describe the history of ORCA and its science objectives, design, and developed prototype.

The first formal PhyLM mission description was given to Dr. Paula Bontempi (Ocean Biology and Biogeochemistry Program Scientist) in September 2003. At this point, the ORCA sensor was envisioned technologically as simply an expansion of the SeaWiFS design, and thus was limited to a set of, albeit greatly expanded, discrete ocean color bands. These bands included a UV band (~340 nm) for atmospheric corrections, longer-wavelength UV bands for assessing CDOM, 11 visible bands for assessing pigment concentrations, taxonomy, particle size distributions, and chlorophyll fluorescence, and two NIR and two SWIR bands for open ocean and coastal water atmospheric corrections, respectively. The PhyLM lidar was envisioned as having emission lines at blue and red wavelengths and providing information on ocean particle concentrations and depth distributions, along with aerosol height information for atmospheric corrections. In October 2003, Mike secured funding from NASA Goddard to conduct the first PhyLM Instrument Design Laboratory (IDL) studies.

The IDL studies conducted in 2004 showed (1) that the two sensor mission (ORCA and Lidar) would cost more than the ESSP cost cap and (2) that a SeaWiFS-like design to accommodate 18 bands was not feasible. Thus, the lidar was dropped from the ESSP mission concept and a second IDL study was conducted through GSFC support that focused on the ORCA sensor alone, where it was decided that a grating spectrometer was the best option (a prism-based design was also considered). Alan Holmes' idea of using a time-delay-integration scheme with the CCDs was also adopted for the ORCA design. In further preparation for an ESSP proposal, an external science team was assembled to define the ORCA Science Traceability Matrix (STM) and GSFC conducted a formal Technical Management Review (TMR). Ultimately, the ESSP solicitation was postponed indefinitely. Nevertheless, GSFC continued to support the PhyLM mission and sensor formulations, thereby keeping the engineering team together.

No longer constrained by the ESSP cost cap and having settled on a grating spectrometer, we returned in 2005 to mission concepts that expanded ocean ecosystem applications and included additional sensors for characterizing aerosols and improving atmospheric corrections. One addition here was the requirement for a full download of high spectral resolution data (5 nm) from the UV and into the NIR. Recognizing the opportunity for interdisciplinary atmosphere-ocean science, our instrument suite was also expanded to include ORCA, a profiling lidar, and a scanning polarimeter. At this point, the mission was called the Ocean Carbon, Ecosystem, and Near-Shore (OCEaNS) mission, and we presented the new concept to NASA HQ in November 2005. In May 2006, we submitted the OCEaNS concept as a white paper for consideration during the NRC Decadal Survey study. Also, during this time, Chuck and Mike participated in a working group to assist the NASA Ocean Biology and Biogeochemistry Program manager, Dr. Paula Bontempi, in formulating the future satellite measurement requirements for her program, (NASA Ocean Biology and Biogeochemistry Working Group, 2007). Both the advanced ocean radiometer and lidar were highlighted in that report.

During the second half of 2006, NASA HQ asked GSFC to lead formulation studies for several mission concepts in preparation for the Decadal Survey results, one of which was a single sensor ocean ecology mission called the Global Ocean Carbon, Ecosystems, and Coastal Processes (GOCECP) mission. ORCA served as the model ocean sensor for the mission planning. A third IDL study was conducted in support of the GOCECP formulation, with further changes and refinements to the ORCA design. This study was delivered to NASA HQ in December 2006. In early 2007, we began drafting a technical memorandum to document all the work on ORCA and the GOCECP mission.

The Decadal Survey results were released in late 2007. One of the recommended missions was an interdisciplinary aerosol, cloud, and ocean mission equivalent to the OCEaNS mission white paper we submitted in 2006, but with the addition of a cloud radar. In June 2008, the ACE science team was formed and the development of mission science traceability matrices (STMs) for each of the science disciplines began. We are members of this science team (Chuck serves as the ocean lead). The STMs require well-defined science objectives, approaches, and measurement requirements. Deliberations by the ACE science team resulted in seven additional required specific bands on ORCA, bring the minimum number of bands to 26 including three bands in the SWIR. The ORCA team refined the IIP prototype design to include a third SWIR band at 2135 μm. In the spring of 2009, as part of an ACE Mission Design Laboratory study of the baseline ACE mission, a fourth ORCA IDL study was conducted. As part of the ACE mission formulation, each discipline working group (oceans, aerosols, clouds, and ocean-aerosol interactions) drafted white papers to explain the STMs. Chuck and Mike were the lead authors of the ocean ecology white paper.

Also in 2008, the ORCA team continued to work on design refinements and received FY08 GSFC Internal Research and Development (IRAD) funds to breadboard the blue "channel" (all optics from the telescope to a detector array), test throughput, and refine component specifications. The ORCA team then submitted a proposal to the

Instrument Incubator Program to build a functioning prototype with the blue and red channels only and to do a system level test at the National Institute of Standards and Technology (NIST, Steve Brown was a co-investigator on the proposal). The team also submitted another IRAD proposal for FY09 funds to support adding three short-wave infrared (SWIR) bands (1245, 1640, and 2135 nm) to the prototype.

In late 2008, Chuck formed a group, mostly from the Ocean Biology Processing Group, to start working on ORCA performance and test specifications. This work was proposed as part of the IIP. Shortly afterwards, Gerhard Meister was asked to lead the ORCA specifications group. The ACE ocean team was also tasked with developing ocean sensor specifications, but they have focused primarily on the spectral band selection and the minimum signal-to-noise ratio requirements. The final document took into account the ACE requirements and was completed in 2011 (Meister et al., 2011).

In 2010, we submitted a second IIP proposal that focused on the design, fabrication, testing and integration of flight-like focal planes and electronics. The final phase of this proposed work would be system testing at flight data rates including scanning at 6 Hz with the telescope synchronized with the focal plane read-out electronics to generate high quality imagery (e.g., replicating images using the NIST Hyperspectral Image Projection system), and a complete calibration and characterization of the sensor. At this time, work on this IIP is well along and on-schedule.

October 31, 2011

Chuck McClain & Mike Behrenfeld

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1. Background

Initial Considerations

In formulating ORCA, the science leads (Chuck McClain and Mike Behrenfeld) wanted to ensure the design would provide the essential global observations required to support future research in ocean biology, biogeochemistry, and marine ecology. These requirements go well beyond the capabilities of the 2nd generation of NASA missions, SeaWiFS and MODIS (Aqua and Terra). The specific issues they identified were:

- Quantification of carbon sequestered into organic matter by ocean primary production,
- Assessment of ocean organic carbon standing stocks
- Evaluation of organic carbon flux through the complex pathways and pools of marine ecosystems,
- Detection of change in ocean production, carbon transfer, and sequestration and resolution of forcing-response relationships,
- Observation of ecosystem responses to aeolian fertilization
- Understanding of ecosystem structure (i.e., phytoplankton functional groups) on carbon uptake,
- Detection of harmful algal blooms,
- Integration of ORCA findings into improved prognostic global ocean circulation-ecosystem models.

Importantly, the first three of the above listed issues were also targeted goals for the previous heritage missions. However, at the time of their conception and design, much less was known about the measurement characteristics necessary to address these issues, so their success in these pursuits has been limited. Nevertheless, it is precisely because of these earlier missions, and the science supported under them, that we now have a far superior understanding of how to tackle the problems. For example, it is now very clear that traditional wavelength-ratio algorithms for deriving single ecosystem properties do not adequately accommodate the natural independent variations of optically active constituents in the upper water column and must be replaced with more sophisticated spectral-matching approaches that allow for such independent behaviors. The first generation spectral matching algorithms have already demonstrated how uncertainty in light absorption by colored dissolved organic matter (CDOM; Siegel et al. 2005) strongly impacts derived surface chlorophyll distributions and thus our understanding of global ocean ecosystem dynamics. The new algorithm products have also demonstrated the severe shortcomings of chlorophyll concentration as a measure of phytoplankton biomass and productivity, while at the same time have shown how chlorophyll data in combination with additional information on particle abundance and size distributions can revolutionize our conception of ocean ecosystem dynamics and carbon cycling. Unfortunately, while these new developments have defined the path to an improved understanding of the oceans and achieving the initial and expanded mission goals (listed above), their effective implementation requires expanded observational capabilities far beyond those of our heritage sensors. These new requirements include, but are not limited to, an expansion in the spectral range of water leaving radiance data, enhanced measurement spectral resolution, and improved accuracy.

In addition to the aforementioned expanded instrument capabilities for improved ocean products, it must also be emphasized that a central goal throughout the Earth Sciences is to reliably detect change in key ecosystem properties and fluxes. This requirement to follow properties over time places additional demands on instrument and mission designs to ensure that sensor stability or drift is accurately characterized. SeaWiFS has achieved an unprecedented level of sensor performance traceability and derived product accuracy using monthly lunar calibrations (Eplee, et al., 2007) for tracking sensor degradation and the ORCA mission, by whatever name it assumes (i.e., OCEaNS, ACE, PACE, etc) will incorporate the same strategy.

ORCA represents the maturation of over three decades of ocean remote sensing experience and the application of state-of-the-art science for derivation of critical ocean and biogeochemistry, no performance or design requirements are compromised, thus enabling the delivery of the highest quality data possible. The ORCA design builds from lessons learned during previous missions, particularly CZCS, SeaWiFS, and MODIS (Aqua and Terra), and VIIRS. The Ocean Ecology Laboratory, which includes the Ocean Biology Processing Group, has worked extensively on all these sensors and missions. Salient considerations were:

- CZCS, SeaWiFS, MODIS, and VIIRS were/are designed to determine chlorophyll-a (although algorithm issues remain) in the surface ocean, not biomass or phytoplankton growth rates. Biomass and growth rates are the real parameters of interest, and ORCA is designed to deliver them.
- VIIRS has a set of seven ocean color bands which is a subset of the SeaWiFS bands (VIIIRS does not have the 510 nm band or the MODIS fluorescence line height bands). Therefore, VIIRS will not advance remote sensing technology or allow new science and applications, even if the sensor meets performance specifications. Additionally, VIIRS does not tilt to avoid sun glint or have a depolarizer to minimize uncertainties in the atmospheric correction algorithm and the sensor polarization characterization. Thus, even our ability to continue the limited set of ocean products at their current level of uncertainty will be compromised. ORCA, on the other hand, meets and greatly exceeds all these capabilities.
- The ORCA design easily accommodates lunar calibration, as did SeaWiFS, for on-orbit stability monitoring (i.e., direct imaging via the Earth-viewing optical train without additional elements and with all detectors illuminated). It will require either a spacecraft maneuver similar to SeaWiFS or additional tilt capability, with an appropriate position on the spacecraft to allow an unobstructed view of the moon without pointing into the spacecraft velocity vector. While VIIRS has a solar diffuser and a stability monitor similar to MODIS, maneuvers required for lunar measurements through the VIIRS space port are limited in terms of frequency and lunar phase angle.
- ORCA addresses all of the ocean measurement requirements identified in the NASA Carbon Cycle, Ecosystems, and Biogeochemistry Roadmap and in the NASA Ocean Biology and Biogeochemisty Programs planning document, *Earth's*

Living Ocean, the Unseen World. It also contributes to terrestrial science objectives and provides new detailed information on atmospheric aerosols (needed for precise atmospheric correction) from additional measurements at ultraviolet (UV), visible, and shortwave near-infrared (SWIR) wavelengths.

- ORCA will provide high quality coastal data products not available from any other ocean color mission, including VIIRS. While VIIRS does have SWIR bands similar to those of MODIS, the SNRs are only slightly higher than the MODIS ocean color bands and not at the desired levels. ORCA will meet SNR requirements and will achieve high quality coastal products by addressing the primary limiting issues in the coastal zone: improved atmospheric corrections and a greatly expanded spectral coverage/dynamic range in water-leaving radiances.
- ORCA takes advantage of recent sensor technology and algorithm science to improve radiometric accuracy, spectral content, and derived product diversity and quality.

There are a number of ocean color radiometer design options as shown in Figure 1. The ORCA team selected a particular design after evaluating pros and cons of each approach. Initially a SeaWiFS design with discrete multispectral bands was considered, but the number of required bands made the design too bulky and cumbersome because of the number of beamsplitters, etc. that were required. The team then considered a spectrometer for the UV-NIR bands and after evaluating a prism-based concept, settled on a grating-based design. Like SeaWiFS, the ORCA system incorporates time-delay integration, yielding the required signal-to-noise ratios, accommodating the lunar calibration of all detectors, and minimizing image striping. More detail on the design is provided in a later section.

The ORCA team has developed a comprehensive

Design / Attribute	TDI-based Hyperspectral Scanner (ORCA)	TDI-based Multispectral Scanner (SeaWiFS)	Whisk Broom Scanner (e.g., MODIS)	Multicamera Spectral Imager (e.g., OCM)	Multicamera Spatial Imager (e.g., MERIS)
Ease of Characterization	+	+	-	-	-
Lunar Calibration	+	+	+	-	-
Spectral Coverage	+	-	+	-	+
Image Quality (Striping)	+	+	-	-	-
Swath Width	+	+	+	-	-

Figure 1. While there are numerous criteria that can be considered when evaluating sensor designs, these 5 are unique. Notes: **(1)** Instrument characterization and degradation modeling is complicated by the number of calibration coefficients that must be tracked (Figure 11). **(2)** Monthly lunar calibrations have proven to be a highly accurate technique to tracking sensor degradation on orbit. For non-scanning designs, only a small subset of detectors see the moon at one instant. A single ORCA lunar scan swath illuminates all of the detectors on the arrays. **(3)** Spectral coverage for multicamera spectral imagers is limited by the number of cameras. **(4)** Stripping is a data quality problem in scanners like MODIS (Figure 12) and imagers like MERIS. ORCA applies the same TDI concept with a rotating telescope used in SeaWiFS to avoid striping. **(5)** Increasing swath width for multicamera instruments requires more cameras or larger arrays, increasing calibration and processing complexity. For example, MERIS employs 5 cameras and achieves half the swath width of SeaWiFS.

pre-launch test plan and has successfully completed detailed component and system level calibration and characterization testing (Meister et al., 2011).

Development History

The Preface of this Technical Memorandum provides a detailed history of the ORCA sensor in the context of an emerging advanced ocean mission concept that began in 2000 and was shepherded by Behrenfeld and McClain. Here, we recall some of this information, but focus more on development details of the ORCA instrument itself.

In 2000-2001, at the request of NASA HQ, GSFC led an agency-wide study on what future satellite observations are required for carbon cycle research. The participants included representatives from other NASA centers, the university community, and other national agencies (e.g., the Department of Energy and the National Science Foundation). The study recommendations were heavily influenced by previous recommendations of the interagency Carbon and Climate Working Group (Sarmiento and Wofsy, 1999). The final presentation was delivered at NASA in the summer of 2001 and subsequently documented in McClain et al. (2002) and Gervin et al. (2002). One of the missions identified was an advanced ocean color mission. Shortly afterwards, HQ began the development of science theme roadmaps (including one on the carbon cycle and ecosystems) which identified timelines for research activities, the existing/approved satellites that would provide data, and the technology infusions required. These planning activities underscored the need to start working on the details of a next generation ocean biology mission, even though the Moderate Resolution Imaging Spectroradiometer (MODIS/Terra) had just been launched and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) had only been on orbit for four years. While the NASA planning effort did not lead to a new carbon initiative, as many had hoped, the recommendations were not forgotten and laid the ground work for the Orbiting Carbon Observatory (OCO) and other carbon mission formulations.

In 2002, Mike Behrenfeld and Chuck McClain formulated a new ocean-focused satellite mission, merging an advanced ocean color instrument (ORCA) with an ocean penetrating lidar. This new mission, called PhyLM, was presented in 2003 to the NASA Ocean Biology and Biogeochemistry Program (OBBP) Program Scientist, Dr. Bontempi, and was then targeted for submission as a proposal to an upcoming Earth System Science Pathfinder (ESSP) mission solicitation. Ultimately, the ESSP solicitation was indefinitely postponed , but development of the PhyLM concept, in general, and the ORCA instrument continued through multiple ISAL and IMDC studies at GSFC. During this period, PhyLM was expanded to include a polarimeter and the mission was renamed to the Ocean Carbon, Ecosystems, and Near-Shore (OCEaNS) mission. In 2005, the OCEaNS concept was presented to NASA HQ and then submitted as a white paper in response to the National Academy of Science (NAS) Decadal Survey request for mission concepts (the Decadal Survey is a broad-based assessment of what Earth science missions are needed in the post Earth Observing System (EOS) era, aside from those included in NPOESS). Throughout development, the PhyLM and then OCEaNS concepts were presented at annual meetings of the OBBP and gained significant community support.

In 2006, NASA HQ requested GSFC to conduct a number of mission concept studies in preparation for the Decadal Survey recommendations. One of the missions studied was an advanced ocean biology and biogeochemistry mission, subsequently labeled the Global Ocean Carbon, Ecosystems and Coastal Processes (GOCECP) mission. The GOCECP study was based on the ORCA instrument and involved additional ISAL and IMDC studies, with the NPOESS Preparatory Project (NPP) Office at GSFC serving as the study lead. This HQ request reflected recommendations of a working group convened in late 2005 by Dr. Paula Bontempi to outline future measurement requirements for her program. This group worked for over a year to develop their recommendations and receive community input. Their final report, *Earth's Living Ocean, the Unseen World*, was released in early 2007 with an advanced radiometer for routine global observations identified as the highest priority.

The GOCECP study was comprehensive, included a budget that cut no corners (e.g. included a complete program for calibration and validation), and, through the associated ISAL, revised the ORCA design to meet all science and sensor performance requirements (e.g., signal-to-noise and maximum radiances). Results of the study were presented in December 2006 to NASA HQ. In 2007, the Decadal Survey report was released, with one of the recommended missions being the OCEaNS concept expanded to include a dual-frequency cloud radar. This revised mission was called the Aerosol-Cloud-Ecosystems (ACE) mission, with the ocean radiometer generically termed the ocean ecosystems radiometer (OES), rather than the specific sensor, ORCA. Development of the ACE mission began in earnest in 2008 with establishment of an interdisciplinary science team. Eventually, ACE was proposed as a phased mission, with the first launch (Pre-ACE, or PACE) including a US-provided OES and, potentially, an internationally contributed polarimeter. In 2009, an ACE-supported ORCA ISAL study was conducted, resulting in a revised sensor layout where the telescope scan plane and optical bench were parallel rather than orthogonal. To date, several ACE IMDC studies have been conducted with various combinations of sensors and platform configurations. Throughout these developments, ORCA has functioned as the model OES.

The current document summarizes the present status of the ORCA. Importantly, the ORCA sensor is designed to support state-of-the-art ocean color remote sensing science. It will expand the range of retrieved carbon-cycle related ocean ecosystem products, reduce uncertainties in key properties, and improved detection and interpretation of observed ocean ecosystem trends by addressing short-comings in heritage sensors and operational sensors. In contrast to ORCA, the VIIRS sensor, the key ocean sensor in the Joint Polar Satellite System (JPSS), has only five ocean bands plus two atmospheric correction bands and is, in many ways, less capable than SeaWiFS and MODIS. Thus, VIIRS can not be viewed as a sensor that will advance understanding of ocean biology and carbon cycling. It should also be noted that the SeaWiFS and MODIS designs were conceived in the late 1980s-early 1990s and do not reflect current science requirements and technology, so copies of these sensors will not suffice.

The ORCA is an advanced instrument that incorporates lessons learned from SeaWiFS, MODIS, and the Sensor Intercomparison and Merger for Biological Interdisciplinary Ocean Studies (SIMBIOS; McClain et al., 2002) programs. ORCA extends measurement capabilities beyond heritage designs to provide the greater spectral information and more accurate derived products needed for new science applications and climate research. ORCA has benefitted from the input and review of multiple science teams, the first being assembled in September of 2004. McClain and Behrenfeld also enlisted the assistance of Alan Holmes (the SeaWiFS system engineer at Hughes/Santa Barbara Research Center) in 2003 and he has remained an important contributor to the ORCA development ever since.

In 2008, GSFC provided Internal Research and Development (IRAD) funds to begin bread-boarding the front end optics and blue spectrograph of ORCA (i.e., the telescope primary mirror, polarization scrambler, half-angle mirror (HAM), collimating mirror, dichroic, grating, and lens assembly). This work led to a 2008 Instrument Incubator Program (IIP) project to build an ORCA prototype (i.e., brass-board) with both the blue and red spectrographs, as well as integration of the rotating telescope and HAM motors and encoders. This brass-board ORCA was aimed at replicating an engineering design unit up to the focal planes, but employed commercial CCD arrays to reduce costs (i.e., rather than custom arrays having the required number of output taps to accommodate actual data rates a flight unit). The 2008 IIP brass-board ORCA had three main objectives: (1) development of accurate component and sensor performance specifications, (2) fabrication of a flight-like system up to the focal planes and associated electronics, and (3) evaluation of sensor calibration and characterization, including development of detailed test and analysis procedures.

In support of the 2008 IIP project, additional IRAD funds were provided in 2009 to include three shortwave infrared (SWIR) bands in the ORCA brass-board, reflecting measurement requirements defined by the ACE mission science team. During the first year and a half of the IIP project, the optical design and physical layout of ORCA was completed, all components where procured and tested (optical and electromechanical), and all structures and mounts were purchased or machined. During the summer and fall of 2010, system alignment was completed and preliminary system level testing (e.g., polarization sensitivity) was conducted at GSFC. Alignment proved to be a challenge, but resulted in many lessons learned. In January 2011, the system was taken to National Institute of Standards and Technology (NIST) for complete system level testing, which was essentially completed by summer 2011. ORCA remained at NIST throughout the fall of 2011 for additional follow-up testing (e.g., the depolarizer was replaced with an updated design that included a wedged front surface to reduce ghosts on the CCDs).

A second ORCA IIP proposal was submitted to and selected under the ROSES 2010 solicitation. This second IIP project was initiated in Feburary 2011 and was focused on replacing original brass-board detectors and electronics with flight-like detector arrays (UV-NIR CCDs and linear SWIR arrays), electronics, and data handling systems, yielding a fully functional prototype capable of collecting flight mission quality hyperspectral data at flight scan rates (i.e., accurately synchronized scan and time delay integration, TDI, mechanisms and read-out electronics). As of the time of this publication, the acquisition of all detector and electronics subsystems is underway and on schedule. The silicon CCDs are being designed and fabricated by STA, with a second design/fabrication pathway proceeding in parallel within the Detector Systems Branch (Code 553) at GSFC. The InGaAs SWIR linear arrays are being provided via an independently funded SBIR project with the SWIR electronics being designed and fabricated by Code 553.

The ORCA concept has been in development for nearly a decade, with Table 1 providing a summary of the milestones over this time. Many important insights have been gained over this time regarding component and sensor performance specification requirements, vendor capabilities, design details and pitfalls, component testing, data analysis methods, and fabrication procedures, to name just a few. The present ORCA reflects an evolution in design, but the basic concept of a scanning telescope coupled with TDI on the focal planes has remained a fundamental property of ORCA since its initial phases of concept development, and for many reasons as outlined in Figure 1.

Table 1. Chronology of ORCA concept development.

•NASA carbon program formulation: 2000-2001
–Carbon cycle missions/sensors included an advanced ocean biology sensor
•Early mission development: 2002-2006
–**PhyLM** (Physiology Lidar-Multispectral Mission): ORCA plus Profiling Lidar
–**OCEaNS** (Ocean Carbon, Ecosystems, and Near-Shore Mission: ocean biology radiometer, aerosol lidar, & polarimeter
–2 ISAL sessions (SeaWiFS-like filter radiometer, prism spectrometer)
•HQ Decadal Survey Preparatory Mission Studies: 2006-2007
–**GOCECP** (Global Ocean Carbon, Ecosystems, & Coastal Processes): Ocean Biology Radiometer only
–ISAL session (3rd), grating spectrometer
• NRC Decadal Survey Report: 2007
• *Earth's Living Ocean, The Unseen World*: 2007
• **ACE** (Aerosol, Cloud, & Ecology) science working group established: 2008.
–Baseline sensors: Ocean Biology Radiometer, Polarimeter, Aerosol Lidar, Cloud Radar
•2008 IR&D Study: ORCA prototype development
–Blue channel breadboard only (335-590 nm)
–3.3 FTEs & over $100K in procurements
•Instrument Incubator Program (IIP, FY09-11): ORCA prototype development
–Red channel (570-885 nm) breadboard integration with blue channel
–Scan mechanisms
–System-level testing at NIST
•2009 IR&D proposal: ORCA Shortwave-IR (SWIR) band development
–Integration of two SWIR bands into ORCA prototype
–1.0 FTE & $55K in procurements
•ACE mission formulation (underway): Spectral band revisions
–26 recommended bands vs. 19 originally specified for ORCA
–Instrument Design Lab (4th) completed in April 2009
•IIP-2 Proposal (2011-2014)
–Incorporate & test flight-like detector arrays and electronics at 6 Hz scan rate
–Instrument Design Lab (5th) to consider addition of 3 additional cloud bands (940, 1388, and 2250 nm) completed in August 2011.

2. ORCA Science Rationale and Requirements

In section 1, we identified eight key science foci for the ORCA instrument, summarized here as:

1. CO_2 uptake by ocean primary production
2. Organic carbon standing stocks
3. Carbon transfer through ecosystems
4. Detection of ecosystem change and links to climate
5. Aeolian fertilization impacts
6. Ecosystem structure
7. Harmful algal blooms,
8. Advance ocean ecosystem modeling.

In this section, we describe how these science objectives are reflected in the ORCA design and build on the methods and science of heritage sensors (McClain, 2009). First, we specify the relationship between science objectives and the spectral range and resolution of the ORCA measurements. We then we discuss additional instrument and mission requirements for achieving ORCA's science goals (e.g., glint avoidance, polarization sensitivity, sensor degradation tracking, swath, etc.). In reflection on the history of ORCA in preparation for drafting this Technical Memorandum, it has been interesting to note that, while many technical aspects of the instrument have evolved over the past decade and our original concept has been vetted regularly with the broader science community, our underlying science objectives and approach have remained largely unchanged since the early years of PhyLM.

Advancing Global Ocean Sciences with ORCA: Spectral range and resolution

(i) <u>Atmospheric Corrections</u>: Climate-quality satellite ocean color retrievals are among the more difficult Earth system measurements to make because, typically, greater than 90% of the signal measured by ocean color sensors at the top of the atmosphere (TOA) is not from the ocean, but from the atmosphere. This dominant atmospheric contribution must be accurately removed in order to effectively retrieve ocean ecosystem properties. Thus, attention to atmospheric correction issues is an essential element in any ocean color mission and key features of the ORCA sensor are aimed at improving atmospheric corrections beyond heritage capabilities.

Open ocean reflectances in the NIR are nearly zero because of low particulate backscatter in the ocean and high absorption by water. TOA radiances in the NIR thus consist essentially of only Rayleigh scattering (which is accurately calculated) and aerosol components. This aerosol reflectance can be accurately estimated using NIR band combinations. Thus, ORCA includes measurement bands in the NIR, similar to SeaWiFS (765-865 nm) and MODIS (748-869 nm). However, when applying these aerosol reflectance values for atmospheric corrections at shorter wavelengths, a spectral slope for the aerosol correction must be applied, which for heritage sensors has been based on a standard set of aerosol models (Gordon and Wang, 1994; Ahmad et al., 2010). These standard models, though, can be problematic, particularly when absorbing aerosols (dust, smoke, smog, etc.) are common. In such cases, incorrect spectral slopes for the atmospheric correction model can result in erroneously retrieved water-leaving radiances at shorter visible wavelengths and long UV-A wavelength, yielding incorrect CDOM and phytoplankton pigment absorption coefficients. In fact, the absorbing aerosols can result in negative water-leaving radiances at 412 and 443 nm when their attenuation effects are not properly corrected. To address these issues, ORCA includes measurements in the shorter (340-350 nm) ultraviolet-A wavelengths. Similar to the NIR region, ocean reflectances at these short wavelengths can be very low, particularly in high CDOM waters, allowing assessment of aerosol contributions and, consequently, an 'anchoring' of the spectral slope for the atmospheric correction model.

In near-shore regions, accurate atmospheric corrections can be even more challenging because particulate loads in these waters can be sufficiently high that ocean reflectance in the NIR is significant. Recently, methods have been developed that employ measurement bands in the SWIR range (e.g., MODIS 1240, 1640, and 2130 nm bands) to address this problem (e.g., Wang and Shi, 2005; Figure 2). At these wavelengths, water absorption is 1-3 orders of magnitude greater than in the NIR, thus ensuring zero ocean reflectance. However, the MODIS SWIR bands have low SNRs that are somewhat problematic, while VIIRS has slightly higher SNR for similar SWIR bands, but even these are inadequate. ORCA will incorporate three SWIR bands with much higher SNRs than MODIS or VIIRS, thus optimizing turbid water atmospheric corrections. Even so, atmospheric corrections of visible and UV bands based on SWIR measurements require extrapolation over a wide spectral range, so OCRA's short UV-A band will again help anchor the slope of the atmospheric correction model.

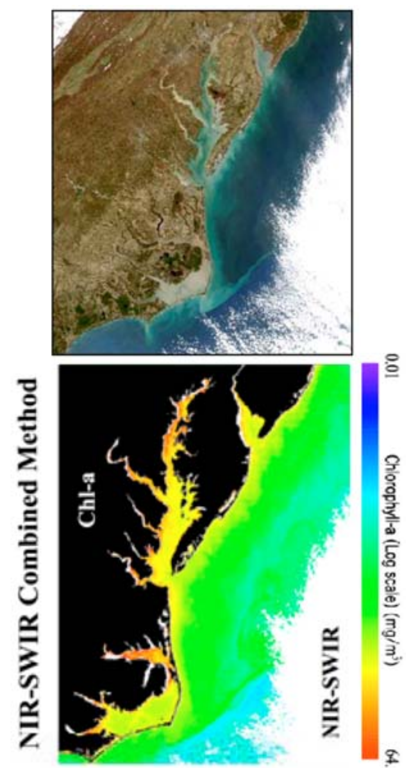
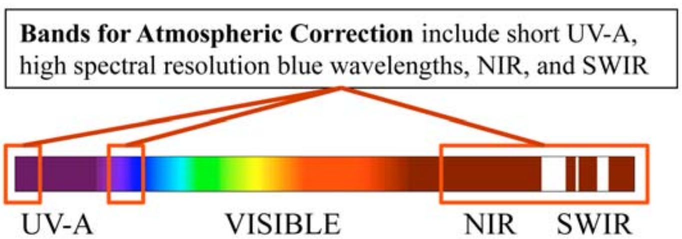


Figure 2. Atmospheric corrections using both NIR and SWIR bands allow for accurate open ocean and coastal ocean color product retrievals. (Top) true color MODIS image with inland waters of North Carolina and Delaware and Chesapeake Bays. (Bottom) Chlorophyll concentration retrieved using SWIR bands for coastal waters and NIR bands for offshore waters.

In addition to absorbing aerosols, NO_2 is a strong absorber in the blue region of the visible spectrum and it notably affects SeaWiFS and MODIS data products in regions where NO_2 concentrations are high (e.g., coastal areas downwind of heavily populated and industrialized regions - Ohio valley, southern California, China, etc). A method has been developed to correct for this absorption (Ahmad et al., 2007) using data from the Ozone Monitoring Instrument (OMI), the Global Ozone Monitoring Experiment (GOME), and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (Sciamachy) satellite sensors. For ORCA, a high spectral resolution subsampling capability around NO_2 absorption features may enable evaluation and correction for its impacts on ocean ecosystems retrievals, although a methodology has not been established.

One other atmospheric correction that was not a concern for SeaWiFS or MODIS ocean color processing, but will be for ORCA is water vapor because some critical bands for new applications, e.g., 710 nm for HABS, overlap water vapor absorption features. To address this, an 820 nm band has been specified. The 820 nm water vapor absorption is not as strong as that at 940 nm, a MODIS band, but is easier to accommodate from a design perspective because it falls within the range of the existing IIP prototype red channel CCD . The 5th IDL study showed that a 940 nm band could be easily added as a fourth discrete band in the SWIR band suite.

ORCA's attention to the atmospheric correction problem will help ensure that the sensor delivers superior ocean ecosystem properties. However, it should also be noted that further improvements could be realized by coupling ORCA with a profiling lidar (as in the PhyLM concept) and additionally a polarimeter (as in the PACE mission). These additional sensors would help constrain atmospheric aerosol loads, species, and heights, thereby improving atmospheric corrections above and beyond the advances enabled by ORCA alone.



Summary: *ORCA includes measurement bands in the UV, NIR, and SWIR for improved atmospheric corrections over open ocean and coastal waters. High resolution measurements in the blue band will also help with assessments of* NO_2.

(ii) <u>Separating Dominant Absorbing Components:</u> One of the important developments during the SeaWiFS/MODIS era has been the demonstration that the 'bio-optical assumption' is invalid. The bio-optical assumption states that all optically active in-water constituents covary in a globally consistent manner with chlorophyll, and it is the foundation upon which traditional wavelength-ratio algorithms rely. It is now understood, however, that the multitude of absorbing and scattering constituents *vary independently* and must be accurately resolved for any one product to be properly assessed. Of particular concern is colored dissolved organic material (CDOM), which is ubiquitous in the surface ocean (Siegel et al, 2005). CDOM contributes significantly to total light absorption at blue and shorter wavelengths and it interferes with chlorophyll retrievals because its distribution can be quite distinct from that of pigment absorption. Figure 3 illustrates the seriousness of this issue. Here, the difference in chlorophyll estimates for a standard wavelength-ratio algorithm and an inversion-based algorithm are shown in the top panel. This difference is compared in the middle panel to the inversion-based estimate of CDOM absorption. This comparison clearly demonstrates that uncertainty in chlorophyll retrievals is directly linked to CDOM. The difference in global annual production for these two chlorophyll estimates is ~16 GtC/yr, in other word an uncertainty ~30% in annual ocean production! However, it is important to note that, at this time, significant uncertainties in both the wavelength ratio product and inversion products remain because of limitations in the heritage measurement bands. In other

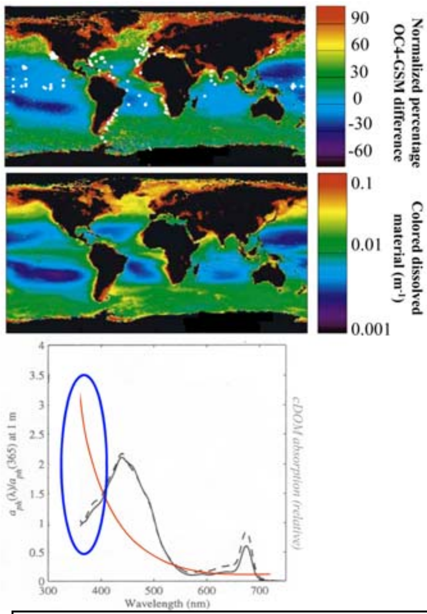
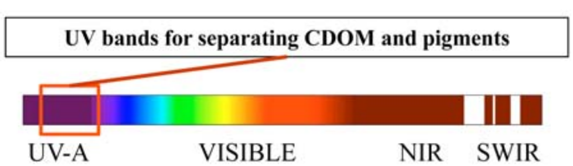


Figure 3. Impact of CDOM on satellite chlorophyll retrievals. (Top) Normalized percentage difference in chlorophyll products between the standard SeaWiFS algorithm (OC4V4) and GSM inversion algorithm, which specifically separates absorption into chlorophyll and CDOM contributions. (Middle) GSM CDOM product. Similarity between the global distributions in the top and middle panel illustrates the important contribution of CDOM to uncertainties in chlorophyll products. (Bottom) Comparison of absorption spectra from phytoplankton pigments (black line) and CDOM (red line). Note the strong divergence between these spectra at near UV wavelengths (blue circle). Measurements in this spectral region will allow improved accuracy in chlorophyll and CDOM retrievals.

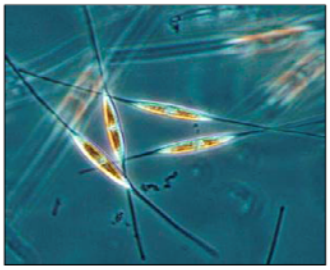
words, we do not yet know which of the two chlorophyll products compared in top panel of figure 3 is more accurate.

The key to resolving the CDOM problem is to extend measurements to shorter wavelengths. Specifically, phytoplankton pigment absorption begins to decrease at wavelengths shorter than roughly 420-440 nm. In contrast, CDOM absorption continues to increase exponentially well into the UV-A region (Fig. 3, bottom panel). The CZCS did not have any bands at these shorter wavelengths to effectively separate pigment and CDOM absorption. SeaWiFS, MODIS, and other “second generation” sensors have incorporated a band at 412 nm, but even at this wavelength retrieval of CDOM is problematic. ORCA will include 2 measurement bands (360 and 380 nm band centers) that will allow superb quantification of CDOM absorption, and thus greatly improved assessment of phytoplankton pigment concentrations. These improvements will be realized by incorporating the UV bands in advanced inversion algorithms. However, challenges of the inversion approach should be noted. Specifically, while inversions allow the simultaneous retrieval of multiple ocean properties, they are much more sensitive to errors in satellite water leaving radiances. This issue arises because inversion products are derived by matching composite algorithm spectra with *absolute radiances*, whereas wavelength ratio algorithms derive products from the *relative* relationship between particular measurement bands. As a consequence, spectrally-independent errors in water leaving radiances will tend to cancel each other in the wavelength ratio approach, but will directly degrade inversion products in proportion to the error in the satellite radiances. This sensitivity to error in absolute radiance retrievals re-emphasizes the importance of accurate atmospheric corrections (as discussed above) and is a driving factor for many of the ORCA instrument requirements discussed later in this document



Summary: *ORCA includes two long-wavelength UV-A bands to effectively separate absorption by CDOM and phytoplankton pigments, yielding far more accurate assessments of productivity.*

(iii) <u>Assessing Phytoplankton Pigment Absorption:</u> Chlorophyll-a is a common photosynthetic pigment across all prokaryotic and eukaryotic phytoplankton. It is not, however, the only pigment. A wide range of accessory pigments are found among different phytoplankton species. These pigments largely function within the light harvesting antennae and function to broaden the spectral range of absorbed light used to drive photosynthetic carbon assimilation (Figure 4). The relative ratio of chlorophyll-a absorption to accessory pigment absorption is highly variable in natural plankton populations and is a function of both taxonomic composition and environmental growth conditions. Pigment diversity amongst phytoplankton gives rise to significant variations in pigment absorption spectra and accounting for this variability is essential for quantifying ocean productivity because photosynthesis is regulated in proportion to total light absorption, not simply chlorophyll absorption.



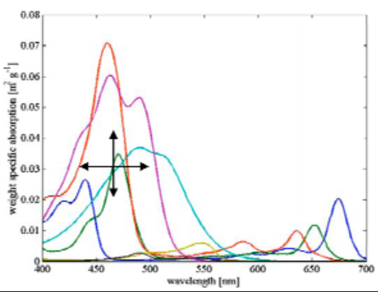
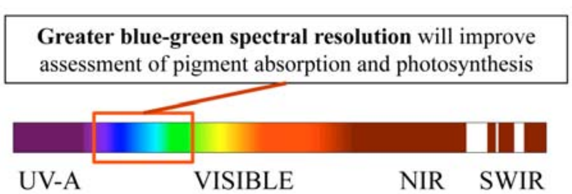


Figure 4. The taxonomic composition of phytoplankton communities impacts bulk phytoplankton absorption spectra through the influence of accessory photosynthetic and protective pigments. (Top) Microscopic image of diatoms showing their characteristic 'brown' color from accessory pigments. (Bottom) Example phytoplankton absorption spectra from different phytoplankton species in laboratory culture.

Improved assessments of phytoplankton light absorption can again be made using advanced ocean color inversion algorithms. However, heritage ocean color bands have not had the spectral resolution to realize this potential. Specifically, current inversion algorithms assume a 'spectral shape' for phytoplankton absorption and then vary the amplitude of this spectrum to quantify pigment concentration. ORCA will provide greater spectral resolution in the blue through green wavelengths to enable effective characterization of phytoplankton pigment absorption spectra, thus yielding a more accurate estimate of ocean production.



Summary: *ORCA provides 15 nm aggregate bands (bands formed by summing higher resolution data) within the visible spectrum, which will enable more accurate assessment of phytoplankton pigment absorption and photosynthesis.*

(iv) <u>Ocean Carbon Stocks:</u> Global variations in water leaving radiance do not reflect changes in the concentration of light absorbing components alone, but also variations in scattering properties. Thus, determination of scattering coefficients is another integral aspect of inversion algorithm solutions. Quite simply, one must accurately characterize variability in scattering to accurately retrieve pigment absorption, and vise versa. In the case of remote sensing analyses, the scattering coefficient resolved is the backscattering coefficient (b_b), which is composed of a contribution by water (b_{bw}) and a particulate contribution (b_{bp}). The important property of b_{bp} is that it registers changes in the population density of particles and can be related to the total phytoplankton carbon biomass. Analysis of b_{bp} data from SeaWiFS shows that it exhibits significant independent variations from chlorophyll, and thus provides additional critical information about phytoplankton communities. Specifically, b_{bp} tracks phytoplankton biomass, while the ratio of chlorophyll:biomass provides information on phytoplankton physiology that can be related to growth rates. However, there are complications in deriving phytoplankton carbon from b_{bp}. Most importantly, the particle population contributing to b_{bp} differs in its size dependence from the populations composing total phytoplankton carbon. Thus, to derive the latter from the former, one needs information on the particle size spectrum. In current inversion algorithms, the restricted range and spectral resolution of heritage remote sensing bands strongly constrains the information available on particle scattering, such that in most approaches a single spectral shape for b_{bp} is assumed (Figure 5). With additional bands, particularly in the green to orange region of the visible spectrum, inversion algorithms can provide information on both the quantity of particles and the particle size distribution, thus yielding more accurate assessments of phytoplankton carbon. The ORCA is designed to realize these improvements.

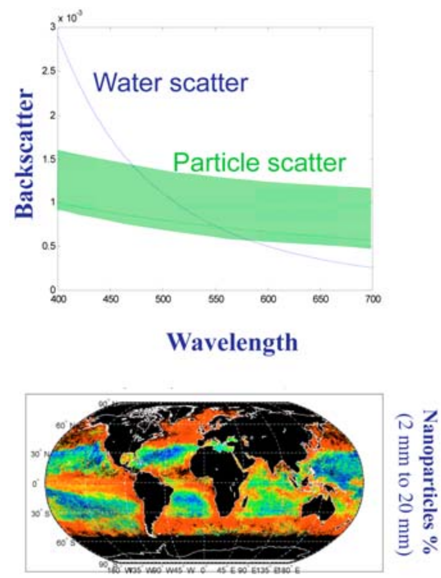
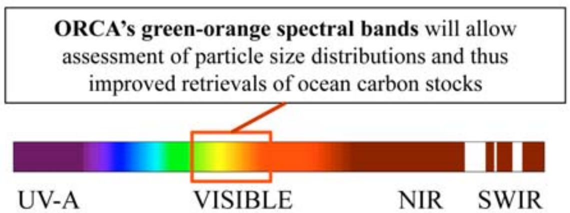


Figure 5. The backscatter spectral slope provides information on properties of the particle assemblage. (Top) Backscattering spectrum for pure seawater (blue line) and the range for natural particle populations (green area). Measurements in the green-orange spectral region of minimal pigment absorption will allow retrieval of the particulate backscattering slope. (Bottom) Example of retrieving a specific plankton population (nanoparticles) through assessment of backscattering slope. (data from Kostadinov et al 2009)

Phytoplankton biomass and productivity are not the only important components of the ocean carbon system. A more complete understanding of ecosystem carbon budgets requires additional estimates of total particulate organic carbon (POC), particulate inorganic carbon (PIC), and dissolved organic carbon (DOC). Again, ORCA will enable advances in our understanding of these diverse carbon pools. With respect to POC, assessments can be made from inversion retrievals of b_{bp} (Gardner et al., 2006 and Stramski et al., 2008), and again these estimates will be significantly improved through information from ORCA on the slope of the particle size distribution (discussed above). Established algorithms also exist for assessing surface ocean PIC concentrations (Gordon et al., 2001, Balch et al.,

2005) and calcification rates (Balch et al., 2007). These algorithms employ heritage ocean color bands in the visible spectrum and will be well supported by ORCA. Global determination of DOC are more challenging and cannot be simply retrieved from CDOM estimates in the open ocean (Siegel et al. 2002; Nelson et al. 2010). However, regional algorithms for estimating DOC from CDOM are effective in coastal regions influenced by terrestrial inputs (e.g., Del Castillo and Miller (2008) and Mannino et al., (2008)). Improvements in CDOM retrievals in coastal areas through ORCA's UV-A bands will significantly reduce uncertainties in important coastal DOM assessments.



Summary: *ORCA provides 15 nm aggregate bands within the visible spectrum, allowing characterization of particle size distributions and, consequently more accurate assessment of ecosystem carbon stocks*

(v) <u>Nutrient Stress:</u> The relationship between surface phytoplankton pigment concentration and photosynthesis is strongly influenced by variations in the light environment that phytoplankton are photoacclimated to, the degree of nutrient stress (mild to severe), and the *type of nutrient stress* (e.g., N, P, Fe). These 'physiological' factors strongly impact our interpretation/understanding of relationships between climate-forcings and ocean carbon cycling. One nutrient stress of particular significance is iron limitation. Iron availability is tightly coupled to climate through its dependence on aeolian dust deposition, and it is a constraint on productivity over an integrated ocean area that is greater in size than the entire area of Earth covered by land. The role of iron as a major factor limiting global phytoplankton concentrations and primary production (Martin and Fitzwater, 1988) has been studied through a number of iron enrichment experiments and through modeling studies of aeolian dust transport and deposition. Diagnostic indicators of iron stress (i.e., properties that allow iron stress assessment without manipulation of plankton populations) have also been developed, including expression of the photosynthetic electron acceptor, flavodoxin, which replaces ferridoxin under low iron conditions (LaRoche et al., 1996), and unique fluorescence properties

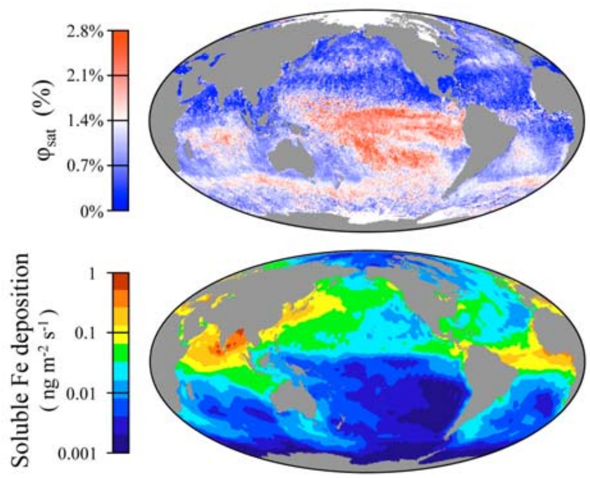
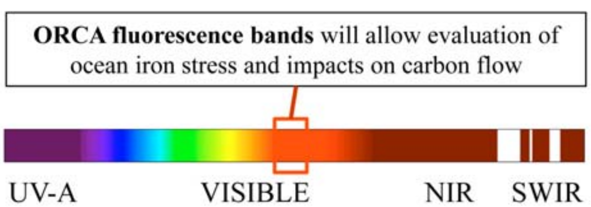


Figure 6. Chlorophyll fluorescence quantum yields provide information on specific nutrient stressors on phytoplankton growth. (Top) MODIS-based chlorophyll fluorescence quantum yields corrected for nonphotochemical quenching for the period March-May, 2004. Red areas indicate high yields and correspond to regions of iron stress. (Bottom) Global distribution of aeolian soluble iron deposition for the March-May period. (data from Behrenfeld et al. 2009a)

of the oxygen-evolving photosystem II complex associated with iron stress (Behrenfeld et al. 2006). This latter diagnostic was thoroughly characterized in a basin-wide field fluorescence study (Behrenfeld et al. 2006) and from this work it was predicted that satellite measurements of solar-induced fluorescence could provide a means for assessing global distributions of iron stress. This prediction was verified in a subsequent study (Behrenfeld et al. 2009) where MODIS fluorescence line height (FLH) data were used to calculate global fluorescence quantum yields (ϕ), after correction for pigment packaging and non-photochemical quenching effects (Figure 6). Specifically, the MODIS fluorescence study demonstrated a strong correspondence between elevated ϕ values, low aeolian dust deposition, and model (Moore et al., 2006; Moore and Braucher, 2008, Wiggert et al., 2006) predictions of iron limited growth.

The demonstration that iron stress can be detected from satellite-sensed chlorophyll fluorescence is very significant because it means that (1) unique iron stress effects can be accounted for in global ocean productivity assessments, (2) ecological responses to natural iron deposition events can be monitored, and (3) changes in the global distribution of iron stressed populations can be evaluated and linked to changes in aeolian dust loads and climate forcings. Unfortunately, chlorophyll fluorescence bands will not be included in the VIIRS sensor suite. ORCA, on the other hand, does include fluorescence detection capabilities and will enable this important measurement of MODIS to be continued. In addition, the higher spectral resolution of the ORCA sensor and its far superior coverage of wavelengths both within and surrounding the fluorescence peak will allow more accurate assessments of fluorescence yields.



Summary: *ORCA bands centered at 665, 678, and 710 nm will yield chlorophyll fluorescence data, and higher spectral resolution capabilities allow fluorescence spectrum characterization. These data will improve understanding of phytoplankton nutrient stress and productivity*

(vi) <u>High Biomass Waters:</u> Unlike SeaWiFS and MODIS (sensors designed for open ocean scientific objectives), the ORCA design will allow significant advances in the remote sensing of the optically complex ocean margins and larger estuarine and freshwater systems. These areas form the interface between the terrestrial and open ocean provinces and are sites of very high primary production rates and biogeochemical transformations of carbon, nitrogen, and phosphorous. These processes are particularly important where freshwater discharge from major terrestrial drainage basins and or/population centers are focused (e.g., Mississippi River delta, Chesapeake Bay, San Francisco Bay, Gulf of Maine, Pamlico Sound, and Pudget Sound). Accordingly, ORCA data will be valuable for supporting coastal management and environmental monitoring, as well as basic science applications. A major remote sensing challenge in regions with high suspended particle loads, dissolved organic matter concentrations, and terrestrial inputs is the separation of these optically active components from each other and from the resident plankton populations. This separation will be enabled through ORCA in a manner unparalleled by heritage sensors through its high spectral resolution in the UV-A to green wavebands. In addition, some of these areas experience significant eutrophication. In waters with high concentrations of absorbing constituents, water-leaving radiances in the UV and blue are very small rendering them of marginal use for deriving geophysical products, i.e., loss of sensitivity. However, algorithms have recently emerged for such aquatic applications that utilize long wavelengths in the red and short NIR bands to extract phytoplankton levels in a manner similar to terrestrial leaf area cover algorithms (Figure 7). ORCA's full resolution in the 'red-edge' spectral region will allow application of these algorithms. **Summary**: *ORCA's high spectral resolution in the UV-A to green wavelength region and in the red-NIR will allow unparalleled evaluation of ecosystem properties in optically complex waters and in regions of increasing eutrophication.*

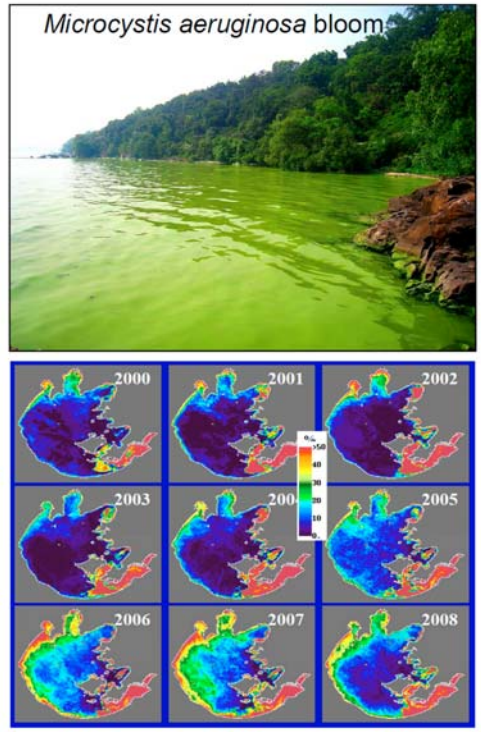
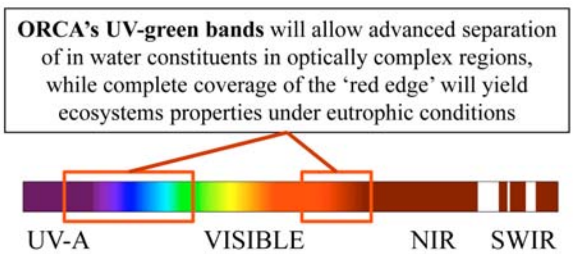


Figure 7. In highly eutrophic waters where radiances at blue wavelengths are negligible, measurement bands in the red-NIR range provide information on phytoplankton abundance. (Top) Photograph of a *Microcystis aeruginosa* bloom in China. (Bottom) Time series of *M. aeruginosa* bloom extent and distribution based on a MODIS red-NIR algorithm for the period 2000 to 2008.



(vii) Phytoplantkon Functional/Taxonomic Groups: The world's oceans represent a mosaic of unique biomes and biogeochemical provinces. Longhurst (1998) identified 56 pelagic provinces based on an examination of the seasonal cycles of phytoplankton production and zooplankton consumption. While species composition can be diverse, often a specific phytoplankton species or functional type dominates. There are different ways of delineating these (e.g., size class – pico/nano/microplankton) and functional groups (diatoms, coccolithophores, *Trichodesmium*, cyanobacteria, etc.). For instance in the subpolar North Atlantic, production early in the year is due primarily to diatoms, but later in the summer, coccolithophores become abundant, preferring more stratified conditions. Thus, phytoplankton populations vary in their biomass, species composition, photosynthetic efficiency, etc. depending on the physical environment, availability of macro- and micro-nutrients, illumination, and concentration of grazers, These variations regulate primary production and, therefore, higher trophic levels within the ecosystem, and play an important role in the cycling of macro- and micro-nutrient concentrations. Identifying these distributions and properties and how they change on seasonal and interannual time scales is key to understanding how ecosystems function and how they respond to changes in the physical environment, whether natural or human-induced.

Until recently, research on optical identification of specific species has focused on coccolithophores and *Trichodesmium* because of their rather unique spectral reflectance signatures. Coccolithophores are made of calcite platelets and can be identified in satellite data because, at high concentrations, the reflectance is uniformly elevated across the spectrum. Global coccolithophore distributions were first assessed using CZCS data (Brown and Yoder, 1994) and will be easily detectable with the ORCA. Another phytoplankton genus with a distinctive spectral signature is the nitrogen-fixing cyanobacterium, *Trichodesmium.* This biogeochemically important species has gas-filled vacuoles or trichomes, elevated specific absorption coefficients below 443 nm, and uniformly high particle backscatter coefficients in the visible spectrum. Westberry et al. (2005) found that if the concentration of trichomes is sufficiently high (3200/l), detection by SeaWiFS is possible. Westberry and Siegel (2006) mapped *Trichodesium* globally using SeaWiFS data and found their derived distribution to be consistent with geochemical inferences made by Deutsch et al. [2007]. The ORCA sensor will advance understanding of *Trichodesium* populations by providing higher SNRs than SeaWiFS to give greater sensitivity to lower trichome concentrations and by providing excellent spectral coverage below 412 nm, which will improve algorithm detection.

Coccolithophores and *Trichodesium* have relatively unique signatures in water leaving radiance spectra. However, characterization of other dominant phytoplankton groups has also been demonstrated through detection of subtle differences in reflectance spectra associated with specific diagnostic pigments. For example, Alvain et al. (2005) used *in situ* databases of reflectance, pigments, functional groups and SeaWiFS reflectances to estimate global open ocean distributions of haptophytes, *Prochlorococcus*, *Synechococcus*-like cyanobacteria (SLC), and diatoms. However, given the limited number of spectral bands that heritage sensors have, this separation is challenging and resultant group distributions have large uncertainties and are difficult to verify.

Enhancing the spectral resolution and spectral range of ocean color measurements can greatly enhance retrieved information on plankton composition. The approach for using such information is referred to as "spectral derivative analysis" and has been demonstrated at 'ground level' by multiple investigators. For example, Lee et al. (2007) used 400 hyperspectral (3 nm resolution) reflectance spectra from coastal and open ocean waters to examine taxonomic signatures in the first- and second-order derivatives. Their analysis

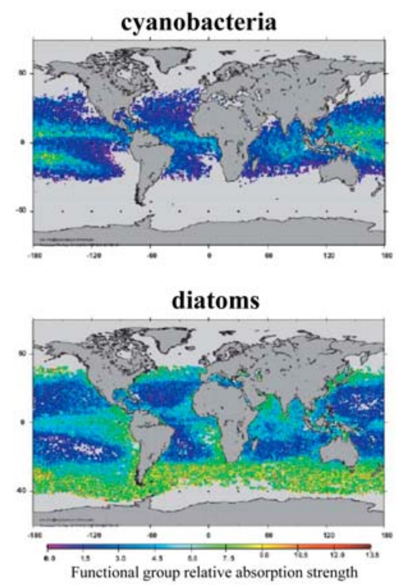
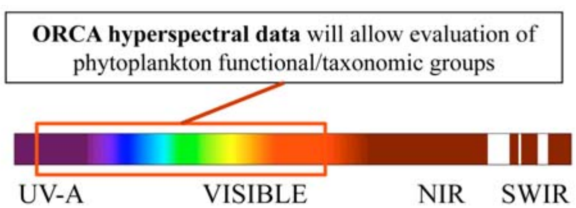


Figure 8. Hyperspectral satellite ocean color measurements provide information on specific phytoplankton groups. Here, hyperspectrral SCIAMACHY data were used to quantify the abundance of two phytoplankton groups: (Top) cyanobacteria and (Bottom) diatoms. (data from Bracher et al. 2009)

indicated very pronounced peaks representing slight spectral inflections due to varying pigment absorption and backscatter characteristics of the water samples. An alternative approach (differential optical absorption spectroscopy) was used by Vountas et al. (2007) and Brachter et al. (2008) and applied to hyperspectral Scanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) imagery (0.2-1.5 nm resolution) to derive global distributions of cyanobacteria and diatoms (Figure 8). These studies show that realistic distributions of functional groups can be extracted using hyperspectral data (5 nm resolution or better) from the UV to the NIR. ORCA will provide this high resolution data and make significant contributions toward improving our understanding of phytoplankton group distributions, their variability, and its link to climate forcings.

One additional application of particular importance for ORCA's high-resolution data will be the detection and tracking of harmful phytoplankton blooms. It is well known that harmful algal blooms (HABs) are often dominated by a single phytoplankton species and that these species can have unique absorption characteristics from those of populations outside the bloom. A band at 710 nm has been incorporated in satellite sensors such as MERIS for detecting HABS. High spectral resolution ORCA data will allow regional algorithms to be developed for identifying such blooms, tracking their progress over a season, and following their interannual variability. This information will lead to a highly sought-after understanding of the environmental forcing factors responsible for their appearance and demise.



Summary: *ORCA UV-A and visible hyperspectral data allows discrimination of functional/taxonomic/harmful algal groups to improve understanding of their dynamics, sensitivity to climate forcings, and impacts on ocean carbon cycles*

(viii) Photosynthesis: Not until the turn of the 19th century did scientists recognize that most major fisheries and other marine ecosystem components were not sustained by carbon compounds coming into the oceans from land, but by the microscopic free-floating plants called phytoplankton. Primary production by phytoplankton (roughly 50 – 65 Pg C y^{-1}) represents at least half of the net plant production of the biosphere and is the major conduit for biologically sequestering atmospheric carbon dioxide into moderate- and long-lifetime organic ocean carbon pools. In addition to being a key climate-controlling process, its quantification allows investigations into energy transfer throughout marine foodwebs and is a critical attribute in near-shore waters with respect to the potential for harmful algal blooms and changes in water quality. Phytoplankton productivity is a key metric of ocean ecosystem health, stability, and structure.

Two terms are needed to quantify net primary production: the standing stock of phytoplankton *biomass* and the biomass-specific productivity *rate*. For 50 years, chlorophyll concentration has functioned as the central metric of phytoplankton biomass. Indeed, NASA's previous ocean color missions (CZCS, SeaWiFS, MODIS) have focused on surface chlorophyll biomass as the primary biologically relevant remote sensing product. Measuring chlorophyll concentration by itself, however, has a critical flaw that will *forever* prevent ocean photosynthesis from being accurately quantified: namely,

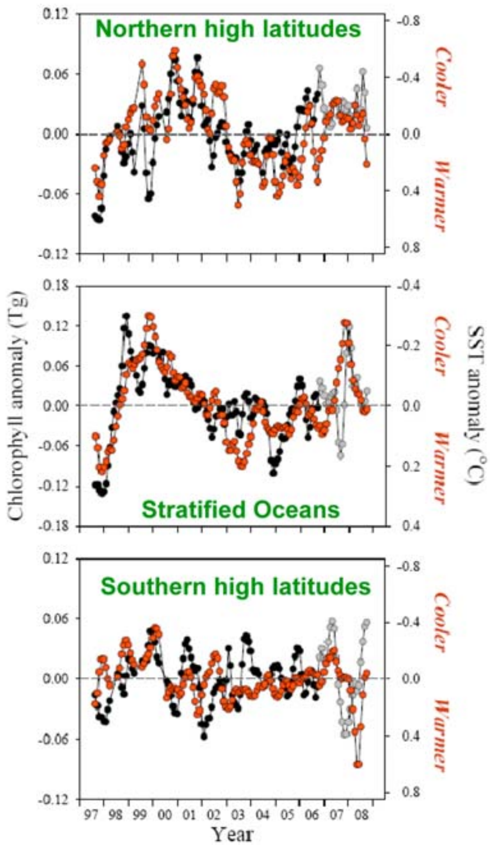


Figure 9. Monthly anomalies in chlorophyll concentration (red, gray) and SST (black) for the period 1997 to 2008. Red symbols = SeaWiFS data. Gray symbols = MODIS Aqua data. (Top) high northern latitudes. (Middle) permanently stratified oceans. (Bottom) high latitude southern oceans. Regions are defined by having annual average SST of greater than (middle) or less than (top and bottom) 15^{o}C. Left axis = chlorophyll anomalies. Right axis = SST anomalies. Note that right hand axes are inverted, such that an increase in SST corresponds to a decrease in chlorophyll. (data from Behrenfeld et al. 2009b)

chlorophyll is not simply a function of biomass, but instead a complex function of growth conditions. The rate term needed to convert chlorophyll biomass into primary production (i.e., chlorophyll-specific photosynthetic efficiency) behaves in a very complicated manner, and its description requires information on growth constraints that are difficult at best to measure in the field and impossible to derive from space. In addition, assessing changes in phytoplankton biomass and physiology relies on an accurate separation of absorption by the diverse suspended components in the upper ocean. So, how important is it to distinguish physiological variability from biomass and pigment changes from other absorbing compounds? A good example is provided by our current ocean color data record.

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) has provided the best calibrated and longest time series of ocean color measurements achieved to date. Figure 9 shows the observed chlorophyll changes for the SeaWiFS record for the high northern latitudes (top panel), the central permanently stratified oceans (middle panel), and the high latitude southern oceans (bottom panel). For this figure, the seasonal cycle in chlorophyll has been removed to illustrate longer term trends. Also shown in Figure 9 are coincident changes in sea surface temperatures (right hand axes). What these data demonstrate, beyond any question, is that there is a very clear relationship between variability in the physical ocean environment (as indexed by SST changes) and variability in the *optical properties* of the upper ocean. If the derived changes in chlorophyll are representative of changes in ocean production, then these SeaWiFS findings also have profound implications on the likely consequences of climate change on the base of the ocean food web (i.e., warming will decrease production). But can we say for certain that this latter conclusion is valid? Unfortunately, not yet, as the relationship between optical properties and productivity is complicated and not accurately described or quantified.

As a first consideration, we must be certain that observed changes in optical properties are indeed associated with changes in pigment. Changes in SST are associated with changes in surface layer stratification, and an increase in stratification will be associated with greater surface residence times for colored dissolved organic matter, which in turn will mean longer periods for CDOM photo-oxidation. Thus, accurately distinguishing CDOM changes from pigment changes is essential. This is one reason why ORCA's UV-B bands are so important.

A second issue is that, if the changes shown in Figure 9 truly do represent changes in chlorophyll, than the covariation in chlorophyll and stratification (i.e., SST) could be due primarily to phytoplankton physiological responses to changes in average mixed layer light levels. In other words, increased surface stratification increases mixed layer light levels and causes phytoplankton to decrease intracellular chlorophyll without a requisite decrease in NPP. Thus, it is absolutely essential to distinguish physiological changes from phytoplankton biomass changes to accurately understand observed relationships between climate variability and ocean ecosystems. Accordingly, ORCA has an expanded band set to quantify phytoplankton carbon stocks from backscattering properties, as well as to improve assessments of phytoplankton pigment absorption. Finally, the relationship between environmental variability and phytoplankton biomass and physiological characteristics is strongly dependent on the type of nutrient limiting growth (e.g., iron) and the taxonomic composition of the phytoplankton community. Thus, ORCA has advanced chlorophyll fluorescence detection capabilities and hyperspectral resolution to evaluate nutrient stress and taxonomic groups.

Throughout this Science section, we have detailed specific attributes of the ORCA sensor that will advance ocean science remote sensing far beyond current capabilities. Many of these advances will collectively lead to major improvements in quantification of ocean productivity and all will improve our understanding of the ocean carbon cycle. Together they define an ORCA instrument with observational capability greatly exceeding those of heritage sensors or the upcoming VIIRS sensor. These capabilities are compared in Figure 10, below. Finally, we began this section with an emphasis on high quality atmospheric corrections, as this aspect of ocean color retrievals is intimately tied to the accuracy of all other derived products. In the next section, we describe specific features of previous sensors and then detail a range of other important factors influencing instrument requirements of the ORCA.

ACE Sensor and Mission Requirements

SeaWiFS and MODIS ocean requirements were defined in the 1980s with an emphasis on global open ocean observations of chlorophyll-a. Both sensors addressed major deficiencies in the proof-of-concept CZCS design and calibration/validation programs, e.g., the addition of NIR bands for atmospheric correction and mission-long on-orbit and field calibration measurements. Since then, the ocean optics and marine biology communities have developed capabilities and applications that far exceed the spectral coverage of these sensors and experience using these sensors has provided many "lessons learned". Together, this cumulative experience has highlighted a number of new requirements, including the following enhancements that are incorporated into the ACE ocean measurement requirements.

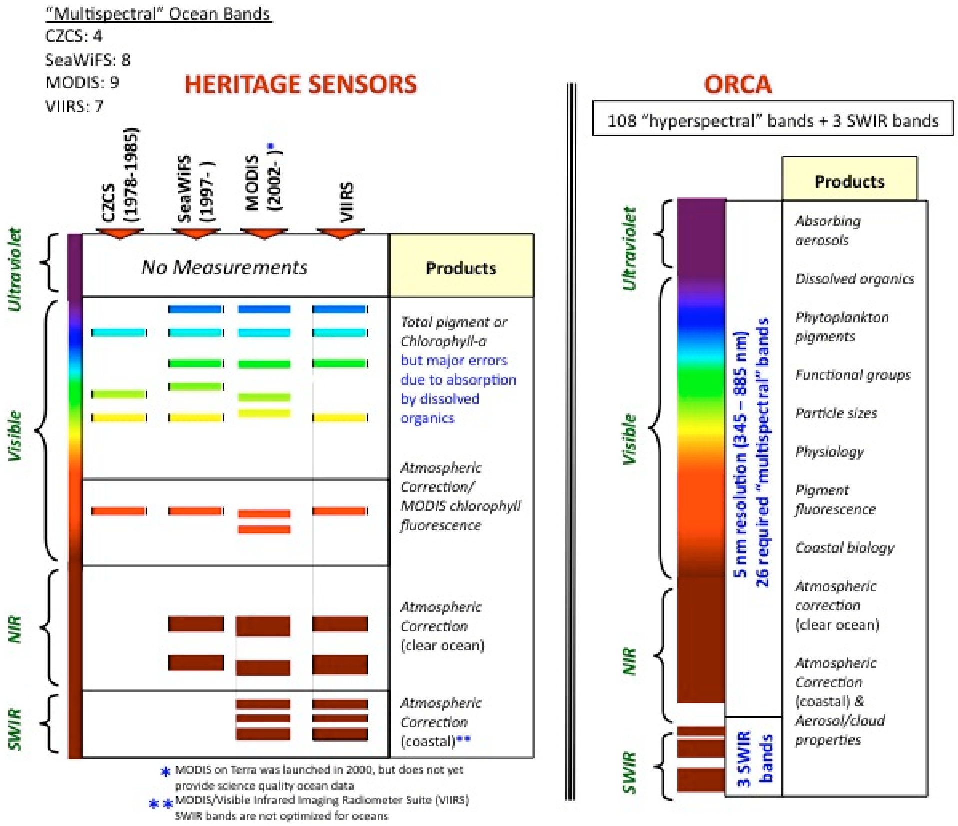


Figure 10. A comparison of ORCA spectral coverage versus other NASA sensors. Nominally, ORCA has a spectral range of 540 nm (345-885 nm) yielding 108 consecutive five nm hyperspectral bands which can be combined into broader multispectral bands. However, the design allows more flexibility in defining bandwidths and band center wavelengths which can be incremented by 0.63 nm.

Table 2. Primary ACE mission and OES measurement requirements.
Spectral resolution: 5 nm (345-775 nm)
"Multispectral" bands and signal-to-noise ratios (see Table 3)
Sensor polarization sensitivity: < 1.0%; characterization to better than 0.2%
Swath: ±58.3° about nadir (2-day global coverage)
Field of view: 400 arcseconds (1 km ground pixel size at 600 km)
Tilt (sun glint avoidance): 20° fore/aft
No multispectral band saturation (see Table 3 for saturation radiances)
Radiance calibration accuracy: within 2% with goal of better than 0.5% (prelaunch)
    Radiometric stability: 0.1% prelaunch verification (one month)
    Radiometric stability: 0.1% knowledge (mission duration)
    Monthly lunar calibrations at ~ 7° phase angle
Minimum design life: 5 years
Complete sensor optical model and engineering design unit (EDU)

Sensor requirements address sun-glint avoidance (sensor tilting), polarization sensitivity, SNRs, image quality (straylight, stripping, crosstalk), 2-day global coverage frequency, data quantization, and saturation radiances. To achieve the radiometric accuracy requirements of the inversion algorithms, well-developed and tested technologies and methodologies for prelaunch sensor characterization must be established in advance of flight unit testing. ORCA provides additional hyperspectral coverage beyond 775 nm to 885 nm. Table 2 lists specific information on measurement and mission requirements and Table 3 provides information on the 26 required multispectral bands. When all the requirements for passive ocean radiometry are tallied, the comparison with heritage sensors is striking, particularly with respect to spectral coverage (Figure 4).

Table 3. OES multispectral band specifications. SNR-spec is the minimum value at Ltyp. Radiances are mW/cm^2 µm str.

λ	∇λ	Ltyp	Lmax	SNR-spec	SeaWiFS SNR
350	15	7,46	35.6	300	
360	15	7.22	37.6	1000	
385	15	6.11	38.1	1000	
412	15	7.86	60.2	1000	897
425	15	6.95	58.5	1000	
443	15	7.02	66.4	1000	967
460	15	6.83	72.4	1000	
475	15	6.19	72.2	1000	
490	15	5.31	68.6	1000	1010
510	15	4.58	66.3	1000	1000
532	15	3.92	65.1	1000	
555	15	3.39	64.3	1000	870
583	15	2.81	62.4	1000	
617	15	2.19	58.2	1000	
640	10	1.90	56.4	1000	
655	15	1.67	53.5	1000	
665	10	1.60	53.6	1000	570
678	10	1.45	51.9	1400	
710	15	1.19	48.9	1000	
748	10	0.93	44.7	600	
765	40	0.83	43.0	600	522
820	15	0.59	39.3	600	
865	40	0.45	33.3	600	364
1245	20	0.088	15.8	250	
1640	40	0.029	8.2	250	
2135	50	0.008	2.2	100	

ACE Geophysical Parameters

The ACE ocean team has defined a variety of geophysical parameters (Table 4) to be derived from the OES, most of which were envisioned for ORCA prior to the ACE mission definition working group was established. ORCA provides all the spectral information required for these products. Many of these products are being derived from SeaWiFS and MODIS, particularly the "Current" and "Candidate" CDRs, although products from the OES will be much improved because, in many cases, the data quality is limited by the spectral coverage, e.g., more accurate chlorophyll-a due to improved CDOM separation. CDR is "Climate Data Record" and the requirements for generating CDRs are discussed in McClain et al. (2006). The NASA Ocean Biology Processing Group (OBPG) seeks data products with accuracies over time sufficient to detect the effects of climate change. "Current" indicates products presently in production that are validated at least to the accuracies indicated (water-leaving radiances and chlorophyll-a). "Candidate" products are available, but unvalidated. "Research" products are those in development and at some level have been shown to be feasible. In the case of some, like export production, estimation will require coupled physical-biological-carbon cycle models, but will assimilate other satellite data products to improve model performance in estimating these parameters.

Table 4. ACE ocean data products.

- Current CDRs
  - Normalized water-leaving radiances (±5%)
  - Chlorophyll-a (± 35%)
  - Diffuse attenuation coefficient (490 nm)
- Candidate CDRs
  - Primary production
  - Inherent optical properties (IOPs; absorption & scattering coefficients)
  - Particulate organic carbon concentration
  - Calcite concentration
  - Colored dissolved organic matter (CDOM)
  - Photosynthetically available radiation (PAR)
  - Fluorescence line height (FLH)
  - Euphotic depth
- Research Products
  - Total suspended matter (TSM)
  - Particle size distributions & composition (biogenic, mineral, etc.)
  - Functional/taxonomic group spatial distributions
  - Phytoplankton carbon
  - Dissolved organic matter/carbon (DOM/DOC)
  - Physiological properties (e.g., C:Chl, fluorescence quantum yields, growth rates)
  - Other plant pigments (e.g., carotenoids)
  - Export production

4. ORCA DESIGN

Heritage sensor descriptions and lessons learned

Coastal Zone Color Scanner (CZCS)

Early airborne radiometer data demonstrated the dependency surface marine reflectance on chlorophyll-a concentrations and the possibility of using remotely sensed data to survey large areas over short periods of time (Clark et al., 1970). These studies also demonstrated the challenge of extracting surface reflectance from observations increasingly contaminated by atmospheric path radiance as altitude increased. As a result, the Coastal Zone Color Scanner (CZCS) was proposed for the Nimbus-7 mission and an aircraft prototype, the Ocean Color Scanner (OCS), was developed for deployment on a NASA U-2 for prelaunch algorithm development. The CZCS was launched in 1978 and provided limited global coverage until 1986 (McClain et al., 1993).

The CZCS was a grating spectrometer design. The fore optics consisted of a rotating mirror that could be tilted in 2º increments up to ±10º (a 10º tilt results in a 20º viewing angle) to avoid sun glint. The CZCS also had another innovative element, the polarization scrambler. This component was inserted because the Rayleigh molecular scattering and surface Fresnel reflections are highly polarized, thus requiring the full Stokes parameters and sensor Mueller matrix for the atmospheric correction if no depolarization was incorporated. The sensor had 6 bands at 443 nm (chlorophyll-a absorption peak), 520 nm (near the spectral location least sensitive to chlorophyll-a, the "hinge point"), 550 nm (a band located here takes advantage of increased water-leaving radiance as particulate concentrations and backscatter increase enhancing the spectral see-saw about the hinge point thus improving estimation of spectral slope in more productive waters), 670 nm (a secondary chlorophyll-a absorption peak), 750 nm (cloud detection), and 11.5 μm (sea surface temperature). The four visible bands have nominal bandpasses of about 20 nm. The sensor also had internal lamps for on-orbit calibration stability tracking, but these proved to be too unstable to be useful. The Nimbus-7 orbit was sun-synchronous at local noon. Earth data was collected at over ±39.36º resulting in a spatial resolution of ~ 800 m at nadir and a swath of 1636 km.

The sensor had four commandable gain settings (visible bands only) to compensate for the range of expected illumination conditions and, as it turns out, decreased sensitivity over time. This was necessitated by the 8-bit digitization in order to maintain the desired quantization. Indeed, over the lifetime of the sensor, the 443 nm band sensitivity decreased by about 40% (Evans and Gordon, 1994). This degradation was presumably due to contamination of the scan mirror. The signal-to-noise ratios (SNR) ranged from about 400 (520 nm) to 140 (670 nm) for typical radiances used in the ORCA formulation (discussed later).

Being a proof-of-concept mission, some components of the system worked well and others did not. The gain on the 750 nm band was coarse so it was used only for cloud detection. In more recent analyses, the 670 band was used because of the lack of sensitivity. Not having NIR bands required an atmospheric correction based solely on 670 nm Rayleigh-corrected radiances for aerosol corrections with the assumption that the water-leaving radiances at 670 nm were zero (Gordon et al., 1983). Ironically, this made the Coastal Zone Color Scanner least reliable for measurements in turbid coastal waters.

The system polarization sensitivity was reduced by inclusion of the depolarizer (two wedges) and by positioning the folding mirror such that it compensated for the scan mirror polarization. All mirrors (scan mirror, two telescope mirrors, three fold mirrors, and the collimating mirror) had protected silver coatings (Ball Aerospace Systems Division, 1979). A dichroic located after the scan and two telescope mirrors separated the visible and infrared light. The polarization wedges were positioned further down the optical train after the first fold mirror and the collimating mirror. Prelaunch testing showed a maximum polarization sensitivity at 443 nm of about 3% for a 10º tilt (most data was collected at a 10º mirror tilt).

Having the depolarizing wedges located in the aft optics increases the polarization uncertainty. The prelaunch characterization indicated a maximum sensitivity at 443 nm of about 3%. Assuming a degree of polarization of 60% and a Rayleigh component of 80% of the total radiance, the effect is roughly 1.4%. If the polarization properties of the system components stay constant, there is no issue, i.e., the Mueller matrix is known. If component reflectances and transmissions change on orbit and are sensitive to polarization, then having the depolarization wedges near the tail end of the optical path means that the system's actual polarization sensitivity is unknown, i.e., the Mueller matrix has changed.

The CZCS and the Ocean Color and Temperature Sensor (OCTS) used a 45º "barrel roll" mirror. In this configuration the sensor aft optics were positioned either forward or aft of the mirror assembly (along the spacecraft velocity direction), and the incoming light was reflected from the Earth-viewing direction along that axis. The tilt mechanism rotated the mirror assembly within the instrument. This had the effect of changing the pixel spacing, and the total scan width, as a function of tilt angle. For example, on OCTS the scan angle per pixel was 0.83 mrad at tilt -20º (aft), 0.72 mrad at tilt 0, and 0.58 mrad at tilt +20º. Since data are collected primarily at ± 20º degrees tilt, this results in a large difference in spatial resolution and coverage north and south of the tilt change (subsolar point).

On OCTS, the 45º mirror, combined with the MODIS-like focal plane design (a large 2-D array of detectors), also had the effect of rotating the effective focal plane footprint on the ground as the mirror scanned from one side to the other. As a result, the individual bands were only co-registered near nadir. As the scan angle increased from nadir, the rotation of the viewed area caused the individual bands to separate in the along-track direction. At the largest scan angles, a given location on the Earth required five consecutive scans to be viewed by all of the bands. This required substantial resampling of the bands to achieve approximate co-registration, and this process increased the noise level in the resampled data.

Finally, the CZCS preamplifiers on the detectors tended to “ring” off bright targets. This electronic overshoot often persisted for tens of down scan pixels (Mueller, 1988) and depended on how bright the up scan pixels were. No completely satisfactory algorithm for masking contaminated pixels was developed.

SeaWiFS

The SeaWiFS sensor has eight bands in the visible (412, 443, 490, 510, 555, and 670 nm) and near-infrared (765 and 876 nm). The 412 nm band was added to improve separation of chlorophyll-a and colored dissolved organic matter (CDOM). The 490 band was added to provide better sensitivity for chlorophyll-a estimation in coastal waters where 443 nm water-leaving radiances are small. The two NIR bands are for aerosol corrections in open ocean waters. The visible bandpasses are roughly 20 nm and the NIR bandpasses are 40 nm. The 765 nm band straddles the O_2 A-band absorption feature and requires a correction for this effect. However, SeaWiFS has significant out-of-band (OOB) contamination or response due to poorly specified filter requirements. The OOB is substantially higher than that of MODIS. Fortunately, the OOB was well characterized in prelaunch testing and is adequately removed in data processing (Gordon, 1995). Nonetheless, the SeaWiFS OOB does complicate the processing and makes comparisons with other sensors more difficult (including those used for in situ validation). The SeaWiFS SNR values are 2-3 times higher than CZCS in the blue and green bands and about 6 times higher at 670 nm for the same radiances.

SeaWiFS was a NASA data buy from Orbital Sciences Corporation (OSC) who subcontracted the sensor to Hughes Santa Barbara Research Center (SBRC).

Contractually, OSC was required to provide technical insight, but NASA did not have technical oversight of the mission. Nonetheless, NASA was allowed almost unrestricted access to information and provided a substantial amount of engineering support, particularly on the spacecraft. The SBRC sensor design was a huge departure from the CZCS. Rather than a scan mirror, a rotating telescope with a HAM was used. The HAM rotated at half the speed of the telescope, so that each side of the mirror is in the optical path on alternating scans. Thus, slight differences in mirror reflectivity are present in the imagery, but this can be normalized out. This design helped minimize polarization and protected the fore optics from contamination, i.e., it was less exposed. VIIRS also uses a rotating telescope, but (presumably) because of the finer spatial resolution a longer focal length was required resulting in 2 additional telescope folding mirrors. These additional reflecting surfaces will increase stray light, but, to date, stray light contamination has not been addressed in either the engineering design unit (EDU) or flight unit testing.

Like the CZCS, SeaWiFS also incorporated four commandable electronic gains and a polarization scrambler. The polarization scrambler was located behind the primary mirror (second optical component) and the sensor polarization sensitivity is estimated to be about 0.25%. Rather than internal lamps for on-orbit calibration, it had a solar diffuser with a solar diffuser cover of the same material. More importantly, the mission executed monthly spacecraft pitch maneuvers allowing the moon to be imaged each month a constant lunar phase angle (~ 7º). The lunar calibration established the long-term stability of the sensor at a very high accuracy (Barnes et al., 2004). The solar diffuser cover was never removed and has provided a record for evaluating short term variations in sensor performance (Eplee et al., 2007). Along with the daily solar calibrations, the electronic gains of each band were checked with calibration pulses.

The SeaWiFS orbit was initially sun-synchronous at noon, but the node has drifted past 2:00 pm over the ensuing 12 years on orbit. The SeaWiFS coverage is global within the solar zenith angle window of about ±75º with a spatial resolution of 1.1 km at nadir and a swath of about 2800 km (±58.3º scan). The data were real time broadcast at full spatial resolution, but the on-board recorded data was subsampled every fourth pixel and line within the ± 45º scan window (1500 km swath). The sensor tilt positions included ±20º and 0º, although the 0º position was not used. Unlike the CZCS, the whole sensor was tilted.

The SeaWiFS focal plane design was also novel. The four detectors viewed the same pixel, but on successive scans, and were then summed, i.e., time-delay integration. This was done to improve SNR. Thus, there is no striping in the imagery due to the detector array. Another strength of the SeaWiFS detector array or focal plane design is the bilinear gain which prevents bright pixels from saturating any band. This design was implemented to allow for a stray light correction. The original copy of SeaWiFS failed to meet stray light specifications and a number of design adjustments were made to ameliorate the problem. The bilinear gain is implemented by setting the saturation of one of the four detectors at a high maximum radiance producing a “knee” in the response as the other three detectors saturate at a lower value. SBRC took a number of measures to reduce straylight once it was determined to be a problem. Higher quality mirrors and the addition of “septums” between the detectors would have reduced straylight even more, but these measures were not implemented because of cost and schedule.

The SeaWiFS subsampling allows small clouds to escape detection in the GAC processing in which case stray light is uncorrected (stray light is scattered light within the instrument that contaminates measurements in adjacent pixels), thereby elevating the total radiance values. The prelaunch characterization data provided enough information for a stray light correction algorithm to be derived. This correction works well in the LAC data processing and for correcting the effects of large bright targets in the GAC.

SeaWiFS data is truncated from 12 bits to 10 bits on the data recorder resulting in coarser digitization, especially in the NIR bands where the SNRs are relatively low. Noise can cause a "jitter" in the aerosol model selection that amplifies the variability in visible water-leaving radiance values via the aerosol correction. Undetected clouds in the GAC data and digitization truncation are thought to be the primary reasons for "speckling" in the SeaWiFS derived products.

Finally, one of the strengths of the SeaWiFS sensor development program was the well-documented prelaunch sensor calibration and characterization program (Barnes et al. 1994a, 1994b) at SBRC and the close working relationship between the SBRC staff and the SeaWiFS Project Office. The open exchange of information and ideas resulted in a thorough understanding of the sensor and expedited a number of improvements. This information and related analyses were documented in the SeaWiFS Technical Memorandum Series (a total of over 70 separate volumes) which is freely distributed in hardcopy and electronic form to the user community.

MODIS

The design for MODIS was targeted to serve a number of research communities and, therefore, had a broader set of design requirements resulting in a much more complex sensor than the CZCS and SeaWiFS. It incorporated 36 bands with wavelengths between 412 nm and 14.4 μm, including bands with different spatial resolutions (1000m, 500 m, and 250 m). Like SeaWiFS, it was built at SBRC, but about the only thing the two sensors have in common is that they both are filter radiometers, i.e., bandpass optical filters are placed over the detectors to provide discrete spectral bands rather than using dispersive optics like gratings or prisms to separate specific wavelengths of light. Also, the MODIS data is recorded at 12 bits and provides global 1 km ocean color data (no subsampling).

The MODIS design uses a large rotating mirror similar to that of the CZCS and OCTS, but with no tilt. Because MODIS does not tilt, sunglint contamination is more serious than for CZCS and SeaWiFS even though the MODIS orbits are 10:30 (Terra) and 1:30 (Aqua) rather than noon. Having the mirror exposed subjects it to contamination, but this is tracked using the solar diffuser and solar diffuser stability monitor which provides a much more robust calibration than the SeaWiFS diffuser. To date, MODIS Terra has experienced degradations as high as 50% (412 nm) for the ocean color bands. The degradations are dramatically different for the two mirror side of MODIS/Terra (data is collected using both sides of the scan mirror). MODIS can view the moon at high phase angles and spacecraft roll maneuvers are executed monthly to provide a time series at a 57^{o} phase angle (a partial moon). One problem with the MODIS lunar calibration is that the bands (667-869 nm) on the NIR focal plane saturate.

The four MODIS focal planes (Visible, NIR, SWIR/MWIR, and LWIR) have 7-10 bands with 10 detectors per band. The MODIS ocean color bands are 412, 443, 531, 547, 667, 678, 748, and 869 nm. The 678 nm band is for chlorophyll-a fluorescence measurements which CZCS and SeaWiFS do not have. The 10 detectors sample 10 adjacent pixels along track allowing for a much slower scan rate (more dwell time) providing higher SNR (~ 1.5-3 times higher than SeaWiFS; average of ~ 2.1 times). This is a very different strategy to achieve SNR than the SeaWiFS TDI scheme. The downside is the intercalibration of the 10 detectors in each band. Slight differences lead to striping in the imagery. MODIS does not have a polarization scrambler and has a polarization sensitivity of as high as 5.4% at 412 nm. Methods for accounting for this in the atmospheric correction have been developed (Gordon et al., 1997; Meister et al., 2005), but uncertainties in the characterization and changes on orbit remain problematic, especially when other sources of error, e.g., response vs. scan uncertainty (RVS), are convolved together. Indeed, for MODIS/Terra the RVS and polarization sensitivity has changed dramatically over time, changes that cannot be accurately estimated using the on-board calibration capabilities such as the solar diffuser. A methodology for correcting these artifacts using concurrent SeaWiFS observations has been demonstrated by Kwaitkowska et al. (2008).

While not designed for ocean color applications, the MODIS 1240, 1640, and 2130 nm SWIR bands (500 m) have applications for aerosol corrections over turbid water where the NIR surface reflectance is nonzero. Water absorption is orders of magnitude higher in the SWIR. The SNR values for these bands are low (Werdell, et al., 2010), but can be used to some degree of success (Wang and Shi, 2005), particularly at higher solar zenith angles (brighter illuminations). VIIRS has similar SWIR bands at 1240 and 1610 nm with slightly higher specified SNR values. For the visible and NIR bands, VIIRS SNR values are generally between SeaWiFS and MODIS values.

Pre- and post-launch sensor calibration.

Satellite instruments usually lose sensitivity over time for a number of reasons (e.g., contamination of optical surfaces), but do not always degrade in the same manner. For example, it has been estimated that the CZCS sensitivity at 443 nm decreased (the reduction in sensor output in volts or digital counts for a given input radiance) by roughly 40% over the eight and a half years of sensor operation, with little degradation at the near-infrared (NIR) wavelengths. The problems encountered in validating the CZCS data underscored the need for improved sensor stability monitoring (the CZCS internal lamps proved unreliable) and a comprehensive mission-long calibration/validation program if subsequent missions are to produce climate data records (CDRs; McClain et al., 2006). Therefore, SeaWiFS incorporated a solar diffuser as well as lunar observations, and the MODIS design included a solar diffuser with a diffuser stability monitor for the purpose of tracking sensor response on orbit. Indeed, over the 13 years of SeaWiFS, sensor degradation has been accurately quantified using the lunar observations and found to be greatest at 865 nm (~ 22% to date). For MODIS, sensitivity loss has been greatest at 412 nm (up to 50% to date). Both the CZCS and MODIS have exposed mirrors and degraded the most in the visible while SeaWiFS with its rotating telescope (protected primary mirror) experienced the greatest degradation in the near-infrared.

In addition to temporal stability issues, the CZCS experience showed that prelaunch calibrations need to be adjusted on orbit to remove calibration and atmospheric correction biases. These corrections are now achieved using accurate field measurements of Lw (i.e., the so-called vicarious calibration). To support the SeaWiFS and MODIS missions, the Marine Optical Buoy (MOBY) was developed by U.S. National Oceanic and Atmospheric Administration personnel under a NASA contract. MOBY has been deployed off Lanai, Hawaii and continuously operated since July 1997 through periodic rotation of duplicate systems to allow system maintenance and recalibration. For SeaWiFS, vicarious calibration has required approximately 30 cloud-free and sun glint-free simultaneous comparisons with MOBY to derive a set of fixed calibration gains (Franz et al., 2007). This relatively small number of optimal observations took over two years to collect. For sensors like MODIS that do not tilt to avoid sun glint, it can take nearly three years to collect enough suitable comparisons. Thus, obtaining a final vicarious calibration data set required for accurate derived products from a single calibration site takes considerable time and investment. The ACE calibration and validation plan will evaluate alternative approaches and technologies for vicarious calibration, rather than only considering the single-site scenario used for SeaWiFS and MODIS.

Besides the system-level radiance calibration, other sensor attributes to be quantified include polarization, temperature, stray light, electronic crosstalk, band-to-band spatial registration, relative spectral response, signal-to-noise ratios (SNR), electronic gain ratios, and response versus scan (RVS) angle. A sensor's sensitivity to each attribute depends on its specific design, and the CZCS, SeaWiFS, MODIS, and VIIRS all have very different designs. For instance, the CZCS and MODIS use a scanning mirror, while SeaWiFS and VIIRS have rotating telescopes. The advantages of a rotating telescope are the protection of the primary optical surfaces from contamination and smaller angles of incident radiation, which reduce RVS and polarization sensitivities. The CZCS and SeaWiFS also incorporated depolarization optics, while MODIS and VIIRS do not. ORCA will have a depolarizer. Also, the prelaunch sensor calibration and characterization plan is a central component of the sensor development program and emphasizes a review of testing methods and technology early in the program with a sensor characterization team, which is in addition to the science team who will handle algorithm development and field data collection.

Errors in the prelaunch quantification of these sensor attributes are almost impossible to resolve on orbit without independent observations because their effects are convolved and can be (e.g., RVS and polarization) a function of solar and sensor viewing geometries, which are superimposed on geometry-dependent atmospheric and surface reflectances. For example, if knowledge of a sensor's polarization sensitivity is incomplete or inaccurate, any vicarious calibration at a particular site will be implicitly tuned to the range of polarizations encountered at that location and may be inadequate for other locations. Also, if the RVS and/or the polarization sensitivity change on orbit as it has with MODIS/Terra, it is virtually impossible to quantify unless there is an independent satellite data set that is known to be stable. Kwaitkowska et al. (2008) demonstrated how large changes in MODIS/Terra RVS and polarization could be quantified using SeaWiFS products. Therefore, in the future, multiple calibration sites may be needed to evaluate these possible sources of error and the ACE calibration and validation program is scoped to do so.

In some instances, the dissimilarities between concurrent sensors can be exploited to identify problems in each. Comparisons between SeaWiFS and MODIS/Aqua provided a mechanism to correct an error in the MODIS polarization sensitivity tables that largely, but not entirely, resolved discrepancies in the Lw's. This was possible because SeaWiFS has a very small polarization sensitivity (~0.25%), whereas the MODIS visible bands have sensitivities of the order of several percent (VIIRS is expected to have polarization sensitivities of the order of 2%). On the other hand, MODIS has higher SNRs and digitization than SeaWiFS and is not subsampled as is SeaWiFS global area coverage data, resulting in MODIS derived products with substantially lower, and more realistic, variances, even though mean values are comparable. In the case of PACE, ORCA data should be indispensable in refining the on-orbit calibration and data products of other ocean color sensors that are simultaneously on-orbit.

ORCA design criteria

Satellite ocean color data is dominated by atmospheric scattering, i.e., Rayleigh molecular and aerosol scattering. Typically, these constitute 85% or more of the top of the atmosphere radiance over the open ocean. In coastal areas where the reflectance in the blue part of the spectrum is low due to absorption by plant pigments and other dissolved constituents, the percentage can be up to ~100%. Thus, errors in the sensor's calibration and characterization information can result in large errors in the derived products. The overall goal is to have derived water-leaving radiances accurate to better than 5% which implies calibration accuracy on-orbit to better than 0.5%, particularly in the blue and green portions of spectrum. Given that there are algorithmic sources of error as well as a variety of sensor calibration error sources, the allocation of error to each source must be small, e.g., 0.1-0.2%. At present, SeaWiFS has achieved this level of accuracy for most of the open ocean regions. At least, the derived water leaving radiances exhibit no significant bias when compared to in situ data and efforts are ongoing to improve the accuracy of both the in situ radiometric measurements and the satellite derived products. This accuracy in SeaWiFS radiometry is the result of an excellent design, a comprehensive prelaunch characterization, and the development of lunar and solar diffuser analysis techniques which accurately depict the sensor's performance on-orbit. However, the SeaWiFS and MODIS derived product accuracies in certain situations, e.g., presence of absorbing aerosols and turbid water, will remain limited because of limitations in the sensor designs. The NPOESS VIIRS instrument will not improve on SeaWiFS and MODIS. ORCA incorporates additional bands that will remove these limitations, i.e., additional bands in the UV and NIR.

The requirements will be discussed in terms of a nominal suite of 26 multispectral bands that include the band sets of SeaWiFS, MODIS, and VIIRS with additional bands for new applications and improved atmospheric corrections. ORCA specifications are designed to remove deficiencies in these previous designs based on extensive experience in the pre- and postlaunch calibration, algorithm development, postlaunch validation, and data processing of each of these sensors. In the case of a hyperspectral instrument design, examination of this suite of multispectral bands greatly simplifies the specifications, e.g., signal-to-noise ratios, and typical and maximum radiances, and the verification that the sensor meets the specifications.

From the discussion above, a number of sensor design attributes are identified. Most are derived from the ACE OES requirements, but in some cases, the ORCA team has defined more rigorous specifications. The ORCA requirements exceed the OES specifications in the following areas:

- SNR to equal or exceed OES minimum requirements (see Table 3)
- Additional 5 nm spectral resolution out to 885 nm.
- Minimal image striping (use same detectors for all pixels, i.e., use a time-delay integration scheme)
- No bilinear gain or automatic electronic gain switching (14 bit digitization over full dynamic range, 0-Lmax).

Also, because of the IIP development (IIP-2007 and IIP-2010), ORCA will have a functional prototype including the complete optical train spanning all required wavelengths, flight-like detectors and electronics, scan mechanisms, and the ability to acquire data at flight data rates while scanning at 6 Hz. The prototype will have been through two calibration and characterization test cycles, one at the end of each IIP.

Certain of these attributes must be associated with sensor performance specifications, e.g., SNR, polarization sensitivity, out-of-band response, and linearity (Barnes et al., 1994a). Requirements include a complete optical model and an EDU. A detailed optical model of the sensor is required for design purposes. These models include the geometry of the sensor layout and the prescriptions of all optical components (dimensions, coatings, index of refraction, etc.) for ray trace and throughput analyses. Ray trace analyses provide information on image quality (sharpness) on the focal plane, stray light and light leak sources and levels, and polarization sensitivity, among other things. Throughput analyses provide information on SNR and detector illumination intensity (important for avoiding saturation). Having an accurate model is also critical for diagnosing problems on orbit. Building and testing an EDU before finalizing the fabrication of the flight unit has been shown to save substantial cost in flight programs and is also useful in diagnosing on-orbit problems. Inevitably, problems with the initial conceptual design are encountered during fabrication and testing which requires refinements to be engineered. This is also true of the test procedures and equipment. Correcting all these prior to flight unit completion and testing streamlines the final certification of flight readiness and sensor performance characterization.

In addition to the sensor design, the characterization program must be developed as part of the instrument build to insure the procedures, test equipment and test configurations are mature and matched to the sensor. In concert with the ACE ocean program for OES, a sensor performance specifications working group was formed. This working group overlaps with the ORCA development team (Table 5).

Table 5. Working group and development team participants

ORCA Performance Specification Working Group	ORCA Development Team
Chuck McClain (Ocean Ecology Laboratory)	Chuck McClain (PI)
Rick Stump (NOAA/National Ocean Survey	Mike Behrenfeld (Science lead, Oregon State University)
Alan Holmes (Santa Barbara Instrument	Alan Holmes

Group)	
Steve Brown (NIST)	Steve Brown
Jim Butler (GSFC/Biospheric Sciences Branch)	Jim Butler
Bryan Monosmith (GSFC/Microwave Instrument Technology Branch)	Bryan Monosmith (Instrument Scientist)
Gerhard Meister (WG chair, Ocean Ecology Laboratory)	Gerhard Meister
Zia Ahmad (OBPG, Science and Data Systems, Inc.)	Mark Wilson (Optical design lead, Optics Branch)
Fred Patt (OBPG, Science Applications International Corporation)	Tim Madison (Optics Branch)
Bryan Franz (Ocean Ecology Laboratory)	Manuel Quijada (Optics Branch)
Sean Bailey (OBPG, Futuretech)	Patrick Thompson (Optics Branch)
Bob Barnes (OBPG, Science Applications International Corporation)	Ken Blumenstock (Electromechanical Systems Branch)
Jeremy Werdell (OBPG, Science Systems and Applications, Inc.)	Pete Shu (Detector Systems Branch)
Wayne Robinson (OBGP, Science Applications International Corporation))	Leroy Sparr (Instrument Manager, Instrument Systems Branch)
	Brian Martin (ORCA mechanical design lead, SGT)
	Pete Petrone (Optics Branch, Sigma Space Corporation)

Specific tests include the following and specifics of the test program are being detailed in Meister et al. (2011):

- Radiance vs counts calibration & linearity (by detector & mirror side)
- Polarization sensitivity
- Temperature sensitivity (instrument & electronics)
- Stray light
- Electronic crosstalk
- Point spread functions
- Spectral dispersion (wavelength vs. CCD detector #)
- Spectral registration
- Response vs. scan angle
- Relative spectral response (in-band and out-of-band)
- Band-to-band (or detector to detector) spatial registration
- Short and long term temporal stability
- Instantaneous field of view (IFOV)
- Pointing knowledge (at all 3 tilts)
- Solar diffuser bidirectional radiance distribution function (BRDF)
- Spectral line calibrator characterization & stability
- Signal to Noise
- Focal plane to focal plane calibration & spectral registration continuity

Certain high level specifications and rationale need to be outlined early as they drive the sensor design and component quality requirements to a large extent.

Spatial Resolution: IFOV of 1.0 km along track at a 20° sensor tilt angle. This is slightly better than SeaWiFS direct broadcast local area coverage (LAC) resolution (1.1 km at nadir) and substantially better than the SeaWiFS global area coverage (GAC; 4.4 km at nadir), but significantly coarser than VIIRS (750 m at nadir). The IFOV is defined as the area measured on the earth by a single pixel from the nominal altitude, with the boundaries of that area given by the isoline of 50% of the maximum response. Each band shall have an IFOV that does not differ from the mean by more than +/-5%. Thus, for a 1 km cross-scan pixel dimension at zero scan angle (along the ground track), the IFOV is 1.44 mrad or 0.0824°. The ground pixel along track dimension along the ground track would be 1.08 km, i.e, the pixel at nadir is not exactly square.

Global Coverage: Complete global coverage every two days is the science requirement. A cross track scan range of ±58.3º at an altitude of 650 km will satisfy this requirement. SeaWiFS and MODIS have similar scan ranges. The 650 km altitude makes it possible to accommodate an aerosol lidar, although ACE will fly at a much lower altitude, e.g., 450 km. A 450 km orbit will leave small gaps between swaths. For a lower orbit than 650 km, 405 km is about optimum as the increase in spacecraft speed adds an additional orbit per day and compensates for the reduced swath width. Data is to be collected over the daylight side of the orbit for solar zenith angles up to 75º.

Digitization: SeaWiFS had four gains (Science 1, Science 2, Lunar, Solar) which were incorporated to provide adequate digitization for maximum Earth, moon, and solar (via a diffuser) radiances. Science 2 allowed for maintaining an adequate digitization should the sensor experience large losses in sensitivity as did the CZCS. To avoid multiple gains, 14-bit digitization is required at a minimum. Lmax values are the set of band-specific radiances somewhat higher than what is expected over bright clouds. It is desirable to quantify radiances up to Lmax in order to correct for stray light contamination in both the spectral and spatial domains. At 14 bits given an Lmax of roughly 600 $W/m^2 \cdot \mu m \cdot ster$, radiance is quantified at about 0.04 $W/m^2 \cdot \mu m \cdot ster$ (0.004 $mW/cm^2 \cdot \mu m \cdot ster$) which is worse case. Typical water-leaving radiances range from 0 to 25 $W/m^2 \cdot \mu m \cdot ster$. Thus, 14 bits would suffice as a minimum requirement. However, 16 bits is preferable in order to ensure noise is accurately quantified per the high SNR requirements. It should be noted that the prelaunch characterization data should be detailed enough to facilitate a correction scheme that effectively removes stray light contamination to within 5 pixels of a bright target, e.g., Lmax (minimum requirement; 3 pixels is preferred).

Table 6. ORCA SNR Goals	
λ	SNR-spec
350	300
360	1125
385	1500
412	1500
425	1500
443	1500
460	1500
475	1500
490	1500
510	1500
532	1500
555	1500
583	1500
617	1500
640	1500
655	1500
665	1500
678	1500
710	1500
748	600
765	600
820	600
865	600
1245	300
1640	180
2135	100

SNR: The SNR minimum requirements are based on what was achieved in SeaWiFS and MODIS. The design goal for ORCA is to have SNRs 1.5-2 (average of 1.65) times those of the actual SeaWiFS SNRs at comparable Ltyp values (typical top of the atmosphere cloud-free radiances over the ocean). The ratio of MODIS to SeaWiFS actual SNRs ranged from about 1.5-3.0 (average ~ 2). The Ltyp and Lmax (radiance value used for sensor saturation threshold) values were derived from model simulations and from analyses of SeaWiFS global data. The model and SeaWiFS analyses yielded similar values. In the case of Lmax, the highest value from the different analyses was used for each band. The ORCA SNR goals (Table 6) are equal to or higher than the minimum OES requirements (Table 3).

Polarization Sensitivity: As mentioned earlier, uncertainty in the polarization sensitivity can introduce significant errors in the level-2 products (Gordon et al., 1997; Meister et al., 2005). Rayleigh scattering in the atmosphere can have a degree of polarization approaching 100% and represent 85% or more of the total radiance in the blue portion of the spectrum. Thus, a 0.1% uncertainty in the polarization sensitivity translates into a 0.1% uncertainty in total radiance and at least a 1% uncertainty in water-leaving radiance. To minimize this uncertainty, a polarization scrambler must be included. ORCA test results show that a SeaWiFS-like scrambler is adequate to meet the <1% polarization sensitivity requirement.

Stray Light: Stray light originates from scattering off optical surfaces (mirrors, gratings, and lenses) which have imperfections and even contamination. For ORCA, very high quality optical components are required and the associated specifications need to be articulated. Stray light was a serious problem in SeaWiFS (Barnes et al., 1995) and after some fixes were implemented a correction scheme was developed (Yeh et al., 1997) that worked reasonably well. It is not clear at this point how stray light will affect ORCA given the current focal plane design (CCD array). NIST has developed methodologies for characterizing stray light in hyperspectral instruments (Brown et al., 2003) as well as new technologies like hyperspectral image projection and these will be tested under the IIP projects.

Cross-talk: Cross-talk is usually categorized as electronic and optical. Electronic cross-talk is further partitioned into dynamic and static, representing different mechanisms in which focal plane circuitry can experience interference across electrical components. In the case of the VIIRS Vis/NIR focal plane, seven moderate resolution bands (16 detectors each), 2 imaging bands (24 detectors each) and the day-night band (a CCD array) are compacted into an area about the size of the MODIS Vis focal plane (five 1-km bands and two 500-meter bands). Optical cross-talk was present in SeaWiFS and is also an issue in VIIRS. Optical cross-talk occurs when photons are reflected within the focal plane assembly, e.g., between the overlying filter and underlying detector arrays, thereby contaminating adjacent bands. In SeaWiFS, optical cross-talk was considered a component of stray light and the addition of septums between detectors or at least between the two sets of detectors on each focal plane would have reduced the contamination significantly, but this option was not implemented. One analog of cross-talk in the case of a CCD array is 'bleeding' across array elements due to saturation.

Relative Spectral Response (RSR) and Out-of-Band Response (OBR): References to spectral bands are with respect to the band center, but the spectrum of light actually contributing to the detector output can be quite broad and irregular in shape. The bandwidth is normally specified as the FWHM and historically has been 10-20 nm for most ocean applications. Contributions outside the 1% level are generally referred to as out-of-band response. In the case of SeaWiFS, the OBR was large (nearly 4% in band 8; Barnes et al., 1994a) because the specification was very lax (less than 5%). The problem is accentuated in the NIR because the top of the atmosphere spectrum is dominated by blue light. This effect also shifts the effective band center. Thus, OBR required a correction and the method of Gordon (1995) was implemented. Having OBR values greater that about 1% unnecsarily complicates about everything in the processing including the vicarious calibration, the atmospheric correction, the incorporation of bio-optical algorithms, and the comparison of derived products with in-situ observations and other satellite sensors.

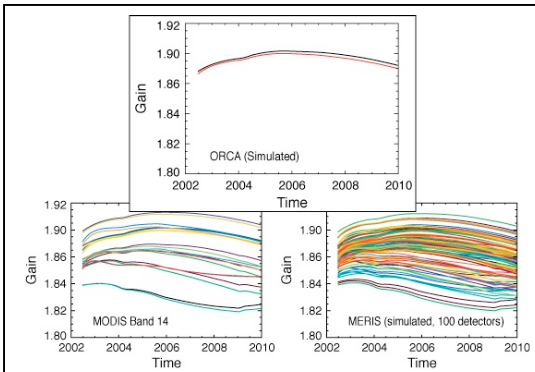


Figure 11. The three plots show the number of gain variables per band that need to be tracked as a function of time for different sensor designs. MODIS has 10 detectors and 2 mirror sides, yielding 20 gain variables. ORCA has only 2 gain variables (2 half-angle HAM sides; differences are easily mitigated, Eplee et al., 2003). A typical pushbroom imager has several hundred gain variables (only 100 shown in the figure for clarity) making accurate calibration much more difficult and inducing more striping (see Figure 12).

Temperature: Temperature effects are usually quantified by correlating sensor output (constant illumination) to focal plane temperature relative to a reference temperature and are measured during thermal-vacuum testing. For SeaWiFS, the prelaunch temperature dependency coefficients were subsequently updated using on-orbit data, Eplee et al., (2003). The SeaWiFS temperature variations range from orbital to seasonal (5-6 ºC) with the correction as high as 1% in band 8. Because of the aft optics design of ORCA using gratings and CCDs requiring accurate alignment, the specification for temperature control of the whole aft optics assembly is 1 ºC.

4.3. ORCA layout and subsystem descriptions

ORCA system design rationale and overview
As discussed above, there are a number of issues or criteria that must be addressed in

designing the optimal ocean color sensor. Figures 11 and 12 illustrate the issues associated with two of the criteria, calibration complexity (prelaunch and on-orbit) and striping, respectively.

The ORCA design was selected specifically to minimize these effects while achieving the required SNRs. The design follows that of SeaWiFS, i.e., a rotating telescope with time-delay integration as illustrated in Figure 13. During a single pixel integration time a ground swath defined by the instantaneous field of view is imaged onto the CCD array. A grating spectrally disperses light onto the array in the orthogonal dimension providing hyperspectral data. As the scan mirror rotates cross track the image on the array moves. Data on the array is clocked or

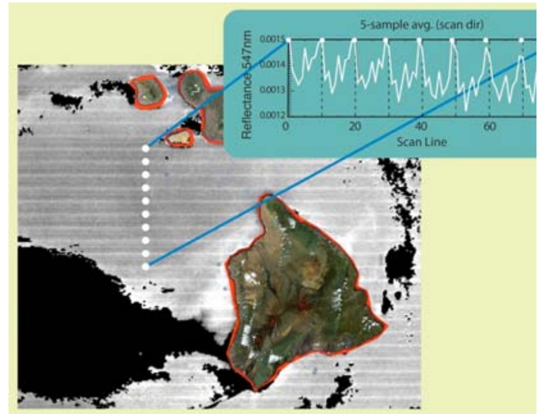


Figure 12. Ocean water-leaving radiances of MODIS Aqua at 547nm around Hawaii show significant along-track striping (10-20%), caused by the MODIS design, which uses 10 different detectors per scan. The inset shows that the striping occurs at a frequency of 10 scan lines. ORCA solves this problem.

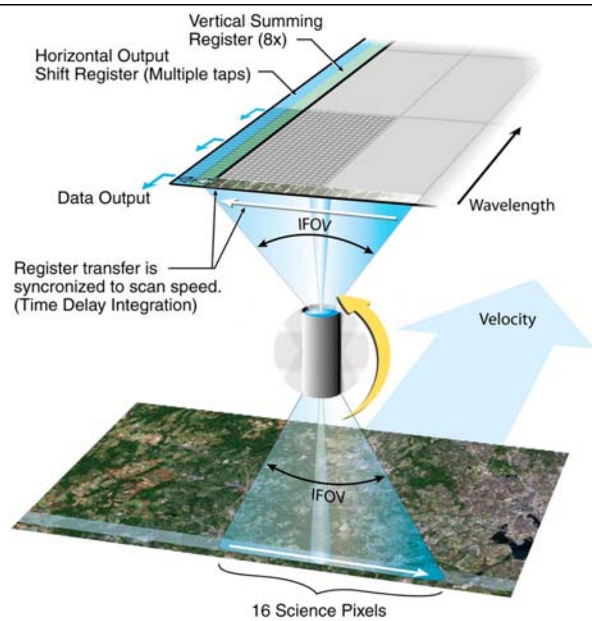


Figure 13. Stylized representation of Time Delay Integration (TDI) technique used by ORCA. As the scan mirror rotates, the motion of the projected ground scene on the CCD array is precisely matched by the column charge transfer rate (the rate at which photoelectrons are shifted towards the accumulation and readout registers). Effective integration times are long, equal to the time it takes to transfer charge across the entire array, and signal-to-noise ratios (SNRs) are very high. Every ground element is sampled by the same detector elements, spatially and spectrally, virtually eliminating striping. A small portion of the ORCA array is illustrated. This design concept can be applied in other Earth science passive sensor designs to great benefit.

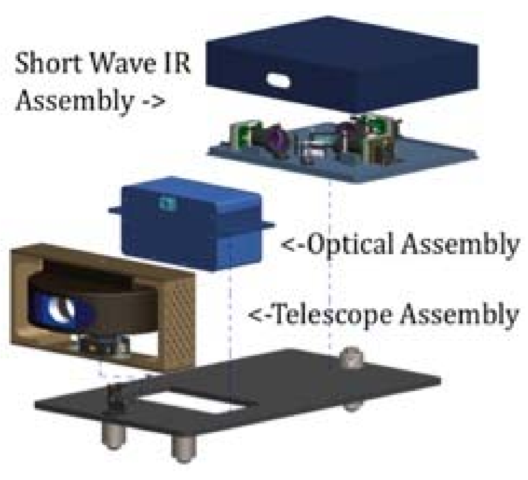
transferred to the accumulation register at the rate that matches the image motion on the CCD. Signal from a single ground pixel is then integrated for a time equal to the time it takes for the image to be clocked across the array. There are 16 ground pixel images on the array, resulting in a factor 16 increase in signal integration time for every ground pixel. The TDI scheme is illustrated in more detail below.

One important advantage of this design over certain others, particularly non-scanner designs, is that all bands are accurately characterized for temporal degradation using lunar calibrations as is done for SeaWiFS (Barnes et al., 2004). For competing designs, different detectors see different parts of the moon at one instant or not at all. In contrast, a single ORCA lunar scan illuminates all of the pixels on the array within a millisecond.

The SeaWiFS rotating telescope/half-angle mirror (HAM) mechanisms continue to work flawlessly after nearly 13 years while providing a wide continuous swath. Also, the design protects the optics from contamination.

Current ORCA Configuration

IIP-2007 produced a laboratory brassboard that focused on optical design and performance (Figures 14 and 15; Wilson et al., 2011). Optical components are mounted in modularly designed mechanical subsystems, one for the blue and red channels, and one for the SWIR channels. The front-end optics and mechanisms are also modularly mounted. The modular design allows test and characterization to occur in parallel. Core optical features consist of "fore-optics" and "aft-optics" components. The fore-optics incorporate a rotating telescope assembly (primary mirror, HAM and depolarizer), similar to SeaWiFS, to achieve a wide swath. The telescope mirror assembly is composed of the off-axis primary mirror and depolarizer rotating as a unit at 6Hz. The primary mirror directs the light to a reflective depolarizer whose function is to eliminate the polarization of the incoming radiance, a



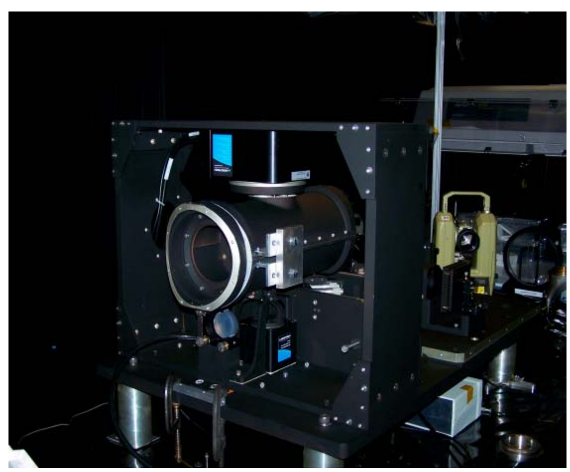


Figure 14. The primary ORCA modules (left) and the prototype or brassboard (right) without the telescope shield and covers.

major source of uncertainty in the atmospheric correction and sensor characterization. Even though the optical layout minimizes sensor polarization, to achieve the science requirement of less than 1% sensitivity, a depolarizer is required. The HAM rotates at half the angular rate of the primary to keep the focused light directed on the slit during rotation of the telescope assembly. The light exiting the slit is collimated and redirected, using wavelength-dependent dichroic beamsplitters, to dispersive reflective gratings. The dispersed light is then imaged onto the CCDs. Each broad blue and red channel has a separate grating and imaging lens assembly and the overall optical quality is such that the RMS spot size at the array is 30 microns. The ORCA brassboard has a SWIR section at the end of the optical path; each of the 3 SWIR channels is used for a specific, narrow wavelength band. Currently, the brassboard design, fabrication, alignment and system

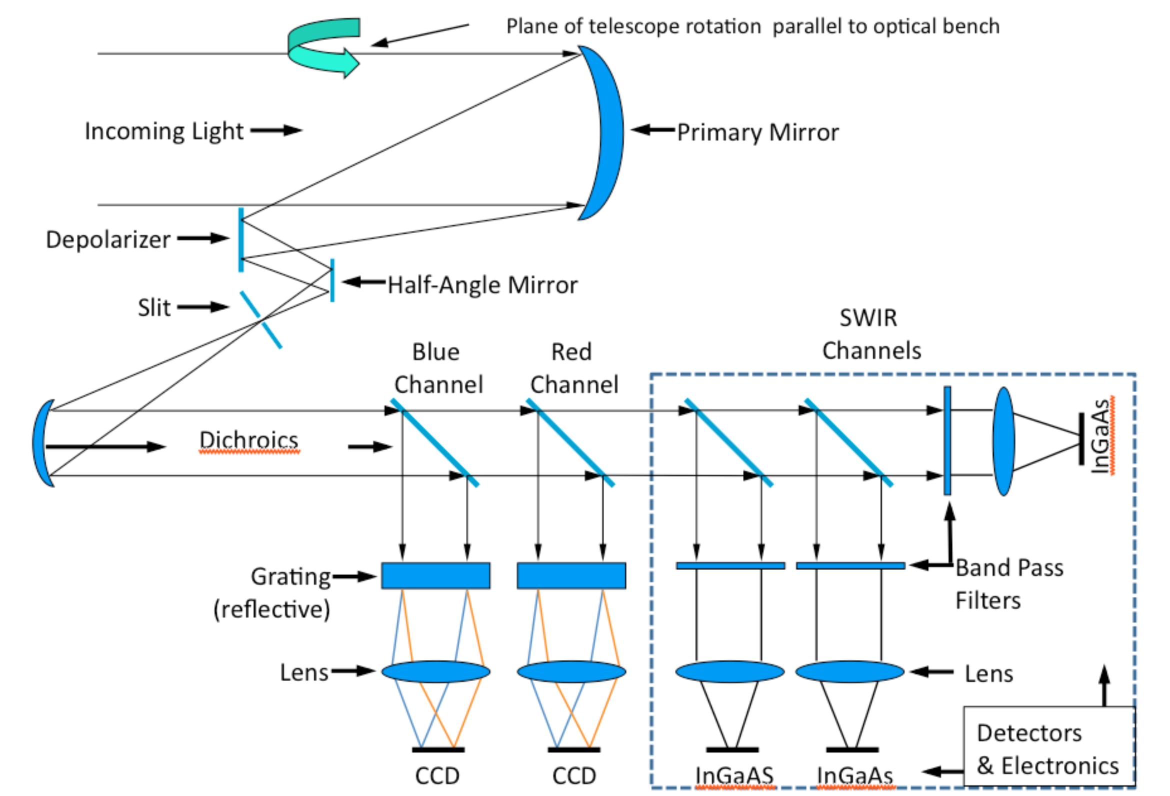


Figure 15. Schematic of the ORCA instrument prototype. The primary mirror is an off axis ellipse of 90mm aperture at f/3.33. In order for the instrument's optical response to be a measure of light intensity and not polarization, the instrument must be made to respond equally to all polarizations which is the purpose of the depolarizer. On successive primary assembly scans, alternate faces of the HAM reflect light onto the slit. The four dichroic beamsplitters preferentially reflect and transmit light in specified wavelength ranges. Diffraction gratings for the blue and red visible subsystems disperse a 5 nm resolution element across 8 pixels of the CCD array after imaging from the lens assemblies. The f/1.5 imaging lens assemblies for the blue and red channels produce an RMS spot on the CCD array of only 30 microns, on the order of the individual pixel dimension. The SWIR bands are sequenced along the optical path in a 1245 nm, 1640 nm, and 2135 nm order.

level testing has been completed. Most of the testing was conducted at NIST. One of the most important aspects of the optical design is that it can be easily adjusted for any of the orbiting altitudes being considered by mission planners, e.g. 450 or 650 km, without impacting system performance or requiring a significant design change.

Two mechanisms in ORCA follow the SeaWiFS design (also being employed in VIIRS) and drive the primary mirror telescope assembly and half angle mirror. The half angle mirror rotates at precisely half the rate of the primary mirror mechanism. In addition, the coupled drive rates for the mechanisms must be in perfect synchrony with the column transfer clock of the CCD array so that the motion of the ground pixel on the array matches the motion of the image on the array as the data is clocked across the array towards the accumulation register.

The TDI technique puts stringent performance requirements on the mechanism subsystem which are met using a Newport RGV100BL drive for the half angle mirror, and an Aerotech ABRS-150MP drive for the primary mirror assembly. This drive was selected (other vendor's products were evaluated) because it has sufficient torque and pointing control to handle the telescope assembly and rotating drum at 6 Hz.

The unique design of ORCA allows the instrument to quantify radiances from bright clouds without saturating the detectors, and without resorting to electronic gain switching or bilinear gains, and still meet SNRs at typical clear sky radiances. This is true across all spectral bands, even in the near IR where the bright cloud radiance is 75 times the clear sky radiance.

Detectors and TDI

It is extremely important to retire detector procurement risk by an early demonstration that ORCA custom detectors can be fabricated and meet specifications. The existing red and blue channel detectors are off-the-shelf parts lacking the required 650,000 photoelectron well depth, clocking speed, accumulation register and multiple readout taps necessary for ORCA. The flight-like ORCA will employ identical custom-fabricated silicon CCD arrays that are being developed under the second IIP.

Figure 16 shows a TDI for 8 superpixels in the scan direction (wavelength dimension of the CCD is ignored here). Note that the ORCA TDI scheme is on 16 superpixels, not 8, but we use 8 here for illustration. The horizontal axis (T1, T2, etc.) shows the time axis, with one time interval being the time difference between two consecutive pixels. The vertical axis shows the scan direction (the movement along the track direction due to the satellite motion is ignored here). At time T1, scene 1 is viewed by superpixel 1. After the charge accumulation period, the accumulated charges of superpixel 1 are transferred to superpixel 2. At time T2, scene 1 is viewed by superpixel 2. In superpixel 2, the newly measured signal from scene 1 is added to the charges that have been transferred from superpixel 1. After the charge accumulation period, all the charges from superpixel 2 are transferred to superpixel 3. This continues until all of the signal measured from scene 1 has been accumulated in superpixel 8. This signal is then sent to the analog-to-digital (A/D) converter.

The custom arrays will have 26 micrometer pixel pitch and column transfer rates (in the 128 pixel direction) of 200 kHz (required to keep up with the 6 Hz scan rate). The

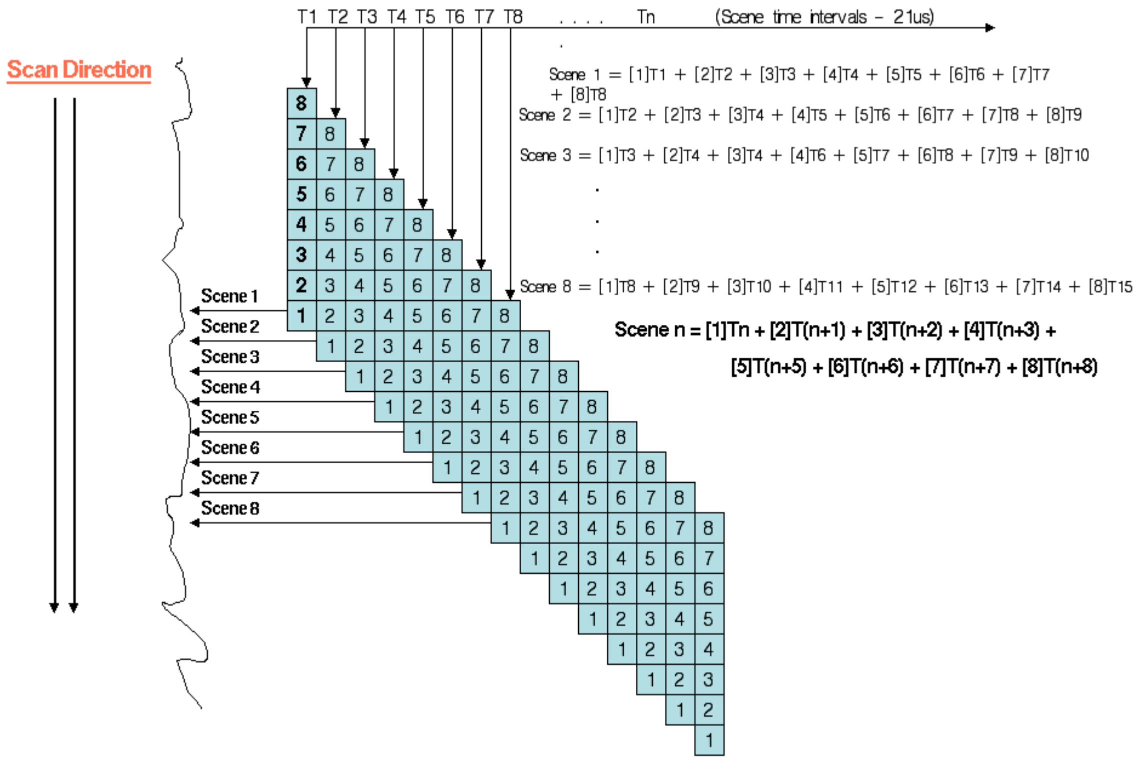


Figure 16. An illustration of the TDI concept using 8 superpixels. ORCA uses 16 superpixels for TDI. The numbers in [#] represent pixel numbers.

instrument slit and the grating dispersion are chosen so that the 5 nm spectral resolution is 8 pixels on the array. The intermediate accumulation register is used to sum 8 spatial pixels before transferring the contents to the readout register. Eight pixels in the spectral direction are summed in software after readout. This design defines an 8 by 8 "super pixel" as the fundamental data unit for the instrument which corresponds to a science ground pixel. Eight readout taps (one of the custom CCD enhancements) on the read register keep the data rate at each tap to less than 2MHz, allowing for a variety of 14 or 16 bit digitization options. This design provides great flexibility, e.g., it allows for (1) evenly spaced 5 nm hyperspectral data, (2) multispectral band centers tuned to within 0.625 nm, and (3) dense overlapping of 5 nm bands with 0.625 nm spacing across spectral features of special interest, e.g., the chlorophyll-a fluorescence peak at 685 nm, the oxygen A-band, and water vapor absorption bands, to derive more detailed information through deconvolution analyses.

An important system driver is that bands do not saturate, even in the presence of large radiance such as those occurring when clouds are in the field of view. This large dynamic range in conjunction with the high SNR requirement of ocean radiance retrievals, drives the pixel full well capacities of the visible detectors to values of at least 650,000 photoelectrons, and eight times that value in the accumulation registers. The requirement not to saturate also limits the digitizer options to those of 14 bits or greater. This guarantees that the specified noise equivalent radiances (NEΔL) values derived using the Ltyp and Lmax values in all bands are greater than the digitized radiance increments, ΔL, in all bands.

The scan rates for the mirrors and the clocking rates for the CCD detectors are derived from an orbital flight mission profile. For a given orbital altitude the array pixel pitch and array/mirror clocking and optical parameters are chosen to meet the science requirement of adjacent 1km ground pixels, corresponding to one 8x8 superpixel.

The existing ORCA brassboard SWIR detectors are not suitable to demonstrate flight performance, though existing optics, mounts and mechanical structures do support the addition of custom SWIR detector arrays. Two linear InGaAs arrays for the 1245 and 1640 nm bands will be installed (identical arrays of 1 x 16 elements). The linear array for the 2135 nm band is different and must be manufactured separately.

<u>Electronics</u>

Because a flight-like ORCA operating at typical orbital mirror rotation rates will deliver a quantity of data that greatly surpasses the capability of the simple detector drive and readout electronics used for the existing ORCA brassboard (a simple commercial Leach Box with limited drive speeds), a custom built electronics subsystem must be designed and fabricated. The electronics architecture is illustrated in Figure 17 and is what is proposed under IIP-2010 and is not what will be used for flight. The rack contains the main electronics module, providing data processing, motor control, housekeeping, and power conditioning and distribution. A master clock from the microcontroller board is distributed to the motor drive circuitry and array clock circuitry to ensure the precise synchronization required for TDI (Figure 18). An electronics module located at the instrument contains microcontroller based array clock drive circuitry and analog-to-digital (A/D) conversion placed close to the arrays to minimize signal degradation. Low Voltage Digital Signals (LVDS) are transmitted to the main electronics module in the rack. For the IIP, a microcontroller architecture was chosen over a Field Programmable Gate Array (FPGA) architecture based on cost, operational flexibility and ease of use. The selected microcontroller is a MIPS Technologies PIC32MX795F512L, a 32 bit 80MHz controller with adequate speed to handle the data rate from the arrays.

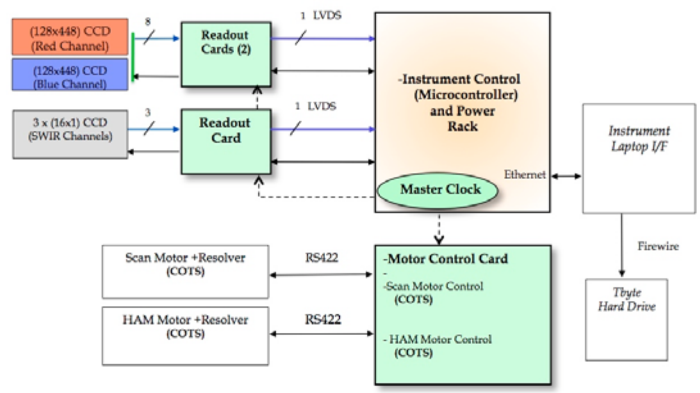


Figure 17. This top level functional block diagram shows the detectors and high speed drive and readout electronics needed to advance the ORCA prototype to an engineering test unit functioning at flight rotation, array clocking, and data speeds. The CCD arrays are a custom fabrication with integrated readout electronics. The SWIR detectors are bare detectors that will be hybridized in-house with custom designed, low noise, readout electronics. The remaining electronics are microcontroller based to reduce cost and increase operating flexibility. A space flight design would be implemented in Field Programmable Gate Arrays (FPFAs).

<u>System Performance: Preliminary Assessment Activities</u> The ORCA team has gone to great lengths to ensure the design addresses issues encountered with heritage sensors and alternative design concepts and meets the PACE science requirements. Members of the ORCA team, along with others in the Ocean Biology

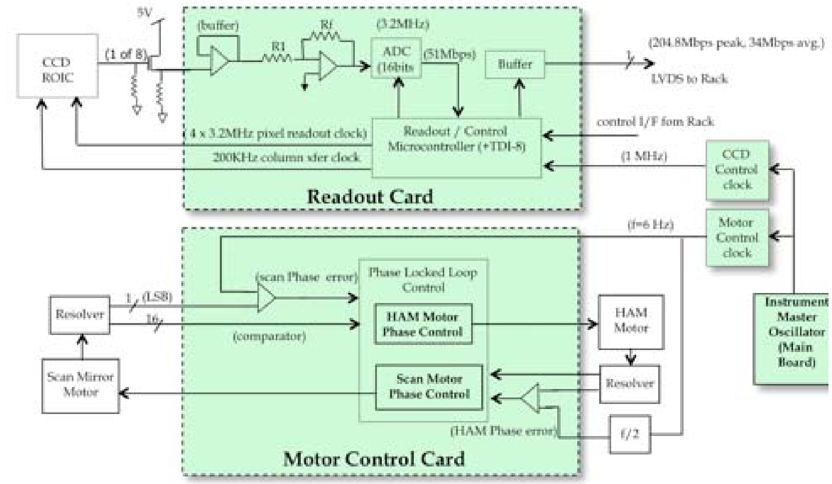


Figure 18. Detector readout and motor control electronics shown at a higher level of functional fidelity. A master clock controls detector charge transfer rates and motor drive rotation rates to keep the two functions synchronized.

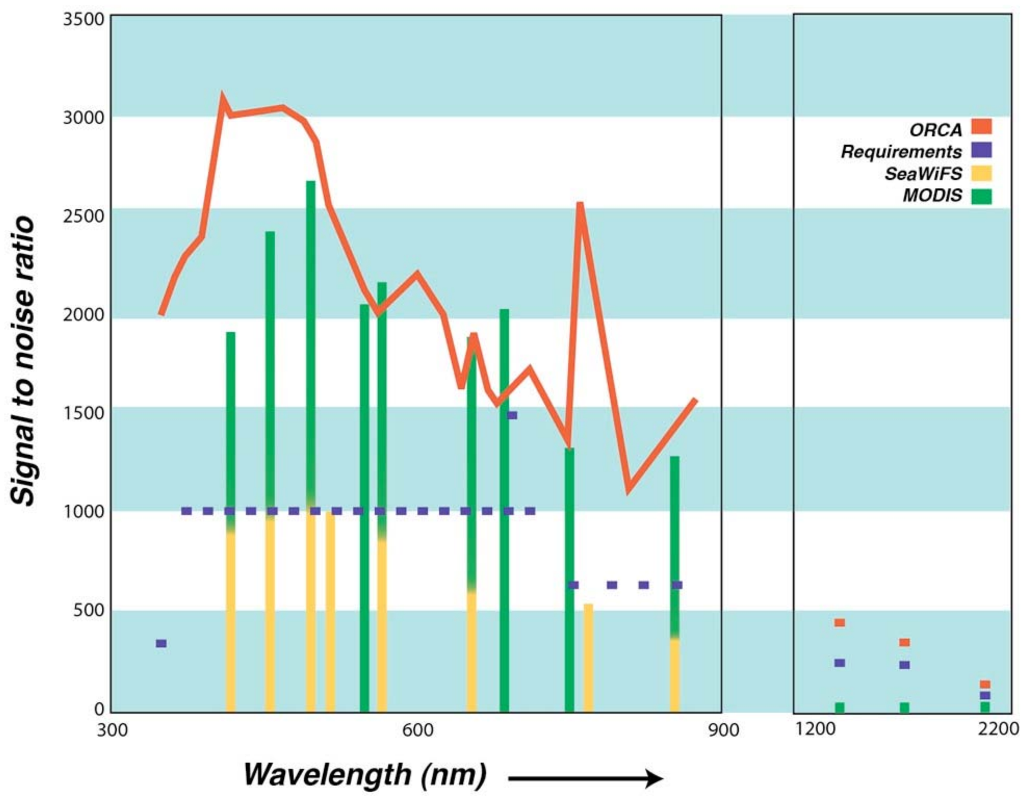


Figure 19. Comparison of estimated ORCA SNR, the ACE ocean radiometer minimum SNR requirements, and those of SeaWiFS and MODIS at Ltyp. ORCA exceeds the ACE specification for all 26 multispectral bands, usually by a factor of 1.5 or more.

Processing Group (OBPG) at GSFC, have completed a document on performance requirements, test protocols, and test equipment and technology needs under the current IIP to ensure that (1) the specifications are concise and consistent with the ACE requirements, and (2) testing is thorough, accurate, unambiguous and efficient (Meister et al., 2011). In addition, a detailed radiometric performance model (Monosmith and McClain, 2011) has been developed under the existing IIP. The model calculates final SNRs at the 26 required multispectral bands from a knowledge of mission altitude, detector photo-electron well capacities and noise parameters as well as other detector and optical design component specifications and measurements (all optical components have been tested at GSFC; Quijada et al., 2011). Figure 19 shows a comparison of estimated ORCA SNRs to the ACE ocean radiometer specifications and those of SeaWiFS and MODIS.

Table 7 provides the ORCA model SNR and NEdL (noise equivalent radiance) values. NEdL is a useful performance metric particularly when compared with dL, the radiance digitization which for ORCA is presently 14 bits. The 14 bit digitization is required because of the "no saturation" requirement, i.e., cloud radiances are to be measured and it is one of the ORCA design criteria not to have multiple gains and a

λ	**Δλ**	**Ltyp**	**Lmax**	**ACE SNR-spec**	**ORCA SNR-model**	**ORCA dL Lmax/N**	**ORCA NEdL @ Ltyp**
350	15	7.46	35.6	300	2020	0.00217	0.00369
360	15	7.22	37.6	1000	2225	0.00229	0.00324
385	15	6.11	38.1	1000	2370	0.00233	0.00258
412	15	7.86	60.2	1000	3156	0.00367	0.00249
425	15	6.95	58.5	1000	3006	0.00357	0.00231
443	15	7.02	66.4	1000	3048	0.00405	0.00230
460	15	6.83	72.4	1000	3062	0.00442	0.00223
475	15	6.19	72.2	1000	2960	0.00441	0.00209
490	15	5.31	68.6	1000	2740	0.00419	0.00194
510	15	4.58	66.3	1000	2575	0.00405	0.00178
532	15	3.92	65.1	1000	2192	0.00397	0.00179
555	15	3.39	64.3	1000	2011	0.00392	0.00169
583	15	2.81	62.4	1000	2203	0.00381	0.00128
617	15	2.19	58.2	1000	2010	0.00355	0.00109
640	10	1.90	56.4	1000	1660	0.00344	0.00114
655	15	1.67	53.5	1000	1830	0.00327	0.00091
665	10	1.60	53.6	1000	1562	0.00327	0.00102
678	10	1.45	51.9	1400	1510	0.00317	0.00096
710	15	1.19	48.9	1000	1616	0.00298	0.00074
748	10	0.93	44.7	600	1305	0.00273	0.00071
765	40	0.83	43.0	600	2512	0.00262	0.00033
820	15	0.59	39.3	600	1200	0.00240	0.00049
865	40	0.45	33.3	600	1640	0.00203	0.00027
1245	20	0.088	15.8	250	415	0.00096	0.00021

1640	40	0.029	8.2	250	273	0.00050	0.00011
2135	50	0.008	2.2	100	146	0.00013	0.00005

Table 7. ORCA SNR and NEdL values.
Units: mW/cm^2 µm str
N = number of digital counts (16,384 for a 14 bit system)
NEdL = Ltyp/SNR @ Ltyp

SeaWiFS-like bilinear gain is not possible with the CCDs. Fourteen bit analog-to-digital (A/D) converters are the highest that are currently space qualified. In the future, 16-bit digitization would be preferable. If the NEdL > dL, the system is digitizing noise. On the other hand, if NEdL < dL, the system is not capturing all of the useful signal available and could be compromising data quality. Ideally, NEdL ~ dL is the best case. However, this is hard to accomplish across the spectrum and it is better to quantify noise rather than loose useful signal, i.e., the NEdL > dL case. As shown in Table 7, ORCA achieves this in all but the three shortest wavelength bands and even there is quite good.

Other Design Considerations

Solar Diffuse & Spectral Calibrator

The primary on-orbit calibration method for ORCA will be lunar measurements. The secondary method of on-orbit calibration will be solar diffuser measurements. The conceptual solar diffuser design (not implemented under the IIP development) has been two white, space grade Spectralon diffusers on the "3-sided calibration wheel" (3SCW). The default position of the 3SCW is with diffuser 1 exposed to the aperture of the solar diffuser housing. There is no diffuser aperture door, so the short wavelength reflectance of diffuser 1 is expected to degrade strongly over time from the exposure to the solar irradiance. Diffuser 2 is on the side of the 3SCW that is usually turned away from the solar aperture, so the reflectance of this diffuser is expected to remain relatively constant over time. This has been the case for the secondary diffusers on MISR and MERIS. Adequate baffling is required to provide a similar radiation protection for diffuser 2 on ORCA.

The solar calibration time series will monitor the relative radiometric stability of each of the 19 nominal aggregate bands of the radiometer. Solar calibrations using diffuser 1 will be performed daily while the spacecraft is over the South Pole, as has been the practice with SeaWiFS. The calibration frequency will provide a check for step-function changes in the instrument response. Solar calibrations using diffuser 2 should be performed on a monthly basis, ideally on the same day as the lunar calibrations. Synchronizing the diffuser 2 and lunar calibrations would allow the diffuser reflectance time series to be closely tied to the lunar calibration time series. For both sets of solar calibrations, the tilt angle should be at nadir.

Parameters required to calculate the expected reflected radiance L_r from the solar diffuser are the solar irradiance E_s (for normal incidence), the angle of incidence on the solar diffuser, θ_i, and the BRDF of the solar diffuser $BRDF_N$ (Nicodemus et al., 1977:

$$L_r = BRDF_N * E_s * \cos(\theta_i)$$

The solar diffuser, which provides an approximately uniformly illuminated light source that fills the instrument aperture, provides a method for monitoring the relative band-to-band calibration of the 19 nominal aggregate bands of the radiometer over time. The solar calibration measurements, particularly for diffuser 2, would allow time series of band ratios to be computed to track the band-to-band calibration.

The strength of solar calibrations is that the radiances reflected by the diffuser can be optimized for the sensor. With a 1-km spatial resolution for nadir earth viewing, the moon appears as a small bright source (only 7 pixels in the scan direction for SeaWiFS, and probably similar in size for ORCA) in a dark area. The solar diffusers provide a full-aperture light source with a large embedded calibration area. For MODIS, the area averaged for calibration extends 50 pixels in the scan direction, with about 50 pixels at a similar radiance level on both sides which are not used in the averaging.

The weakness of solar calibrations is that the reflectance characteristics of the diffusers will change over time. Over time, the reflectance at the short wavelengths will degrade significantly, but secondary effects such as changes in the angular distribution of the reflected light (changes in the BRDF of the diffusers) should be considered as well. The use of the protected second diffuser should mitigate, but not eliminate, these effects. The largest degradation over time will affect the short wavelengths, e.g., the degradation of the MODIS diffuser as presented in Erives et al. (2004). Meister et al. (2011) discuss the solar diffuser performance requirements for future missions like PACE and ACE.

5. Orbit Considerations

The PACE and ACE mission orbit should meet two overall requirements:

1. Maintain a near-constant (+/- 15 minutes) equator crossing time.
2. Achieve global coverage every two days.

The first requirement is simply met by the choice of a Sun-synchronous polar orbit, i.e., with the inclination selected to achieve a node precession rate of 360 degrees per year. According to Wertz (1978), the precession rate is given by:

$$\Omega = -2.06474\times10^{14}\, a^{-7/2}\, (1-e^2)^{-2} \cos(i)$$

where Ω is the orbit node longitude, a is the semimajor axis in km, e is the eccentricity, and i is the inclination. If the product of the terms in a, e and i is -4.7737×10^{-15}, the precession rate will be 0.9856 degree/day, or 360 degrees/year. Since the orbit will be near-circular, the eccentricity will be small and its effect negligible. Therefore, the Sun-synchronous orbit is achieved by selecting the inclination to correspond to the semimajor axis:

$$i = \cos^{-1}(-4.7737\times10^{-15}\, a^{7/2})$$

For example, at an altitude of 650 km (a = 7028.14 km), this equation gives an inclination of 97.98 degrees.

Meeting the second requirement is somewhat more complicated. The two-day coverage is a function of the effective viewed swath width and the orbit period. The latter is a straightforward function of the semimajor axis. Kepler's third law states that the period varies as $a^{3/2}$; for low Earth orbits, there is a small perturbation (also given by Wertz) caused by the Earth's oblateness. At an altitude of 650 km, the orbit period is 97.82 minutes, or 14.72 orbits per day. The spacing of the orbit tracks is the Earth's equatorial circumference, 40075 km, divided by the orbits per day; for a 650 km orbit, the spacing is 2722 km.

The effective swath width depends upon the sensor viewing geometry and the spacecraft altitude. For ORCA, the sensor geometry includes both the scan angle range (+/-58.3 degrees around nadir) and the sensor tilt of +/- 20 degrees along-track. For ocean color measurements, an additional constraint is imposed by the atmospheric correction algorithm, which is currently effective up to a sensor zenith angle of 60 degrees. This restricts the useful part of the swath to somewhat less than the full width. At an altitude of 650 km and a tilt of 20 degrees, the effective swath width is 1962 km. Combined with the orbit spacing of 2722 km, this produces effective daily coverage of 72% at the equator.

Achieving two-day coverage requires that the orbits be staggered on successive days, such that the areas not viewed on the first day, are seen on the second. In the ideal case, there would be an odd number of half-orbits per day, so that the orbit tracks on the second day fall exactly between those on the first day. In the worst case, the orbits per day figure is an integer value, and the same areas are viewed every day.

To determine the two-day coverage, the relative offset between orbit tracks on successive days is combined with the single-day coverage to determine the total coverage at the equator. If the sum is at least 100%, then two-day coverage is achieved. The orbit track offset is the difference between the orbits per day and the nearest integer. For the 650 km orbit, corresponding to 14.72 orbits per day, the offset is 28%. Combined with the single-day coverage of 72%, this achieves (barely) 100% coverage in two days.

Based on the possible need to accommodate a different suite of instruments, a range of altitudes from 400 to 1000 km was analyzed for two-day coverage. At each altitude, the orbit period and effective swath width (based on the 60-degree sensor zenith angle limit) were computed, and from these the single-day and two-day coverage were determined. The results are shown in Figure 20. As shown in the figure, two-day coverage is achieved at approximately 410 km; from 650 to 825 km; and above 930 km. Although not shown on the plot, single-day coverage of 100% is achieved at an altitude of 1200 km.

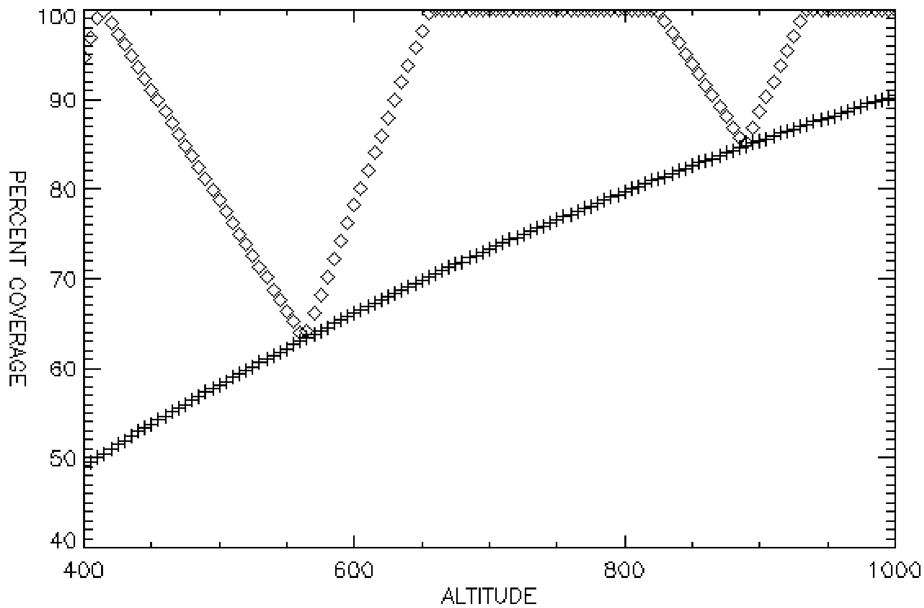


Figure 20. Single-day (+) and two-day (◊) coverage at the equator vs. altitude, based on a sensor tilt angle of 20 degrees and a sensor zenith angle limit of 60 degrees.

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14. ABSTRACT

The Ocean Radiometer for Carbon Assessment (ORCA) has been in development since 2001 as a next generation advanced ocean color sensor concept to follow the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate resolution Imaging Spectroradiometer (MODIS). This document reviews the science objectives the authors envision for an advance sensor, background on heritage sensors like SeaWiFS and MODIS, the history of the ORCA development, the ORCA measurement and performance requirements, and the basic design of ORCA.

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