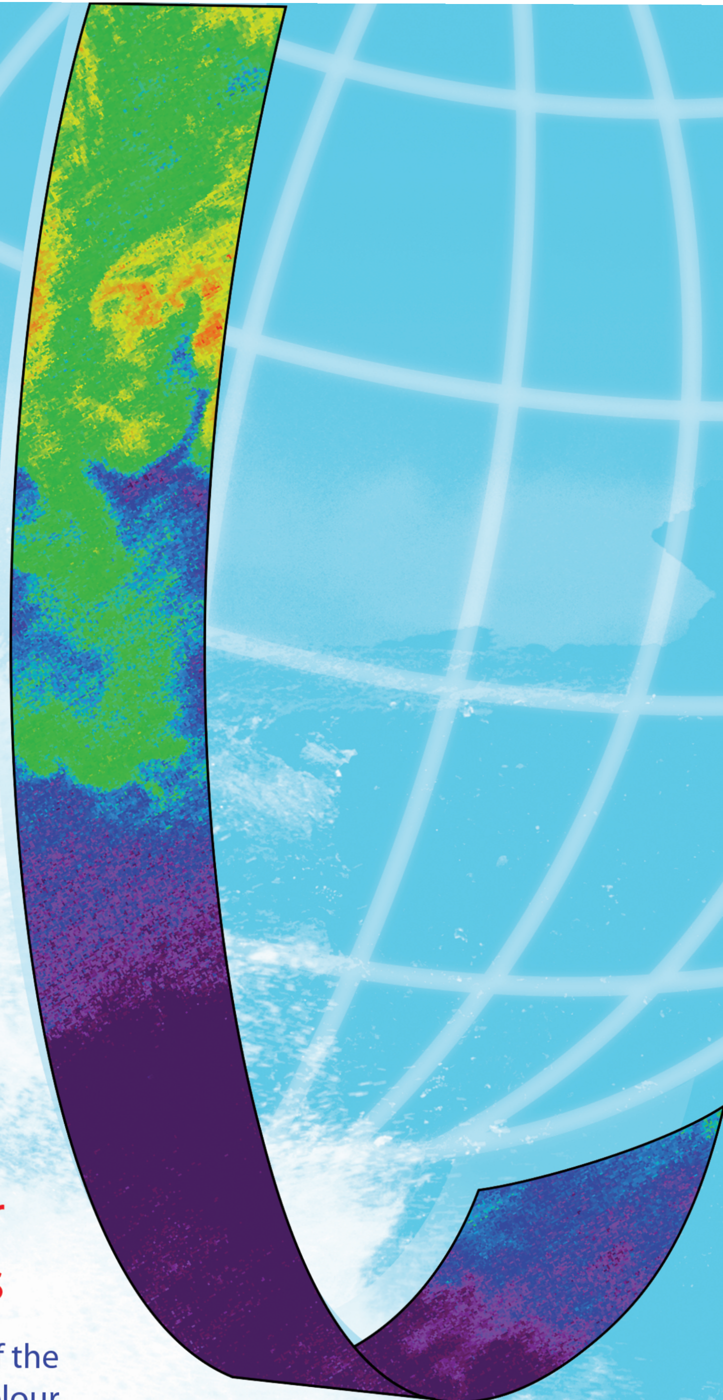

Mission Requirements for Future Ocean-Colour Sensors

Reports of the International Ocean-Colour Coordinating Group

REPORT NUMBER 13

IOCCG

An Affiliated Program of SCOR
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IOCCG Report Number 13, 2012

Mission Requirements for Future Ocean-Colour Sensors

Edited by:
Charles McClain and Gerhard Meister (NASA Goddard Space Flight Center, Greenbelt, MD, USA)

Report of an IOCCG working group on Mission Requirements for Future Ocean-Colour Sensors, chaired by Charles McClain, Gerhard Meister and Paula Bontempi and based on contributions from (in alphabetical order):

Yu-Hwan Ahn	Korea Institute of Ocean Science and Technology (KIOST)
Paula Bontempi	NASA Headquarters, USA
Steven Delwart	ESA/ESTEC, The Netherlands
Bertrand Fougnie	Centre National d'Etudes Spatiales (CNES), France
Charles McClain	NASA Goddard Space Flight Center (GSFC), USA
Gerhard Meister	NASA Goddard Space Flight Center (GSFC), USA
Hiroshi Murakami	Japan Aerospace Exploration Agency (JAXA), Japan
Menghua Wang	NOAA/NESDIS/Center for Satellite Applications and Research, USA

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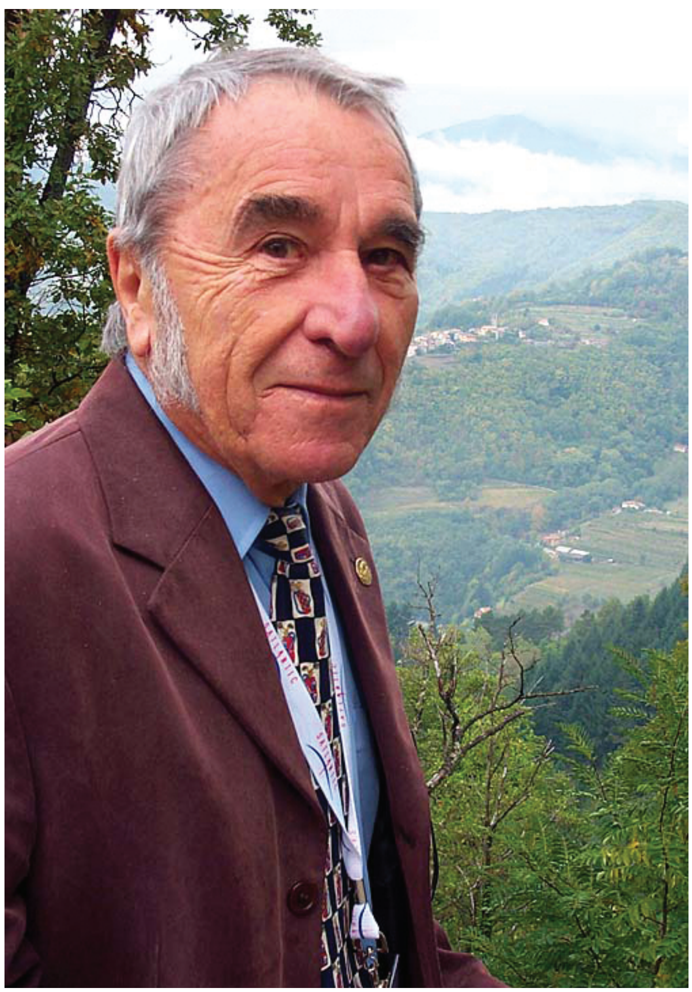
— *In Memoriam* —

This report is dedicated to the memory of

Professor André Morel

1933 — 2012

Professor André Morel was a pioneer in the field of ocean optics and satellite ocean colour science, he was a founding member of the International Ocean Colour Coordinating Group (IOCCG), the author of the first IOCCG report on minimum requirements for ocean-colour sensors (IOCCG Report 1, 1998), and above all, he was a true gentleman.



Photograph courtesy of Gene Carl Feldman, NASA GSFC, USA

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Chapter 1

Introduction

Ocean-colour remote sensing began with the launch of the Coastal Zone Color Scanner (CZCS) proof-of-concept mission in 1978. The first IOCCG report by Morel et al. (IOCCG, 1998) used the lessons learned from the CZCS data to quantify the minimum requirements for retrieving phytoplankton chlorophyll-a from space for subsequent ocean-colour sensors. Since the CZCS and the first IOCCG report, more complex and sophisticated ocean-colour sensors have been on orbit, (`http://ioccg.org/sensors/historical.html`), with thirteen sensors functioning between 1996 and 2011. Another eight polar-orbiting ocean colour-sensors are currently on orbit (`http://ioccg.org/sensors/current.html`), with launches since 1999. Ten more polar-orbiting ocean-colour sensors are planned for launch through 2018 (`http://ioccg.org/sensors/scheduled.html`). The proliferation of ocean-colour sensors and the recognized value of the associated data for a range of basic and applied research as well as operational applications are astounding. The result has been thousands of peer-reviewed publications detailing the scientific discoveries of the past several decades. Given the future planning activities underway for more ocean-colour sensors, this report seeks to establish the minimum basic radiometric and sensor requirements for detailing global observations of the ocean's chemistry and biology from space. The report requirements recognize not only the evolution of oceanographic and Earth system science questions and multi-decadal scientific discoveries since the CZCS era, but also the value of a continuous time series of global, climate quality, ocean-colour data to support a virtual constellation of ocean-colour sensors and enable large-scale oceanographic research. These data support the estimation of dozens of biological, chemical, biogeochemical, and ecological properties of the ocean critical to understand the Earth and the ocean's role in the Earth system and manage its resources.

Many scientific discoveries have resulted from ocean-colour remote sensing. Notable compilations of results include the special issue of the Journal of Geophysical Research on CZCS results (*Ocean Color from Space: A Coastal Zone Color Scanner Retrospective*, 99(C4), 1994), two special issues of Deep-Sea Research, Part II (*Views of Ocean Processes from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Mission*: Volumes 1 and 2, 2004) and a recent review by McClain (2009). We have confirmed that a close coupling exists between ocean climate and primary production. We know that the biologically productive ocean is extremely sensitive to vertical mixing.

We have also verified and then found cause to revisit the general Sverdrup/Riley concepts: that the combination of vertical mixing and light in a water column has major effects on the seasonal and temporal appearance of phytoplankton in the ocean. Satellite data of the ocean also allow ready identification of ocean and coastal fronts, which are key sites of high productivity and support tremendous upper trophic level biomass. Global ocean satellite data have also improved our understanding of important interactive relationships between coastal (e.g., squirts, jets, eddies) and oceanic waters, revealing a far greater influence of coastal processes on global ocean basins than anticipated. A global ocean view has additionally enabled previously unattainable synoptic estimates of primary production that can be resolved seasonally and decadally.

We have also realized a 15-year time series in several ocean-colour sensors globally, which is a major milestone for the ocean research community. Discovery and confirmation of oceanographic phenomena from ocean-colour remote sensing included the impact of sunlight absorption by phytoplankton on the heat budget of the ocean (Falkowski et al., 1998), and elucidation of the linkage between biological production, associated carbon fixation, and climate (Behrenfeld et al., 2006). These findings and others concerning light penetration, photosynthesis, and phytoplankton growth within the oceans confirmed ideas that were established long before satellites existed. However, the use of satellites grounded these theories concerning the ocean biosphere and placed these theories within the context of Earth's global ecology. However, we must also recognize the advancement of our science questions and application of ocean-colour data to operational problems. Therein, we must plan for the future by assuring a minimum series of requirements for ocean-colour sensors, as well as considering the addition of capabilities that will continue to advance our scientific discoveries within Earth's living ocean, and delineate the role of the ocean in the Earth system and climate. In fact, much effort is now focused on the development of long term climate data records (CDRs) which are generated by merging multiple satellite data sets requiring consistency in the data products and accurate tracking of sensor stability on orbit (McClain et al., 1996). These data streams support research needs as well as applications (internationally) with regard to defence, fisheries management, environmental and water quality, shipping, and recreation.

To gain insight into climate variability and change, one requirement is a continuous time series of observations to estimate ocean properties such as phytoplankton chlorophyll-a with the radiometric accuracy of current sensors, such as SeaWiFS, or better. Describing and quantifying new properties of ocean biology and chemistry from satellites allows developments in basic research, such as the mechanistic understanding of phytoplankton physiology, habitat health, and carbon fluxes, to move from the laboratory to the global context of Earth's biosphere. These advances require an evolution in satellite instruments and missions beyond traditional measurements that enable scientific discovery. And it is here that the challenge lies; to ensure that developments in ocean-colour remote sensing match the rapid pace of scientific research while continuing to produce a series of data critical to the quality of our existing ocean time series.

The advancement of ocean-colour sensor technology and observations necessarily implies coincident advances in *in situ* technologies for data product validation and vicarious gain adjustments in conjunction with new protocol developments, new algorithm development activities as well as modelling capabilities, new atmospheric corrections, etc., but specifically a significant, sustained, and complementary investment in scientific research. Some of these requirements are the subject of other IOCCG reports either completed or in development, and will not be addressed here. This report references these topics where necessary, but remains focussed on topics including better radiometric performances (e.g., in terms of dynamical range and signal-to-noise ratios), placement of, and an increased number of spectral channels as linked to scientific questions.

The views presented in this document will hopefully direct the reader to ascertain the trade-offs between scientific objectives and instrument requirements to achieve these objectives. We seek to relate the listed band set to the overall scientific questions, allowing each agency to choose for themselves how to best design a sensor; however, we encourage the agencies to consider the full range of ocean-colour remote sensing scientific questions when deciding on their sensor requirements. We wish to echo the view of the first report as such: a commonality in the spectral acquisition provides important practical, as well as scientific, advantages, including:

1. easy intercomparison between sensors, and even radiometric intercalibration in well-defined conditions;
2. a full compatibility of operational algorithms for atmospheric correction and derivation of end products;
3. a meaningful data merging, at the level of geophysical products (pigment index, aerosol optical thickness) or at the level of the initial quantities (e.g., spectral normalized radiances);
4. a long-term continuity of ocean-colour observations, based on stable, entirely comparable, parameters; and therefore
5. the building up of a coherent data base for global biogeochemical studies and related modelling activities, for physical studies and models (heating rate, mixed layer dynamics), and for climatological purposes involving the radiative budget and the effect of aerosol loading.

Geographically and optically, the areas of interest have long been expanded beyond the so-called Morel Case I/open ocean waters or blue waters in to the range of optically complex, coloured (generally coastal) waters. “Ocean” colour can also be used to examine the biology, chemistry, and ecology of lakes, rivers, and estuaries.

The advent of the Virtual Constellation for Ocean-Colour Radiometry (CEOS, GCOS-IP) necessarily begs for this report to be written. Such a constellation, if desired to be successful, would require several “identical” instruments operating simultaneously on orbit, regardless of the need for additional advancements or observational capabilities to advance science.

The opinions expressed here are those of the authors; in no way do they represent the policy of agencies that support or participate in the IOCCG. The authors are the members of a working group established by the IOCCG for addressing the aforementioned issues.

Chapter 2

Science Questions and Applications

2.1 Background

Level-1 requirements begin with the science objectives, questions, and applications a satellite sensor and mission is to address and provide answers to. Initially, in the 1970s when the ocean-colour proof-of-concept sensor, the Nimbus-7 Coastal Zone Color Scanner (CZCS), was conceived, the objective was quite basic and focused on whether or not total pigment could be quantified. Total pigment was defined as the sum of chlorophyll-a and phaeophytin. Sensitivity of the ocean reflectance spectrum to chlorophyll-a had been demonstrated using an airborne instrument (Clark et al., 1970), which also underscored the challenge of removing atmospheric radiance from high altitude observations. Because of the relatively weak signal from the open ocean, most thought that the best opportunity to obtain useful ocean reflectances would be in the more turbid coastal waters where reflectances would be higher (hence the name Coastal Zone Color Scanner). The CZCS was designed with four bands in the visible to quantify the spectral "see-saw" as higher pigment concentrations suppressed the reflectance at the chlorophyll absorption maximum (443 nm) and enhanced reflectance in the red through increased particulate scattering. Because of the proof-of-concept nature of the CZCS, routine global coverage was not a requirement and time series from only a few regions identified by the CZCS Nimbus Experiment Team (NET) were collected, e.g., U.S. coastal waters, Adriatic Sea, and the Arabian Sea. Also, the mission plan only provided for a one-year post-launch field program and very limited data processing and distribution primarily for the NET.

After launch, methods to remove the Rayleigh (molecules) and aerosol radiances were refined, demonstrating that open ocean reflectances could be quantified accurately. The imagery showed open ocean mesoscale structures not previously imagined and regional time series analyses unveiled the seasonal cycles and even inter-annual variability that could not be observed using *in situ* observations. These findings resulted in a whole new perspective in ocean ecology and biogeochemistry and greatly expanded the objectives of the next generation of ocean-colour missions. Thus, as a result, mission objectives leapt forward from a simple demonstration of pigment quantification in coastal regions to routine global observations over an extended period of time.

In the second generation of sensors, e.g., OCTS, POLDER, SeaWiFS, MODIS, MERIS,

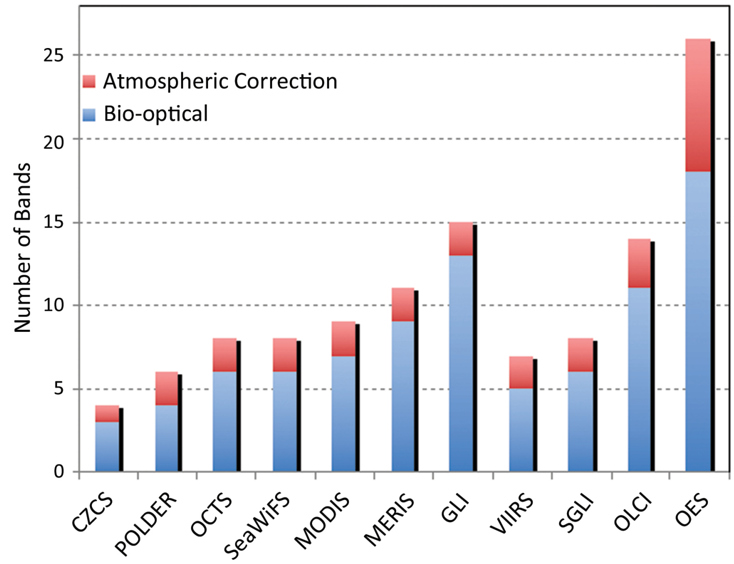

Figure 2.1 Chronological sequence of global ocean-colour satellite sensors and the number of specified multispectral ocean-colour atmospheric correction and bio-optical bands.

and GLI, additional bio-optical and atmospheric correction bands were incorporated to transition from total pigment to chlorophyll-a, and improve derived product accuracy via more accurate aerosol corrections. The science objectives expanded to include estimation of global primary production and quantification of ocean biological variability on global scales, for at least five years. The emphasis of these missions essentially shifted to the open ocean. Figure 2.1 illustrates the progression of sensors and their ocean spectral bands (bio-optical and atmospheric correction). The increase in spectral coverage was monotonic from the CZCS through GLI. Clearly, the GLI sensor was designed to move ocean science forward well beyond what the previous sensors would support. To meet these science objectives required comprehensive mission long calibration and validation programs, new strategies for tracking sensor degradation on orbit, e.g., the SeaWiFS lunar calibration, and greatly increased data storage, processing/reprocessing, and distribution capabilities. The first of these sensors, OCTS and POLDER on ADEOS-1, were launched in 1996. Thus, there is a 10-year gap between the CZCS and the next ocean-colour satellite sensors. Today, after almost continuous global observations since 1996 (the only gap is a two month interval between the ADEOS-1 data sets and SeaWiFS), the goal of accurate chlorophyll-a estimates has largely been achieved, although degradation in the product due to CDOM (Siegel et al., 2005) and suspended sediments (particularly in coastal and estuarine areas) remains an issue, and much progress has been made on primary production algorithms (Carr et al., 2006). Also, in these fourteen years, algorithms for inherent optical properties (IOPs), ocean carbon constituents (dissolved and particulate), fluorescence line height, phytoplankton functional group identification, and particle size distributions have been developed. Research in coastal and estuarine waters (see IOCCG, 2000) has been facilitated as a result of improved aerosol corrections over turbid water, e.g., Wang and Shi (2005) and Bailey et al. (2010). These algorithm developments have expanded the original science themes to include the ocean carbon budget, ecosystem composition, estuarine studies and coastal zone management. Nonetheless, spectral coverage limits the accuracy or feasibility of many of these new products and applications. Thus, these new themes have become the focus of future missions like OLCI and PACE.

After GLI, Figure 2.1 shows a marked decrease in spectral coverage beginning with VIIRS. Together, VIIRS and SGLI should continue the existing ocean-colour time series without a gap given their launches in 2011 and 2015, respectively. The Sentinel-3 OLCI and the PACE OES missions represent the third generation of ocean-colour sensors. The expanded science objectives of this next generation of missions are the topic of this chapter that begins with a brief overview of the science traceability matrix (STM) structure.

In order to develop sensor requirements, a sequence of steps needs to be devised that establishes the linkage between the scientific questions and objectives of the mission and the satellite sensor attributes (spectral coverage, spatial resolution, calibration accuracy, etc.). The sequence of steps is outlined in Table 2.1 It must be noted that it is often difficult to state how accurate the derived products must be in order to answer a scientific question. In fact, some mission objectives may not have a clearly defensible measurement accuracy requirement for a particular derived product. For instance, if the objective is to estimate annual global ocean net primary production, what considerations determine the accuracy requirement, i.e., why do we need to know net production at a particular accuracy? In the case of SeaWiFS and MODIS, the primary parameter to be derived was chlorophyll-a and an accuracy goal of 35% in the open ocean (range of 0.5-50 mg m^{-3}) was set by community consensus primarily because uncertainties in the *in situ* measurements and physiological variability precluded a more accurate goal. The accuracy really was not associated with a scientific question requiring a particular accuracy. Nonetheless, where possible, the research community should articulate science objectives and rationale in quantitative terms rather than simply taking what is thought to be the best possible accuracy using existing field and laboratory measurements and adding some margin. These points are underscored by efforts to estimate decadal changes in global primary production by comparing estimates from CZCS and SeaWiFS (Gregg et al., 2003; Antoine et al., 2005) that are substantially different. The CZCS mission was designed simply as a proof-of-concept demonstration, e.g., limited sensor capabilities, global coverage, and validation program, whereas the SeaWiFS mission was executed with the intent of improving global estimates of primary production even if a specific accuracy was not defined. McClain et al. (2006) discuss the mission requirements for climate change research such as decadal variations in

Table 2.1 The logical or ideal sequence of steps for determining sensor spectral coverage and performance requirements

Requirements Flow Steps	**Description**
1. Science objectives and questions	Define what science issues the mission is to address, e.g., global carbon budget, coastal zone management.
2. Products and product accuracy requirements	Outline what derived products are needed to address the science questions, e.g., net primary production, total suspended matter.
3. Algorithms and spectral band selection	Identify the bio-optical algorithms to be used to derive the required products and what spectral bands are needed for each algorithm. The atmospheric correction bands are identified at this step.
4. Bio-optical algorithm accuracy requirements	Determine the accuracy of the bio-optical algorithms needed to address the science questions.
5. L_{wN} or R_{rs} accuracy requirements	Based on the algorithm accuracy requirement, quantify the spectral L_{wN} or R_{rs} accuracy required (assumes a "perfect" bio-optical algorithm.
6. TOA radiance accuracy requirements	By propagating the L_w's to the top of the atmosphere using the typical atmospheric parameter values, e.g., aerosol optical thickness, determine an acceptable partitioning of bio-optical and atmospheric correction algorithm uncertainties to arrive at a top-of-atmosphere radiance uncertainty budget that will achieve the L_{wN} or R_{rs} spectral accuracy requirements.
7. Single set of "most stringent" spectral accuracy requirements	Because different bio-optical products require various spectral accuracies, synthesize one set of spectral accuracies that satisfies all product accuracy requirements.
8. Sensor spectral calibration and characterization requirements and test specifications	Based on the TOA spectral radiance accuracy requirements, specify the sensor calibration accuracies for the various sensor sensitivity parameters, e.g., radiometric linearity, polarization, temperature, out-of-band response.

marine primary productivity.

In deriving a sensor performance specification, it must be understood that a spaceborne instrument cannot compensate for uncertainties in the bio-optical and atmospheric correction algorithms, e.g., biological variability in specific absorption and aerosol model phase function parameterizations. However, inaccuracies in the sensor calibration or inadequate sensor specifications will broaden the error bars in the estimation of geophysical products. Also, there are practical limitations of time, budget, and test facility technology that can limit the accuracy and comprehensiveness of the satellite sensor characterization. Similarly, the accuracy of the bio-optical and atmospheric correction algorithms is limited, to some degree, by the field program funding, e.g., variety of environments sampled, instrument technology and measurement methodologies (protocol development).

Ideally these steps are incorporated in what is called a Science Traceability Matrix

(STM) which is discussed below. It is beyond the scope of this Level-1 requirements document to develop in detail all the analyses and considerations that can be involved in the steps outlined in Table 2.1, but does address many of them at some level.

2.2 The IOCCG Science Traceability Matrix

A NASA mission STM is designed to show the flow between mission science objectives or questions and the sensor and mission requirements. Typically, the STM has columns for science questions, approach, measurement requirements, sensor requirements, platform requirements, and other mission requirements. For this report, the "IOCCG" STM was simplified to four columns (science questions, approach using space ocean-colour data, space product requirements, and space measurement requirements). Figure 2.2 is the IOCCG STM and each column is briefly defined below.

2.2.1 Science questions

The questions and applications define the scope of the mission and are linked to the research themes that the international community is pursuing in partnership with other agencies such as the U.S. National Science Foundation, various climate programs, and fisheries services. This being the case, the nine science themes in the STM cover a wide range of topics, some of which include multiple questions.

2.2.2 Approach using space ocean-colour data

This is a set of brief statements about the methods to be used to address the science questions. Most methods apply to more than one question, but several are unique to a specific question. In the STM, this mapping of methods to questions is shown by the colour coded question indices imbedded in each method description.

2.2.3 Space product requirements

With each method, and therefore, each question, there are certain geophysical parameters that are needed which can be estimated from space, e.g., chlorophyll-a. This column is the list of parameters as well as the basic radiometric input for the parameter algorithms, i.e., normalized water-leaving radiance. Also, the temporal and spatial coverage requirements are listed. These set the requirements on the satellite sensor, orbit, etc.

Global Ocean and Climate Change STM

IOCCG

Category	Scientific Questions
Global Ocean Science and Climate Change	1 What are the phytoplankton standing stocks, composition, & productivity of ocean ecosystems? How and why are marine ecosystems changing and what changes are expected in the future? How are these changes related to human activities (e.g., climate change) and what are the feedbacks to the climate system?
	2 How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? How to monitor them?
	3 How are the material exchanges between land & ocean varying and changing? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing?
	4 How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system?
	5 How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics?
	6 What are the distributions and magnitudes of algal blooms? How do human activities, such as eutrophication, and climate change, affect blooms. Can harmful blooms be differentiated from other blooms?
	7 How can satellite remote sensing be used to investigate and monitor coastal ecosystems (e.g., water quality and coral reef health)?
	8 How are changes in marine ecosystems and habitat affecting fisheries.
	9 Can ocean dumping be observed using satellite ocean color radiometry and can aggregation zones be identified?

Approach using space OC data	Maps to Science Question
Quantify phytoplankton biomass, pigments, optical properties, key groups (functional/HABS), and productivity using bio-optical models & chlorophyll fluorescence. Quantify relationship between physiological state and bio-optical properties.	1, 2, 6, 7
Measure particulate and dissolved carbon pools, their characteristics and optical properties.	2, 3
Quantify ocean photobiochemical and photobiological processes.	2, 4
Estimate particle abundance, size distribution (PSD), & characteristics.	1, 3, 7, 2
Assimilate observations into ocean biogeochemical model fields of key properties (cf., air-sea CO_2 fluxes, carbon export, pH, etc.).	2
Compare observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc).	3, 4, 5, 6, 7
Combine ocean & atmosphere observations with models to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol & cloud properties.	4
Assess ocean radiant heating and feedbacks.	5
Correlate fish stocks, year class survival rates, and life cycles with bloom concentrations, timing and taxonomic composition.	8
Evaluate anomalous ocean reflectance signatures due to floating debris and refuse.	9

Space Product Requirements	Mission Measurement Requirements
1 km spatial resolution grid Global 2-day coverage Level 2 and Level 3 ▸ **Intermediate products:** Aerosol optical thickness, Angström exponent ▸ **Basic products:** nLw (normalized water-leaving radiances) or Rrs (remote sensing reflectances) in UV, VIS, and NIR (μW cm^{-2} μm^{-1} sr^{-1}) at either a set of spectral bands or hyperspectral data depending on mission objectives ▸ **Derived products:** • Chl (mg m^{-3}) Chlorophyll concentration for Case-1, Case-2 and merged cases • Primary production (g C m^{-2} d^{-1}) • YSBPA (m^{-1}) Yellow substance and bleached particle absorption • DOM (m^{-1}) Dissolved organic matter absorption • CDOM (m^{-1}) Colored dissolved organic matter absorption • TSM (g m^{-3}) Total suspended matter • K_d(490) diffuse attenuation coefficient at 490 nm (m^{-1}) • PAR (μEin m^{-2}) daily photosynthetic available radiation • iPAR (μEin m^{-2}) instantaneous photosynthetic available radiation • a, absorption coefficient (m^{-1}): total, CDM, CDOM, phytoplankton, non-algal detritus • b_b, backscattering coefficients (m^{-1}): total, particulate (small, large) • FLH Fluorescence Line Height • PIC/POC Particle inorganic/organic carbon (moles m^{-3}) • Eutrophic depth (m), Secchi depth (m) • Phytoplankton physiological parameters: Growth rate, C:Chl, Chlorophyll fluorescence efficiency & quantum yields • Classification : Phytoplankton type (PHYSAT) • Particle size distribution	**1. Ocean Radiometer** Total radiances in UV, VIS, NIR, & SWIR. For example: Bio-optical bands: 360, 385, 412, 443, 460, 490, 510, 555, 583, 617, 640, 665, 678, 710 nm Atmospheric correction bands: 748, 765, 865, 1245, 1640 nm Pre-launch characterization data & documentation **2. Field validation program** **3. Vicarious calibration program** **4. Data system** Latency: 3 hrs – operational; 2 weeks – science Reprocessing capacity **5. Ancillary data** Ozone Surface vector winds NO_2 Surface pressure Water vapor concentration Relative humidity

Figure 2.2 Science traceability matrix for future ocean-colour missions.

2.2.4 Space measurement requirements

Based on the atmospheric correction and derived product algorithm requirements, the spectral measurement requirements can be defined. While not shown in the STM, sensitivity and error analysis studies are required to further specify instrument performance characteristics like signal-to-noise ratios, quantization, saturation radiances, polarization sensitivity, and others. This is addressed in more detail in Chapter 4.

2.3 Science Questions

The IOCCG Mission Requirements working group identified nine science themes, each with at least one question. Each is discussed briefly below. A comprehensive evaluation of benefits and applications of ocean-colour data for science and society is provided in IOCCG Report Number 7, *Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology* (IOCCG, 2008).

1. Marine Ecosystems: *What are the phytoplankton standing stocks, composition, and productivity of ocean ecosystems? How and why are marine ecosystems changing and what changes are expected in the future? How are these changes related to human activities (e.g., climate change) and what are the feedbacks to the climate system?*

The questions regarding marine ecosystems are fundamental to understanding the living ocean and were the impetus for the original research in remote sensing of ocean colour. The ocean is so difficult to sample even on mesoscales that until the CZCS data became available, only a crude picture of the phytoplankton distributions and primary production was available based on climatologies using very coarsely sampled data in space and time (Berger, et al., 1989). Chlorophyll-a is an indicator of phytoplankton distributions and the current satellite time series reveal global patterns that vary to a degree that was not imagined earlier. "Standing stocks" really refer to carbon concentrations in living plants. To infer standing stocks from chlorophyll-a requires knowledge of the C:Chl-a ratio which is variable depending on the species of plants present and their physiological state. Physiology, in turn, is dependent on light and nutrient availability and history. Thus, research is moving beyond chlorophyll-a to carbon biomass and a number of approaches are being pursued including those that bypass chlorophyll and focus on particulate backscatter (Behrenfeld et al., 2005).

How ecosystems change over time on global scales is an obvious application for remote sensing. However, it is not simply a matter of estimating changes in chlorophyll concentration or even biomass. This question asks how the phytoplankton assemblage changes over time. It is well known that species change in many, if not most, locales as a seasonal succession (Signorini et al., 2006), but documentation of such changes is sparse over much of the ocean. How assemblages vary over interannual time scales is even more uncertain, especially with the onset of global warming and ocean acidification (Doney et al., 2009). To address this question requires algorithms for differentiating species. Species like coccolithophores are readily identified using calcite concentrations (Balch et al., 2007) and some progress on *Trichodesmium* (Westberry et al., 2005) has been published. Several approaches to identify several groups simultaneously have been published in recent years (Alvain et al., 2005), some of which focus on size classes and others on functional groups. All seem to be limited by the databases used and the remote sensing spectral information available. Determining the spectral coverage and resolution needed to improve these products is a primary theme for future missions such as NASA's PACE and ACE missions.

A consequence of changes in ecosystem structure and composition is the concomitant impacts on biogeochemical cycles like carbon, nitrogen, and phosphorus. As ecosystem structure and composition change, so will net primary production and related carbon cycling processes. These changes also ripple up the food chain, eventually affecting fish stocks. Acidification adversely impacts species' (phytoplankton and zooplankton) abilities to maintain calcite and aragonite structures by increasing the solubility. Acidification is the direct result of increasing atmospheric CO_2 concentrations. The ocean carbonate buffer system will continue to maintain an equilibrium with the atmosphere resulting in higher $p\mathrm{CO}_2$ and decreasing pH, although the ocean's ability to absorb CO_2 will decline over the next two centuries (Doney et al., 2009).

2. Biogeochemical Cycles: *How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? How to monitor them?*

As mentioned above, climate change and increasing anthropogenic CO_2 are having an impact on marine ecosystems and the carbon cycle. These biogeochemical cycles are not independent, but are intertwined via complex biological, chemical, and photochemical processes which in some respects are understood, but in others, not well at all. While remote sensing can provide estimates of surface carbon pools (PIC, POC and regional DOC) and rates (NPP), for example, coupled circulation-biogeochemical models can provide details of the depth resolved interplay of the myriad of processes. Programs such as the Joint Global Ocean Flux Study (JGOFS), the Surface Ocean-Lower Atmosphere Study (SOLAS), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), and others seek to improve our knowledge of these complex systems. Coordination between programs like these and future satellite missions is essential. For example, the SeaWiFS launch was initially set to overlap much of JGOFS and did launch in time for the Southern Ocean JGOFS program.

3. Land-Ocean Interactions: *How are the material exchanges between land and* *ocean varying and changing? How do they influence coastal ecosystems, biogeochemistry and habitats? How are they changing?*

With human populations and land use expanding, particularly in coastal areas, concentrations of suspended particulates and dissolved nutrients have increased dramatically. Reclamation of wetlands for development also has a major impact by reducing the area of marshes, mangrove swamps, and wetlands which naturally capture and hold much of the terrestrial run-off. Water clarity is a major issue for estuarine systems like the Chesapeake Bay which has seen pronounced reductions in sea grass beds over the past few decades. These are critical to many marine animal populations, particularly shellfish, crab, and other commercial fisheries. Riverine systems like the Mississippi River transport large amounts of anthropogenic nutrients into their delta regions and adjacent shelves resulting in eutrophication and even "dead zones" (Goolsby, 2000). Regulation of agricultural, sewage, and construction practices has helped reduce these fluxes, but presently rely on *in situ* data monitoring. With climate warming and sea level rise, monitoring and managing coastal and estuarine systems becomes even more urgent. Remote sensing of key parameters at appropriate spatial and temporal scales can provide valuable complementary information that in many situations may not be available from *in situ* data, e.g., where economies or infrastructure do not allow.

4. Ocean-Atmosphere Biogeochemical Interactions: *How do aerosols and clouds influence ocean ecosystems and biogeochemical cycles? How do ocean biological and photochemical processes affect the atmosphere and Earth system?*

Cloud cover is the most obvious of the ocean-atmosphere interactions and while the impact of surface illumination on marine phytoplankton growth is easy to appreciate, phytoplankton species are photoadapted to compensate for too much or too little light, a process that is not easily quantified or modelled. Also, light intensity has indirect effects on stratification and, therefore, vertical nutrient fluxes and so on. Over the past twenty years, Aeolian fluxes of iron (Martin and Fitzwater, 1988), nitrogen, sulfur and other nutrients have received increasing attention. Quantifying the sources, deposition rates, and chemical processes affecting these nutrients while in the atmosphere, and their bio-availability once in the water column, remains a challenge. While satellite ocean-colour remote sensing is not intended to measure atmospheric compounds, even those required for processing, such as ozone and NO_2, it should be able to identify and distinguish certain types of absorbing aerosols (dust, smoke, etc.) and possibly estimate layer height and material concentrations.

Other ocean-atmosphere interactions are important to consider such as the biological generation of dimethyl sulfide (DMS) and its role in aerosol and cloud formation (Charlson et al., 1987). Also, volatile organics play an important role in marine aerosol formation (Meskhidze and Nenes, 2006). The feedbacks between ocean biogeochemistry and atmospheric properties and the magnitude of the intermediate air-sea fluxes have implications for climate forecasting and are the objectives of international research programs like The Surface Ocean - Lower Atmosphere Study (SOLAS; http://www.solas-int.org). There have been only a few publications on the use of remote sensing to study these interactions (Thompson et al., 1990; see also *Advances in Meteorology*, special issue on Marine Aerosol-Cloud-Climate Interaction, 2010), but in the future, with more advanced ocean colour and atmospheric chemistry sensors, research on this topic should be much more feasible.

5. Biological-Dynamical Interactions: *How do physical ocean processes affect ocean ecosystems and biogeochemistry? How do ocean biological processes influence ocean physics?*

Physical processes include mechanical turbulent mixing such as breaking waves and shear instabilities, buoyancy fluxes related to air-sea heat exchange, stratification, and upwelling/downwelling via Ekman transport, planetary wave circulations (Rossby, Kelvin, etc.), Langmuir circulation, and frontal oscillations. The influences of physical processes on nutrient concentrations, surface layer stability, and mixed layer depth have been studied extensively. Phytoplankton and dissolved light-absorbing constituents do modulate light penetration (Lewis et al., 1990; Ohlman et al., 1996) and such feedbacks on near surface ocean structure and circulation (Murtugudde et al., 2002), even tropical storm frequency (Gnanadesikan et al., 2010), has not been as well documented, although these interactions are becoming more fully appreciated. In the future, satellite observations that more accurately quantify the surface layer optical properties will improve quantification of these feedbacks in process and climate models.

6. Algal Blooms: *What are the distributions and magnitudes of algal blooms? How do human activities, such as eutrophication, and climate change, affect blooms? Can harmful blooms be differentiated from other blooms?*

Algal blooms refer to high concentrations of phytoplankton that can occur suddenly on local scales when conditions are optimal, e.g., coastal upwelling events, or on basin-wide seasonal scales, e.g., the North Atlantic spring bloom. Blooms can be short-lived (days), or persistent (months). Satellite ocean-colour remote sensing provides the spatial and temporal coverage required to determine the locations and frequencies of these events and, when correlated with other environmental data such as surface winds, SST, and sea level observations, can be used to understand the causes of bloom formation and collapse. Because blooms occur under particular conditions, the timing, frequency, composition and intensity are expected to change with climate in ways that may be hard to predict. Blooms of certain species of phytoplankton can be toxic (harmful algal blooms or HABs) or unpleasant (Berthon et al., 2000) and require monitoring for public health purposes. Thus, reliable and accurate detection of these types of blooms is an objective for future missions.

7. Coastal and Estuarine Ecosystem Health: *How can satellite remote sensing be used to investigate and monitor coastal ecosystems (e.g., water quality and coral reef health)?*

Ecosystem health is a rather broad term referring to the state of the ecosystem relative to its state under normal unperturbed conditions, e.g., density of animal and plant life, species composition, ability to withstand adverse conditions. Environmental factors such as water temperature, nutrient loading, sedimentation, water clarity, water depth, pollutants, and salinity influence ecosystem health. Changes in these factors can be natural, e.g., El Niño, or anthropogenic, e.g., agricultural and municipal runoff. Considering corals for instance, abnormally warm conditions result in coral bleaching which can decimate large tracts of reef systems. Starfish infestations can have similar results. Healthy ecosystems are critical to fisheries, recreation, tourism, and other industries. These ecosystems are not just those within the water column, but include adjacent areas such as wetlands and mangroves that serve as buffers between terrestrial and marine systems. Kelp and seagrass beds are other examples. With advances in sensor and satellite technologies allowing for broader spectral coverage and dynamic range, higher signal-to-noise, and much greater onboard storage and telemetry bandwidth, a single ocean-colour satellite sensor can be used for this area of research as well as the open ocean.

8. Fisheries: *How are changes in marine ecosystems and habitat affecting fisheries?*. This topic is discussed in much detail from a number of perspectives in IOCCG Report Number 8, *Remote Sensing of Fisheries and Aquaculture* (IOCCG, 2009).

9. Ocean Pollution: *Can ocean dumping be observed using satellite ocean-colour radiometry and can aggregation zones be identified?*

Certain types of ocean pollution and ocean property changes are easily observed from space such as dump sites (Elrod, 1988; Son et al., 2011). Ocean fronts can be sites of surface confluence where material collects, as is often observed with *Sargassum*. More recently, areas within basin scale features like the North Pacific gyre have been identified as the sites of concentrated human generated debris that does not readily deteriorate. The western islands in the Hawaiian chain recently set aside as marine preserves are littered with such material. Fishing nets and plastic bottles are very common. Whether satellite ocean-colour data can be used to identify aggregations of such material in the ocean has yet to be demonstrated, but deserves attention. The Deep Water Horizon oil spill in the Gulf of Mexico is another example of where ocean-colour satellite imagery might be used to track pollution and, perhaps, even quantify the surface oil volumes.

Chapter 3

Approaches and Data Product Requirements

3.1 Background

In Chapter 2, the science questions to be addressed in the future are briefly discussed in the context of the Science Traceability Matrix (STM). Associated with each science question are approaches that describe the methodologies to be pursued to answer the question. The STM lists a number of approaches, some of which are applicable to more than one question, as shown in Figure 2.2. The approaches, as stated, are rather general and could be expressed in a variety of ways. In the context of this document, the approaches are meant to point to specific properties that can be estimated from space and, therefore, link the questions to ocean-colour satellite products. Certainly, approaches can also include extensive field campaigns and ocean model development with data assimilation, designed to unravel complex processes that are far beyond the limited measurements from space. Ideally, satellite missions would at least be coordinated with such programs, as was the plan for JGOFS and SeaWiFS, or even support them directly. Supporting field campaigns as part of a satellite mission helps to ensure a tight coupling between the mission science, calibration and validation data collection, product development, and the field program objectives and design. This avoids the collection of partial bio-optical data sets on cruises of opportunity, and allows the mission science team to tailor field campaigns to mission science issues that require very specific field measurement strategies that would not be possible on cruises of opportunity with different sampling requirements.

Clearly, the satellite data products alone cannot answer many of the scientific questions at the level of detail required, particularly with respect to the processes within ocean biogeochemical systems that regulate transformations of materials and the associated rates or concentrations below the first optical depth. This is the province of coupled models (atmospheric, ocean dynamics/circulation, biogeochemical). The satellite products can be used for model validation or incorporated into models as inputs via data assimilation schemes to improve model performance, e.g., Gregg (2008).

The specific approaches can be tied to particular satellite products as shown in Table 3.1. Consequently, products can be mapped to scientific questions as shown in Tables 3.2 and 3.3. While the specifics of the flow down from questions to approaches to data products can be debated, the tables do illustrate a rationale for what products are needed with an indication of their relative importance which, in turn, can be used in cost-benefit considerations for algorithm development and validation planning. The definitions of the satellite product parameters are also provided below.

Table 3.1: Correspondence between approaches for addressing scientific questions and ocean-colour satellite data products.

Approach	**Satellite Products**
Quantify phytoplankton biomass, pigments, optical properties, key groups (functional/HABs), and productivity using bio-optical models and chlorophyll fluorescence. Quantify relationship between physiological state and bio-optical properties. Scientific questions 1, 2, and 6.	Chlorophyll-a, other phytoplankton pigments, primary production, particulate inorganic carbon, dissolved organic matter/carbon, taxonomic groups (e.g., coccolithophore and *Trichodesmium* concentrations), physiological properties, particle size distribution, normalized water-leaving radiances (or remote sensing reflectances).
Measure particulate and dissolved carbon pools, their characteristics and optical properties. Scientific questions 2 and 3.	Particulate organic carbon, particulate inorganic carbon, dissolved organic carbon/matter, *Trichodesmium* concentration, particle size distribution, total suspended matter, coloured dissolved organic matter, yellow substance and bleached particle absorption, diffuse attenuation coefficient.
Quantify ocean photobiochemical and photobiological processes. Scientific questions 2 and 4.	Primary production, dissolved organic carbon/matter, particle size distribution, photosynthetically available radiation, fluorescence line height, taxonomic groups.
Estimate particle abundance, size distribution (PSD), and characteristics. Scientific questions 1, 2 and 3.	Particulate inorganic carbon, taxonomic groups (e.g., coccolithophore and *Trichodesmium* concentrations), particle size distribution, total suspended matter.
Assimilate observations into ocean biogeochemical model fields of key properties (cf., air-sea CO_2 fluxes, carbon export, pH, etc.). Scientific question 2.	Primary production, particulate organic carbon, particulate inorganic carbon, dissolved organic carbon/matter, *Trichodesmium* concentration, taxonomic groups.

Continued on next page

Table 3.1 – *Continued from previous page*

Approach	Satellite Products
Compare observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc.), and circulation (ML dynamics, horizontal divergence, etc.) Scientific questions 3, 4, 5, and 6.	Total suspended matter, coloured dissolved organic matter, diffuse attenuation coefficient, particle size distribution, photosynthetically available radiation, fluorescence line height, aerosol properties, taxonomic groups, chlorophyll-a, primary production, euphotic depth, diffuse attenuation coefficient, normalized water-leaving radiances (or remote sensing reflectances.)
Combine ocean and atmosphere observations with models to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol and cloud properties. Scientific question 4.	Aerosol properties, taxonomic groups.
Assess ocean radiant heating and feedbacks. Scientific question 5.	Photosynthetically available radiation, euphotic depth, diffuse attenuation coefficient.
Correlate fish stocks, year class survival rates, and life cycles with bloom concentrations, timing and taxonomic composition. Scientific question 8.	Chlorophyll-a, primary production, taxonomic groups.
Evaluate anomalous ocean reflectance signatures due to floating debris and refuse. Scientific question 9.	Normalized water-leaving radiances (or remote sensing reflectances), diffuse attenuation coefficient.

3.2 Product Definitions

Normalized water-leaving radiance, normalized reflectance, and remote sensing reflectance: These are the basic quantities derived from ocean-colour satellite sensors and are the inputs to the bio-optical algorithms for the other ocean geophysical quantities in Tables 3.1 and 3.2. Each are used by different groups within the ocean-colour community. The relationship between these two radiometric quantities is straightforward and described below. Normalized marine reflectance or ρ_{wN} (non-dimensional) is defined as π times the remote sensing reflectance which is the ratio of the water-leaving radiance (L_w) divided by the downwelling solar irradiance (E_d) above the surface, i.e.,

$$\rho_{wN} = \pi L_w / E_d^+$$

The initial definition of the normalized water-leaving radiance (measured at the wavelength λ and solar-zenith, sensor-zenith, and relative azimuth angles of θ_0, θ,

Table 3.2: Mapping of scientific questions to satellite data products needed to address the questions.

Scientific Question	**Satellite Data Products**
1. What are the phytoplankton standing stocks, composition, and productivity of ocean ecosystems? How and why are marine ecosystems changing and what changes are expected in the future? How are these changes related to human activities (e.g., climate change) and what are the feedbacks to the climate system?	Chlorophyll-a, other phytoplankton pigments, primary production, particulate inorganic carbon, dissolved organic matter/carbon, taxonomic groups (e.g., coccolithophore and *Trichodesmium* concentrations), physiological properties.
2. How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? How to monitor them?	Primary production, particulate organic carbon, particulate inorganic carbon, dissolved organic carbon/matter, *Trichodesmium* concentration, particle size distribution, taxonomic groups.
3. How are the material exchanges between land and ocean varying and changing? How do they influence coastal ecosystems, biogeochemistry and habitats? How are they changing?	Total suspended matter, coloured dissolved organic matter, yellow substance and bleached particle absorption, diffuse attenuation coefficient, particle size distribution.
4. How do aerosols and clouds influence ocean ecosystems and biogeochemical cycles? How do ocean biological and photochemical processes affect the atmosphere and Earth system?	Photosynthetically available radiation, fluorescence line height, aerosol properties, taxonomic groups.
5. How do physical ocean processes affect ocean ecosystems and biogeochemistry? How do ocean biological processes influence ocean physics?	Chlorophyll-a, primary production, photosynthetically available radiation, euphotic depth, diffuse attenuation coefficient.
6. What are the distributions and magnitudes of algal blooms? How do human activities, such as eutrophication, and climate change, affect blooms. Can harmful blooms be differentiated from other blooms?	Chlorophyll-a, normalized water-leaving radiances (or remote sensing reflectances).
7. How can satellite remote sensing be used to investigate and monitor coastal ecosystems (e.g., water quality and coral reef health)?	Total suspended matter, chlorophyll-a, diffuse attenuation coefficient, particle size distribution.
8. How are changes in marine ecosystems and habitat affecting fisheries?	Chlorophyll-a, primary production, taxonomic groups.
9. Can ocean dumping be observed using satellite ocean-colour radiometry and can aggregation zones be identified?	Normalized water-leaving radiances (or remote sensing reflectances), diffuse attenuation coefficient.

and $\Delta\phi$) (Gordon and Clark, 1981; Morel and Gentili, 1991; 1993; 1996; Gordon, 2005; Wang, 2006) is given by:

$$[L_w(\lambda, \theta_0, \theta, \Delta\phi)]_N = L_w(\lambda, \theta_0, \theta, \Delta\phi)\frac{\overline{F}_0(\lambda)}{E_d^{(+)}(\lambda, \theta_0)} \cong \left(\frac{d}{d_0}\right)^2 \frac{L_w(\lambda, \theta_0, \theta, \Delta\phi)}{t(\lambda, \theta_0)\cos\theta_0},$$

where $F_0(\lambda)$ is the mean extraterrestrial solar irradiance, $E^+(\lambda, \theta_0)$ is the downwelling irradiance just above the surface, $t(\lambda, \theta_0)$ is the atmospheric transmittance, and $(d/d_0)^2$ corrects for variations in Earth-Sun distance during the year. Morel and Gentili (1991; 1993; 1996) extended the definition to account for additional effects due to angular variations in reflection and refraction at the sea surface and for the in-water BRDF, introducing a quantity they dubbed the exact normalized water-leaving radiance,

$$[L_w(\lambda)]_N^{Exact} = [L_w(\lambda, \theta_0, \theta, \Delta\phi)]_N \{(f/Q)_{Eff}\} \left[\frac{\Re_0(\lambda, \tau_a, W)}{\Re(\lambda, \theta_0, \theta, \tau_a, W)}\right],$$

where term $(f/Q)_{Eff}$ represents effects of the in-water ocean BRDF, while the term $\Re$ ratio accounts for angular variations in all effects of reflection and refraction of radiance at the sea surface. In effect, this representation separates BRDF effects attributed to the ocean surface (term with $\Re$ ratio) from effects associated with the angular distribution of upwelling radiance just beneath the water surface,

$$\{(f/Q)_{Eff}\} = \left\{\left(\frac{f_0(\lambda, \mathrm{IOP})}{Q_0(\lambda, \mathrm{IOP})}\right) \Big/ \left(\frac{f(\lambda, \theta_0, \mathrm{IOP})}{Q(\lambda, \theta_0, \theta, \Delta\phi, \mathrm{IOP})}\right)\right\}$$

which depends on solar-sensor geometry and the ocean inherent optical properties (IOPs). In the above, f is a coefficient that relates ocean upwelling irradiance reflectance to the ocean inherent optical properties and the Q factor is defined as the ratio of the upwelling irradiance just beneath the ocean surface to the upwelling radiance just beneath the ocean surface. f_0 and Q_0 are defined for $f(\lambda, \theta_0 = 0, \mathrm{IOP})$ and $Q(\lambda, \theta_0 = 0, \theta = 0, \mathrm{IOP})$, respectively. Note that, for a uniform angular distribution of upwelling radiance just beneath the ocean surface, $\{(f/Q)_{Eff}\} \equiv 1$. More recent refinements to the L_{wN} formulation can be found in Morel et al. (2002), Gordon (2005), and Wang (2006).

The normalized marine reflectance is related to the normalized water leaving radiance by:

$$\rho_{wN} = \pi[L_w]_N/\overline{F}_0$$

and remote sensing reflectance is

$$R_{\mathrm{rs}} = L_w/E_d^+.$$

Aerosol Properties: Properties such as optical depth, Ångström exponent, size distribution, index of refraction (real and imaginary components).

Table 3.3: A reverse mapping from Table 3.2 of satellite data products to relevant scientific questions.

Satellite Data Products	Scientific Questions
Normalized water-leaving radiances or remote sensing reflectances	6, 9 (Note: all products are derived using L_{wN}'s or remote sensing reflectances)
Chlorophyll-a	1, 5, 6, 8
Diffuse attenuation	3, 5, 7, 9
Inherent optical properties	All
Particulate inorganic carbon	2
Particulate organic carbon	1, 2
Primary production	1, 2, 5, 8
Coloured dissolved organic matter	3
Yellow substance and bleached particle absorption	3
Photosynthetically available radiation	4, 5
Fluorescence line height	4
Euphotic depth	5
Total suspended matter	3, 7
Trichodesmium concentration	1, 2
Particle size distribution	2, 3, 7
Dissolved organic matter/carbon	1, 2
Phytoplankton physiological properties (C:Chl, fluorescence yield, growth rate, etc.)	1
Other phytoplankton pigments	1
Phytoplankton taxonomic groups	1, 4, 8
Aerosol properties	4

Chlorophyll-a (Chl-a): The concentration of the photosynthetic pigment, chlorophyll-a (mg m^{-3}, or $\mu g\ l^{-1}$).

Coloured Dissolved Organic Matter (CDOM): The component of dissolved organic matter (DOM) that is optically active, i.e., absorbs visible light. Also known as chromaphoric dissolved organic matter, yellow substance, gelbstoff, or gilvin. Practically, the quantity in remote sensing is expressed as the absorption coefficient (m^{-1}) in the blue part of the spectrum, i.e., $a_{cdom}(412)$

Diffuse Attenuation Coefficient (K_d): An apparent optical property of seawater in remote sensing, it is the attenuation coefficient of downwelling diffused light, i.e, the inverse of the vertical length scale (e-folding length) of downwelling irradiance reduction at a given wavelength (m^{-1}).

Dissolved Organic Matter/Carbon (DOM, DOC): The collective concentration of various organic compounds with sizes less than about 0.4 microns usually measured in [μmol C l^{-1}].

Euphotic Depth (Z_{eu}): The depth where 1% of surface PAR (photosynthetic available radiation, 350 – 700 nm or 400 – 700 nm) remains.

Fluorescence Line Height (FLH): FLH represents the difference between upwelling radiance in the chlorophyll fluorescence band (typically measured at 683 nm) and the upwelling radiance that would result in the absence of fluorescence.

Inherent Optical Properties (IOP): Absorption, scattering (including backscatter), and beam attenuation coefficients (a, b, c), where $c = a + b$ (m^{-1}).

Normalized Water-Leaving Radiance (L_{wN}): The water-leaving radiance transformed to remove the effects of atmosphere and solar zenith and sensor viewing angles (see discussion below); an apparent optical property (AOP).

Other Phytoplankton Pigments: Pigments other than chlorophyll-a having sufficient absorption properties that would allow them to be used in remote sensing applications such as taxonomic group identification. Examples include chlorophyll-b and -c, phycoerythrin, and carotenoids.

Particle Size Distribution (PSD): A histogram of particle number counts in a given volume of water over some specified diameter bin size (dimensionless).

Particulate Inorganic Carbon (PIC): Concentration of calcium carbonate particles mostly in the form of calcite and aragonite (μg C l^{-1} or μmol C l^{-1}).

Particulate Organic Carbon (POC): The collective concentration of various organic compounds with sizes greater than about 0.4 microns (μg C l^{-1} or μmol C l^{-1}).

Photosynthetically Available Radiation (PAR): Photosynthetically available radiation is defined as the solar quantum flux (i.e., number of solar photons per unit of time and surface) available for aquatic photosynthesis, i.e.,

$$\mathrm{PAR} = \int_{400\mathrm{nm}}^{700\mathrm{nm}} (\lambda/hc)E(\lambda)\,d\lambda$$

where λ is wavelength, E is spectral downward plane irradiance (energy per unit of time, surface, and wavelength), h is the Plank constant, and c is the velocity of light.

Phytoplankton Physiological Properties: These include Carbon:Chlorophyll ratio, fluorescence quantum yield, and growth rate among others.

Phytoplankton Taxonomic Groups: This term refers to different classes of phytoplankton based on either size (e.g., microplankton, nanoplankton, and picoplankton) or species (diatoms, dinoflagellates, coccolithophores, etc.).

Primary Production (PP): This usually refers to “net” primary production, which is the rate of carbon fixation via photosynthesis minus the loss due to respiration.

Remote Sensing Reflectance (RSR): The ratio of water-leaving radiance to downwelling irradiance just above the surface (sr^{-1}).

Total Suspended Matter (TSM): The dry weight of particles in a unit volume of water ($mg\ l^{-1}$, or $g\ m^{-3}$).

***Trichodesmium* Concentration:** The number of trichomes per litre of this nitrogen-fixing, photosynthetic cyanobacteria (Westberry et al., 2005).

Yellow Substance and Bleached Particle Absorption (YSBPA): The sum of dissolved organic matter absorption at 443 nm and bleached particle absorption at 443 nm.

These geophysical parameters have natural ranges of variability and researchers need data products that accurately quantify this range to the greatest extent possible. Covering the entire range may not always be possible because of basic limitations in the radiometry, e.g., the change in spectral signature is simply too small to differentiate concentration variations. Table 3.4 provides the natural ranges of these parameters.

Table 3.4: Range of observed geophysical parameter values. The geophysical ranges were determined after an extensive literature survey and data analyses by the Aerosol, Cloud, Ecology (ACE) mission ocean working group.

Geophysical Parameter	Geophysical Range	Comments
Normalized water-leaving radiances	0 - 10 $mW\ cm^{-2}\ \mu m^{-1}\ sr^{-1}$	Wavelength dependent
Remote sensing reflectances	0 - 0.08 sr^{-1}	Wavelength dependent
Chlorophyll-a	0 - 500 $mg\ m^{-3}$	
Diffuse attenuation coefficient	0.02 - 8.0 m^{-1}	Heritage missions focused on $K_d(490)$
Inherent optical properties: - Absorption coefficient - Backscatter coeff. (b_b) - Beam-c	 0.02 - 2 m^{-1} 0.0003 - 0.1 m^{-1} 0.03 - 10 m^{-1}	Wavelength dependent. Specific ranges for absorption can be subdivided into phytoplankton, detrital (or perhaps “depigmented or bleached SPM”) and CDOM.
Particulate inorganic carbon	0.000012 - 0.00053 $mol\ m^{-3}$	
Particulate organic carbon	15 - 2000 $mg\ m^{-3}$	POC can reach nearly 3000 $mg\ m^{-3}$ in Chesapeake Bay and even higher in rivers throughout the globe.
Dissolved organic carbon	35 - 800 $\mu mol\ C\ l^{-1}$	Such high values are only found in rivers. Estuarine values generally do not exceed 500 $\mu mol\ C\ l^{-1}$

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Table 3.4 – *Continued from previous page*

Geophysical Parameter	**Geophysical Range**	**Comments**
Coloured dissolved organic matter (also known as yellow substance, and gelbstoff), bleached particle absorption	0.002 - 0.9 m^{-1}	CDOM is not quantified in the same way as DOC or Chl-a. One approach is to measure CDOM fluorescence (UV excitation & blue emission) and scale response to the concentration of quinine sulfate for the same fluorescence response.
PAR: - Instantaneous - 24-hr average	0 - 2,200 μmol m^{-2} s^{-1} 0 - 60 mol m^{-2} s^{-1}	
Normalized fluorescence line height	0.0001 - 0.025 mW cm^{-2} m^{-1} sr	
Fluorescence quantum yield	0.0003 - 0.05 fluoresced photons per absorbed photons	
Euphotic depth	1 - 200 m	
Suspended particulate matter	25 - 70,000 mg m^{-3}	
Trichodesmium concentration	0 - 10^4 filaments l^{-1}	
Particle size distribution (size range)	1 - 500 μm	
Phytoplankton physiological properties (C:Chl, growth rate, etc.)	C:Chl ratio: 0.0005 - 0.3 mg mg^{-1} Growth rate: 0 - 1.9 doublings/day	
Other phytoplankton pigments	To be defined	
Phytoplankton taxonomic groups	To be defined	
Aerosol properties (type, AOT etc.)	AOT: 0 - 0.3 (for ocean colour retrievals)	

These products must be tied to spectral information via product algorithms. Based on our knowledge of the optical properties of these parameters and previous algorithm development in support of past and present ocean-colour satellite missions, a table of minimum spectral bands can be developed. Table 3.5 provides an estimate of this minimum band set, the rationale, related considerations, typical clear-sky top-of-atmosphere radiances, and maximum radiances if there is a requirement for no band saturation.

Table 3.5: A set of recommended minimum spectral bands (nm) required for addressing **all** the STM science questions. The missions listed below are the global missions. Note that some instruments have some of the bands listed but only those bands specifically designed for ocean-colour applications are indicated, e.g., the MODIS SWIR bands have been used for turbid water aerosol corrections, but the signal-to-noise ratios are very low and would not meet an ocean-colour specification. Where "comments" indicate strong trace gas absorption (oxygen, ozone, nitrogen dioxide, and water vapour), atmospheric corrections are necessary for retrieving accurate water-leaving radiances or ocean reflectances.

Band Center (nm)	CZCS	POLDER	OCTS	SeaWiFS	MODIS	MERIS	GLI	VIIRS	SGLI	OLCI	PACE	Application	Comments
350											350	Absorbing aerosol detection	
360											360	CDOM-Chl separation	Strong NO_2 absorption
385							380		380		385	CDOM-Chl separation	Strong NO_2 absorption; avoid precipitous drop in solar spectrum at 400 nm
400							400			400		CDOM-Chl separation	Not required if other UV bands available, strong NO_2 absorption
412			412	412	412	412	412	412	412	412	412	CDOM-Chl separation	Strong NO_2 absorption
425											425	CDOM-Chl separation	Strong NO_2 absorption
443	443	443	443	443	443	443	443	445	443	443	443	Chl-a absorption peak	Strong NO_2 absorption
460							460				460	Accessory pigments & Chl	
475											475	Accessory pigments & Chl	
490	490	490	490	490	488	490	490	488	490	490	490	Chl band-ratio algorithm	
510			520	510		510	520			510	510	Chl band-ratio algorithm	Strong O_3 absorption
532					531		545		530		532	MODIS band (10 nm)	Aerosol lidar transmission band; strong O_3 absorption
555	550	565	565	555	547	560	565	555	565	560	555	Bio-optical algorithms (e.g., band-ratio Chl)	Strong O_3 absorption
583											583	Phycoerythrin	Strong O_3 absorption

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Table 3.5 – *Continued from previous page*

Band Center (nm)	CZCS	POLDER	OCTS	SeaWiFS	MODIS	MERIS	GLI	VIIRS	SGLI	OLCI	PACE	Application	Comments
620						620	625			620	617	Cyanobacteria, suspended sediment, phycocyanin	Strong O_3 absorption; bounded at 628 nm by water vapour absorption band
640											640	Particulate backscatter	Sits between O_3 and water vapour absorption peaks
655											655	Chl-b	Strong O_3 absorption, weak water vapour absorption
670	670	670	670	670	667	665	666	672	670	665	670	Fluorescence line height baseline; chlorophyll in highly turbid water	Bandwidth constrained by water vapour absorption line and 678 band proximity (avoid band overlap)
678					678	681	678			674, 681	678	Fluorescence line height	Band center offset from fluorescence peak by O_2 absorption line
710						709	710			709	710	FLH baseline; HABs detection; Chl in highly turbid water; turbid water atmospheric correction	Straddles water vapour absorption band
748					748	753	749	746		753	748	Atmospheric correction-open ocean; Chl in highly turbid water	Sits between O_2 A-band and water vapour absorption peaks
765		765	765	765		779			763	779	765	Atmospheric correction-open ocean	O_2 A-band absorption (not at 779 nm)
820											820	Water vapour concentration corrections	There are other water vapour absorption features that could be used
865		865	865	865	869	865	865	865	865	865	865	Atmospheric correction-open ocean	
1020										1020		Atmospheric correction-turbid water, total suspended matter (very high concentrations)	Optional for atmospheric correction if other SWIR bands are available.

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Table 3.5 – *Continued from previous page*

Band Center (nm)	CZCS	POLDER	OCTS	SeaWiFS	MODIS	MERIS	GLI	VIIRS	SGLI	OLCI	PACE	Application	Comments
1245											1245	Atmospheric correction-turbid water	Bandwidth constrained by water vapour and O_2 absorption peaks
1375					1375		1380		1380			Cirrus detection	Cloud masking, useful but not required (small impact on ocean-colour products: Meister *et al.*, 2009)
1640											1640	Atmospheric correction-turbid water	
2135											2135	Aerosol properties, turbid water aerosol correction	

Given the progress in satellite and *in situ* (field and laboratory) methodologies and instrumentation, a baseline set of product accuracy goals can be suggested based on Table 3.4. Of course, these should be verified or revised per comprehensive analyses as outlined in Chapter 2. Such analyses should be the focus of a separate IOCCG report because such analyses are beyond the scope of this report.

To summarize, the spectral bands have been selected with specific applications in mind as indicated in Table 3.5. Table 3.6 provides a more specific mapping of the products listed in Tables 3.3 and 3.4 to the spectral bands in Table 3.5.

Table 3.6: Mapping of products to spectral bands. For many parameters, there are a variety of algorithms in the literature and it is difficult to predict what algorithms and spectral bands will be used in the future. This mapping corresponds to the algorithms currently being used or being considered by national space agency operational ocean-colour data systems (with some exceptions, e.g., red bands for chlorophyll, Gilerson *et al.*, 2010). It should be noted that the research community is moving toward spectral inversion algorithms, e.g., IOPs (Werdell, 2009). The performance of these algorithms improves as the number of spectral bands increase. Currently, these algorithms rely primarily on UV-visible wavelengths, but future use of NIR bands is likely. Additional bands in the blue and green have been added to improve plant pigment separation (460, 475, 583, 617, 640, 655 nm). Some products like DOC or DOM may require regional algorithms (Mannino *et al.*, 2008).

Products	**Spectral Bands/Considerations**
Normalized water-leaving radiances or remote sensing reflectances	Specific wavelength and atmospheric correction bands
Chlorophyll-a	360, 385, 400, 412, 443, 425, 490, 510 (Chl sensitive) 555, 565 (baseline/non-Chl sensitive) 670, 710, 748 (highly turbid waters)
Diffuse attenuation	490, 555 for $K_d(490)$
Inherent optical properties	Spectral inversion algorithms (inversions improve as spectral inputs increase)
Particulate inorganic carbon	443, 555, 670, 765, 865
Particulate organic carbon	443, 490, 555
Primary production	Derived from other derived products (Chl-a, SST, b_p, etc.), algorithm dependent
CDOM Yellow substance Bleached particle absorption	350 – 555 nm, spectral inversion algorithms (inversions improve as spectral inputs increase)
Photosynthetically available radiation	Multiple wavelengths from 400 – 700nm
Fluorescence line height	667, 678, 710, 748
Euphotic depth	Derived using IOP or Chl-based algorithms

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Table 3.6 – *Continued from previous page*

Products	**Spectral Bands/Considerations**
Total suspended matter	412, 443, 555, 617, 640 1020 (high concentrations) Neural network algorithm: multiple bands (412 - 709, excluding fluorescence band)
Trichodesmium concentration	495, 545, 625
Particle size distribution	IOP derived
Dissolved organic matter/carbon	350 – 555 nm (regional algorithms)
Phytoplankton physiological properties (C:Chl, fluorescence yield, growth rate, etc.)	Algorithms to be determined in the future. Additional spectral bands (Table 3.5) not anticipated.
Other phytoplankton pigments (e.g., chlorophyll-b and -c, phycoerythrin)	Chlorophyll-b: 655 Carotenods: 470 Phycoerythrin: 490, 550 Phycocyanin: 620
Phytoplankton taxonomic groups	TBD (depends on the classification scheme, e.g., size classes, specific phytoplankton groups like diatoms, cyanobacteria, coccolithophores, dinoflagellates, etc.) 710
Atmospheric correction & masks - Aerosol properties (type, AOT etc.) - Cirrus detection - Water vapour corrections	350, 748, 865, 1020, 1245, 1640, 2130 (atmospheric correction bands; water type dependent) 1375 820

Chapter 4

Space Measurement and Mission Requirements

4.1 Introduction: From Mission, To System, To Instrument Requirements

Mission needs are elaborated and compiled to address scientific aspects (referring to previous chapters). Next, a space system needs to be defined to provide measurements that are identified in the Mission Requirements (hereafter called MR). The space system includes not only the instrument, but also all possible contributors such as the spacecraft capabilities and its orbital properties, the on-board data processing and downloading, and the ground segment including the Level-1 data processing chain. Requirements for all these sub-systems have to be defined in a System Requirements (hereafter called SR), allocating a budget for each process to guarantee the global space system performance. Considering this, specifications regarding the instrument (Instrumental Requirements, hereafter called IR) are only a sub-system.

User needs are expressed, or must be expressed, at the mission level. This means that mission specifications are applicable to the final product delivered by the space system, i.e., the Level-1 product. Consequently, this leads to two main observations:

- The final performance is a function of the system, and not only of the instrument itself. Consequently, mission requirements must not be derived directly from instrumental specifications;
- Contributions from all parts of the system have to be analyzed and considered as individual contributions to the total performance.

In fact, this is an iterative process, but being aware of some aspects when defining the system may be useful. In the following sections, an overview of all aspects in the system and instrument design will be considered. The system level issues will be addressed first, with a focus on the instrument, and its characterization and calibration, once these issues have been defined. Because the calibration approach is a crucial aspect, it must be the primary consideration because of possible important implications for spacecraft capabilities (e.g., manoeuvres to image the Moon), instrumental design (through an on-board calibration device), or the system in general.

Since CZCS in 1978, and the more recent generation of ocean-colour sensors starting from 1996 – 1997 up until now, a lot of feedback is available on how requirements were under/over specified and how current and future systems consider these updated recommendations. Nevertheless, for such ocean-colour space systems, it is not the case for all aspects of the requirements. It must be stressed that some requirements are well established today, and offer a number of alternatives. But for others, the requirements are still "best estimates", sometimes coming from preliminary evaluations, and/or for which proper justifications still need to be developed.

4.2 Calibration Approach

For ocean-colour applications, a final vicarious adjustment is always performed (regardless of the calibration of Level-1) to correct both residual calibration errors and residual atmospheric correction errors. Independently to this final vicarious approach, the most common on-orbit calibration and validation methods employed for Level-1 in past/current missions are:

- Solar diffuser calibration: an on-board solar diffuser is illuminated by the Sun and the radiance reflected off the diffuser is measured by the sensor (SeaWiFS). The reflectance of the diffuser is either monitored by a separate device (MODIS, GLI, GOCI) or by comparison to another diffuser with significantly less exposure to solar irradiance (MERIS).
- Lunar calibration: the sensor measures the lunar irradiance, and the result is compared to lunar irradiance model predictions, or to the previous measurement (SeaWiFS, MODIS).
- Lamp sources: lamps on-board the satellite, usually integrated into the sensor housing (MODIS, GLI).
- Deep convective clouds:
    1. assumption that nearly all light is reflected from these clouds allows calibration measurements, and
    2. their spectral signature is nearly white allowing inter-band calibration (POLDER, MERIS).
- Desert sites: measurement of homogeneous desert areas are compared with a database of reflectance measurements (POLDER, MERIS).
- Oceanic sites: on the Rayleigh method, after selection, the molecular scattering over a clear ocean provides an absolute target accurately computable knowing the surface pressure (POLDER, MERIS). With the sunglint method, the white spectral behaviour of sunglint is used to propagate the absolute calibration of VIS bands to NIR and SWIR bands.

These methods will be described in more detail and referenced in Section 4.10 "On-Orbit Validation and Calibration". It is pointed out that two different and complementary aspects of the radiometric calibration are identified: the absolute radiometric calibration, and the monitoring (or trending) of its temporal evolution.

The working group agrees on the fact that it is not possible to fully cover the radiometric calibration accuracy needs of ocean colour using one single method. Consequently, it may be necessary to use information from different approaches or methods. As such, on-board calibration is very important to guarantee key aspects of radiometric calibration. For example, for lunar calibrations, the instrument design must allow for the instrument to be tilted towards the Moon during the night part of the orbit. This can be achieved by placing the radiometer on the front or the back end of the satellite platform, and extending the radiometer's tilt range to at least 90 degrees. Alternatively, the satellite must perform a manoeuvre.

Whatever the calibration technique, the measurement should be made with an optical path identical to that used during observations, i.e., there should be no additional optical elements such as an additional folding mirror for the lunar view. Such calibration techniques have a direct impact on both spacecraft and instrument designs.

Recommendation:

- The absolute calibration of the sensor should be distinguished from monitoring the degradation via trending (two separate ways can be defined);
- The ideal method for monitoring is a double approach using solar diffuser and lunar acquisitions (or diffuser redundancy);
- Complementary and independent methods must be applied to validate both absolute calibration and degradation trending;
- An additional final vicarious adjustment (independent of the Level-1 calibration) is required to reach optimal accuracy for Level-2 products;
- The goal should be an uncertainty of 0.5% for the TOA radiances after vicarious calibration (see IOCCG Report 10, 2010).

4.3 Orbit

Global coverage is referred to in this document as the time it takes for a sensor to obtain a complete image of the Earth, not considering cloud cover or glint contamination. Global ocean-colour missions must image every part of the Earth several times a month to accumulate sufficient data for meaningful Level-3 products. Operational products often require a weekly (or even daily) retrieval. Retrievals over specific areas are often limited by cloud cover and glint contamination. SeaWiFS, MODIS, and MERIS have a revisit time of 2 or 3 days (ignoring cloud and glint issues) for any point on the Earth.

Polar orbiting satellites provide global coverage because the swath progresses in latitude by several degrees per orbit. A side effect, which cannot be avoided for polar orbiting satellites, is that the revisiting frequency is much higher at the polar regions (once per orbit) than at the equator (every 2 or 3 days for SeaWiFS, MODIS, and MERIS). Orbit characteristics and sensor swath width determine the revisit time. The swath width is determined by the orbit altitude and the maximum scan angle. For a discussion of the maximum scan angle, see Section 4.8.2.1. Typical orbit heights for heritage ocean-colour sensors are ~700 – 800 km.

Note that the orbit altitude is related to the duration of the orbit: the lower the altitude of the orbit, the shorter the duration of the orbit. This means that during one day, a radiometer on a lower orbit will image smaller swaths than a radiometer on a higher orbit (which decreases global coverage), but will produce more swaths (which increases global coverage). In one specific example, the global coverage of a given radiometer on a polar orbiting satellite produced very similar coverage for a 450 km altitude and a 700 km altitude. Generally, lower orbit altitudes put less demands on the design of the radiometer because of the increased availability of photons per pixel, and can achieve smaller footprints with the pixel angular extent.

The equator crossing time of the satellite should be close to noon to benefit from the higher radiance levels that are associated with a low solar zenith angle. MODIS and MERIS have demonstrated that an acceptable range is probably from 10:00 AM to 2:00 PM. However, note that the along track tilt procedure described in Section 4.8.3 for SeaWiFS is optimized for a noon equator crossing time and may need to be adapted for other orbits.

To obtain consistent global coverage, it is beneficial to acquire the data at a constant equator crossing time. This can be achieved for polar orbiting satellites by maintaining the orbit. The orbit drift of SeaWiFS (from noon to 2:30PM, over a period of 13 years) complicated the calibration effort significantly, and reduced coverage at the end of the mission.

Recommendation:

- ❖ An equator crossing time close to noon provides optimal radiance levels.
- ❖ It is more important that the orbit be maintained to keep the equator crossing time constant, rather than the actual equator crossing time.

4.4 Spacecraft Requirements

The spacecraft needs to perform several essential functions:

1. provide power to the radiometer;
2. downlink data from the radiometer to a ground station and transmit commands from the ground to the radiometer;
3. position the radiometer; and
4. manoeuvre to redirect the radiometer's FOV.

4.4.1 Power considerations

Power is usually generated via solar panels. The day/night cycle of polar orbiting satellites can lead to voltage fluctuations that should either be buffered, or the radiometer should be designed so that it can withstand these fluctuations without loss of accuracy. Most ocean-colour radiometers do not acquire data during the night-time path of the orbit, so their power needs will fluctuate. Power requirements for passive sensors such as ocean-colour radiometers do not pose a challenge for current technologies in normal operation modes. In the case of spacecraft manoeuvres, rotation of the spacecraft often rotates the solar panels away from the direction of optimal solar flux reception, which should be considered when executing the manoeuvres. As an example, it may not be possible to schedule manoeuvres for consecutive orbits.

4.4.2 Data downlink

There are two main methods to downlink data for polar orbiting satellites: direct broadcast of the data as it is being acquired, and on-board storage of the data until a specific ground receiving station is within communication reach. The latter method is usually the primary data transmission method.

A receiving station at very high latitudes (e.g., the Svalbard station at a latitude of 78.3°N in Norway) can receive data from a polar orbiting satellite nearly every orbit. The on-board data storage capacity should be sufficient to bridge gaps in case the satellite cannot communicate with the receiving station for one or several overpasses. The downlink data transfer rate should be sufficient to transmit the data of at least one orbit (or more than one orbit to catch up, in case the previous downlinks failed) during the limited time of contact between the satellite and receiving station (usually only a few minutes). The transmitted data include the actual radiometer image data, radiometer telemetry (e.g., instrument temperatures and scan speed) and satellite telemetry (e.g., power variables and satellite location).

Some real time applications benefit from the direct broadcast method, because the data is received almost immediately after the radiometer measurements. For example, NOAA's various offices and programs use satellite ocean-colour radiances to derive changes in chlorophyll-a over time, which is a key requirement driving the harmful algal bloom (HAB) algorithm. It is important to provide timely HAB information regarding the location, extent, and potential for development or movement of harmful algal blooms in various coastal regions. In addition, satellite ocean-colour measurements can be used to assess ecosystem health, water quality (for public health and safety), fish recruitment (some species), as well as provide important inputs for integrated ecosystem assessments and help manage living marine resources.

In the case of SeaWiFS, direct broadcast data were acquired by several ground stations around the world. The direct broadcast data of SeaWiFS consisted of a full resolution data set (Local Area Coverage, or LAC data), whereas the data that had to be stored by the on-board data recorder was sub-sampled (Global Area Coverage, or GAC data) to reduce data volume because the on-board data recorder did not have sufficient memory. The SeaWiFS Project obtained many of these high resolution data sets from the ground stations, so that the current SeaWiFS data archive contains a mixture of LAC and GAC data.

The satellite also needs to transmit commands sent from a ground station to the radiometer. These commands include transitioning the radiometer into different operational modes (e.g., safe mode, operational mode, calibration mode) or operating on-board devices (e.g., the SRCA on MODIS for spectral and spatial calibrations, rotating the solar diffuser wheel on MERIS, opening and closing of protective doors).

4.4.3 Position of the radiometer

The radiometer position on the spacecraft should provide:

- a clear FOV,
- thermal stability,
- no light reflections from surrounding structures into the instrument,
- permanent shadow for the instrument's radiators (MERIS radiators are partially sunlit, complicating thermal stability control),
- no contamination of solar diffuser entrance port by Earth shine (VIIRS solar diffuser screen had to be redesigned to minimize Earth shine, some MODIS Terra solar diffuser measurements are affected by Earth shine),
- protection from micro debris, by moving the sensor to the back of the spacecraft (also, solar diffuser should not face flight direction),
- protection from micro vibration from other payloads (to ensure highest possible geolocation accuracy).

4.4.4 Spacecraft manoeuvres

In Section 4.2 (Calibration Approach) it was recommended that the space system should have the ability to view the Moon. One option is to manoeuvre the satellite to view the Moon once a month at the same phase angle, during the night part of the orbit. In this approach, the steering of the line of sight of the instrument has to be adapted to point and sample the lunar disc. Additionally, the MODIS sensors required a manoeuvre to characterize the solar diffuser BRDF and screen vignetting function. This type of manoeuvre (if needed) should be performed regularly (e.g., once every three years).

4.5 Ground Segment Requirements

The data processing and distribution is a key element for a successful mission. Even if a space system is built with a perfect sensor delivering very high quality data, the service provided by such a system can be seriously degraded if Level-1 data are not delivered rapidly after launch, are not delivered with a reasonable delay after the acquisition, and/or if the reprocessing capabilities of the system are too limited to be able to improve the data quality, when necessary.

4.5.1 Data delivery

Once in orbit, the full capabilities of the space system are required and devoted for tests, calibrations and performance evaluations. An acceptable availability for Level-1 and Level-2 data after launch, during or at the end of the commissioning phase, is a few months, ideally 3 months to begin the scientific exploitation and evaluation.

During the operational phase, a data latency of 24 hours after the acquisition (D+1) for Level-1 and Level-2 data, seems a good compromise as most scientific applications do not require real-time data. For near real-time operational data applications, a data latency within 12 hours is required. With such a capability, near real-time applications are possible, such as coastal monitoring, fisheries and resources management.

Recommendation:

- ❖ The working group recommends a commissioning phase limited to about 3 months.
- ❖ Data availability for Level-1 and Level-2 data should be 1 – 24 hours from acquisition, depending on mission objectives.

4.5.2 Data accessibility

It is well known that ocean-colour data must be delivered to the community for scientific application with no limitation regarding the amount of data, the cost (free of charge), and the nationality of the scientific program. At the opposite end of the spectrum, a specific data policy could be defined for commercial applications. Informatics and network improvements in the last decade allow a full electronic publishing of the Level-1 (and Level-2 and Level-3) data and web-based delivery to the user.

Recommendation: All ocean-colour data should be free of charge for scientific research and should be available for download over the Internet.

4.5.3 Data management

Archiving and reprocessing capabilities have to be dimensioned to allow multiple updating of the Level-1 products with an occurrence of typically once every 2 years during the mission life, and also possibly after the end of the mission. This 2-year reprocessing, based on the historical experience over several missions, is consistent with regular improvements in calibration and scientific algorithms. After stated and decided by a dedicated mission group, a reprocessing must be performed within a reasonable amount of time (typically 3 months for a full reprocessing of 5-years of data).

Information and traceability regarding the reprocessing, as well as the expected impacts on the Level-1 product, must be provided to the users for an adequate consideration. The information must be provided for every modification of the Level-1 processing e.g., calibration changes, geometrical correction, improvement of instrumental defects, degradation with time and algorithm improvements.

Recommendation:

- ❖ Provisions should be made for a global reprocessing of the existing data archive (sufficient computer capacity) every 2 years.
- ❖ All ancillary data plus Level-1, -2, and -3 data should be updated at the same time (assuming sufficient computer capacity).

4.5.4 Evaluation processing support

A thorough evaluation of calibration improvements and new algorithms often requires processing a full mission time-series to verify or investigate changes to the global products over the life of the mission. Prior to the decision to reprocess and redistribute the SeaWiFS and MODIS products in 2010, for example, the NASA ocean-colour team performed approximately 25 evaluation processing tests per mission, starting from Level-1 products and producing global Level-3 products with a temporal sub-sampling of 4-days per 32-day period ($1/8^{th}$ of the mission). These tests were critical to verifying algorithm performance, resolving ambiguities in the on-board calibration (Meister et al., 2005a), and supporting mission cross-calibration analyses (Kwiatkowska et al., 2008; Meister et al., 2012) to complement the on-board calibration. Thorough evaluation processing also provides the information needed to inform the data provider and the user community of the changes they can expect to see when the reprocessed data are made available, thus ensuring data quality is maintained, and avoiding costly mistakes. The processing system must be scaled to support these evaluation activities, and access to that processing capacity must be readily available to the calibration and algorithm development team.

Recommendation:

- ❖ The processing system should be sized and dedicated to support large-scale evaluation processing (e.g., $1/8^{th}$ of the mission dataset reprocessed within 1-2 days).
- ❖ Ideally, the processing system and support staff should be co-located with the calibration and algorithm development team to ensure that the dynamics of development, global test, analysis, and further development, is established.

4.5.5 Data format

Recommendation: The working group recommends that:

- The necessary tools be provided to promote a fast and easy access to Level-1 data, especially for the complex step of Level-1 format decoding;
- Data should be processed to Level-2; and
- Tools to convert the data into common formats are also recommended.

4.6 Ancillary Data

Ancillary data, such as the total column ozone amount, sea surface wind speed, atmospheric pressure, and total column water-vapour amount, as well as atmospheric NO_2 concentrations are required inputs for satellite ocean-colour data processing for deriving accurate ocean-colour products, e.g., normalized water-leaving radiance spectra, chlorophyll-a concentration and water diffuse attenuation coefficient.

Recommendation: Ancillary data should be provided, and in a separate file (or in a separate set of files), not merged with the Level-1 data files.

4.6.1 Ancillary data requirements

To derive the normalized water-leaving radiance spectra accurately from satellite-measured top-of-atmosphere (TOA) radiance, atmospheric and ocean surface effects, i.e., radiance contributions from air molecules (Rayleigh scattering), aerosols (including Rayleigh-aerosol interaction), ocean whitecaps, and sun glint need to be removed accurately (IOCCG, 2010). For this purpose, ocean-colour data processing computes the Rayleigh-scattering reflectance from the pre-generated Rayleigh lookup tables with inputs of solar-sensor geometry, atmospheric pressure (Gordon, et al., 1988; Wang, 2005), and sea surface wind speed (Gordon and Wang, 1992; Wang, 2002). The aerosol reflectance can be estimated using two near-infrared (NIR) bands (Gordon and Wang, 1994a) or shortwave infrared (SWIR) bands (Wang, 2007) with the assumption of the black ocean at the NIR or SWIR wavelengths (Shi and Wang, 2009). Estimation of aerosol reflectance at the NIR or SWIR bands requires an input of the atmospheric water-vapour amount for the correction of the water-vapour absorption in the sensor-measured reflectance (Gordon, 1995). The contribution from whitecaps reflectance is modelled using the sea surface wind speed (Gordon and Wang, 1994b), and the sun glint reflectance is mostly masked out and residual contamination is corrected (Wang and Bailey, 2001), based on a model of sea surface slope distribution (with an input of wind speed) (Cox and Munk, 1954). In addition, the effect of ozone absorption on the TOA reflectance in the visible wavelengths, in particular, at the green bands, needs to be corrected. This requires an input of the total ozone amount in the atmospheric column. Thus, for the satellite ocean-colour data processing, e.g., deriving ocean-colour products from SeaWiFS and MODIS (McClain, et al., 2004), ancillary data inputs of atmospheric total column ozone amount, sea surface wind speed, atmospheric pressure, and total column water-vapour amount are required. Accuracy of these ancillary data directly affects the quality of the satellite-derived ocean-colour products (Ramachandran and Wang, 2011). Furthermore, it should be noted that some other additional ancillary data may be needed for further improving satellite-derived ocean-colour (or aerosol) product data. e.g., atmospheric NO_2 amount that is required for the correction of absorption at the blue bands (Ahmad, et al., 2007) or relative humidity data for refining aerosol models (Ahmad, et al., 2010).

4.6.2 Ancillary data sources

A variety of ancillary data sources are used by various space agencies. For example, NASA's SeaWiFS and MODIS ocean-colour datasets have been processed using some ancillary inputs from the National Center for Environmental Prediction (NCEP), while for the ESA MERIS ocean-colour products, ancillary data from the European Centre for Medium-Range Weather Forecasts (ECMWF, `http://www.ecmwf.int`) have been used. ESA also plans to use ECMWF data for Sentinel-3 OLCI ocean-colour data processing (ESA, 2010). For Japan's GCOM-C data processing, JAXA plans to use Japan Meteorological Agency (JMA) global meteorological model data (`www.jma.go.jp/jma/en/Activities/nwp.html`). Here details of some ancillary data sources, particularly those used for SeaWiFS and MODIS ocean-colour data processing, are described.

The NCEP ancillary data, which are routinely used for NASA science-quality ocean-colour data processing, are archived on the NASA GSFC ocean-colour website (`http://oceancolor.gsfc.nasa.gov/`). The NCEP ancillary data set is an assimilated data product from one of the NCEP operational systems called the Global Data Assimilation System (GDAS) (Kanamitsu, 1989; Derber, et al., 1991; Parrish and Derber, 1992). GDAS is the archive of the final analysis run at 6-hourly intervals of the Global Forecast System (GFS) model runs, after all the conventional and satellite data are assimilated. Some pre-processing converts data to the 1° x 1° resolution latitude-longitude with 360 x 181 gridded form for different pressure surfaces to gridded binary format.

Currently, the ancillary data source for ozone is from the Total Ozone Analysis using SBUV/2 (Solar Backscatter Ultraviolet Radiometer) and TOVS (TIROS Operational Vertical Sounder) (TOAST) product from NOAA. This is a combination product comprising satellite observation from the two different platforms with radiances in UV bands (252-340 nm) as well as the 9.7 μm band from TOVS, which is sensitive to ozone retrievals in the altitude of 4 - 23 km range. Since the SBUV/2 data collected over 14 orbits per day has data gaps, spatial smoothing is implemented using the Cressman interpolation scheme. Similarly, for the meteorological data inputs, the data sources are NASA's Quick Scatterometer (QuikSCAT) winds at 0.5 degrees, Advanced Microwave Sounding Unit-A (AMSU-A) channels 12 and 13 from NOAA-15 and NOAA-16 satellites, High-resolution Infrared Radiation Sounder (HIRS) from NOAA-16, Atmospheric Infrared Sounder (AIRS) and AMSU-A on Aqua, and NCEP's new land-surface model. Various other Rawinsonde, ships, and aviation measurements from regular and data-of-opportunity sources, as well as non-U.S. satellite platforms such as Meteorological Operational Satellite (METOP), Multi-Function Transport Satellite (MTSAT), and Meteorological Satellite (METEOSAT), etc., are also included in the assimilation. A complete list of all such sources can be found at the NCEP website containing the GFS data dump text (http://www.nco.ncep.noaa.gov/).

4.6.3 Ancillary data for science quality and operational ocean-colour data processing

The science-quality ocean-colour data (McClain, et al., 2006) archived at NASA uses the NCEP definitive ancillary data, which are created with a lag of at least a day or more from the time of satellite measurements. Noticeable exceptions to this timeframe, however, have occurred when the NCEP ancillary data files were not available for over three to five days. High quality ocean-colour products over global open oceans are being produced from the NASA standard ocean-colour data processing using the NCEP definitive ancillary data (McClain, et al., 2004; Wang et al., 2005; Bailey and Werdell, 2006). Some validation results show that, over open oceans, the mean ratio values (SeaWiFS vs. *in situ* data) of SeaWiFS-derived normalized water-leaving radiances for bands of 412 – 555 nm are in the range of 0.956 - 1.030 (Bailey and Werdell, 2006).

Operational ocean-colour data processing, however, requires routine ocean-colour product production in near-real time. For example, NOAA CoastWatch program requires generating ocean-colour products within 12 hours of the satellite data acquisition for various applications, e.g., harmful algal bloom (HAB) prediction and management. For such ocean-colour data applications, timely data production is most important and critical. In a recent study, Ramachandran and Wang (2011) investigated three alternative ancillary data schemes for the near-real time ocean-colour data processing, i.e., climatology ancillary data, a time-lagged NCEP data, and the Global Forecast System (GFS) model data. Their results (Ramachandran and Wang, 2011) show conclusively that the GFS model produces significantly better-quality ancillary data than those from the other two methods, and the operational ocean-colour products can be substantially improved with inputs of ancillary data from the GFS model for the near-real time ocean-colour data processing. In particular, using ancillary data from the GFS model, ocean-colour products in the coastal region can be significantly improved.

4.7 Definitions

4.7.1 Definition of angles

Sensor zenith angle is defined as the angle between the ocean surface normal and the vector pointing from the ocean surface to the sensor. Scan angle is defined as the angle of the sensor's line of sight to the nadir point of the scan (this angle is independent of the tilt angle of the sensor). View angle is defined as the angle of the sensor's line of sight to nadir (this angle is dependent on the tilt angle of the sensor). Solar zenith angle is defined as the angle between the local surface normal and the vector pointing from the local surface to the sun. (The local surface can be any surface, e.g., the ocean surface or the solar diffuser surface.)

4.7.2 Precision and accuracy

The total error obtained when comparing a given measurement to a reference or exact value, can be separated into two very different contributions: a bias, and a noise. In the end, the quality of the system is described by both the accuracy (bias) and the precision (noise), and it is not sufficient to document one of these two values without documenting the other. It is important to note here that some applications can be very demanding as far as accuracy is concerned, while the precision is not really crucial, and vice versa. For example, front detection is very demanding on precision, while climatologic surveys are more demanding on accuracy.

When elaborating the system error budget, it is necessary to identify, for each configuration, what is considered as a bias and what is considered as a noise. These configurations may be a temporal scale, a spatial scale, or different geometrical conditions.

4.7.3 Signal-to-noise ratio and system uncertainty

The noise level can be expressed in different ways:

- For a given geographical point, the noise can be defined by the fluctuation of the retrieved signal for different observations. These observations can be considered for the same viewing conditions or for different conditions. It can be seen as a multi-temporal noise.
- For a given date or viewing condition, the noise can be defined by the fluctuation of the retrieved signal over a given geographic area. This is the noise that affects the visual aspect of an image.

The noise aspect must be clarified in the MR (Mission Requirements), regarding user needs. It must be pointed out that an indication of the noise levels is required in the final product (i.e., the Level-1 product). The noise expressed at the instrument level is usually a temporal fluctuation, i.e., the root-mean-square of a large number of measurements for the same target. It may include all possible contributions from the system. The following contributors can be summarized non-exhaustively as follows:

- natural temporal fluctuation of the signal (photonic noise);
- quantification noise;
- noise from the data compression/uncompression if not lossless;
- noise added by the imperfection of the radiometric model;
- noise added by uncertainties on the knowledge of all the parameters of the radiometric model (e.g., equalization noise after calibration, non-linearity, dark current, offset stability);
- resampling noise depending on the way data are resampled;
- noise due to stray light or residue from the correction;
- noise due to the polarization or residue from the correction.

Consequently, noise defined at the mission level must not be directly transferred at the instrument level, but an allocation over the whole system must be made. Ignoring this step may lead to an incomplete, underestimated and thus unrealistic noise budget. The SNR is often used when designing the instrument because it is a practical and easily measurable or predictable number. At system level (for Level-1 products), it is more convenient to speak about total- or system- uncertainty.

For some applications, ocean-colour measurements are merged from different sensors for spatial coverage improvement or to build a longer time series. In this circumstance, and for an easier comparison, it can be useful to try to standardize the conditions for which the noise is expressed. First, whatever the spatial full resolution of the sensor, an evaluation of the noise for a 1 km-like resolution may be provided in addition to the noise evaluation at the resolution of this sensor. In the same way, this "1 km-like" noise may be evaluated for a typical standardized radiance (see above). Providing this information may help users to combine or analyze data from various sensors.

It may be more convenient to express the noise as an absolute contribution, not relative, when the final major derived product is water-leaving radiances. The noise-equivalent derived radiance, NEΔL, can be derived using the ratio of typical radiance to SNR, where the typical radiances are defined in the following section. Such a value can also be converted into noise-equivalent derived normalized radiance, after normalization to the solar irradiance (times π).

If the relative noise (SNR) is constant for the entire field-of-view (this is generally not the case), the absolute noise NEΔL varies with the viewing angle along the swath because of the variation of the radiance. In addition, because the solar irradiance varies strongly along the orbit, the NEΔL also varies in the same way along the orbit, from the equator/tropics to the upper/lower latitudes. It is possible to homogenize the NEΔL performance, for example, through a variation of the integration time to compensate for this variation of the solar irradiance along the orbit.

4.7.4 Spatial resolution

The spatial resolution of the Level-1 product must not be mistaken for the spatial resolution of the space system. The first one is defined in the Mission Requirements and corresponds to the spatial resolution of the geographical or cartographical projection of the Level-1 product required by users. This user product resolution is fixed, and is the same regardless of the Level-1 product, the viewing conditions, or date of capture.

In contrast, the acquisition resolution, i.e., the spatial resolution of the space system, may vary strongly depending on the instrumental concept, and the viewing angles. Consequently, two measurements made for two different viewing angles will not have the same spatial resolution. The same conclusion applies for two measurements of the same point on the ground but acquired for two different dates. Thus, when resampling data from the sensor geometry to the Level-1 product geometry, the spatial resolution becomes the same for the final product whatever the viewing condition.

The resolution varies from the nadir to the 50° cross-track viewing angle for two different concepts: 1) a wide field-of-view optic, preserving the ground resolution inside the field of view; and 2) a scanner for which the instantaneous field of view is constant whatever the viewing direction. This variation of the acquisition resolution has to be considered when designing the instrument. It is emphasized here that a space system should not be dimensioned with a nadir resolution corresponding to the Level-1 product resolution because the major part of the field-of-view will, in fact, be acquired with a lower resolution. It is recommended that the instrument be dimensioned with a mean resolution (not nadir resolution) corresponding to the Level-1 product resolution, or to adjust the Level-1 resolution to the real mean spatial resolution.

Finally it should be emphasized that the spatial resolution of the system is not only defined by the sampling on the focal plane (size of pixel projected on the Earth's surface), but it also depends on the way the system will be able to acquire such a spatial resolution (see MTF, Section 4.7.6).

4.7.5 Typical radiances and reflectances

When addressing mission requirements, a typical spectral radiance has to be considered to express the system noise at this given radiance, or to define the dynamic range. Historically, each space system adopted its own typical radiance. Since some significant differences may exist, this can lead to a scrambled comparative overview of all sensor performances. It is proposed here that a standardized radiance be provided.

Regarding the space system, minimum and maximum radiances define the range of radiances over which system's performance requirements have to be met. With respect to the mission, the minimum/maximum radiance is the smallest/largest level of radiance that each spectral band will observe during the mission. Here, it is important to point out that the scope of the mission may change the definition of min/max radiances. Radiance levels may differ for a mission devoted to the global open ocean or to one devoted only to coastal waters.

In Table 4.1 the minimum, typical and maximum radiances for a global ocean mission are provided. Under these conditions, minimum radiances for shorter wavelengths will be observed over coastal regions while minimum radiances for longer wavelengths will be observed over Case-1 waters. Consequently, the resulting minimum spectrum will be a combination of these conditions. These radiances can be converted into reflectances using the extraterrestrial solar irradiance recommended by IOCCG (see http://www.ioccg.org/groups/mueller.html, also Thuillier et al., 2003).

Since it is prudent to avoid saturation over bright targets, at least for some spectral bands, the dynamic range from very low radiances (ocean) to very bright radiances (clouds with no saturation) may be rather large. A wide dynamic range can be used to assess this need, but this can also be managed by using a bi-linear gain instrument (e.g., SeaWiFS), or through a pixel interleave technique (resulting in different gains for different acquisitions).

4.7.6 Modulation Transfer Function and Point Spread Function

The spatial resolution of an instrument is sometimes (incorrectly) associated with a unique single spatial sampling, i.e., corresponding to the pixel size on the focal plane. In fact, the spatial sampling must be associated with the way the optical system is able to transmit this spatial information. For example, if the instrument is not able to transmit correctly a spatial frequency of 250 m, it cannot be qualified as a 250-m instrument, as if pixels on the focal plane correspond to a 250-m sampling. The way the instrument is transmitting all the spatial frequencies is called the Modulation Transfer Function (MTF). The 2-dimensional Fourier Transform of the Point Spread Function (PSF), is the 2-dimensional MTF, which is the response of the instrumental system to an impulsion source.

The MTF of a space system is not only the instrument's MTF. Other contributions, such as satellite motion during acquisition, micro-vibrations of the platform and resampling methods can contribute significantly to the final MTF available in the Level-1 product.

4.7.7 Spectral band and an out-of-band contribution (spectral rejection)

In general, a spectral band is that part of the electromagnetic spectrum which is transmitted by, for example, a filter, while the rest of the spectrum is not transmitted or blocked by the instrument (filter or detector). A spectral band is characterized

Table 4.1 Multispectral band centers, bandwidths, typical top-of-atmosphere clear sky ocean radiances (L_{typ}), saturation radiances (L_{max}), and minimum SNRs at L_{typ}. Radiance units are W m^{-2} μm^{-1} sr^{-1}. SNR is measured at L_{typ}. L_{min} and L_{high} are TOA radiance ranges for valid ocean-colour retrievals derived from a SeaWiFS global one-day data set for the respective SeaWiFS bands, after removing the 0.5% highest and 0.5% lowest radiances. In future, these values should be derived for the remaining bands. Adjustments may be necessary for sensors with different solar and viewing geometries.

λ	$\Delta\lambda$	L_{typ}	L_{max}	L_{min}	L_{high}	SNR-Spec
350	15	74.6	356			300
360	15	72.2	376			1000
385	15	61.1	381			1000
412	15	78.6	602	50	125	1000
425	15	69.5	585			1000
443	15	70.2	664	42	101	1000
460	15	68.3	724			1000
475	15	61.9	722			1000
490	15	53.1	686	32	78	1000
510	15	45.8	663	28	66	1000
532	15	39.2	651			1000
555	15	33.9	643	19	52	1000
583	15	28.1	624			1000
617	15	21.9	582			1000
640	10	19.0	564			1000
655	15	16.7	535			1000
665	10	16.0	536	10	38	1000
678	10	14.5	519			1400
710	15	11.9	489			1000
748	10	9.3	447			600
765	40	8.3	430	3.8	19	600
820	15	5.9	393			600
865	40	4.5	333	2.2	16	600
1245	20	0.88	158	0.2	5	250
1640	40	0.29	82	0.08	2	180
2135	50	0.08	22	0.02	0.8	100

by its transmission profile, usually summarized by a central wavelength and a full bandwidth at half maximum (FWHM). Nevertheless, it is necessary to define a spectral shape bounded by the two wavelengths for which the transmission is equal to 0.01 (in-band). All the spectral information outside of this spectral shape is an out-of-band contribution, leading to spectral contamination. This contamination has to be limited to avoid mixing information not only from neighbouring bands (e.g., contamination from 565 nm on band 490 nm), but also from bands further away (e.g., contamination from the near-infrared).

4.7.8 Polarization sensitivity

When observing the ocean from space, the polarization of the incoming light is mainly due to the Rayleigh contribution for the molecular scattering. Consequently, the polarization sensitivity becomes a crucial aspect in the blue part of the spectrum: for a scattering angle close to 90°, the observed radiance is nearly fully polarized (clear atmosphere, dark surface). If not corrected, a polarization sensitivity of 1% may lead to an error of up to 1% on the TOA reflectance.

Thus, depending on the polarization of the incoming light, the response of the instrument will differ. For this reason it is important to limit this polarisation sensitivity through careful instrument design.

To quantify this contribution, a polarization sensitivity is defined for each point of the field-of-view by the ratio $(P_{max} - P_{min})/(P_{max} + P_{min})$, where P_{max} is the maximum of transmittance under all possible polarization conditions and P_{min} is the minimum.

4.7.9 Atmospheric correction and impact on requirements

User needs are often expressed in marine reflectances, the main parameter from which several secondary products are derived. The important step of atmospheric correction is crucial to derive marine reflectances from Level-1 measurements with the necessary accuracy. IOCCG Report 10 (2010) summarizes a large set of atmospheric correction algorithms that differ by the sets of spectral bands they use, and how they combine this spectral information. Consequently, depending on the mission, the way to derive requirements for Level-1 from the initial marine reflectances may depend strongly on the atmospheric correction algorithm used. Some atmospheric correction algorithms demonstrate strong potential and robustness regarding noise propagation (IOCCG, 2010). In the current report, we assume that classical algorithms are used and that margins exist.

4.8 Radiometer Design

There are four types of requirements that a radiometer must satisfy to produce measurements necessary to derive ocean-colour products described in the previous sections:

1. spectral coverage,
2. spatial coverage and resolution,
3. radiometric quality, and
4. temporal coverage and revisit time.

. These requirements are addressed in the sections below.

4.8.1 Spectral coverage and dynamic range

Different science questions and applications require normalized water-leaving radiances at various wavelengths. An overview of the wavelengths to address all issues presented in Chapter 3 is given in Table 4.1. In general, it is not necessary to match the exact wavelengths given in Table 4.1, apart from the bands used in the fluorescent line height algorithm (665 and 678 nm), where the center wavelength of each band should be within ∼1 nm of the specification. For all bands, the center wavelength should be known to within ∼0.1 nm.

To identify phytoplankton functional groups, hyperspectral data with 5 nm resolution is required. The requirements listed in Table 4.1 should be applied to the hyperspectral data after aggregating the 5 nm bands to the bandwidths specified in the table. Table 4.1 also provides the typical radiances (L_{typ}), the required bandwidth, as well as the required SNR. The L_{typ} at the wavelengths common to SeaWiFS and MODIS sensors was derived from actual experience with those sensors (MODIS values were scaled to the SeaWiFS values). The L_{typ} of the remaining bands were calculated using the Thuillier et al. (2003) solar irradiance (F_0) and an interpolation or extrapolation of the L_{typ}/F_0 ratios of the SeaWiFS/MODIS bands.

The maximum radiance (L_{max}) is also provided in Table 4.1 to help define the dynamic range. It is calculated using an albedo of 1.1 and 0 degrees incidence angle to simulate the brightest case of a white cloud for an orbit with an equator overpass time of around noon. It may be sufficient that only a subset of the bands is capable of measuring L_{max}; the values for the bands that saturate could be interpolated (or even extrapolated) from the valid measurements. Cloud radiances are not used directly for any ocean-colour product (they are only needed to radiometrically correct the surrounding pixels for stray light, if applicable), therefore the cloud radiances are only needed with an accuracy of a few percent. The radiances from at least two different wavelengths in the NIR are required for atmospheric correction over the open ocean, while the SWIR radiances are used for atmospheric correction over coastal regions (see Wang, 2007).

Recommendation:

- ❖ It is recommended that bands with center wavelengths similar to those given in Table 4.1 be used. Bandwidth specifications should also consider nearby atmospheric absorption features.
- ❖ No band should saturate below L_{high} (L_{high} needs to be calculated for those bands where values are missing in Table 4.1).
- ❖ At least some bands should not saturate at L_{max} (to allow the estimation of the radiances of the saturated bands) to assess stray light effects for all bands.

4.8.2 Spatial coverage and resolution

4.8.2.1 Swath width

The swath width is determined by the orbit altitude and the maximum incident angle. At very large sensor zenith angles and/or at very large solar zenith angles, the TOA radiances contributed from atmosphere and ocean surface become very large relative to the desired ocean-colour signals (thus it is more difficult to derive accurate L_{wN}s due to the even smaller portion of its radiance contribution), which limits the useful solar and sensor zenith angle range for ocean-colour products (IOCCG, 2010). In addition, for large solar and/or sensor zenith angles, Earth's curvature effects must be accounted for (Ding and Gordon, 1994; Wang, 2003). The plane-parallel atmosphere (PPA) has been used for atmospheric correction and ocean-colour data processing, instead of true spherical-shell atmosphere (SSA). The PPA model is generally valid for the solar and sensor zenith angles < ~80°. For SeaWiFS and MODIS, 60° is the maximum sensor zenith angle that is used for Level-3 ocean-colour data processing. For SeaWiFS, this translates to a maximum scan angle that is used for Level-3 data processing of about 45° (because of the SeaWiFS tilt). MODIS is not tilted; its maximum scan angle used for Level-3 data processing is about 50° (because of the Earth's curvature). Another drawback to a large sensor zenith (at surface level) angle is the variation of solar zenith angle within the swath.

ESA's OLCI radiometer has a smaller swath width (1269 km) than SeaWiFS (SeaWiFS swath width: 2800 km for scan angles up to 58°, 1500 km for sensor zenith angles ≤60°) and MODIS (MODIS swath width: 2330 km for scan angles up to 55°, 2100 km for sensor zenith angles ≤60°), resulting in a relatively infrequent revisit time. This will be compensated for by operating two OLCI radiometers on two separate platforms, which significantly increases the revisit time for any point on Earth for the combined data product of the two missions. However, this approach requires a successful merger of the ocean-colour products from the two sensors.

In fact, the limitations of solar and/or sensor-zenith angles are mainly associated with the limitation in deriving accurate satellite-measured normalized water-leaving radiance, i.e., performance limitation in atmospheric correction algorithm for the larger solar- and/or sensor-zenith angles in deriving normalized water-leaving radiance spectra. It has been shown that atmospheric correction algorithms perform well with an airmass value $\leq\sim 5$ (IOCCG, 2010). The airmass is defined as $(1/\cos\theta_0 + 1/\cos\theta)$, where θ_0 and θ are the solar and sensor zenith angle, respectively. Experience from SeaWiFS, MODIS, MERIS sensors has show that, for cases with solar zenith angles $\leq\sim 70$ – 75° and sensor zenith angles $\leq\sim 60°$, reasonable L_{wN} data can be derived. However, it should be noted that the solar zenith angle limitation would limit ocean-colour data coverage in high latitude regions. Therefore, considering future improvements in atmospheric correction algorithms, a maximum solar zenith angle of 75° is deemed appropriate.

Recommendation: It is recommended that the satellite swath should cover solar zenith angles to at least 75° and sensor zenith angles up to 60°.

4.8.2.2 Spatial resolution

Orbit altitude also influences the spatial resolution. The instantaneous field-of-view (IFOV) of the sensor must be designed to meet the spatial resolution requirement. For global ocean-colour applications, a spatial resolution of 1 km at nadir has proven to be sufficient. Regarding the possibly strong variation of the spatial resolution inside the field-of-view, it is important to consider not only the spatial resolution at nadir, but also the mean spatial resolution across track. For coastal waters, a resolution of 250 – 300 m is a good target, but some specific application (e.g., HABs monitoring in European waters, North Sea, Baltic) would need a higher resolution, closer to 50 m.

Recommendation:

- ❖ The working group recommends a mean spatial resolution of 1 km for the open ocean (Case-1).
- ❖ For coastal waters (Case-2) the working group recommends a mean spatial resolution of approximately 300 m, with a higher resolution for HABs detection and monitoring.

4.8.3 Tilt capability

To improve the global coverage provided by an ocean-colour sensor, it is necessary to take into account contamination by sun glint and clouds. The SeaWiFS sensor tilts away from the specular direction every orbit (when it is close to the equator) by ±20° to increase its effective global coverage. Such a mechanism should be considered for any ocean-colour sensor. According to Gregg and Patt (1994), a tilted sensor can obtain 20% more coverage than an untilted one (in the absence of clouds). ISRO's OCM-2 sensor is also tilted, but its tilt angle is only changed twice per year, in spring and fall. This reduces glint contamination in one half of the hemisphere (in the case of OCM-2, the northern half), but increases it in the other half. Therefore, this tilt strategy is only beneficial to increase regional effective coverage, but does not increase global effective coverage. The tilt should be performed by the instrument itself as was successfully done by SeaWiFS.

Other possibilities may be to adopt an instrumental design with a dual view, aft/fore, but with a lot of redundancy inside the payload. The same concept is employed in multidirectional instruments (e.g., POLDER). However, multi-angular (or even multi-instrument) solutions to the glint issue usually increase the calibration complexity.

Recommendation:

- ❖ The optimal method to avoid sun glint is to tilt the instrument on each orbit such that its sensor zenith angles avoid specular reflection i.e., as was done for SeaWiFs.
- ❖ The entire instrument should be tilted to avoid changes of the optical path within the instrument.

4.8.4 Radiometric quality

IOCCG Report 10 (2010) states that a goal of 0.5% for the accuracy of the TOA radiance at 443 nm is required to achieve a water-leaving radiance accuracy of 5% (at 443 nm) and an accuracy of the chlorophyll product of ~30%. The radiance accuracy of 5% at 443 nm for clear water corresponds to an absolute normalized water-leaving reflectance error of 0.001 (Gordon and Wang, 1994a). It has been shown that, with the 0.001 reflectance error in 443 nm, the normalized water-leaving reflectance errors for other wavelengths are within 0.001 (Gordon and Wang, 1994a; Wang, 2007; IOCCG 2010). It is recommended that a goal of 0.5% be set for the TOA radiance uncertainty for all bands. Vicarious calibration (see Section 4.11.1) is required to obtain such a high level of accuracy (Gordon, 2010). Note that the combined standard uncertainty of the upwelling radiance measured by the top arm of MOBY is reported to be 2 – 3% (Brown et al., 2007), which is sufficient because the water-leaving radiances contribute less than 15% to the TOA radiance.

Recommendation: The goal for the uncertainty of the TOA radiance should be 0.5% after vicarious calibration.

4.8.4.1 SNR and quantization

The SNR requirements in Table 4.1 are results of studies for the ACE mission (ACE Science Team, 2010). The NIR and SWIR values were derived from a study of atmospheric correction algorithms. The SNR for the visible bands were derived from an analysis of the sensitivity of the Garver, Siegel, Maritorena (GSM) model. The SNR requirement of 300 in the UV is derived from heritage UV sensors; the detection of absorbing aerosols does not require a high SNR. The value of 1400 for the 678 nm band reflects the sensitivity of the FLH algorithm.

A 14-bit resolution analog-to-digital converter (ADC) is sufficient for ocean-colour applications even when bright cloud radiance levels are included in the dynamic range. The requirements for quantization depend strongly on the radiance level: a very high degree of quantization is required at radiances typical of ocean scenes, but at higher radiance levels (e.g., over clouds and over land) a reduced degree of quantization is acceptable. This was achieved in the SeaWiFS instrument with a bi-linear gain. However, bi-linear gains (or different gain modes) add considerable complexity to the sensor characterization and on-orbit calibration, and are generally not recommended. The main reason is that many on-orbit calibration or validation methods (e.g., lunar measurements or deep convective cloud analysis) operate at radiance levels higher than the typical ocean radiances. For bi-linear gains or different gain modes, results obtained from these methods need additional analysis before they can be applied to the lower radiance levels, which always increases the uncertainty.

Recommendation: The SNRs of Table 4.1 are recommended as a baseline. A 14-bit ADC is sufficient even when cloud radiances are included in the dynamic range.

4.8.4.2 Polarization

Polarization sensitivity is an undesirable feature of many radiometers. The preferred approach is to reduce this sensitivity with a polarization scrambler (e.g., SeaWiFS, MERIS) to levels well below 0.5%. Higher sensitivities must be corrected, e.g., with the methodology presented in Gordon et al. (1997). A characterization of the instrument polarization sensitivity is required; the accuracy should be about 0.2% (ACE Science Team, 2010).

Recommendation:

- The working group recommends a reduction of the polarization sensitivity of the instrument to levels below 1.0% by design, or by using a polarization scrambler.
- Polarization scramblers are recommended whenever possible, i.e., for optical systems with small effective apertures such as imaging spectrometers.
- The working group recommends a characterization of the instrument polarization sensitivity with an accuracy of about 0.2%.

4.8.4.3 Stray light

Stray light is defined here as restricted to optical processes within the sensor, such as ghosts and optical scatter. Stray light should be reduced as much as possible. It is recommended to include stray light reduction early on in the design process of the radiometer. However, stray light is part of any optical sensor. In the vicinity of strong radiance gradients, stray light effects often exceed the accuracy goal of 0.5%. To correct for this, stray light should be characterized thoroughly to identify pixels that can be used with a high degree of confidence, and apply a stray light correction to increase the number of usable pixels (see Section 4.9.7). The sensor stray light performances should allow ocean-colour processing at a distance of about 3-4 km from a cloud, for sensors with a 1-km spatial resolution. In the case of MODIS-Aqua, this requirement leads to a data loss of about 50% of all cloud-free Level-2 ocean pixels for a given day (see Meister and McClain, 2010) (Note: a cloud-free pixel is defined as a pixel not identified by the cloud mask; it may contain stray light from the cloud.)

Recommendation:

- ❖ The working group recommends that stray light be considered early on the design process of the radiometer, and minimized.
- ❖ The working group recommends that stray light be characterized with a high degree of confidence to define the range of useful pixels (e.g., regarding the distance to clouds) and for possible use in straylight correction algorithms.

4.8.4.4 Temperature dependence

Most detectors, focal plane assemblies and digital converters are very sensitive to temperature variations, both in offset and in gain. In addition, mechanical structure modification with temperature may also lead to geometrical impact on the measurements. There are two main temperature cycles on-orbit: a yearly cycle, affected by the Sun-Earth distance and seasonally varying solar angles, and a per-orbit cycle, mainly characterized by a temperature increase while the spacecraft receives direct sunlight, and a temperature decrease while the spacecraft is in the Earth's shadow. Additionally, there will be long term trends in the average temperature, for example, due to drifting orbit characteristics in the case of SeaWiFS, or degradation of the radiators.

The most rigorous approach to reducing the sensitivity to temperature variations is to maintain temperature control of the focal plane, the readout system, and the video chain. Another approach is to characterize the temperature dependence of the instrument during pre-launch thermal vacuum measurements and correct for this. Thermal vacuum chambers, however, only provide a temperature equilibrium, whereas on orbit, the temperature environment is characterized by a rapid succession of heating and cooling, and equilibrium is usually not achieved. Therefore, a temperature controlled focal plane and readout system is preferred.

Recommendation: A temperature controlled focal plane and readout system is recommended.

4.8.5 Calibration requirements

For an instrument to be traceable to a metrological standard, it is important that it includes all the corrections mentioned above in its calibration approach. Ideally, the entire FOV and the entrance pupil of the sensor should be illuminated during calibration. Lunar calibrations will not cover the entire FOV for push-broom instruments (e.g., OCM-2 and MERIS). For these types of sensors, lunar measurements alone are not recommended for calibration.

Solar diffuser radiometric calibrations require the design of a mechanism to deploy one or preferably two solar diffusers, as done in MERIS and OLCI. The radiances reflected from these solar diffusers completely fill the pupil and the FOV of the sensor. Further, the mechanism is designed to protect the solar diffuser from solar radiation in between calibrations, to minimize the degradation which is mainly due to solar ultraviolet radiation. The degradation of the solar diffuser should either be monitored with a separate device (MODIS approach, Sun et al., 2005) or by adding a second solar diffuser that is much less exposed to solar radiation (MERIS approach, Chommeloux et al., 1998). One potential problem of the MODIS approach is that the device that monitors the solar diffuser does not see the solar diffuser at the same angle as the MODIS scan mirror.

It is recommended that the optical path for the calibration measurements be identical to that of the Earth view measurements. This is a potential problem for VIIRS, where the solar diffuser is viewed at a scan angle that is outside of the range of Earth view measurements.

Especially for solar diffuser calibrations (but also potentially for lunar calibrations), seasonal variations (i.e., variations with a yearly repeat cycle) of the derived calibration coefficients are a common problem. They are usually caused by the seasonal variation of the solar incidence angles on the diffuser. A multi-year time series is ideal to remove such variations (Meister et al., 2005b), but corrections are possible in certain cases earlier in the mission by means of normalization to the NIR (Delwart and Bourg, 2004; 2011).

An on-board lamp was used to calibrate CZCS (Evans and Gordon, 1994). Although specific calibration goals may be achievable with this type of source such as spectral calibration (Che et al., 2003) or short term monitoring, long term monitoring cannot be achieved with a sufficient accuracy (Frouin, in prep.), therefore lamp based sources are not recommended as primary radiometric degradation monitors for ocean-colour sensors.

Recommendation:

- ❖ Ideally, the FOV and the entrance pupil of the sensor should be filled with light during the calibration measurement.
- ❖ The optical path for the calibration measurements should be identical to that of the Earth view measurements.

- ❖ Lunar calibration is recommended for trending when the instrument design is appropriate (e.g., SeaWiFS and MODIS). Lunar calibrations will not cover the FOV for push-broom instruments (e.g., MERIS and OCM-2) so for these types of sensors, lunar measurements alone are not recommended for calibration.
- ❖ On-board calibrations using a diffuser are recommended, provided a method for monitoring the diffuser degradation is included in the calibration procedure (either keeping a "pristine" reference diffuser as done with MERIS, or by means of a degradation monitoring device as done with MODIS).
- ❖ Lamp-based sources are not recommended as primary radiometric degradation monitors for ocean-colour sensors.

4.8.6 Temporal coverage and revisit time

The fourth type of requirement addresses the issue that, for most tasks, it is not sufficient to have a single measurement at one point in time, but rather several measurements are required over a period of time (e.g., to study the seasonal variation of an ocean-colour product). Cloud coverage strongly reduces the amount of valid retrievals, such that in many areas of the world (e.g., equatorial regions), even with a revisit time of every other day, there are monthly Level-3 bins with no observations. Other examples are found in the Arctic and Antarctic regions, where the revisit time is even higher. Revisit time is influenced by orbit characteristics (discussed in Section 4.3) and the FOV or maximum scan angle (discussed in Section 4.8.2.1).

The length of the mission can be shortened by the lifetime of the radiometer, therefore it is reasonable to design a radiometer in such a way that it is expected to exceed the mission life time, which is often limited by satellite resources such as fuel to maintain the orbit. For this reason, ocean-colour radiometers should be designed with a life expectancy of at least five years. Note that it takes about one year of observations to obtain sufficient matchups with a vicarious calibration site to calculate valid vicarious gains.

Recommendation:

- ❖ At least one year of observations over a vicarious calibration site is required to obtain enough matchups to calculate valid vicarious gains.
- ❖ Ocean-colour radiometers should be designed with a life expectancy of at least five years.

4.9 Radiometer Pre-launch Characterization

Ocean-colour products are extremely sensitive to radiometric errors, because the water-leaving radiance is only a small part of the TOA signal (0-15%). To achieve an accuracy of the chlorophyll product of 35%, the water-leaving radiance at 443 nm must be determined with an accuracy of about 5% (Gordon, 1998). This requires an accuracy of the TOA signal of about 0.5%, which is very challenging. The brutal math of the law of error propagation (basically taking the square root of the sum of the squares of all individual uncorrelated uncertainty components) requires that the uncertainty of each individual component (like polarization, linearity, stray light, etc.) is much smaller than 0.5%, preferably around 0.2%.

There are two separate phases of the radiometer characterization: pre-launch (Section 4.9) and on-orbit (Section 4.10). The pre-launch characterization is very extensive and characterizes as many aspects of the instrument as possible, whereas the on-orbit characterization is usually restricted to the measurement of the radiometric gain and the signal-to-noise ratio, and possibly a trending of the spectral responsivity. The testing protocols and procedures should be mature and vetted with the science community well before the start of the characterization phase.

Although a post-launch vicarious calibration will remove a global bias from the data, it cannot correct scene specific errors (e.g., effects of instrumental polarization sensitivity, stray light, etc.). In addition, without accounting for these instrument effects accurately, the derived post-launch vicarious gains will be in error, significantly impacting the quality of the satellite ocean-colour product. Therefore, the vicarious calibration should not be used to avoid a stringent calibration and characterization effort, both pre-launch and on-orbit.

Although the required radiance uncertainties for heritage sensors are often high, the required reflectance uncertainties are often low (for MODIS there is a 5% radiance uncertainty requirement, and 2% reflectance uncertainty requirement). This may seem surprising, because radiance can be converted to reflectance using the solar irradiance, which is known with an uncertainty of less than 1%. The reason for this disconnect is that instruments like MODIS and MERIS act like ratioing radiometers; they effectively relate the signal measured from the Earth to the signal measured from the solar diffuser, so that the solar diffuser is the main source of uncertainty for the reflectance measurement. The TOA radiance product, at least for MODIS, is not calculated from the reflectance measurement using the solar irradiance, but from the pre-launch gains, adjusted by the change as measured by the solar diffuser. So the absolute calibration of the reflectance and the radiance products are independent of each other, and therefore they deserve different uncertainty requirements. These are discussed in the following two sections.

Recommendation:

- ❖ The vicarious calibration should not be used to avoid a stringent calibration and characterization effort, both pre-launch and on-orbit.
- ❖ Radiometer characterization protocols and procedures should be developed, tested, and approved well before the actual characterization begins.
- ❖ Radiance and reflectance uncertainty requirements are usually different as they serve different purposes. The type of approach chosen for the on-orbit calibration determines which requirement needs to be more restrictive.

4.9.1 Absolute radiance-based radiometric calibration

The absolute radiometric calibration of the instrument is achieved by letting the sensor measure a calibrated light source. The radiance level of the light source should be SI (International System of Units) traceable to standards from National Metrology Institutes. Spherical Integrating Spheres (SIS) are a popular light source, because their spectral output can be easily traced to National Metrology Institutes, and they can achieve a high level of spatial uniformity at their exit aperture. Note that for non-scanning instrument such as MERIS, calibration of the complete FOV of the sensor can only be covered using an SIS by scanning the sensors FOV across the aperture of the SIS, increasing the errors significantly. The spheres are often illuminated by light from tungsten lamps, and a large number of lamps (placed at different positions in the sphere, in conjunction with the scattering inside the sphere, which is coated on the inside with a diffuse, highly reflective material such as Spectralon) assures a high degree of spatial uniformity of the light output; actual non-uniformity of both the output aperture and the back of the sphere needs to be characterized (in the sensor's geometric configuration - pupil location and FOV) to reduce the errors. The multiple scattering inside the sphere leads to a very low degree of polarization of the radiance exiting the SIS; the goal should be a degree of polarization of less than 0.2%. After the light output of the SIS has been calibrated, it needs to be monitored (by sensors internal to the sphere) to ensure that the SIS radiance does not change from the time of the sphere calibration to the time of the radiometer calibration.

The gain (or responsivity) of a radiometer should be calculated as the ratio of the calibration source radiance to the measured digital counts (after offset and other corrections)

$$g = L_c / dn,$$

where L_c is the calibration source radiance and dn is the sensor-measured radiance. Radiometers are sensitive to light outside of the desired band-pass to a certain degree. This effect is called out-of-band response (see Section 4.9.4). To account for this effect, the radiance L_c of the calibration source should be calculated as:

$$L_c = \int L_s(\lambda)^* \mathrm{RSR}(\lambda)\, d\lambda,$$

where $L_s(\lambda)$ is the radiance of the source at wavelength and RSR(λ) is the sensor spectral response function with

$$\int \mathrm{RSR}(\lambda)\, d\lambda = 1.$$

This equation also handles correctly any source spectrum variations in the in-band and out-of-band responses.

One important disadvantage of a SIS illuminated by tungsten lamps is that the spectrum of the tungsten lamp is very different from the typical on-orbit spectrum:

the spectrum of tungsten lamps peaks in the NIR, whereas the solar spectrum has its maximum below 500 nm. This is especially problematic if the radiometer has significant out-of-band response. In the case of the NPP VIIRS 412 nm band, its significant out-of-band response leads to a difference of about 30% when measuring a SIS spectrum and a TOA spectrum that have identical $L_s(\lambda=412$ nm) (Barnes et al., 2010).

The uncertainty budgets for the radiance calibration of heritage sensors are very generous (e.g., 5% for MODIS and SeaWiFS). The National Institute of Standards and Technology (NIST) of the USA has developed a new method for absolute calibration called SIRCUS (Brown, 2003). A SIS is illuminated by tuneable lasers. Each laser has a very narrow spectral band-pass, typically less than 1 nm. The wavelengths of the laser are incremented at small intervals (e.g., 1 nm). This approach eliminates the out-of-band component completely, and combines the absolute calibration and the spectral response characterization (see below). The uncertainties of this method can be as low as 0.5%, but they have not yet been demonstrated on a flight instrument.

Many remote sensing radiometers rely on a solar diffuser as their main on-orbit calibration source (e.g., MERIS, MODIS, and VIIRS). It is desirable to perform a system level test, where the solar diffuser (installed in the sensor) is illuminated with a light source of known irradiance to calibrate the radiometer, but this approach is rarely followed because the uncertainties from an irradiance source are difficult to evaluate, and the differences between a light source in the laboratory and the on-orbit solar illumination are considerable. In effect, this approach was tried for NPP VIIRS using a laser as a light source, but the accuracy of the results was deemed insufficient. Nevertheless, such a test can be an important part of the validation of the pre-launch characterization.

It may seem unnecessary to define a pre-launch radiance uncertainty requirement for sensors like MODIS or MERIS, whose ocean-colour products do not use the pre-launch gain. However, many of the pre-launch characterization tests (e.g., stray light, saturation) require an instrument gain for radiance, and therefore such a requirement is justified. The requirement for SeaWiFS and MODIS of 5% is relatively high; modern technology can achieve better accuracies.

Recommendation:

- ❖ The absolute radiometric calibration of the instrument is achieved by letting the sensor measure a calibrated light source. The radiance level of the light source should be SI (International System of Units) traceable to standards from National Metrology Institutes.
- ❖ On-ground calibration should be made with a spectrum similar to that of the Sun, to minimize the error from out-of-band contributions.
- ❖ The uncertainty budgets for the radiance calibration of heritage sensors are very generous (e.g., 5% for MODIS and SeaWiFS) and should be improved upon for future sensors.

- It may seem unnecessary to define a pre-launch radiance uncertainty requirement for sensors whose ocean-colour products do not use the pre-launch gain for processing of the on-orbit data. However, many of the pre-launch characterization tests (e.g., stray light, saturation, etc.) require an instrument gain to calculate radiance, and therefore such a requirement is justified.

4.9.2 Absolute reflectance-based radiometric calibration

The reflectance calibration of an instrument applies to instruments that use a solar diffuser as their main on-orbit calibration source. The Bidirectional Reflectance Distribution Function (BRDF) of the solar diffuser needs to be determined. As defined by Nicodemus et al. (1977), it describes the absolute reflectance of a surface, as well as the dependence of the reflectance on incidence and view angle. These measurements need to be made so that all combinations of angles that are expected on-orbit are bracketed, with an angular resolution of better than 5 degrees. The absolute uncertainty for the reflectance measurements should be better than 1%, and the relative uncertainty at different angles with respect to each other should be about 0.2%. If a device like a solar diffuser screen is used (e.g., MODIS), the characterization measurements should be done with the screen in place to determine the combined effect.

In case different detectors of the radiometer see different areas of the solar diffuser, the spatial homogeneity of the reflectance of the solar diffuser becomes an important factor. For large aperture sensors such as scanning radiometers, it may be impossible to characterize the spatial variations of the BRDF of the solar diffuser and apply this characterization to the calibration. A more realistic approach is to choose a solar diffuser that shows spatial inhomogeneity below a certain level, e.g., reflectance variations < 0.2% for different areas of the solar diffuser. For imaging spectrometers with small entrance apertures, characterization of the BRDF "as seen" by the sensor on the diffuser plate is possible, and was performed for MERIS with a relative accuracy of better than 0.5%. The illumination size should be chosen so that it matches the area any detector observes according to the BRDF characterization method chosen.

Recommendation:

- The solar diffuser characterization measurements need to be made so that all combinations of angles that are expected on-orbit are bracketed, with an angular resolution of better than 5 degrees.
- The absolute uncertainty for the reflectance measurements should be better than 1%, and the relative uncertainty at different angles with respect to each other should be about 0.2%.
- Spatial homogeneity of the solar diffuser reflectance is an important aspect, and should be reduced to reflectance variations of less than ~0.2% for different

areas of the solar diffuser.

4.9.3 Relative radiometric calibration

The two previous sections described uncertainty goals for the absolute calibration. The calibration requirements of different sensor elements relative to each other (e.g., mirror sides for SeaWiFS, detectors or cameras for MERIS) need to be even tighter since small relative calibration inaccuracies for adjacent sensor elements are easily identifiable in images of ocean-colour products as stripes. These reduce the confidence of the user community in the overall product quality and are detrimental to the detection of spatial features in the Level-2 data. A SIS can provide a spatially homogeneous light field that can be used for relative calibration measurements. The gains of detector elements should be calibrated with an uncertainty of about 0.2%, relative to each other.

Recommendation: The gains of detector elements should be calibrated with an uncertainty of about 0.2%, relative to each other.

4.9.4 Spectral characterization

The spectral response must be measured for each channel and each sensor element. The characterization is typically achieved by shining a light of a well defined wavelength and a small bandwidth (e.g., < 1 nm) into the sensor. Ideally, the spectral sampling is related to the response: the larger the response, the finer the sampling. Filter radiometers like VIIRS have used 1 nm spectral intervals in the in-band region, and 5 nm spectral intervals in the out-of-band regions. The bandwidth should be matched to the sampling interval to minimize spectral aliasing effects. Separate measurements are made for each band. For the out-of-band measurements, the light intensity is increased because of the low expected response. For the in-band measurements, the light intensity is decreased to avoid saturation.

For imaging spectrometers, the spectral calibration should be sufficient to derive a precise instrument model of the spectral dispersion over the complete FOV and spectral range. This implies characterizing not only the defined band set, but preferably all spectral samples, to be able to derive an instrument model of sufficient accuracy.

The center wavelength λ_c can be calculated with the full-width-half-maximum (FWHM) value and should be known with an accuracy of about < 0.5 nm. To achieve the 0.5 nm accuracy, it is suggested that the in-band region be sampled every 0.5 nm. The out-of-band response should be less than 1% of the total response (where out-of-band response is defined as RSR<0.01).

VIIRS on NPP has also been characterized with SIRCUS (Brown 2000, see also Section 4.9.1 for a description of SIRCUS). It was shown that the SIRCUS calibration yields more consistent center wavelengths than the traditional approach with a double monochromator. The reason is that SIRCUS can provide a spatially and spectrally homogenous light field, which is a challenge for double monochromators due to the large aperture of scanning radiometers.

The RSR should be characterized for every sensor element (mirror, detector, camera, etc.), or at least for a representative subset. Variations of the center wavelength for different sensor elements should be less than 0.5 nm. For sensors scanning in the across-track direction, it is generally sufficient to characterize the RSR at one view angle, especially if an instrument model has shown that the dependence of the RSR on scan angle is negligible. The RSR should be characterized over the complete optical path, as far as possible,

Recommendation:

- The spectral response needs to be measured for each channel and each sensor element.
- For imaging spectrometers, the spectral calibration should be sufficient to derive a precise instrument model of the spectral dispersion over the complete FOV and spectral range.
- The center wavelength λ_c can be calculated with the full-width-half-maximum (FWHM) value and should be known with an accuracy of $\sim$<0.5 nm. To achieve the 0.5 nm accuracy, it is suggested that the in-band region be sampled every 0.5 nm.
- Variations of the center wavelengths for different sensor elements should be less than 0.5 nm.
- The out-of-band response should be less than 1% of the total response (where out-of-band response is defined as RSR<0.01).

4.9.5 Linearity, dynamic range, and SNR

The linearity of the sensor's response must be measured. At instrument level, the uncertainty of such measurements may be larger than the non-linearity of the sensor itself; in this case, a linear relation between sensor output *dn* and radiance should be used for data processing, and the non-linearity measurements can serve as an upper limit for the estimation of the uncertainty due to non-linearity. The linearity can be measured, however, at a unit level, in particular at the detector level where most of the radiometric non-linearity occurs in imaging spectrometers. This is required and needs to be corrected for in the processing.

The instrument signal-to-noise ratio (SNR) is calculated using the noise of a single detector element when viewing a constant light source. The SNR must be determined for each band at L_{typ} (see Table 4.1). A SIS with a spatially-homogenous output is often used for this test. Obviously, an excellent (and well characterized) short term temporal stability of the SIS light output is crucial for this test. Additionally, the SNR should be determined at various light levels within the dynamic range. This is often done in conjunction with the dynamic range test, and leads to a reduction in schedule and cost associated with sensor characterization.

Recommendation:

- ❖ The linearity of the sensor's response must be characterized as far as possible, from the component level (e.g., CCDs) up to the system level, to correct for it at Level-1.
- ❖ Bilinear sensor types (e.g., SeaWiFS or VIIRS) are not recommended.
- ❖ The sensor should be illuminated by L_{min} and L_{max} to verify that it functions as expected over the whole dynamic range. The SNR should be determined at various radiance levels.

4.9.6 Temperature dependence

The temperature dependence of the radiometer needs to be characterized for the temperature range expected for the on-orbit operation. Historically, this has been accomplished in thermal vacuum chambers, where the whole instrument is at thermal equilibrium. However, this approach does not capture the temperature gradients that occur on-orbit due to the varying solar angles relative to the spacecraft.

Recommendation: The temperature dependence of the radiometer needs to be characterized for the temperature range expected for the on-orbit operation.

4.9.7 Stray light characterization

In a broad sense, stray light is defined as light that deviates from the ideal optical path through the sensor. Stray light becomes a problem when it reaches a detector that is not supposed to measure it. There are two main types of stray light: light that is measured by a detector from the same band, and light that is measured by a detector from a different band. In the latter case, this is referred to as "optical cross-talk". If the stray light is detected in a different band, but at the equivalent sensor element (so that it affects the same pixel in the image), it becomes part of the out-of-band response.

For obvious reasons, stray light should be kept to a minimum. If the overall accuracy goal is 0.5%, stray light effects (after correction for stray light) should be less than half that amount, because other error sources will consume part of the uncertainty budget as well. It is difficult to give specific recommendations for stray light testing, because the optimal approach depends on the sensor design. In general, stray light testing will involve measuring high contrast scenes such as point sources, slits, or hard transitions from a dark to a bright zone or vice versa. For ocean colour, it is more important to analyze how the dark regions are affected, because over a typical ocean scene, clouds are significant contributors to scattering into the relatively dark ocean scenes.

An important stray light criterion is how many pixels away from a bright region the stray light affects the dark region, because this determines the masking needed around clouds in ocean-colour processing. Additionally, accurate stray light characterization can be used to correct the on-orbit data (Zong et al., 2007), and has been applied to MERIS. Although it is very difficult to properly correct the pixels immediately adjacent to clouds, such corrections can be used to correct those pixels that are only moderately affected, as has been demonstrated with MERIS.

Recommendation:

- ❖ Stray light should be kept to a minimum. Since stray light is a natural part of any imaging system, it should be characterized so that a correction can be applied to reduce the residual stray light to acceptable levels. If the overall accuracy goal is 0.5%, residual stray light (after correction) should be less than about half that amount, and flagged appropriately.
- ❖ For imaging spectrometers, a detailed stray light model needs to be developed; the Total Integrated Scatter (TIS) of each optical surface should be measured on witness samples, introduced in an optical model (i.e. ASAP) of the sensor to compute the (de)convolution kernels used in a stray light correction scheme.

4.9.8 Polarization characterization

Circular polarization of the TOA signal is very low (Gordon et al., 1997) and therefore does not need to be considered during sensor characterization. The degree of *linear* polarization of the TOA signal over the ocean, however, can be up to 70% (Meister et al., 2005a). This is not a problem for a sensor without polarization sensitivity. On the other hand, a sensor such as MODIS-Aqua, with a polarization sensitivity of up to 5.4%, may produce radiance errors of up to 2.7% if the TOA signal is 50% polarized. Sensors like MERIS and SeaWiFS use polarization scramblers to reduce the instrument polarization sensitivity to low levels (SeaWiFS: about 0.3% or less, MERIS: less than 0.1 % in the blue, ~0.2% in the NIR) and the residual polarization sensitivity is carried as an uncertainty without modifying the measured radiances. Sensors with significant polarization sensitivity such as MODIS, require a correction to the TOA measured radiances using the sensor pre-launch polarization characterization data and radiative transfer model (Gordon et al., 1997). Thus, it is important to characterize accurately the instrument polarization sensitivity (Meister et al., 2005a).

One proven polarization characterization method is to use a SIS with a low degree of polarization, and to place a linear polarizer sheet (with well characterized polarization characteristics) between the SIS and the sensor. This method was used to characterize the polarization sensitivity of the NPP VIIRS sensor. The polarizer sheet must be rotated around an axis along the optical path by 180° (or preferably 360°, to confirm that the results from the second 180° agree with the results from the first 180°), taking measurements with the sensor at intervals of about 15°. These measurements must be obtained in such a way that all scan angles (or the desired FOV) are covered. In many cases, this requires repeating the measurement sequence with different orientations of the sensor relative to the SIS. The overall goal should be to characterize the sensor polarization sensitivity with an uncertainty of about 0.2%.

Recommendation: The overall goal should be to characterize the sensor polarization sensitivity with an uncertainty of about 0.2%.

4.9.9 Instrument model

An instrument model predicts the optical and electronic characteristics of a sensor. Component measurements (e.g., mirror reflection, mirror BRDF, dichroic transmission, detector efficiency, etc.) are combined to provide sensor characteristics such as SNR, radiometric sensitivity as a function of scan angle for scanning radiometers, spectral model for imaging spectrometers, polarization sensitivity and stray light. Component measurements and model accuracy must be sufficient to allow meaningful comparisons with system-level measurements. The instrument model increases the understanding of the instrument. Unexpected on-orbit characteristics can often be understood through refinements of the instrument model; if the instrument model cannot even predict the pre-launch characteristics, however, it is very unlikely that it can help in understanding on-orbit behaviour.

Recommendation: An instrument model should be developed for at least those terms that need corrections, i.e., non-linearity, stray light, spectral response and polarization sensitivity, based on unit or component level characterization. The results of the model should be validated with dedicated tests on-ground and on-orbit.

4.9.10 Other required characterizations

Several other sensor characteristics must be determined pre-launch, a few of them are listed below:

1. Sensor response to different integration times should be measured (unless not allowed by the sensor design).
2. All external conditions that influence the offset (including dark current and other video electronics offsets), for example, temperature and power supply, should be identified. This is especially important for sensors that measure the offsets only infrequently, like MERIS and SeaWiFS. The offset should be monitored periodically throughout the pre-launch phase to detect anomalies. Both the absolute value of the offset as well as its noise is worth analyzing. Different types of detectors may require specialized offset characterization. When applicable, dark current should be characterized at different integration times.

3. Spectral registration (or band co-registration) refers to the area sampled for a single pixel by two different bands. The overlap between each combination of bands should be at least 80% for any scan angle.
4. The Modulation Transfer Function (MTF) should be determined.
5. Pointing accuracy and knowledge should be characterized, with accuracy goals that are related to the spatial resolution of the sensor. Note that this characterization is not only a sensor issue, but also related to spacecraft performance.

4.10 On-Orbit Validation and Calibration

Ideally, all the tasks described under the “Radiometric Characterization” in Section 4.9 must be checked, and possibly adjusted, once on orbit. To build a complete and sophisticated on-board device capable of reaching this full coverage of the instrumental characterization is unrealistic, however, due to cost, accommodation issues and technical complexity. Consequently, the on-orbit characterization for ocean-colour sensors has been limited to the most crucial aspects: the absolute calibration, the temporal trending, the spectral response (only for imaging spectrometers), and the noise trending. This characterization can be assessed through:

- lunar measurements;
- solar diffuser measurements;
- on-board light sources; and
- acquisitions over natural targets.

Various calibration and validation approaches are summarized in Table 4.2 where the main interest for each of the methods is listed. Recommended (RECOM) and desired solutions are also identified for the main calibration aspects. Absolute, temporal and spectral properties are detailed in the following subsections.

4.10.1 Absolute calibration on-orbit

The IOCCG Report on Calibration of Ocean-colour Sensors, edited by Robert Frouin (in prep.) reports that the on-orbit calibration is currently not able to reach the required goal of typically 0.5% of uncertainty on the gain adjustment. For ocean-colour sensors, a final vicarious adjustment is always performed to minimize both residual bias on calibration and possible bias on the atmospheric correction.

For past and current ocean-colour missions, the in-flight calibration relies on the pre-flight calibration, whether adjusted or not through a transfer-to-orbit approach using an on-board device (diffuser). This Level-1 calibration was considered to be sufficient as a first step before the final vicarious adjustment in case some limitations still exist (e.g., the 865 nm band on SeaWiFS which is not vicariously calibrated). Despite that, increasing scientific objectives (mainly for coastal applications) push for a future improvement in the accuracy of the Level-1 calibration.

Table 4.2 Overview of on-orbit calibration and validation methods (rows) and suggestions regarding various calibration or validation applications (columns). RECOM - recommended; Desired - nice to have; NR - not recommended; N/A - not applicable.

	Absolute Calibration	**Interband Calibration**	**Trending**	**Spatial Uniformity Calibration**	**Spectral Calibration**	**Sensor Cross-Calibration**
Lunar views	Desired, N/A for pushbroom	Desired	RECOM, not suited for pushbroom	N/A	N/A	Desired
Solar diffuser	RECOM (requires ref. diffuser or monitoring device)	RECOM (requires ref. diffuser or monitoring device)	RECOM (requires ref. diffuser or monitoring device)	RECOM (good BRDF model needed)	RECOM (N/A for bandpass filters) (rare Earth doped diffuser)	N/A
Lamp sources	Desired (ground-to-orbit transfer needed)	Desired (ground-to-orbit transfer needed)	NR	NR	Desired for hyperspectral instruments using monochromator)	N/A
Deep convective clouds	NR	Desired	Desired as validation for VIS-NIR	N/A	N/A	NR (only for sensors on same platform)
Desert sites	NR	Desired	RECOM for trend validation	NR	N/A	RECOM
Oceanic sites (VIS: Rayleigh scattering; NIR: glint)	Desired	RECOM for validation	Desired	NR	N/A	NR
In-situ measurements	RECOM for VIS vicarious adjustment	NR	NR	NR	N/A	Desired

In this context, the Level-1 product must not be seen as a simple intermediate product, but a mandatory step for which the best calibration possible must be performed. This is motivated by the following points:

- since the vicarious adjustment is linked to the atmospheric correction algorithms, a well-calibrated Level-1 is a proxy for the development of other algorithms that could improve on those used for the vicarious step, or ones that could use different approaches;
- atmospheric correction over coastal water is not an easy task: future improvements on coastal algorithms will clearly benefit from a reduced calibration uncertainty in the longer wavelengths (NIR and SWIR bands);
- data merging from different missions, necessary to construct long time series or global scale analysis, would also benefit from a better product consistency at Level-1;
- since the vicarious calibration is a correction of an overall bias due to calibration and atmospheric correction residues, the smaller the calibration error, the more accurate the vicarious adjustment will be.

Consequently, if the 0.5% accuracy goal is only reachable through vicarious calibration, a specification at Level-1 has to be kept on the in-flight absolute calibration. A goal of 2% or better seems a realistic target, even if challenging. The calibration can be done either reflectance based or radiance based. The standard SeaWiFS calibration is radiance based, but a reflectance based calibration provided similar results (Barnes and Zalewski 2003a; 2003b). To assess the in-flight absolute calibration, strategies for past and current ocean-colour sensors are based on different approaches.

- Solar diffuser measurements usually provide an absolute calibration of sufficient quality, provided that the pre-launch characterization of the solar diffuser reflectance is sufficiently accurate and did not change during the transition from pre-launch to on-orbit. MODIS and MERIS rely on this method to provide the absolute calibration of the instrument.
- Although lunar calibrations can provide an absolute calibration as well, via the ROLO model, the accuracy of the absolute calibration of the ROLO model is relatively low (around 5%, Eplee et al., 2009). For SeaWiFS, the preferred method was to use the pre-launch gains for the absolute calibration, and to estimate the uncertainty for the transition from the pre-launch period to the first lunar measurement (Barnes et al., 2000). The pre-launch gains are then modified by the on-orbit change derived by the lunar measurements. The absolute calibration of the ROLO model is not used.
- Alternative methods were used for POLDER instruments for which a statistical approach using molecular scattering was used to derive an absolute calibration for visible bands despite the lack of an on-board calibration device (Fougnie et al., 2007). This method was combined with an interband calibration over sunglint primarily to calibrate NIR and SWIR bands (Hagolle et al., 2004). Such

methods were also used to validate the MERIS calibration derived through the solar diffuser (Hagolle et al., 2006).

Recommendation: Since the 0.5% accuracy goal is only reachable through the vicarious calibration, a specification at Level-1 has to be kept for the in-flight absolute calibration. A goal of 2% or better seems a realistic target, albeit challenging. This accuracy is required whatever the considered period of the mission life, and consequently must include trending. If this accuracy is not currently required, it is important for future algorithmic improvements and development of new approaches, mainly for coastal applications.

4.10.2 Temporal trending

Temporal trending refers to monitoring the evaluation of the radiometric sensitivity of the sensor with time. The results are usually applied in the processing stream as temporally changing gains. Ideally, the ocean-colour data is processed after a reliable determination of the sensor gain at the time of the ocean-colour data acquisition. This requires calibration measurements before and after the time of the ocean-colour data acquisition. This creates a conflict with the desire of many users to obtain the data in near real time. To address this issue, the instrument calibration team usually develops an analytical function from calibration measurements that allows the extrapolation of the gain evolution from the time the calibration measurements were acquired into the future. This extrapolation is generally used to process the operational data stream.

Subsequent calibration measurements may suggest a different gain trending function. In case the difference surpasses the accuracy requirements (see Section 4.2), the affected data should be reprocessed.

Only lunar and solar diffuser techniques have been successfully used by ocean-colour sensors for long-term gain trending. On-board light sources were available for MODIS (as part of the SRCA, see Xiong et al., 2006), but the stability of the light bulbs was not sufficient to establish a record over several years. Monitoring over Earth natural targets has shown good potential, mainly through desert sites and deep convective clouds, as shown for POLDER/PARASOL instruments. The fourth column of Table 4.2 evaluates the suitability of various approaches for temporal trending for calibration and validation purposes; further details are provided in the subsections below.

Recommendation: Gain trending is mandatory and should be given high priority.

4.10.2.1 Lunar trending

Lunar measurements have provided the longest calibration time series for ocean-colour sensors to date. SeaWiFS was calibrated using lunar measurements throughout its mission life (1997 to 2010). The trends of the ocean-colour products covering this 13.5 year span show an impressive consistency (Franz et al., 2005; http://oceancolor.gsfc.nasa.gov/). The main advantage of lunar calibrations is that the Moon provides a reflectance that is constant over geological time scales (Kieffer, 1997), exceeding reasonable instrument goals by five orders of magnitude. It is also available at all wavelengths required for ocean-colour products.

The main disadvantage of the Moon is that it is a small source that does not fill the FOV of any heritage ocean-colour sensor, since it typically illuminates only an area on the focal plane equivalent to 10 km x 10 km for Earth view imaging. Therefore, the Moon can only be used to track one part of the sensor degradation; the degradation of the scan angle dependence must be monitored with other sources. A sensor design such as SeaWiFS is well suited for this approach, because its scan angle dependence did not change on-orbit and all detectors see the Moon with equal weighting.

It should be noted that the use of lunar trending is not suited to imaging spectrometers that require the complete field-of-view to be illuminated during calibration, as it would require a complex manoeuvre to scan the Moon across the complete field-of-view of the sensor. Another disadvantage is that the sensor must be directed away from the Earth towards the Moon for the calibration measurement, a manoeuvre that poses no challenge to the sensor itself or the satellite platform, but may be undesirable for other sensors that share the platform.

Although the reflectance of the Moon is extremely stable, the irradiance as calculated from the measurements of the ocean-colour sensor varies considerably, due to varying solar-Moon-Earth distances and libration effects, even for constant phase angles. The ROLO model has been developed by the USGS to account for these effects for wavelengths from 350 nm to 2450 nm, with an accuracy of about 0.1% (Kieffer and Stone, 2005). Although the ROLO model also accounts for phase angle variations, heritage sensors (SeaWiFS and MODIS) have restricted the lunar measurements to a constant phase angle to eliminate this potential source of uncertainty. Note that the accuracy for the ROLO model only applies to the relative trending. The absolute uncertainty of the ROLO model is several percent and has not been shown to be adequate for ocean-colour calibration. It must also be noted that the ROLO model is only available in the U.S., as it is classified as strategic technology not available for export.

Recommendation: The main advantage of lunar calibrations is that the Moon provides a reflectance that is constant over geological time scales (Kieffer, 1997). Lunar calibration measurements are strongly recommended if the sensor design allows such measurements. Lunar trending is not suited for sensors that require the complete field-of-view to be illuminated during calibration.

4.10.2.2 Solar diffuser trending

The main advantage of solar diffuser measurements relative to lunar measurements is that the solar diffuser can fill the full FOV of the sensor, thereby allowing the calibration of every sensor element (detectors, cameras, etc.) from a single measurement. Also, the frequency of measurements can be as high as once per orbit, compared to once per month for the lunar calibrations (phase angle restriction). To limit the exposure to solar UV light, the solar diffuser is typically used about once or twice a month.

The solar diffuser in the MODIS design provided a reasonably good calibration source for the first four years of the Terra mission. After four years, however, a door to protect the solar diffuser malfunctioned, and the door has been left open ever since. The subsequent solar diffuser calibration measurements show a clearly erroneous trend at 412 nm (Kwiatkowska et al., 2008). This is very likely due to the increased solar exposure of the solar diffuser, although it is not clear why this is not corrected by the Solar Diffuser Stability Monitor (SDSM), a separate sensor inside MODIS that ratios measurements of the solar diffuser and direct solar measurements. MODIS-Aqua did not have a problem with its solar diffuser door, but its solar diffuser trending also started to show an erroneous trend at 412 nm after 8 years on-orbit (Meister et al., 2010). On the other hand, lunar trends from both MODIS-Aqua and Terra did not show any inconsistencies relative to SeaWiFS throughout the mission.

The MERIS approach to solar diffuser trending seems to be more robust than the MODIS approach. It is expected that results from the 2010 reprocessing of MERIS data will show that the well-protected second solar diffuser has been able to correct the aging of the more frequently used first solar diffuser to an accuracy of better than 0.2 %.

Over sufficiently long time periods, even a well protected solar diffuser will show changes in reflectance. The MERIS experience demonstrated a degradation of less than 0.2% per year for the frequently used first diffuser, and this limit may well be sufficient to cover the entire lifespan of a mission. Nevertheless, a combination of lunar calibrations and solar diffuser calibrations is the most likely path to provide the accuracy required for climate data records over 10 years or more.

Recommendation: Solar diffusers are a well established tool for on-orbit calibration and have been used successfully in ocean-colour remote sensing. The main disadvantage is the change of reflectance of the solar diffuser on-orbit, which must be monitored.

4.10.2.3 Trending over natural targets

In general, calibration over natural Earth targets is a good way to validate the monitoring derived from on-board devices. The main limitation is that a long time series is necessary to guarantee sufficient confidence in the derived temporal trend. Nevertheless, very good potential has been found using desert sites and deep convective clouds (DCC), not only for their robustness, but also for short-term assessments of the trending. Desert sites are very stable targets with surface reflectance nearly invariable with time, except for bidirectional effects. Land can be used to derive an accurate check of the trending (Lachérade et al., 2012; Gamet et al., 2011). An accurate temporal monitoring was derived from an operational method using DCC for the POLDER-3 (PARASOL) instrument (Fougnie et al., 2007). On the other hand, such a method requires acquisitions over very bright clouds which are not always accessible for an ocean-colour sensor because of possible saturation.

Recommendation: Using natural targets for trending is recommended for validation of trending performed by other methods, or to enhance trending performed by other methods.

4.10.2.4 Spectral trending

On-orbit characterization of the instrumental spectral response offers the advantage of optimizing the data processing at least at Level-2. A typical 1 nm shift or uncertainty in the spectral response results in a direct error of 1% on the TOA reflectance or radiance, and about 10% on marine reflectance. If not identified, such an error can be cancelled at the first order through the vicarious calibration, but very complex second order artifacts would remain in the data, leading to unexplained behaviour, for instance with the viewing geometries (solar or viewing) or atmospheric turbidities (difficulties to obtain a fully efficient atmospheric correction).

For imaging spectrometers such as MERIS, spectral trending is possible by comparing the results from the regularly performed spectral calibration activities. By configuring the instrument band set around well-defined spectral features covering the spectral extent of the sensor, and monitoring their evolution, an estimate of the spectral drifts can be made. Such techniques have shown, for example, that cameras 2 and 4 of MERIS drifted by 0.15 nm the first year in orbit, but were stable <0.05 nm since (see Delwart et al. 2004; Delwart and Bourg, 2011).

Most filter radiometers assume that spectral characteristics of the bands do not change after the pre-launch characterization. For the two MODIS instruments on Aqua and Terra, this assumption can be verified with the Spectroradiometric Calibration Assembly (SRCA, see Xiong et al., 2006). The SRCA contains a monochromator that is used every 3 months to determine the center wavelengths of the bands from 412 nm to 940 nm. The center wavelengths for the MODIS-Terra bands from 443 nm to 940 nm have changed by less than 0.5 nm. At 412 nm, a difference of 0.5 - 1.0 nm was measured when comparing pre-launch and on-orbit, but the uncertainties of the SRCA in that band are higher than in the other bands.

Recommendation: Spectral calibration trending is mandatory, except for filter-based radiometers.

4.10.2.5 Noise trending

The SNR can be monitored by observing spatially-homogeneous targets, such as a solar diffuser. For the MODIS sensor, an analysis of the solar diffuser data at different illumination conditions led to a derivation of the SNR as a function of radiance (unpublished). For SeaWiFS, the SNR was evaluated throughout the mission. The SNR did not change on-orbit to within the uncertainties of the analysis (Eplee et al., 2007). For narrow bands and longer wavelengths, the speckle on the diffusers can be as high as 0.2% and will influence the SNR determination for high precision instruments (van Brug et al., 2004). Care should be taken to minimize such effects.

The SNR could also be monitored using Earth view data by choosing homogeneous targets. However, true variability of the incoming light field is likely to be higher than for solar diffuser measurements and must be accounted for when evaluating the results, which is challenging.

Recommendation: Noise trending is recommended.

4.11 Field Segment Requirements

4.11.1 Vicarious calibration

In addition to the efforts to calibrate the sensor data with solar diffuser and lunar measurements, an on-orbit vicarious adjustment is required to achieve the desired levels of accuracy (Gordon, 1987; 1998; Antoine et al., 2008). The vicarious calibration process results in a set of multiplicative correction factors that force the instrument response at each sensor wavelength to retrieve expected normalized water-leaving radiance values. These adjustment factors account for characterization errors or undetermined post-launch changes in instrument response, as well as any systematic bias associated with the atmospheric correction algorithm (Gordon, 1998; Eplee et al., 2001; Wang and Gordon, 2002; Franz et al., 2007). Such an adjustment is necessary as the satellite-derived normalized water-leaving radiance is a relatively small fraction of the TOA radiance measured by the instrument, i.e., typically <10% of sensor-measured radiance is from ocean radiance contributions. Small errors in the sensor calibration will therefore be unacceptably magnified as a total contribution to the water-leaving component of the measured signal.

The basic strategy of vicarious calibration is to calculate the TOA radiance a satellite sensor should retrieve, based on *in situ* measurements of the water-leaving radiance and radiative transfer modelling to account for the atmospheric and ocean surface effects (Gordon, 1998). The radiative transfer modelling should be consistent with the algorithms used for standard ocean-colour processing (calculating water-leaving radiances from TOA radiances).

Data collected from radiometers mounted to buoys have been used as target water-leaving radiance values for the vicarious calibration process, e.g., from the

Marine Optical Buoy (MOBY) near Hawaii (Clark et al., 1997; 2002) and the BOUSSOLE (Bouée pour l'acquisition d'une Série Optique à Long terme) site in the Mediterranean Sea (Antoine et al., 2002). Since individual matchups of *in situ* measurements and satellite measurements are relatively noisy (Franz et al., 2007), it is usually not possible to correct temporal trends, scan angle dependence or detector/camera/mirror side artifacts with the *in situ* data (unless the on-board calibration is severely compromised). Thus, the vicarious calibration method has been limited to adjustments of the on-board calibration as a set of time-independent factors, one for each of the sensor bands. Given the limitations of *in situ* measurement collection at one site, the time needed to obtain reliable vicarious calibration coefficients is about 2 – 3 years (Franz et al., 2007). In the early part of a mission (when matchups to *in situ* data are still rare), alternative sources may be employed (Werdell et al., 2007). Should the need arise, model-derived *in situ* radiances may serve as an acceptable source (Werdell et al., 2007) and may also be considered.

Instruments that provide hyperspectral water-leaving radiance spectra (e.g., MOBY) can be used for deriving water-leaving radiance data accounting for the effect of sensor spectral responses (in-band and out-of-band). Such data can be used for vicarious calibration for all satellite ocean-colour sensors, as radiance values for the specific band-passes of ocean-colour sensors can be obtained. Filter radiometers (e.g., BOUSSOLE) can also be used for vicarious calibration, even if the center wavelengths of their bands do not agree exactly with those of the satellite radiometer (Bailey et al., 2008). To account for the lack of full bandpass *in situ* values, Wang et al. (2001) proposed a correction method to remove spectral bandpass differences between satellite and *in situ* sensors.

The uncertainty of the *in situ* measurements is an important aspect of the vicarious calibration. MOBY has provided uncertainties in the order of ~3% (Brown et al., 2007), and BOUSSOLE about 6% (Antoine et al., 2008). Uncertainties below 5% are required to meet the ambitious goals outlined in this report.

For the NIR bands, an additional set of assumptions are employed. The satellite data is not compared to *in situ* radiance measurements; rather regions are selected where the assumption of negligible water-leaving radiances in the NIR can be made and where a high degree of fidelity exists in the knowledge of the actual (or typical) atmospheric (i.e., aerosols) constituents. The TOA radiance is modelled based on this information and compared to the actual satellite radiance measurements. It has been shown that for atmospheric corrections using the NIR bands, as long as the sensor is well characterized and the calibration error of the longer NIR band (865 nm) are within ~5%, the vicarious-calibration is sufficient to derive accurate water-leaving radiances (Wang and Gordon, 2002). Results are completely independent of the pre-launch calibration errors in wavelengths < 865 nm.

Franz et al. (2007) demonstrated that the vicarious coefficients can be derived with a standard error of about 0.1%. To achieve such results, the determination of the vicarious coefficients must be made carefully, avoiding measurements where instrument or algorithm uncertainties are high (e.g., data affected by stray light; geometries with high polarization sensitivity, etc.). In addition, it is important to have a sufficient number of samples. Given these constraints, the creation and operation of a vicarious calibration data facility is a resource intensive task. It is important that any ocean-colour mission has a well-defined strategy for obtaining the *in situ* data necessary for vicarious calibration.

Recommendation: It is important that any ocean-colour mission has a well-defined strategy for:

- obtaining the *in situ* data necessary for vicarious calibration, and
- calculating the TOA radiance a satellite sensor should retrieve given the *in situ* measurements.

4.11.2 Validation of normalized water-leaving radiance

In order to derive Level-1 requirements based on water-leaving radiance products, one must consider the way these products are validated, and discuss the accuracy requirements of such *in situ* measurements. An *in situ* measurement of ρ_w involves measuring L_w and E_s separately, either directly or indirectly. Note that in Case-1 waters, where well-defined relationships relate marine reflectances to chlorophyll concentrations, one can also use the chlorophyll concentration as a proxy for reflectance (Werdell et al., 2007). Ocean-colour radiometers, however, measure only the TOA radiances, which after removal of the atmospheric contributions is transformed into normalized water-leaving radiance (after further removal of the atmospheric transmittance, based on a model) and then converted to reflectance (by dividing by an assumed E_s value based on a the same model used to remove the atmospheric contribution) and the atmospheric transmittance is computed.

Two important points must be considered here:

- in principle, only *in situ* L_w measurements are required for satellite calibration/validation activities;
- *in situ* measurement of E_s, and comparison with the modelled E_s, provides another important quality control of the performance of the *in situ* system.

L_w can be measured directly by above-water radiometry or indirectly by interpolation across the surface of underwater measurement of the upwelling radiance just below the surface L_u(0-). Above-water and under water measurement of L_w or L_u are usually not performed for the viewing geometry of the satellite, and must be converted to this geometry for cal/val purposes. Alternatively, both the *in situ*-derived and the satellite-derived L_w can be converted to the same, usually nadir, viewing geometry (IOCCG 10, 2010). E_s can similarly be measured directly above water, or obtained by extrapolation of underwater measurements of the downwelling irradiance.

Recommendation: Since the primary vicarious calibration site is usually in an open ocean environment, care should be taken to obtain sufficient *in situ* data from turbid waters for validation purposes.

4.11.3 *In situ* measurements of L_w and L_u(0-)

Measurements of above-water L_w require either one single radiometer, as in the OC-Aeronet Sea-PRISM system, or two as in the TRIOS-Ramses and SIMBADA systems. The measurement of underwater L_u(0-) requires either one single radiance sensor, in the case of profilers, or two at fixed depths separated by a few meters, in the case of large optical buoys (MOBY, BOUSSOLE), or the combination of a single radiance sensor for the upwelling radiance at fixed depth and a vertical chain of irradiance sensors as used in the TACSS systems. The radiance sensors can be either multispectral, with well-characterized channel responses, or hyperspectral using spectrometers, however, these suffer from poorly characterized stray light distributions.

In normal deployment conditions, above-water L_w measurements from moving platforms are little affected by the tilt of the platform, due to the mainly Lambertian characteristics of the f/Q term. On the other hand, in-water L_u(0-) measurements can be affected by tilt if the absolute depths of the radiance sensors from which L_u(0-) is extrapolated just below the surface is unknown.

4.11.4 *In situ* measurements of E_s

Above-water E_s measurements with a well calibrated dry radiometer on a stable platform come very close to the theoretical value computed with a model, to the extent that they can reveal inter-band calibration anomalies of the irradiance sensor.

Above-water E_s measurements from a tilting platform are severely affected by tilt. Exact tilt correction is extremely difficult and requires, as a minimum, the exact knowledge of the tilt magnitude and that of the azimuth of the normal of the tilted surface. It also requires information of the aerosol optical thickness and Ångström coefficient. Crude estimates of tilt influence on E_s can be used to derive information on the systematic tilt of a platform.

Finally, it is probably incorrect to assume that tilt effects average zero during a measurement sequence, even if the tilt angle averages zero during the same period of time, because fluctuations of tilt angle could be correlated with tilt azimuth variations during the same period. Underwater measurements of E_d are also severely affected by tilt and by the defocusing effect of the incoming light by the wave field at the air-sea interface.

4.12 Documentation requirements

Comprehensive documentation of mission-related activities and processes, in a form that the user community can access and comprehend, remains one of the most overlooked requirements of many flight projects. The length of time from mission conception to completion can be a couple of decades, with inevitable staffing turnover. The risk of loosing valuable information is therefore a serious concern. Much flight project documentation is in the form of contractor reports and presentations that are not generally available to the public, and often not organized in a single repository allowing for easy access. Information is often published in conference proceedings such as SPIE, which are not catalogued by a flight project. The preservation of information is essential because the data from the missions will be used well beyond the end of the mission, and understanding such topics as sensor design and performance test data can be critical to future improvements in the data processing algorithms and in the design of future sensors. The topics of interest to the user community can be quite broad and include at least the following:

- science objectives and traceability matrix;
- mission review presentations and documents, e.g., mission confirmation review, preliminary design review including project management structure and responsibilities;
- sensor design rationale and component and subsystem descriptions;
- pre-launch sensor characterization and calibration procedures, data, and analyses;
- data processing algorithm descriptions;
    - sensor calibration
    - on-orbit sensor degradation data and corrections
    - vicarious calibration data and methods
    - atmospheric corrections - quality masks and flags
    - ancillary data descriptions and quality evaluations
    - bio-optical properties
    - end-to-end processing algorithm sequence
    - algorithm test results including sensitivity and time-series analyses
- derived product validation data and product quality evaluations;
- data formats and metadata descriptions;
- data acquisition and processing system architecture and flow;
- data distribution system architecture and data access procedures;
- field campaign descriptions.

Of the ocean-colour missions to date, the SeaWiFS Project has made the most concerted effort to document procedures and provide the information to the user community in a systematic manner, primarily through the SeaWiFS Pre-launch and Post-launch Technical Memorandum Series. This series totalled some 70 documents and includes index volumes that allow users to find information on various topics across the memorandum series. The technical memorandum series required a full-time technical editor working under the supervision of the deputy project scientist. In addition, the NASA Ocean Color web site at Goddard Space Flight Center maintains an on-line archive of all documents published by the staff including the Technical Memorandum Series, conference proceedings, and refereed journal articles. The web site also provides access to results of various algorithm evaluations conducted by the Ocean Biology Processing Group, algorithm updates for each reprocessing, and other related information.

Chapter 5

International Cooperation

International (inter-mission) cooperation and collaboration is essential to support ocean-colour satellite missions that will enable observations to answer the presented science questions (Table 5.1). A formalized team of international space agency partners will facilitate improvement of polar, and some aspects of geostationary/geosynchronous, orbiters' temporal and spatial coverage, international reliability and compatibility of ocean-colour sensor datasets, quantify the dataset uncertainty, produce algorithm theoretical basis documents (i.e., methods and database used to develop the algorithms), validation basis documents (procedures and data repository), some basic ocean-colour instrument and mission requirements, and data products to be in a standard format and publicly available via a mechanism such as the world wide web. NASA initiated an international partnership in the 1990's called "SIMBIOS" that began the coordination of international research efforts for the *in situ* component of ocean-colour remote sensing. Given the planning that is involved in ocean-colour satellite missions and the interest in standardizing some key requirements for the observations and sensors, a comparable program should be initiated to enable the international ocean-colour community to address the aforementioned tasks. The program should support ocean-colour essential climate variables (ECVs), build international consensus regarding the many scientific and programmatic aspects of ocean-colour sensors and data, and plan for and facilitate the tools and data needed to address the current and future research and applications of ocean biological, ecology and bio-geochemical observations of natural waters.

International governmental bodies should coordinate their Earth observations to support basic and applied research needs to address current and future global change, as well as the Group on Earth Observations (GEO). The Committee on Earth Observing Satellites (CEOS) Ocean-Colour Radiometry Virtual Constellation (OCR-VC) was established in 2009 (Yoder et al., 2009a; 2009b). A virtual constellation is a set of space- and ground-segment capabilities operating together in a coordinated virtual system to achieve political visibility and increase mutual benefit among space and other environmental agencies in support of cross-cutting GEO tasks and targets. The OCR-VC identified priorities to establish a concerted inter-agency effort for activities relating to sensor inter-comparison and uncertainty assessment of datasets required for ECV generation. This coordinating program is tentatively named "International

Table 5.1 Traceability of the international collaboration items to Scientific Questions.

<table>
<tr><th rowspan="2">Scientific Question</th><th colspan="2">Required International Collaboration</th></tr>
<tr><th>Specific items</th><th>Common items</th></tr>
<tr><td>1. Marine ecosystems
2. Biogeochemical cycles
3. Land-ocean interactions
6. Algal blooms
7. Coastal ecosystem</td><td>(E) International strategy and collaboration on regional/coastal measurements and research</td><td rowspan="5">(A) Ensure sustainable ocean-colour satellite missions with sufficient coverage
(B) Inter-usability of multiple satellite products
- Standardization of in situ bio-optical measurements (comparison of instruments and methods, training courses, protocols)
- Standardization of product validation and quality assurance (uncertainty assessment) methods
(C) Accessibility of products and algorithm basis
- Data distribution policy
- Documents and in situ database
- User software
(D) Sufficient in situ measurements (number and coverage) for satellite algorithm basis and validation
- International coordinated sites
- Cal/Val field campaign</td></tr>
<tr><td>4. Ocean-atmosphere interactions</td><td>(F) Collaboration with atmosphere research/ observations</td></tr>
<tr><td>5. Biological-dynamical interactions</td><td>(G) Collaboration with physical research/ observations</td></tr>
<tr><td>8. Fisheries</td><td rowspan="2">(H) Collaboration with application researchers and user communities</td></tr>
<tr><td>9. Ocean pollution</td></tr>
</table>

Network for Sensor InTercomparison and Uncertainty assessment for Ocean-Colour Radiometry (INSITU-OCR)".

In addition to the product levels, international cooperation of satellite orbit/sensor design may improve interoperability, traceability, and observation frequency through data merging. Accumulation of international expertise of data applications will enhance transition from proof-of-concept missions and applications to operational use and societal benefit. The objectives of this chapter are to show inter-mission collaboration requirements for the scientific questions, and propose the possible networking structure (INSITU-OCR, see Section 5.2 below), except for topics which have been discussed in previous chapters.

5.1 Collaboration requirements

The core scientific questions proposed in this report, and at the center of basic scientific goals of ocean-colour remote sensing, require international collaboration including mission design, satellite instruments/carrier, *in situ* instruments, processing/evaluation, receiving/distribution, and product applications. Areas of collaboration are identified as common and specific.

5.1.1 Common requirements

5.1.1.1 Ensure sustainable and global coverage of ocean-colour satellite missions

Polar-orbiting ocean-colour satellite missions should maintain public launch and operations schedules, and ensure that successive development plans are public to ensure continuous, long-term, research-quality data from ocean-colour satellites. International collaborations must organize science teams and construct international agreements to facilitate the international collaboration required to support a high-quality, continuous time series of ocean-colour data.

International coordination of mission planning, development, building and operation would allow frequent and long-term climate quality data sets at a cost-savings for all space agencies. For example, local equatorial crossing time of polar orbiting satellites and longitudinal coverage for geostationary satellites can be shared internationally to facilitate reduction in duplication of effort. This will facilitate the ability of satellite developers to look for launches of opportunity for ocean-colour instruments on available platforms.

5.1.1.2 Inter-usability of satellite products

Inter-usability of satellite variables, such as small data bias, definition of variables (e.g., BRDF consideration for L_{wN} (or R_{rs}), methods of *in situ* bio-optical measurements), center wavelength of L_{wN} (or R_{rs}), temporal and spatial grids, and calibration consistency are key issues for the merging of ocean-colour products (see, IOCCG Report 6, 2007, "Ocean-Colour Data Merging").

It is important to be clear concerning the differences in sensor data products and the associated data product error budgets when attempting to merge multi-sensor satellite data products. We must ensure commonly applicable protocols through international collaboration. Knowledge of errors/biases is required for some merger methods like optimal interpolation and model assimilation. The center-wavelength difference of L_{wN} (or R_{rs}) can be considered in some methods such as spectral-matching schemes. Calibration consistency among the products (especially bias and stability) is still a fundamental issue that needs to be addressed to produce climate quality datasets and time series from which long-term trend analyses can be undertaken. Critical areas to ensure satellite data product inter-usability include:

- Cooperation on instrument pre-launch, vicarious, and on-orbit calibration and characterization, including sharing of instrument calibration and characterization expertise, facilities (round-robins, joint field campaigns), and data/measurements, are the key to improving the Level-1 data accuracy and consistency.
- Dataset consistency can be improved by cross calibration of sensors and intercomparison of their products through, for example, comparison of the calibration sources (e.g., measuring integrating spheres by standard portable radiometers) during the pre-launch ground tests, and radiance or product comparison at *in situ* observation sites. International coordination (e.g., CEOS IVOS/WGCV, OCR-VC/INSITU-OCR) has benefits such as exchange of the satellite and *in situ* data, information and instrument, and common cross-calibration and validation sites (or areas). International sharing of remote and *in situ* data is critical to the success of ocean, climate and Earth System science. A commitment is not enough to ensure that the international community will capitalize on long-term time series science data quality and cost benefits.
- The "dataset consistency" includes convertibility among different ocean property definitions. For example, there are a number of definitions of "ocean colour" as well as a range of variables, including L_{wN} and R_{rs} and detailed definitions of directional normalization. In the case of binned data, the grid definition, quality control, and statistical averaging methods should be noted and convertible (see, IOCCG Report 4, 2004, "*Guide to the Creation and Use of Ocean-Colour, Level-3, Binned Data Products*").
- Definitions and uncertainties associated with satellite data products generally depend on *in situ* measurement methods used for the algorithm development and validation. Several methods of *in situ* bio/optical measurements have been used for vicarious calibration and data product validation. All methods, uncertainties, and limitations for the calibration and validation measurements should be well understood and quantified, based on the published NASA

protocols for *in situ* measurements (*Ocean Optics Protocols for Satellite Ocean Color Sensor Validation*, NASA/GSFC). The common protocol approach for existing instruments should be developed, and those collecting field data should participate in round-robins to ensure data quality continuity supported by the agencies.

Internationally coordinated training courses are critical for ensuring *in situ* instrumentation guidelines and protocols are followed, and data are submitted to a central database for international use.

5.1.1.3 Accessibility of products and algorithm basis

International scientific and management success will be realized by broad and unrestricted accessibility of the data products and, to some extent, common but shared algorithm theoretical basis documents. Data sharing and common data formatting should be encouraged through international cooperation.

- ❖ Satellite ocean-colour data, including TOA radiance data (Level-1 or Level-0 to enable calibration updates and reprocessing), geophysical data products (Level-2), and statistical products (Level-3), should be freely available for research and operational environmental monitoring (open data policy). Encryption/unencryption and processing software should be shared, along with direct broadcast capabilities and data products.
- ❖ User access should be web-based and standardized for the algorithm theoretical basis documents, data format description, and data product quality (validation and flagging) information, along with the satellite data themselves. This associated information is essential for data users. Selection and coordination of a common data format such as HDF and Net-CDF will improve user capability to handle and merge data from different missions and instruments. Validation results and their methodology should be documented and made available to data users as an indicator of product accuracy as recommended by the QA4EO (`http://qa4eo.org/`), for example.
- ❖ A consistently measured, protocol-followed, common set of *in situ* data that is maintained by individual data providers (agencies/institutes) should be independent of the actual database systems and distribution points to support validation and modelling activities.

Data processing and visualization software should be standardized and free to all research and operational/management users. If a new sensor is launched, a processing module may be added to the core software package. User software should support data from multiple ocean-colour sensors. A single core data processing/visualization package (e.g., SeaDAS, BEAM, ODESA) will help users to read data values, convert data in different formats, enable radiometric calibration, geo-correction, and re-mapping, and calculate from satellite-observed radiance (Level-1) to the ocean-colour products (Level-2), including statistical products (Level-3). The processor from Level-1 to Level-2 enables users to produce ocean-colour products by common or user-specific parameters using multiple sensor data e.g., Wang et al. (2002). Open policy of core package source code is recommended to encourage software improvement by international research communities and will facilitate the use of data from a new satellite mission.

5.1.1.4 Geographically- and optically-diverse *in situ* measurements for satellite algorithm basis and validation

In situ data are essential for both algorithm development and validation of satellite data products. Bio-optical properties often vary within global coastal, open ocean and regional water masses. However, it is inefficient for a single mission to try to obtain a large number and global coverage of *in situ* data to address science data algorithm development and validation.

- ❖ International field campaigns in optically-diverse waters, and at varying latitudes, are critical to obtain enough *in situ* samples, and to coordinate consistent measurement methods and protocols.
- ❖ Having a dedicated active portal operated by a central *in situ* office for historical/current/future international field campaigns will allow the agencies and individual researchers to better plan and coordinate their efforts, as well as leverage sampling opportunities.

5.1.2 Specific requirements

5.1.2.1 Collaboration with atmosphere/interdisciplinary research/observations

Several international programs are focused on collection of atmospheric data or research (e.g., AERONET, SOLAS). These programs also investigate data, approaches, and models of processes and measurements of aerosol and cloud properties that are related to the ocean-atmosphere interaction, and are needed for radiative transfer problems such as the atmospheric correction of ocean-colour data. Establishing active and international collaborations between the atmospheric and ocean-colour communities will facilitate collaborations to improve the ocean-colour atmospheric correction. In turn, precise ocean-colour data will enable more accurate retrievals of aerosols.

5.1.2.2 Collaboration with ocean physics research/observations

Collaboration between ocean colour and physical oceanography programs, including model comparisons and global *in situ* physical measurements (such as Argo, TAO/TRITON, PIRATA, RAMA) are needed to effectively investigate coupled biological-dynamical interactions, as well as climate impacts on ocean biology, ecology, and chemistry.

5.1.2.3 Collaboration with the applied research and user communities

Applied research, management and conservation, such as fisheries management and ocean pollution monitoring, are important applications and uses of satellite ocean-colour data. Arguably, use of satellite ocean-colour data is the only method available to understand the impacts and feedbacks of environmental variability on a global scale. All ocean-colour data sources (ocean-colour products and *in situ* measurements) and the analysis methods should be comparable through international collaboration e.g., Forget et al. (2009) to provide accurate estimates of global marine resources and to contribute towards resource and environmental management.

5.2 International Network for Sensor InTercomparison and Uncertainty assessment for Ocean-colour Radiometry (INSITU-OCR)

While the previous chapter focused on the critical strategic requirements for ensuring internationally supported, global, climate research quality, ocean-colour observations from polar orbiting satellites, this chapter focuses on a few ideas as to the implementation of such a program. At the time of writing, the IOCCG has selected a writing team to develop a strategic and implementation approach for such a program. We will touch on some of the key points here. The INSITU-OCR is a concept of concerted international and inter-agency effort to coordinate activities relating to satellite ocean-colour sensor inter-comparison and uncertainty assessment of datasets required for essential climate variable (ECV) generation. The related activities will include calibration, validation, merging of satellite and *in situ* data, satellite data product generation, as well as development and demonstrations of new and improved applications. The concept of the INSITU-OCR builds upon the lessons learned from the international SIMBIOS program that began in the 1990's and terminated in 2003. Coordinating some of these international activities that are critical to allowing production of research quality ocean-colour data products and ensuring ECVs will be cost-effective for the space agencies, as it avoids each agency duplicating the effort (e.g., each sensor having its own software packages to processes data).

The Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS, McClain et al. 2002) program was initiated and organized to be truly international in scope due to the number and variety of ocean-colour missions planned for launch in the 1995-2005 time frame. Many elements of the program and its organization built upon activities initiated under the SeaWiFS Project, e.g., SeaDAS, SeaBASS, calibration round-robins, protocol development, and *in situ* instrumentation development. Together, the two programs spanned the period of 1991-2003 as the SeaWiFS calibration and validation program funding tapered off after its launch and the SIMBIOS program activities began in 1997. The SeaWiFS program was focused on the SeaWiFS mission, but the main objective of SIMBIOS was to promote consistency between data products from different ocean-colour satellite missions and establish international data quality standards. While SIMBIOS ended before many of its objectives were met, particularly the merger of global SeaWiFS, MODIS (Aqua and Terra), MERIS and GLI data sets, it established an unprecedented level of international cooperation via the SIMBIOS science team, e.g., the collaboration with NASDA (now JAXA) on the OCTS global reprocessing. One portion of the SIMBIOS effort focused on developing and releasing research opportunities to which the U.S. community could respond. These were mainly focused on key topics that the international community prioritized based on gaps in research. To achieve international collaboration in the aforementioned areas, the following issues are currently being addressed:

- Ensure development of internally consistent products and time series from multiple satellite ocean-colour data sources;
- Develop methodologies for cross-calibration of satellite ocean-colour sensors;
- Develop methodologies for merging data from multiple ocean-colour missions;
- Promote cooperation between satellite ocean-colour missions and programs.

To progress with these issues, the INSITU-OCR should have the following components:

5.2.1 Project office

The project office would coordinate and manage the INSITU-OCR components. It could draft and coordinate release of research announcements with international participation, and establish or expand a centralized database like SeaBASS with coordination of quality assurance/control and data submission requirements (e.g., three months for data submission from the time of collection), and focus on *in situ* sensor protocol development and lead round-robin activities such as SeaHARRE. The office could be populated by members from international institutions to ensure the greatest diversity of scientific interests are represented. The project office will allow the space agencies to target and lead specific scientific problems of interest through a vehicle such as coordinated research announcements, and therein allow each agency to invest in some aspect of the science that is of greatest interest.

5.2.2 Calibration

International cooperation on pre-launch sensor calibration and characterization, and post-launch sensor data comparisons are essential to develop accurate ocean-colour products. The INSITU-OCR could use an existing framework, such as CEOS (WGCV/IVOS, QA4EO) to construct an international cal/val system and connect to the GEO activities. The IVOS has the following objectives:

- Construction of a mechanism for information exchange and coordinated international cal/val activities with appropriate synergies by the expertise of the full cal/val community.
- Establishment of robust protocols and procedures for traceability and cross-calibration with sufficient flexibility for the future innovation (a pilot comparison of land surface reflectance captured in 2010 is planned for establishing detailed protocols for post-launch cross-calibration as a pre-cursor to potential wider international efforts in the 2011-2013 timescale under the QA4EO initiatives). IVOS is planning OCR comparison as one of the next targets.
- Establishment of robust traceability to SI and cooperation with independent expertise from national metrology institutes (such as NIST and NPL) to support this activity.

The INSITU-OCR will connect the space-based ocean-colour requirements to the cal/val interoperability activities within CEOS agencies, allowing for improvement and consistency in satellite data products.

5.2.3 *In situ* data and validation data for higher level ocean-colour data products

Agreed upon protocols, round robins, technology *in situ* observations, data sharing, and consistent match-up analysis are needed to ensure international coordination in current and future satellite missions. There are existing mechanisms that could be used for this purpose (e.g., SeaBASS).

5.2.4 Algorithm development

Coordinate algorithm theoretical basis documents and algorithm round-robins for model skill assessment, as well as organize international science team structure.

5.2.5 Numerical model use

Earth system/climate model comparison and ocean-colour data assimilation is one of the key objectives of Earth system science. The INSITU-OCR could support use of appropriate ocean-colour data with error/uncertainty information, and feedback the requirements from the model assessment activities to the ocean-colour and Earth science communities.

5.2.6 User processing software

Maintain a single package of user processing software (e.g., SeaDAS, BEAM, ODESA) to enable processing and visualizations of multiple mission datasets. Historically each space agency and mission develops their own data processing and visualization software. The INSITU-OCR would encourage the agencies and users to converge on a single ocean-colour data processing software and visualization package, which can be developed and expanded, as needed, with subsequent missions.

Chapter 6

Conclusions

Implicit in this report is the assumption that global, climate-quality ocean-colour data records will be sustained for the sake of ocean research, monitoring, and management and overall Earth system and climate science. It is also assumed, at the time of writing, that the international space agencies will continue to support the ideas of scientific coordination put forth by bodies such as the international CEOS. One would hope that the desired capacity of imaging for all ocean-colour sensors goes beyond the sponsoring agency's coastal waters.

This report focuses on ensuring a set of minimum requirements for any ocean-colour sensor to ensure high quality data. While a single point of interest may be in making these sensors cheap and of similar design, the minimum set of requirements includes comments regarding on orbit and vicarious calibration, as well as data validation. While these topics are not covered in depth here and are the subject of other IOCCG reports and working groups, they are critical to the overall success of the flight mission and therein deserve some attention in this report.

Since the advent of the CZCS in 1976, the desired science return, as well as applications, has evolved well beyond retrievals of algal biomass, sediments, and aerosol optical thickness to study ocean biogeochemistry. While these properties remain of utmost importance and are critical to understand ocean ecology, biology, biogeochemistry, and interdisciplinary Earth system science, key ocean science includes marine ecology, biogeochemical (carbon) cycling, land-ocean and ocean-atmosphere interactions, biological-dynamical interactions, algal blooms, coastal and estuarine ecosystem health, fisheries, and ocean pollution. A sensor able to address this science list requires a much more capable sensor beyond CZCS and SeaWiFS, as well as implementation of instrument and mission aspects listed below.

- A coordinated "constellation" of similarly specified sensors to assure global coverage of high quality data.
- A common set of spectral channels to address the scientific retrievals identified in the science section of the report, with the understanding that the science will evolve over time and this report is a living document.
- A range of approaches to connect science questions to the satellite data. These approaches must involve field campaigns and ocean model development. This will ensure a tight coupling among mission science, calibration and validation data collection, product development, and the field program objectives and

design.

- The expression of user needs at the mission level. Mission specifications are applicable to the final product delivered by the space system, i.e., the Level-1 product. This means that the final performance is made by the system, and not only by the instrument itself. Consequently, mission requirements must not be derived directly into instrumental specification, and contributions from all parts of the system have to be analyzed and considered as individual contributions to the total performance.
- Establishment of INSITU-OCR to enable the highest quality science data records that will facilitate ocean-colour research, management, and climate science objectives. This may include common software packages for data visualization and processing, *in situ* data collection and protocols, and a centralized data portal, amongst others.

Appendix: Tabular Summaries of Previous, Current, and Future Ocean Colour Missions

In Tables A1 to A4 on the following pages, previous ocean colour missions refer to:

CZCS (NIMBUS-7)
POLDER (ADEOS)
OCTS (ADEOS)
SeaWiFS (SeaStar)
OCI (ROCSAT)
OCM (IRS-P4)
MERIS (ENVISAT)
GLI (ADEOS-II)

Current ocean colour missions (at the time of writing) include:

MODIS Terra/Aqua (EOS-AM1/EOS-PM1)
COCTS (HY-1B)
GOCI-I (COMS)
VIIRS (Suomi NPP)
OCM-2 (Oceansat-2); very similar characteristics as OCM, therefore not listed in Tables A1 to A4.

Future ocean colour missions include:

OLCI (SENTINEL-3)
SGLI (GCOM-C1)
GOCI-II (GeoKOMPSAT-2B)

Other future ocean colour missions under consideration include two VIIRS instruments on the JPSS-1 and JPSS-2 platforms (nominal launch in 2016 and 2022) and the Ocean Ecology Sensor (OES) on NASA's PACE platform, which is in the initial planning phase (nominal launch in 2019). It is anticipated that the OES instrument will have hyperspectral bands (every 5 nm) from the UV to NIR, as well as three SWIR bands.

Table A1. Ocean colour satellite orbit and basic characteristics for various satellite payloads.

	CZCS (NIMBUS-7)	**POLDER (ADEOS)**	**OCTS (ADEOS)**	**SeaWiFS (SeaStar)**	**OCI (ROCSAT)**	**OCM (IRS-P4)**	**MODIS (Terra/Aqua)**	**MERIS (ENVISAT)**	**GLI (ADEOS-II)**	**COCTS (HY-1B)**	**GOCI-I (COMS)**	**VIIRS (Suomi NPP)**	**OLCI (SENTINEL 3)**	**SGLI (GCOM-C1)**	**GOCI-II GeoKOMPSAT-2B**
Orbit	Sun Sync	Sun Sync	Sun Sync	Sun Sync	Non-Sun Sync	Sun Sync	Sun Sync	Sun Sync	Sun Sync	Sun Sync	Geo	Sun Sync	Sun Sync	Sun Sync	Geo
Altitude (km)	955	797/ 802/ 705	800	705	600	720	705	800/ 783	803	798	35,786	824	815	800	35,800
Inclination (Deg)	104.9	98.66/ 98.2	98.60	98.25	35	98.28	98.2	98.5	98.6	98.8	0	98.6	98.6	98.6	0
Equatorial Crossing Time (h)	12:00	10:41	10:41	12:00	Various	12:00	10:30 13:30	10:00	10:30	10:30	–	10:30	10:00	10:30	–
Period (min)	104	99	101	98.2	96.7	99.3	99	100.6	101	100.8	-	101.4	~100	101	-
Spatial Res. (m)	825	6000	700	1100	800	350	1000	300 & 1200	1000	1100	500	750	300	250 & 1000	250 & 1000
Swath (km)	1,566	2400/ 1600	1400	2800	702	1420	2330	1150	1600	2800	2500	3000	1120	1150 - 1400	Earth disk & 2500
Tilting (Deg)	±20	–	±20	±20	–	±20	–	–	±18	–	–	–	12.2 west	–	–

Table A2. Optical design and detector specification

	CZCS (NIMBUS-7)	POLDER (ADEOS)	OCTS (ADEOS)	SeaWiFS (SeaStar)	OCI (ROCSAT)	OCM (IRS-P4)	MODIS Terra/Aqua	MERIS (ENVISAT)	GLI (ADEOS-II)	COCTS (HY-1B)	GOCI-I (COMS)	VIIRS (Suomi NPP)	OLCI (SENTINEL 3)	SGLI (GCOM-C1)	GOCI-II GeoKOMPSAT-2B
Image Acqui.	Scanning	Frame Capt.	Scanning	Scanning	Push broom	Push broom	Scanning	Push broom	Scanning	Scanning	Frame Capt.	Scanning	Push broom	Push broom	Frame Capt.
Detector (Type)	CCD	CCD (2D)	FPA	FPA	CCD	CCD	FPA	CCD (2D)	FPA	Si Detect. (1D)	CMOS (2D)	CCD	FPA	CCD (1D)	CMOS (2D)
Diameter of Pupil (mm)	?	1	270	?	356	?	177.8	25.5	Not Open	200	140	NA	25.3	Not Open	>250
Digitization (bit)	8	12	10	10	12	12	12	16	12	10	12	12	16	12	13
No. of bands	6	9	12 (8 VIS-NIR)	8	6	8	36 (16 Vis-NIR)	15	36 (15 VIS-NIR)	10	8	22	21	19 (9 VIS-NIR)	12-15 (TBD)
Band widths (nm)	20-100	10-40	20-40	20-40	20-40	20-40	10-15	2.5-20	8-20	20	10-40	18-39	2.5-40	10-20	10-50
S/N Range	50-350	149-196	200-550	726-1170	790-934	350-450	1118-1727	575-1060	500-1400	200-500	600-1050	387-1536	152-2188	200-400	1000-1500
MTF	>0.35	0.2	0.37-0.73	>0.3	>0.53	>0.26	>0.3	0.6 (1.2km) 0.35 (300m)	0.35 (1km) 0.25 (250m)	>0.3	0.2~0.3	>0.3	0.28 (300m)	>0.35	0.12~0.3
Polarization Sensitivity (%)	>2	<5	<2	0.25	<2	?	0.5-6.0	<0.3	<2	5	<2	<3	<0.3	<2	<1

Table A3. Radiometric and geometric calibration. (**Registration accuracy error* refers to band-to-band registration accuracy error (pixel area)).

	CZCS (NIMBUS-7)	POLDER (ADEOS)	OCTS (ADEOS)	SeaWiFS (SeaStar)	OCI (ROCSAT)	OCM (IRS-P4)	MODIS (Terra/Aqua)	MERIS (ENVISAT)	GLI (ADEOS-II)	COCTS (HY-1B)	GOCI-I (COMS)	VIIRS (Suomi NPP)	OLCI (SENTINEL-3)	SGLI (GCOM- C1)	GOCI-II GeoKOMPSAT-2B
Max Radiance (444)	54.2	604	112 (Hi)/ 168 (Low)	132.5	132.5	28.5	69.9	540	110/ 680	145	145.8 (Hi)/ 679.1 (Low)	127 (Hi)/ 687 (Low)	582.6	400	150
NEΔL (444)	0.34	0.05-0.22	0.2	0.013	0.093	0.0218	0.05	0.035	0.06	0.031	0.085	0.093	0.036	<0.2	0.03
Max Radiance (865)	?	309	14 (Hi)/ 21 (Low)	21.3	21.3	17.2	25.0	345	7 (Hi)/ 339 (Low)	35	23.4 (Hi)/ 343.8 (Low)	29 (Hi)/ 349 (Low)	286.8	30	23.4
NEΔL (865)	?	0.15	0.03	0.023	0.014	0.008	0.012	0.009	0.004 (Hi) 0.013 (Low)	327 (SNR)	0.016	0.015	0.009	<0.075	<0.01
Sensor optical calibration	Solar Lamp	Ground target	Solar Lamp	Lunar	Solar	Lunar	Solar Lunar	Solar (x2)	Solar Lamp	–	Solar	Solar Lunar (TBD)	Solar (x2)	Solar LED Lunar	Solar Lunar
Ground calibr. error (%)	>1	2-3	<10 (TBC)	5	3	?	<2	<10	n/a	10%	<1	<2	n/a	<5	<1
Geo. accuracy (km)	?	~2km	<10km (TBC)	1km	<0.8 km	?	50m	50m	3km	5km	1km	50m (TBD)	<0.3 km	<0.25	1km 200m
*Registration accuracy error**	?	0.2	0.5	0.2	0.3	?	0.2	0.05	0.5	0.3	0.5	0.2	<0.2	<0.5	<0.5

Table A4. Operations (*SW* refers to Software and *OS* refers to Operating System).

	CZCS (NIMBUS-7)	POLDER (ADEOS)	OCTS (ADEOS)	SeaWiFS (SeaStar)	OCI (ROCSAT)	OCM (IRS-P4)	MODIS (Terra/Aqua)	MERIS (ENVISAT)	GLI (ADEOS-II)	COCTS (HY-1B)	GOCI-I (COMS)	VIIRS (Suomi NPP)	OLCI (SENTINEL-3)	SGLI (GCOM-C1)	GOCI-II GeoKOMPSAT-2B
Data format	HDF4	Specific	HDF4	HDF4	HDF	?	HDF4	En-visat	HDF4	HDF4	HDF EOS5	HDF5	Net-CDF	HDF5	TBD
Data pro-cessing SW	NA	NA	Sea-DAS	Sea-DAS	?	?	Sea-DAS	BEAM	NA	HYDAS	GDPS	IDPS, ADL	BEAM	TBD	TBD
OS	NA	NA	Unix/ Linux	Unix/ Win-dows	Unix	?	Unix/ Win-dows	All Plat-forms	Unix/ Linux	Unix	Win-dows	Unix/ Linux	All Plat-forms	Linux	Win-dows
Mission Devel-opment	NASA USA	CNES France	JAXA Japan	NASA USA	NSPO Tai-wan	ISRO India	NASA USA	ESA EU	JAXA Japan	CAST China	KIOST Ko-rea	NOAA NASA	ESA EU	JAXA Japan	KIOST Korea
Launch date	Oct. 1978	1996 2002 2005	Aug. 1996	Aug. 1997	Jan. 1999	1999 2009	1999 2002	Mar. 2002	Dec. 2002	Apr 2007	Jun 2010	Oct. 2011	2014	2015	2018

- Radiance unit: W m^{-2} sr^{-1} μm^{-1}
- $NE\Delta L = L_{nominal}/SNR$
- *Nominal radiance*: Typical TOA radiance contributed from atmosphere (clear sky) and ocean
- *Max. radiance*: Defined as the maximum radiance that a sensor can measure without saturation.
- Definition of radiance levels for detectors: Max cloud radiance ≥ Saturation radiance ≥ maximum radiance ≥ nominal radiance

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Acronyms and Abbreviations

ACE	Aerosol - Cloud - Ecosystems (NASA)
ADC	Analog-to-Digital Converter
ADEOS	Advanced Earth Observing Satellite (Japan)
AERONET	Aerosol Robotic Network
AOP	Apparent Optical Property
Argo	Global array of ~3,000 free-drifting profiling floats
AIRS	Atmospheric Infrared Sounder
AMSU-A	Advanced Microwave Sounding Unit-A
BEAM	Basic ERS & Envisat (A)ATSR and MERIS Toolbox
BOUSSOLE	Buoy for the acquisition of a long-term optical series (Mediterranean Sea)
BRDF	Bidirectional Reflectance Distribution Function
cal/val	Calibration and Validation
CDOM	Coloured Dissolved Organic Matter
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
Chl-a	Chlorophyll-a
CZCS	Coastal Zone Color Scanner
DCC	Deep Convective Clouds
DMS	Dimethyl Sulfide
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
Envisat	Environmental Satellite (ESA)
ESA	European Space Agency
FLH	Fluorescence Line Height
FOV	Field-of-View
FWHM	Full Bandwidth at Half Maximum
GAC	Global Area Coverage
GCOM-C	Global Change Observation Mission for Climate (Japan)
GCOS-IP	Global Climate Observing System Implementation Plan
GDAS	Global Data Assimilation System
GEO	Group on Earth Observations
GFS	Global Forecast System
GLI	Global Imager (Japan)

GOCI	Geostationary Ocean Colour Imager (Korea)
GSFC	Goddard Space Flight Center (NASA)
GSM	Garver, Siegel, Maritorena Model
HAB	Harmful Algal Bloom
HDF	Hierarchical Data Format
HIRS	High-resolution Infrared Radiation Sounder (NOAA)
IFOV	Instantaneous Field-of-View
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
INSAT	Indian National Satellite
INSITU-OCR	International Network for Sensor InTercomparison and Uncertainty assessment for Ocean-Colour Radiometry
IOCCG	International Ocean-Colour Coordinating Group
IOP	Inherent Optical Properties
IR	Instrumental Requirements
ISRO	Indian Space Research Organization
IVOS	Infrared and Visible Optical Sensors (subgroup of WGCV)
JAXA	Japan Aerospace Exploration Agency
JGOFS	Joint Global Ocean Flux Study
JMA	Japan Meteorological Agency
JPSS	Joint Polar Satellite System (NOAA)
K_d	Diffuse Attenuation Coefficient
KIOST	Korea Institute of Ocean Science and Technology
LAC	Local Area Coverage
L_{wN}	Normalized Water-Leaving Radiance
MERIS	Medium Resolution Imaging Spectrometer (ESA)
METEOSAT	Meteorological Satellite
METOP	Meteorological Operational Satellite
ML	Mixed Layer
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer (NASA)
MR	Mission Requirements
MTF	Modulation Transfer Function
MTSAT	Multi-Function Transport Satellite
NASA	National Aeronautics & Space Administration
NASDA	National Space Development Agency of Japan (now JAXA)
NCEP	National Center for Environmental Prediction
NET	Nimbus Experiment Team
NetCDF	Network Common Data Form
NIR	Near-Infrared
NIST	National Institute of Standards and Technology (USA)
NOAA	National Oceanographic and Atmospheric Administration (USA)

NPL	National Physical Laboratory (UK)
NPP	National Polar-orbiting Partnership
OCM	Ocean Colour Monitor (India)
OCR-VC	Ocean Colour Radiometry - Virtual Constellation
OCTS	Ocean Color and Temperature Scanner (Japan)
OES	Ocean Ecology Spectrometer (for ACE/PACE)
OLCI	Ocean and Land Colour Imager (ESA)
PACE	Pre-Aerosol, Clouds, and ocean Ecosystem (NASA)
PAR	Photosynthetically Available Radiation
PIC	Particulate Inorganic Carbon
PIRATA	Prediction and Research Moored Array in the Tropical Atlantic
POC	Particulate Organic Carbon
POLDER	Polarization and Directionality of the Earth's Reflectances (CNES)
PP	Primary Production
PPA	Plane-Parallel Atmosphere
PSD	Particle Size Distribution
PSF	Point Spread Function
QA4EO	The Quality Assurance Framework for Earth Observation (GEO)
QuikSCAT	Quick Scatterometer (NASA)
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
ROLO	Robotic Lunar Observatory model (USGS)
RSR	Remote Sensing Reflectance
SBUV	Solar Backscatter Ultraviolet Radiometer
SeaDAS	SeaWiFS Data Analysis System
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SeaHARRE	SeaWiFS HPLC Analysis Round-Robin Experiment
SeaWiFS	Sea-viewing Wide Field-of-view Sensor (NASA)
SGLI	Second Generation Global Imager (JAXA)
SI	International System of Units
SIMBIOS	Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SIS	Spherical Integrating Spheres
SNR	Signal-to-Noise Ratio
SOLAS	Surface Ocean-Lower Atmosphere Study
SPM	Suspended Particulate Matter
SR	System Requirements
SRCA	Spectroradiometric Calibration Assembly (on MODIS)
SSA	Spherical-Shell Atmosphere
SSH	Sea Surface Height
SST	Sea Surface Temperature
STM	Science Traceability Matrix
SWIR	Short Wave Infrared

TACCS	Tethered Attenuation Coefficient Chain Sensor
TIS	Total Integrated Scatter
TAO	Tropical Atmosphere Ocean
TOA	Top of Atmosphere
TOAST	Total Ozone Analysis using SBUV/2 and TOVS
TOVS	TIROS Operational Vertical Sounder
TRITON	Triangle Trans-Ocean Buoy Network
TSM	Total Suspended Matter
USGS	U.S. Geological Survey
UV	Ultra Violet
VIIRS	Visible Infrared Imager Radiometer Suite
VNIR	Visible and Near Infra-Red
VIS	Visible
WGCV	Working Group on Calibration and Validation
YSBPA	Yellow Substance and Bleached Particle Absorption
Z_{eu}	Euphotic Depth