The Ocean Radiometer for Carbon Assessment (ORCA)

C. R. McClain
Ocean Ecology Branch
NASA Goddard Space Flight Center
Greenbelt, MD 20771

***Abstract*-A design concept for an advanced ocean color radiometer, the Ocean Radiometer for Carbon Assessment (ORCA) has been underway at NASA Goddard Space Flight Center (GSFC) since 2002. In that time, the design has undergone a number of revisions and is now configured to meet all the measurement requirements for the Decadal Survey Aerosol, Cloud, and Ecology (ACE) ocean ecosystem radiometer (OES). Under the Instrument Incubator Program, the ORCA development objectives are threefold: (1) design and fabricate a functional sensor prototype, (2) document sensor performance and test specifications, and (3) conduct a comprehensive component and system-level calibration and characterization test program. Specifically, the prototype has flight-like fore and aft optics and mechanisms, but, due to cost constraints, nonflight-like commercial off-the-shelf (COTS) focal plane detector arrays. COTS arrays cannot handle flight data rates. However, the COTS arrays are adequate for optical alignment and performance testing. The incorporation of flight-like arrays and associated electronics is being proposed in response to the ROSES2010 IIP solicitation. To date, an initial draft document for Objective 1 has been completed, all optical components have been tested, and the prototype is being fabricated and aligned. Complete sensor characterization is scheduled at the National Institute of Standards and Technology (NIST) later this summer. The presentation will review the ORCA performance requirements, the basic design concept, and performance test results to date.**

I. Introduction

Ocean color satellite remote sensing began with the first proof-of-concept mission, the Nimbus-7 Coastal Zone Color Scanner (CZCS), launched in 1978. The primary CZCS wavelengths (443, 520, 550, and 670 nm) were adequate for demonstrating the basic concepts of atmospheric correction and "pigment" (chlorophyll + phaeophytin) concentration estimation. As the name implies, the CZCS was conceived to monitor coastal waters, not the open ocean. However, the derived products were most valid in the open ocean. The CZCS incorporated a number of novel concepts, e.g., a depolarizer and a sun glint avoidance tilt mechanism. Subsequent sensors like the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) incorporated additional near-infrared spectral bands for atmospheric aerosol correction and chlorophyll-a concentration. To better separate chlorophyll-a from colored dissolved organic matter (CDOM), a 410 nm band was added to the baseline. MODIS also included a 678 nm band for chlorophyll fluorescence line height (FLH). The sensor requirements for SeaWiFS and MODIS were developed based on the CZCS experience and science goals as articulated in the early and mid-1980s [1]. At that time, the primary goal was to make more accurate estimates of chlorophyll-a which would be required for estimating primary production, the rate of carbon fixation by phytoplankton (microscopic plants) via photosynthesis. Primary production was considered the essential link to the ocean carbon cycle. SeaWiFS and MODIS were designed for open ocean science.

Since the late 1980s, the science and operational applications of satellite ocean color data have expanded dramatically [2]. The required product suite defined by the Decadal Survey (DS) Aerosol, Cloud, and Ecology (ACE) ocean team includes inherent optical properties (absorption and scattering coefficients of various dissolved and particulate constituents), phytoplankton taxonomic groups, particle size distributions, concentrations of various quantities in addition to chlorophyll-a (calcite, particulate organic matter, dissolved organic matter, total suspended matter, etc.) and others, many of which will be used for climate research and the continuation of the climate data records (CDRs) initiated with SeaWiFS and MODIS data. Also, the ACE radiometer must provide high quality data products in near-shore and estuarine regions. Such a suite of derived products puts additional requirements (spectral bands, calibration accuracy, polarization sensitivity, on-orbit stability, etc.) on future ocean radiometers. One important lesson learned is that the ocean radiometer should be a dedicated sensor, i.e., not a multipurpose instrument designed to meet the requirements of multiple science communities because this inevitably leads to compromises that impact the ocean requirements. SeaWiFS is such an instrument and has provided the highest quality ocean color data to date [3] and has been used for the on-orbit recharacterization of MODIS [4].

ORCA is being developed under the Instrument Incubator Program with the primary objective of meeting the ACE ocean requirements. The ORCA team is Charles McClain (GSFC, PI), Michael Behrenfeld (Oregon State U., science lead), Leroy Sparr (GSFC, instrument manager), Bryan Monosmith (GSFC, instrument scientist), Mark Wilson (GSFC, optical design lead), Peter Shu (GSFC, detector systems lead), Manuel Quijada (GSFC, optical component test lead), Brian Martin (SGT, Inc., mechanical design lead), Alan Holmes (design consultant), Steve Brown (NIST, system performance test lead), Timothy Madison (GSFC, optical alignment lead), Peter Petrone (Sigma Space Corp., optical testing and alignment), Ken Blumenstock (GSFC, electromechanical lead), and James Butler (GSFC, system calibration advisor). In this paper, the ACE ocean radiometer specifications will be presented along with the ORCA design concept.

II. ACE Ocean Measurement Requirements

The ACE ocean team has worked over the past two years to define measurement requirements. This has included specifying spectral bands, bandpasses, signal-to-noise ratios (SNR), typical top-of-the-atmosphere radiance (Ltyp), saturation radiances (Lmax), and derived products. At this time, 26 specific spectral bands have been identified with an additional requirement that between 345-775 nm the data be at 5 nm resolution. The 5 nm resolution requirement was the result of recent publications, e.g. [5], indicating that derivative and other analysis techniques can allow the identification of specific pigments from ocean reflectance spectra allowing for phytoplankton taxonomic groups to be mapped globally. Initial efforts to map taxonomic groups using size classes or specific species, e.g., diatoms have been attempted using heritage sensors like SeaWiFS, but the algorithms are essentially limited by the spectral content of these data sets. Table I provides the bands, band passes, the typical clear sky top-of-atmosphere radiances (Ltyp), the maximum cloud top radiances (Lmax), and minimum SNR values. The Lmax values are the saturation radiances. The ACE requirement is that no bands saturate. The ORCA SNR-model values are for a 650 km altitude which was the initial ACE altitude and the ORCA prototype is based on this. Moving to a 450 km orbit, which is being considered, allows for a smaller primary mirror and a "slower" optical layout while still meeting the ACE SNR specifications. Also, the ORCA modeled SNRs are based on measured component reflectances and transmittances and vendor quotes on "flight-like" detector performance. The primary performance and design requirements are listed below:

1. A minimum of 26 multispectral bands (Table 1)
2 Spectral resolution: 5 nm (345-775 nm)
3. Sensor polarization sensitivity: < 1.0%; characterization to better than 0.2%
4. Global coverage every two days
5. Spatial resolution: 1 km
6. Tilt (sun glint avoidance): 20° fore/aft
7. No multispectral band saturation
8. Stability: < 0.1% knowledge – mission duration, < 0.1% over one month – prelaunch demonstration
9. Prelaunch calibration uncertainty < 2% maximum, 0.5 % goal.
10. Accommodate lunar calibration

All these requirements impact the sensor design in one way or another. The lunar calibration requirement is also a mission requirement in that the mission must support whatever maneuvers or sensor positioning on the spacecraft to allow monthly views of the moon at a constant phase angle, i.e. 7° like SeaWiFS [6].

TABLE I
ACE Ocean Radiometer SNR Specifications and ORCA Model Values

λ	**∇λ**	**Ltyp**	**Lmax**	**ACE SNR-specification**	**ORCA SNR-model**
350	15	7.46	35.6	300	2020
360	15	7.22	37.6	1000	2225
385	15	6.11	38.1	1000	2370
412	15	7.86	60.2	1000	3156
425	15	6.95	58.5	1000	3006
443	15	7.02	66.4	1000	3048
460	15	6.83	72.4	1000	3062
475	15	6.19	72.2	1000	2960
490	15	5.31	68.6	1000	2740
510	15	4.58	66.3	1000	2575
532	15	3.92	65.1	1000	2192
555	15	3.39	64.3	1000	2011
583	15	2.81	62.4	1000	2203
617	15	2.19	58.2	1000	2010
640	10	1.90	56.4	1000	1660
655	15	1.67	53.5	1000	1830
665	10	1.60	53.6	1000	1562
678	10	1.45	51.9	1400	1510
710	15	1.19	48.9	1000	1616
748	10	0.93	44.7	600	1305
765	40	0.83	43.0	600	2512
820	15	0.59	39.3	600	1200
865	40	0.45	33.3	600	1640
1245	20	0.088	15.8	250	415
1640	40	0.029	8.2	250	273
2135	50	0.008	2.2	100	146
Radiance units: mW/cm^2 nm str					

III. The ORCA Prototype

The ORCA development actually began in 2002 as a result of a NASA-wide carbon program formulation activity [7] that recommended an advanced ocean color sensor to follow SeaWiFS and MODIS. At that time, Charles McClain and Michael Behrenfeld formed a sensor team to respond to an anticipated Earth System Science Pathfinder (ESSP) mission. The ESSP solicitation was never released, but the team continued the sensor concept development through a number of instrument design laboratory studies and internal GSFC research and development support. The overall philosophy has been to incorporate proven design concepts and lessons learned from previous sensors like the SeaWiFS rotating telescope and half-angle mirror, avoid technology development to keep cost and risk low, and adopt designs that maximize data quality, i.e. do not trade quality for simplicity. For example, designs that inherently produced striping in the imagery (e.g., MODIS) were not considered acceptable. Under the present IIP, the ORCA development has three objectives or goals:

1. Design and fabricate a functional sensor prototype. The prototype includes scan mechanisms, optics, and detector elements with the objective of evaluating system optical performance. The objective includes detailed and accurate component specifications required for procurement. Because of the cost, simple off-the-shelf detector arrays are used which

cannot support flight data rates, but are adequate for testing. Under separate support from GSFC, the three SWIR bands have been added. “Flight-like” custom focal planes and associated electronics require additional funding, e.g., a second IIP.

2. Documentation of performance and test specifications. Under the IIP, the ORCA team will review the ACE performance specifications and document test specifications to verify sensor performance, e.g., polarization sensitivity, stray light contamination, out-of-band response. The ORCA team is to review all such test plans from SeaWiFS, MODIS, and other sensors to determine what improvements are required.
3. A comprehensive component and system-level calibration and characterization test program including refinement of measurement protocols where needed. The component level test data are to be used in a model of the sensor throughtput performance, i.e., SNR. The system level testing is to be supported by NIST (Steve Brown, co-I). One objective of the test plan is to determine if current technology, as available at NIST and GSFC, is adequate, what refinements in the test protocols are needed, and what new technologies need to be developed. Another objective is to determine whether or not the sensor meets the ACE ocean performance specifications, and, if not, what design improvements are required.

The basic ORCA design is illustrated in Fig. 1. The fore-optics consists of a rotating telescope assembly, a polarization scrambler, a half angle mirror (HAM), a collimating mirror, a slit, and a baffle. The aft-optics includes four wavelength-specific dichroic beamsplitters, and 5 subsystems (UV-visible, near-infrared or NIR, and three shortwave infrared or SWIR). The UV-visible and NIR subsystems are spectrographs and include a focusing lens assembly and a CCD array. The SWIR subsystems each incorporate a bandpass filter, a focusing lens assembly and a detector array. For three SWIR channels or bands, the design is considered the most economical and straightforward to implement while providing the required performance.

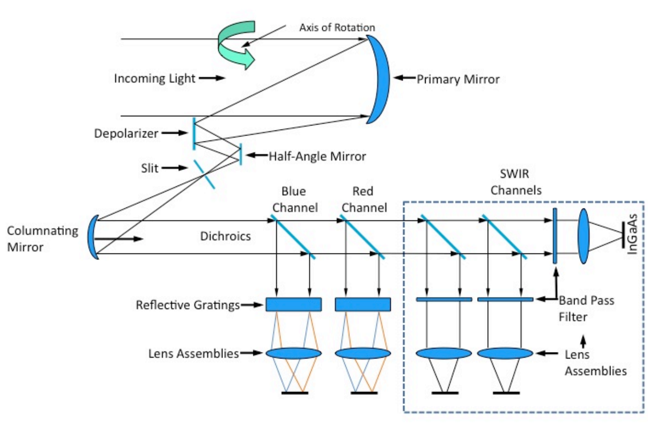

Fig. 1. ORCA optical layout.

In developing the final design before fabrication, much attention via modeling, component testing, etc., was paid to minimizing potential sources of stray light, light leaks, and polarization sensitivity. The rotating telescope-HAM concept minimizes the range of the angle of incidence of light on the fore-optics surfaces as compared to a MODIS rotating mirror. The design also protects the optical surfaces from contamination and degradation by situating them well within the instrument housings. The SeaWiFS-like sampling implementation also minimizes image striping, a major complaint from the research community regarding MODIS and other sensor designs. The only source of striping in the ORCA design is slight variations in the HAM mirror sides that can be accurately removed with a one-time calibration table adjustment [8]. The depolarizer is an improved version of the SeaWiFS depolarizer. The overall SeaWiFS polarization sensitivity was ~0.25% [9].

Since the beginning of the IIP in October 2008, the following tasks have been completed:

1. The prototype optical and electromechanical design has been finalized. This includes the three SWIR bands.
2. All optical components (lens assemblies, gratings, dichoics, slit, mirrors, depolarizer, filters, etc.) and detector systems have been specified, ordered, and delivered. All structural components (telescope housing, mounts, optical bench, etc.) have been fabricated and painted.
3. All optical components have been performance tested. All meet or exceed specifications (transmission, reflectivity, efficiency, etc.).
4. Working drafts of the system-level performance test specifications and performance modeling documents have been completed. An overview of the ORCA program is being drafted. Other documents are being outlined, e.g., optical design.
5. Assembly and alignment work is underway (Figure 2.)

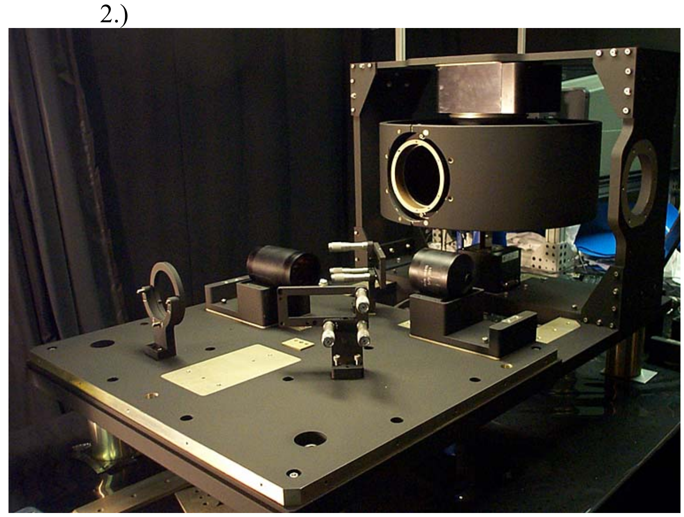

Fig. 2. ORCA prototype partially assembled during fabrication and alignment at GSFC.

Once the system is aligned, NIST will perform an initial system level test at GSFC using the portable version of the Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) system [10]. Any obvious performance issues based on these data will be addressed, i.e., design modifications. Then the ORCA prototype will be delivered to NIST for a complete characterization (stray light contamination, polarization sensitivity, SNR, etc.) using the SIRCUS facility and a hyperspectral image projection system [11].

IV. Conclusions

The ORCA prototype development under ESTO IIP support is moving forward on schedule and within budget. The preliminary estimated throughput performance (Table 1) exceeds the ACE ocean radiometer minimum requirements in all bands. The instrument achieves this without saturation in any band and without a bilinear gain as in SeaWiFS or the Visible Infrared Imaging Radiometer Suite (VIIRS). Barring any significant problem in meeting other performance requirements, the optical performance testing should be completed by the end of 2010. To complete the prototype, flight-like detector arrays and electronics will need to be incorporated and will be proposed in response to the ROSES10 IIP solicitation. Having these components in the prototype would allow testing of the sychronization of the scanning mechanisms, detectors, and readout electronics at on-orbit scan and data rates. The prototype could then be easily modified, e.g., light-weighted, for aircraft deployment or upgraded to a flight engineering design unit.

V. Acknowledgements

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VI. References

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