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Chapter 1

Introduction

This document suggests requirements for an advanced ocean radiometer, such as e.g. the ACE (Aerosol/Cloud/Ecosystem) ocean radiometer, see http://dsm.gsfc.nasa.gov/ace/index.html for a description of all components of the ACE mission. The ACE ocean biology mission objectives have been defined in the ACE Ocean Biology white paper[22]. The general requirements presented therein were chosen as the basis for the requirements provided in this document, which have been transformed into specific, testable requirements. Specific mission requirements of SeaWiFS, MODIS, and VIIRS were often used as a model for the requirements presented here, which are in most cases more demanding than the heritage requirements. Experience with on-orbit performance and calibration (from SeaWiFS and MODIS) and prelaunch testing (from SeaWiFS, MODIS, and VIIRS) were important considerations when formulating the requirements. Guidelines from NIST for prelaunch characterization and calibration[5] were followed as close as possible, e.g. regarding

- Inclusion of radiometric experts from a National Metrology Institute (NMI) in the formulation of the requirements.
- Characterization of components/subsystem, if possible independent of instrument/component vendor.
- Confirmation of component characterization by comparing instrument model predictions with system level measurements.
- Conduct tests in a flight like configuration (and flight like environment, if necessary).
- SI (International System of Units) traceable calibration, using expertise and facilities of a NMI.

This document describes requirements in terms of the science data products, with a focus on qualities that can be verified by prelaunch radiometric characterization. All specifications in this document are for beginning of life, unless otherwise noted. It is expected that a more comprehensive requirements document will be developed during mission formulation. This document does not include important aspects like redundancy in sensor design (e.g. two independent electronics) or functional tests (e.g. operation of a nadir door). A flight-like Engineering Design Unit is required to detect performance issues before building the flight unit.

The requirements are couched in terms of the minimum or least stringent mission and instrument design objectives. To achieve performance less than these minimum requirements would significantly undermine the science objectives and the support of the ocean biogeochemistry community.

The requirements are discussed in terms of a nominal suite of 26 multispectral bands (see table 3.1 below, originally defined in the appendix of the ACE Ocean Biology white paper[23]) that include the band sets of SeaWiFS, MODIS, and VIIRS, with additional bands for new applications and improved atmospheric corrections. The radiometer specifications are designed to remove deficiencies in these previous designs based on extensive experience in the pre- and postlaunch calibration, algorithm development, postlaunch validation, and data processing of each of these sensors. In the case of a hyperspectral instrument design, examination of this suite of multispectral bands greatly simplifies the specifications, e.g., signal-to-noise ratios, and typical and maximum radiances, and the verification that the sensor meets the specifications. Although most of the requirements are written for multispectral bands, hyperspectral data is required (see sections 2.7 and 3.2.2). All accuracy and precision requirement values are provided as 1-sigma values, see [24].

The goal for SeaWiFS and MODIS has been the retrieval of the water-leaving reflectance in the blue wavelengths in waters with low phytoplankton concentrations with an uncertainty of $\pm 5\%$ (relative)[14]. This translates into an uncertainty of the top-of-atmosphere (TOA) radiance of $\pm 0.5\%$ for the blue bands, because the contribution of the water-leaving reflectance to the TOA reflectance of the ocean-atmosphere system is $\leq 10\%$[14]. These uncertainty goals have so far not been specifically formulated for other parts of the spectrum, but since the ratio of water-leaving reflectance to TOA reflectance decreases with increasing wavelength[13], it is highly unlikely that uncertainties larger than $\pm 0.5\%$ can be tolerated for higher wavelengths. Therefore, the overall accuracy goal for the advanced ocean radiometer is that the total uncertainties are 0.5% or smaller for all bands. Note that this total uncertainty does not include the uncertainty due to absolute calibration, because absolute calibration errors can be largely removed by vicarious calibration[13]. The total uncertainty is calculated as the square root of the sum of all individual uncertainties (e.g. due to polarization, stray light, etc.) squared, therefore each individual uncertainty has to be on the order of 0.2% or less[1]. In this document, this conclusion will be called the *square summation limit*.

A complete optical model is a required deliverable. This model shall be capable of predicting system performance parameters such as spectral resolution, signal-to-noise ratio, dynamic range, point-spread function, polarization sensitivity, response-versus-scan angle, and instantaneous field of view. In the instrument proposal selection phase, the model may rely on modeled

[1] In this document, performance parameters shall be rounded; e.g. a measured uncertainty of 0.24% does not fail a specification calling for an accuracy of 0.2% or less.

component characteristics. At this stage, the goal is to evaluate if the proposed design can meet expectations, and only the results of the optical model are a deliverable. After an instrument design and a vendor have been chosen, the model shall rely on measured component characteristics. The optical model shall be made fully available (including code and input parameters), so that NASA analysts can independently exercise the model. The goals are

- to compare predicted instrument performance to measured instrument performance to detect problems in the design or assembly of the instrument and
- to provide a basis for modeling of unexpected features detected during on-orbit operations.

The component characteristics shall be measured in a configuration as in the final instrument design (e.g. at the angles of incidence of the final instrument design for the optical components). All component characteristics that influence the radiometric properties of the system shall be measured independently of the component vendor. The uncertainties associated with the component measurements shall be based on measurements using state-of-the-art technology.

Chapter 2 describes requirements that are related to either the spacecraft or to both the spacecraft and the sensor. The three sections in the following chapter (3.1, 3.2, and 3.3) describe the radiometric, spectral, and spatial sensor requirements, respectively. Note that the requirements in sections 3.1 and 3.3 refer to the multispectral bands given in table 3.1. The requirements in section 3.2 refer to the hyperspectral channels (or SWIR bands, where applicable), except for section 3.2.1.

The radiance units in this document are those used by MODIS and VIIRS ($W/(m^2 sr \mu m)$). These values can be converted to units used by SeaWiFS ($mW/(cm^2 sr \mu m)$) by dividing them by 10.

Chapter 2

Spacecraft and Global Coverage Specifications

2.1 Local Equator Crossing Time

The spacecraft shall be flown on a sun synchronous orbit with a local equator crossing time within 10 minutes of noon. A solar zenith angle close to zero provides the best illumination intensity, which is important for accurate measurements of the relatively dark ocean. Also, reducing the path length in the atmosphere improves the atmospheric correction accuracy. Having a noontime sun-synchronous orbit reduces the range of scattering angles and provides more even coverage at high latitudes.

The orbit shall be maintained throughout the mission design life time. A constant local equator crossing time will ensure that the average solar zenith angles do not change during the mission, removing a potential uncertainty in the atmospheric correction algorithm. It will also ensure that the heating and cooling cycles of the spacecraft remain constant, which reduces potential sensor characterization issues[1].

2.2 Orbit Altitude

The orbit altitude shall be chosen such that the sensor in nadir viewing mode would provide two-day global coverage (ACE requirement[23]). This means that there would be no gaps in a gridded composite of sensor data (including clouds and glint) covering all areas of the Earth illuminated at solar zenith angles less than 75°. Clouds and glint will reduce the effective global coverage. Oceanic blooms can exist for as few as 4 days, two-day global coverage provides a

[1] A change in the SeaWiFS sensor temperature sensitivity in the later half of its mission was attributed to a change in the local equator crossing time of the satellite

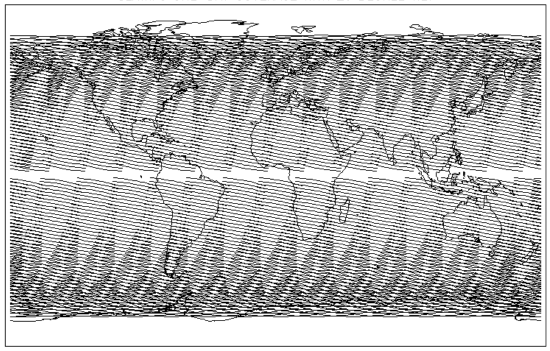

Figure 2.1: Daily global coverage plot of SeaWiFS (sensor with scan angle range of 58.3°, tilt of ±20°, at an altitude of 705 km in a circular, noon sun-synchronous orbit; the sensor zenith angle limit for ocean color applications (currently 60°) is not considered here). The data gap around the equator is due to the change in tilt angle, and can be filled by staggering the tilt change to occur at slightly varying latitudes on different days.

reasonable chance of detecting such blooms. One-day global coverage is not achievable considering restrictions on the maximum scan angle, see section 2.3 below.

The solar zenith angle for processing ocean color data is usually limited to 75° because at larger angles, the water-leaving radiance becomes too low (cosine effect of incident radiance and increased Fresnel reflection at large incidence angles). Also, the atmospheric optical path for the downwelling light is large and Earth curvature effects start to limit the plane parallel assumption in the radiative transfer calculations (Ding and Gordon, 1994)[7].

2.3 Scan Angle Range

The earth view data shall be acquired for scan angles of $58.3° \pm 0.05°$ about nadir, i.e. a range of $116.6 \pm 0.1°$. This provides two-day global coverage (for the appropriate orbit altitude, see section 2.2; Fig. 2.1 shows an example). For scan angles larger than 58.3°, the path length in the atmosphere becomes too long for the atmospheric correction algorithm to be reliable. Large scan angles also lead to large, overlapping pixels.

2.4 Tilt Angles

Sun glint off the ocean immensely complicates the atmospheric correction process. Due to the complicated surface structure of the ocean (determined mainly by wind speed and direction), an accurate removal of sun glint is a challenge. Sun glint contamination shall be minimized by varying the along-track view angle (tilting). The sensor shall be able to acquire data at three different tilt angles (in track direction) without obstruction from any spacecraft structure: $-20°, 0°, 20°$ (ACE requirement[23]). The tilt angle change from $-20°$ to $20°$ (or from $20°$ to $-20°$) shall occur in less than 15 seconds[2]. The tilt change shall occur twice per orbit, near the subsolar point and on the dark side of the orbit. Only the tilt change on the bright side of the orbit needs to occur in less than 15 seconds. No satellelite maneuver shall be neccessary to execute the tilt change. Data describing the tilt angle shall be accurate to within 0.01 degrees. The operation of the tilt maneuver on subsequent orbits shall not occur at the same latitude, but staggered, see Watson and Patt[15]. Staggering of the tilt location ensures full coverage of the earth surface for multiple orbits.

The benefits of tilting can be clearly seen in the example shown in Fig. 2.2. The SeaWiFS tilt of either $-20°$ or $20°$ results in only 2.1% of the SeaWiFS data of March 22nd 2006 being classified as 'High Glint' ('High Glint' data are masked in the NASA ocean color processing, effectively reducing the daily global coverage of a sensor). MODIS Aqua does not have a tilt capability, and 14.2% of its data from March 22nd 2006 are classified as 'High Glint'. Additionally, a significant portion of the MODIS Aqua data (10.3%, versus only 6.8% for SeaWiFS) is flagged as 'Moderate Glint', which means the data is processed, but the data is expected to be of lower quality.

The SeaWiFS data used in Fig.2.2 is GAC data, which is limited to scan angles less than 45° (the swath width of SeaWiFS GAC data is about 20% smaller than the MODIS Aqua swath). For SeaWiFS LAC data, with scan angles up to 58°, the percentage of glint would be even lower.

2.5 Pointing Knowledge

The spacecraft attitude and location and the sensor pointing angles required for calculation of the location (in latitude and longitude) of each ocean IFOV (see section 3.3.1) to within 0.2 IFOV shall be known at all scan angles and tilt angles[3].

2.6 Lunar Calibrations

As demonstrated during the SeaWiFS mission, monthly observations of the moon through the earth viewing port of the sensor are absolutely essential for tracking the degradation of the sensor over time. Accordingly, monthly lunar observations are viewed as an essential element of the mission.

The sensor shall be capable of viewing the moon through its earth-view port at both $\pm 7°$ lunar phase angle once a month (ACE requirement[23]) on the dark side of the orbit, either by a pitch maneuver of the spacecraft or by a reorientation of the sensor relative to the spacecraft. The oversampling rate of the lunar measurement shall be larger than the number of gain coefficients K_1 per band (see eq.3.1 below) that need to be derived. (For example, for a design identical to SeaWiFS with a double sided half angle mirror, the lunar image shall be acquired with an oversampling rate larger than 2). Sufficient detail about spacecraft and/or sensor orientation

[2] The SeaWiFS sensor tilt angle change from $-20°$ to $20°$ takes about 13 seconds.
[3] MODIS has achieved 0.2 IFOV geolocation accuracy for its 250m bands.

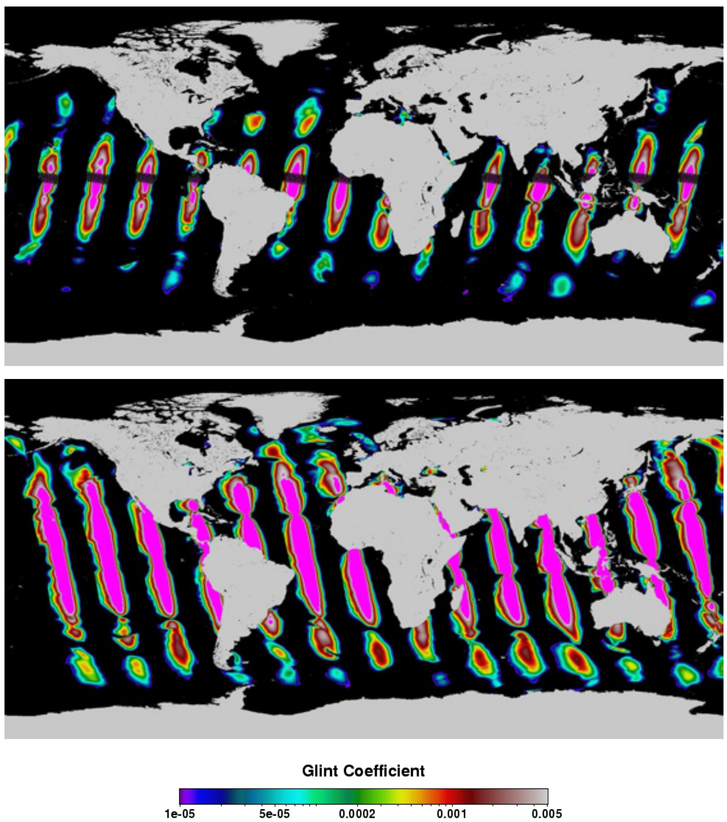

Figure 2.2: Global map of SeaWiFS (top) and MODIS Aqua (bottom) glint coefficients for March 22nd of 2006. Glint coefficients larger than 0.005 are classified as 'High Glint' in NASA ocean color processing and colored pink in the above images. Glint coefficients from 0.001 to 0.005 are classified as 'Moderate Glint' and colored red/white. The tilt capability of SeaWiFS significantly increases the amount of data available for ocean color processing.

shall be provided to allow a determination of the oversampling rate with an uncertainty of 0.1%. The moon shall be viewed through the earth-viewing aperture with the same optical path inside the instrument as during regular earth-viewing measurements (e.g. no additional optics).

Rationale: The uncertainty of the oversampling rate adds directly to the uncertainty of the lunar measurement, so it must be restricted to 0.1% to achieve the long term trending requirements outlined below, see section 3.1.12. It is desirable to measure the moon when the moon is close to full illumination. However, at 0° lunar phase angle, coherent backscatter[16] complicates the lunar reflectance modeling. At 7° phase angle, the coherent backscatter is small, and the moon is still very close to full illumination. Another reason to set the phase angle at 7° is that due to the inclination of the Moon's orbit relative to the ecliptic, in any given month the minimum phase angle can be as much as 5 degrees.

For more background information on lunar calibration, see Barnes et al.[1] and Eplee et al.[8]. The oversampling rate shall be greater than the number of gain coefficients K_1 per band (e.g. 20 for the MODIS band 8, which has independent calibration coefficients for 10 detectors and two mirror sides) so that sufficient data is available to derive independent calibration coefficients.

2.7 Date Types, Data Transmission and Acquisition

All instrument data (including earth view data, i.e. all 5nm hyperspectral channels, the NIR and SWIR bands, instrument status and health) and spacecraft data required for data processing (including time, ephemeris and spacecraft attitude) shall be transmitted in the broadcast every orbit. The 5nm hyperspectral coverage shall extend from 345nm to 755nm (ACE requirement[23]). There shall be sufficient capacity on the data recorder to store 2 orbits of data. The storage requirement serves to bridge a possible failed transmission event. Sensor data only needs to be acquired for solar zenith angles less than 75° and for calibration purposes.

In order to reduce data volume, the SeaWiFS global data set was spatially subsampled on-orbit before transmission to the ground station. This or similar techniques shall not be considered, coastal and estuarine studies require full spatial resolution.[4]

2.8 Design Life Time

The instrument and spacecraft shall be designed with a minimum design life time of 5 years (ACE requirement[23]). Expendables shall be sufficient for at least 10 years (one of the main strengths of the SeaWiFS climate data record is its length of 13 years).

[4] Another problem of the subsampling of the SeaWiFS global data set is that it caused speckling because the stray light correction was missing the data from the discarded pixels.

Chapter 3

Instrument Specifications

3.1 Radiometric Calibration Specifications

3.1.1 Background

All specifications in this section apply to each multispectral band (defined in table 3.1) individually.

In the following, the difference between the sensor output for a radiance measurement (DN_R) and a background measurement (DN_B) will be called dn.

The general goal for the radiometric calibration is to achieve a radiometric accuracy of 0.5% (relative, not absolute). Therefore, most specifications are on the order of 0.2% or less, so that the combined error (root mean square error) does not exceed 0.5%.

The absolute calibration uncertainty is defined here as the uncertainty related to the absolute calibration only (e.g. to the factor $k_2(g)$ in Barnes *et al.*, 2001[2], or to the factor K_2 of Barnes et al., 1994[3]. Similar to the later publication, we define the at-sensor radiance equation for unpolarized light (before vicarious calibration) for each band as

$$L_T = K_1(t) \cdot K_2 \cdot (1 - K_3(T - T_{\text{ref}})) \cdot K_4(\theta) \cdot K_5(dn) \cdot dn \quad (3.1)$$

where

- L_T is the radiance reaching the sensor entrance aperture (e.g. the top-of-atmosphere radiance).
- K_1 is the relative gain factor as a function of time t. This factor is set to 1 for prelaunch.
- K_2 is the absolute gain factor (determined prelaunch and from on-orbit calibration devices).
- K_3 is the temperature dependence of the output of the detectors, T is the focal plane temperature during the measurement of L_T, and T_{ref} is the focal plane temperature at which K_2 was measured. In case another temperature is better suited to describe the total

temperature dependence of the sensor output (e.g. the temperature of the electronics), this temperature shall replace the focal plane temperature.

- K_4 is the scan modulation correction (inverse of the response versus scan factor as defined for MODIS) as a function of scan angle θ.
- K_5 is the nonlinearity factor ($K_5 = 1$ for a sensor whose output dn increases linearly with L_T).

Furthermore, we define the *total radiance uncertainty* as the uncertainty of L_t, i.e. it is a combination of all error sources (even those not explicitly mentioned in equation 3.1, e.g. error due to polarization sensitivity). The *relative radiance uncertainty* is defined here as the combined uncertainty from all error sources, except the absolute uncertainty (i.e. the uncertainty of K_2).

A vicarious calibration factor is usually applied when producing ocean color products:

$$L_T^V = L_T \cdot V_C \tag{3.2}$$

where V_C is the vicarious calibration factor, determined from an analysis of on-orbit radiances and in-situ measurements(Franz et al., 2007[11]). This factor is not known prelaunch. Note that the uncertainty of V_C does not enter into the calculation of the total radiance uncertainty or the relative radiance uncertainty.

The vendor is expected to describe the specific design attributes that address each performance category, which includes properties such as polarization sensitivity, temperature sensitivity, etc. as well as stray light and crosstalk, and provide the data that quantifies how the specifications were met.

3.1.2 Dynamic Range and SNR

The sensor shall operate over a dynamic range that extends from the noise floor to $L_{\max}$ (see table 3.1 for $L_{\max}$ values). Operation at $L_{\max}$ is required for the on-orbit measurement of clouds (to be used in a stray light correction algorithm), operation at the noise floor is required for prelaunch characterization measurements (see e.g. sections 3.1.8, 3.1.11, 3.2.1, and 3.3.1). Avoiding saturation over clouds and land allows research by the cloud, aerosol, and land science communities.

Signal to noise ratio (SNR) shall be verified at L_{typ} (or within 2% of L_{typ}) for each multispectral band. For the hyperspectral channels, each 5nm channel (from 345nm to 755nm) shall have a SNR ratio greater than 1000 after averaging over a 2x2 pixel area. Note that for hyperspectral bands, no spatial averaging shall be needed to achieve the required SNR.

The SNR shall also be determined for all multispectral bands at L_{low}, L_{high}, and $L_{\max}$ to characterize the signal dependence of the system noise. L_{low}, L_{typ}, L_{high}, $L_{\max}$ and the required SNR are provided in tables 3.1 and 3.2. The data shall be digitized to 14bit or better[1]. 14bit

[1] At least 14bit in order to provide sufficient resolution at L_{typ} to achieve the SNR of table 3.1; the digitization radiance (dL) should be similar to NedLs (noise equivalent delta radiance); if it is much smaller, it only quantizes noise; if it is much larger, potentially useful information is lost

digitization or higher eliminates the need for multiple gains, simplifying the electronics. SeaWiFS and VIIRS had different versions of variable gain settings. These designs usually complicate the calibration effort.

The values in table 3.1 are partly based on statistics compiled from a SeaWiFS global 1-day L3 data set, presented in table 3.2. The TOA radiances in table 3.2 and Figure 3.1 are for clear sky conditions only, i.e., pixels that pass all the quality masks and flags at Level-3 for derived products like chlorophyll-a.

3.1.3 Absolute Gain Factor

The accuracy of the absolute gain factor K_2 (see eq. 3.1) shall be 0.5% (one sigma[24]) for bands 1-25 in table 3.1, and 1.0% for band 26 (2135nm), traceable to NIST standards, and shall be established at L_{typ} for unpolarized light during prelaunch measurements. The light source shall be viewed at nadir, and the light source shall provide a spatially homogeneous light field (e.g. the aperture of a Spherical Integrating Sphere). Note that the specifications provided here (0.5% and 1.0%) are lower than in the ACE Ocean Biology White paper appendix[23], which only require a prelaunch accuracy of less than 2%. The reason for requiring a better accuracy in this document is the expectation that the additional efforts spent on a more accurate prelaunch characterization will translate into a better understanding of the instrument. Note that the on-orbit calibration accuracy after vicarious calibration needs to be 0.2% (ACE requirement[23]), therefore it would raise serious concerns if the instrument cannot be calibrated to 0.5% prelaunch. The accuracy of calibration sources has been demonstrated to be better than 0.5%[4].

3.1.4 Linearity

The nonlinearity factor K_5 shall be characterized with an uncertainty of 0.1% (square summation limit) for all radiances from $0.5 \cdot L_{\text{low}}$ to L_{max}. The sample points shall at least include $0.5 \cdot L_{\text{low}}$, L_{low}, L_{typ}, L_{high}, $L_{\text{max}}/2$, and L_{max}. L_{low}, L_{typ}, L_{high} and L_{max} are provided in tables 3.1 and 3.2. The number of sample points shall be high enough to determine K_5 in between the sample points to within 0.1%.

Additionally, the linearity shall be measured down to the one dn level, in order to evaluate prelaunch characterization measurements like RSR and stray light. The uncertainty shall be

- 0.5dn from 1dn to 10dn
- 5.0% from 10dn to 100dn
- 1.0% from 100dn to L_{low}.

The design of the instrument shall lead to the expectation that the linearity will not change on-orbit.

Furthermore, an upper radiance limit (the saturation radiance 'Lsat' where the instrument saturates) shall be determined in order to detect saturation events and flag the surrounding regions (see section 3.1.10).

Table 3.1: Requirements for center wavelengths λ_{CW}, bandwidth (BW), SNR at L_{typ}, typical radiances (L_{typ}), and maximum radiances (L_{max}) of the nominal 26 multispectral bands. Radiance units are $W/(m^2 \mu m\ sr)$. Values are taken from Table 2 in the ACE Ocean Biology White Paper, Appendix[23]. The SeaWiFS (SeaW) SNR are given for comparison. For each band, its spectral classification (ultraviolet (UV), visible (VIS), near infrared (NIR), and short wave infrared (SWIR)) is provided.

Band	λ_{CW} [nm]	BW [nm]	SNR (req.)	SNR* (SeaW)	L_{typ}	L_{max}	Spectral region
1	350	15	300		74.6	356	UV
2	360	15	1000		72.2	376	UV
3	385	15	1000		61.1	381	UV
4	412	15	1000	897	78.6	602	VIS
5	425	15	1000		69.5	585	VIS
6	443	15	1000	967	70.2	664	VIS
7	460	15	1000		68.3	724	VIS
8	475	15	1000		61.9	722	VIS
9	490	15	1000	1010	53.1	686	VIS
10	510	15	1000	1000	45.8	663	VIS
11	532	15	1000		39.2	651	VIS
12	555	15	1000	870	33.9	643	VIS
13	583	15	1000		38.1	624	VIS
14	617	15	1000		21.9	582	VIS
15	640	10	1000		19.0	564	VIS
16	655	15	1000		16.7	535	VIS
17	665	10	1000	570	16.0	536	VIS
18	678	10	1400		14.5	519	VIS
19	710	15	1000		11.9	489	VIS
20	748	10	600		9.3	447	NIR
21	765	40	600	522	8.3	430	NIR
22	820	15	600		5.9	393	NIR
23	865	40	600	364	4.5	333	NIR
24	1245	20	250		0.88	158	SWIR
25	1640	40	180		0.29	82	SWIR
26	2135	50	100		0.08	22	SWIR

*: SeaWiFS bands have bandwidths of 20nm for the VIS bands, 40nm for the NIR bands.

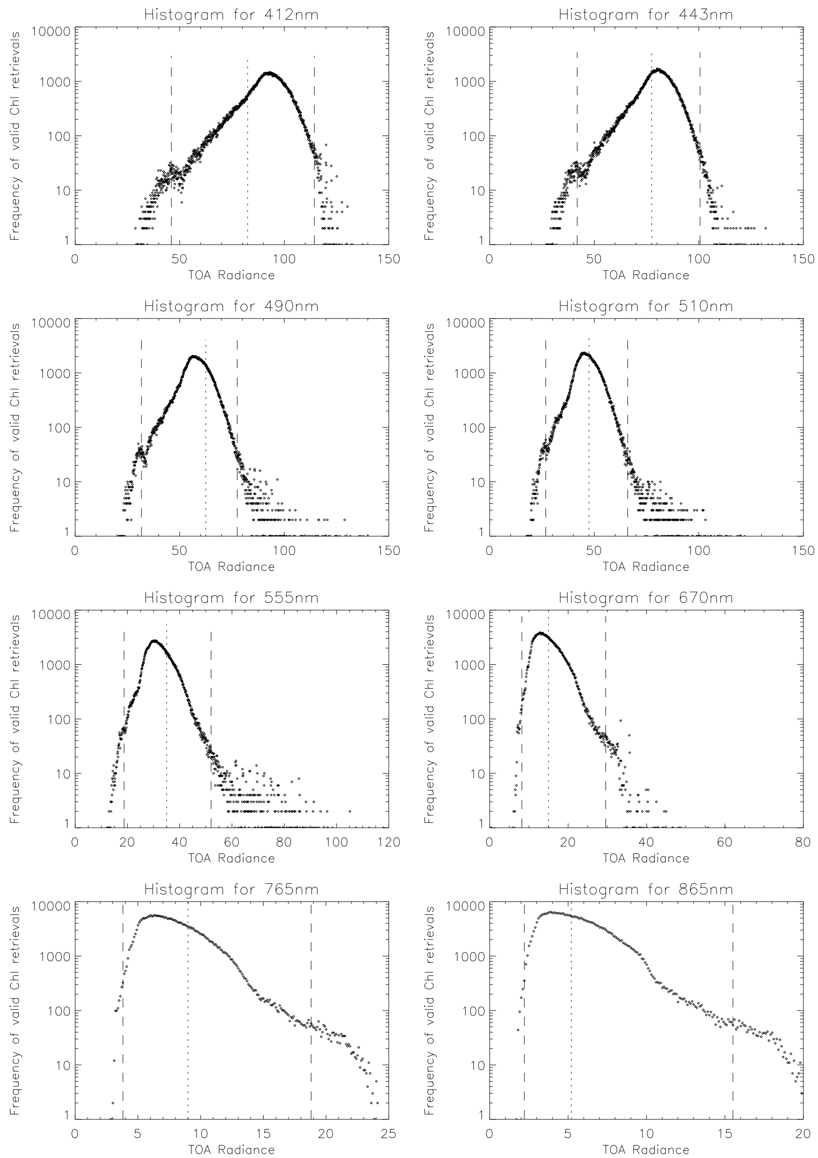

Figure 3.1: Histogram of the TOA radiances for each SeaWiFS band from a one day level 3 file (from September 21st of 2002, provided by Sean Bailey, total of about 300,000 bins; clear-sky data only). The radiance range between the two vertical dashed lines encloses 99% of the data, with 0.5% of the data having higher radiances (right of the second dashed line) and 0.5% of the data having lower radiances (left of the first dashed line). The radiance values at the dashed lines are given in table 3.2. The vertical dotted line is the typical radiance from table 3.1.

Table 3.2: TOA radiance range encountered in a SeaWiFS global 1-day L3 data set (clear-sky data only) after removing the 0.5% highest and the 0.5% lowest radiances. See also Fig. 3.1. The values for those bands with no equivalent SeaWiFS band shall be obtained by scaling the ranges of the closest SeaWiFS band by the ratios of the L_{typ} from Table 3.1.

SeaWiFS Band number	SeaWiFS Center-wavelength [nm]	L_{low} [W/ ($m^2 \mu m$ sr)]	L_{high} [W/ ($m^2 \mu m$ sr)]
1	412	50	125
2	443	42	101
3	490	32	78
4	510	28	66
5	555	19	52
6	670	10	38
7	765	3.8	19
8	865	2.2	16

3.1.5 Response Versus Scan Angle

The response of the instrument (in terms of dn) to a constant radiance source shall vary with scan angle by less than 5.0% for the whole scan angle range and by less than 0.5% for scan angles that differ by less than 1°.[2] The scan angle sample points shall be chosen such that there is not more than 0.2% difference in the measured dn between adjacent sample points, the angular difference between adjacent sample points shall be 10° or less, and the scan edges shall be included. The response shall be characterized with an accuracy of 0.1% (square summation limit) for each sample point, at a radiance level between L_{low} and L_{high}.

3.1.6 Polarization Sensitivity

The response of the instrument to completely linearly polarized light is expected to vary as a function of the polarization angle β (which describes the axis of vibration of the electric field vector, see Fig. 8 in Meister et al., 2005[19]) as:

$$dn = dn_0(1 + p_a \cos(2\beta - 2\delta)) \tag{3.3}$$

where p_a is called the polarization amplitude and δ is called the polarization phase. Both p_a and δ are instrument characteristics that shall be derived from characterization measurements. dn_0 is the instrument response to unpolarized light. The ratio dn/dn_0 is the polarization sensitivity of the instrument. p_a shall be less than 0.01 for each band given in table 3.1. This requirement is given in the Appendix of the ACE Ocean Biology White paper[23]. Gordon et al.[13] indicate that a 2% polarization sensitivity can lead to errors in the atmospheric correction that increase

[2] The maximum variation of 5% limits the NEdL variation with scan angle to a reasonably small number; the 0.5% limits any sharp variations that could be difficult to characterize on-orbit.

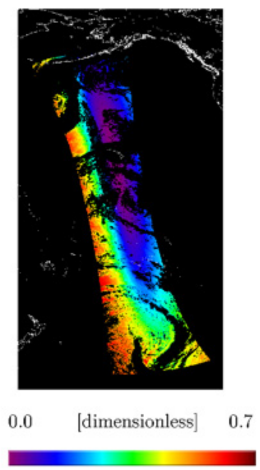

Figure 3.2: Degree of linear polarization (a dimensionless quantity from 0 to 1, where 0 is unpolarized light and 1 is completely linear polarized light, see Meister et al., 2005[19]) of the TOA radiances for an orbit of MODIS Aqua data over the Pacific Ocean for August 14, 2002. MODIS Aqua equator crossing time is 1:30PM; for a sensor with a noon equator crossing time, a more symmetric distribution around nadir is expected.

the uncertainty of the resulting nLw at 443nm to up to 10%, twice the goal of 5%. The ACE team agreed on a 1% polarization sensitivity requirement as it is achievable from an engineering perspective without serious impact on sensor design and cost[3].

There is no requirement for the absolute value of δ. p_a and δ must be derived with an accuracy such that the polarization sensitivity predicted by eq. 3.3 is accurate to within 0.2% (most of the TOA radiances have a degree of linear polarization of less than 50% (see Fig. 3.2), so an accuracy of 0.2% of eq.3.3 would lead to an uncertainty due to polarization of the TOA radiance of less than 0.1% in a large majority of cases). This requirement is also given in the Appendix of the ACE Ocean Biology White paper[23]. The polarization sensitivity shall be characterized at scan angles that include at least nadir, the scan edge, and two additional intermediate scan angles at $\pm 30°$. Measurements at additional scan angles are required until the difference in polarization sensitivity predicted by eq. 3.3 for any β is less than 0.005 between adjacent scan angles.

[3] The SeaWiFS design minimized inherent polarization sensitivity by limiting the range of the angle of incidence of light on the HAM whereas the MODIS rotating mirror had a much larger range and the point of reflection off the mirror into the aft optics migrated across the mirror during the scan which is why the mirror had to be so large. Of course, SeaWiFS had a depolarizer as well. The CZCS also had a depolarizer, but it was placed further down the optical train after the IR had been split off. This is only a problem if the optical components forward of the depolarizer change significantly affecting the Mueller matrix in an unknown manner (MODIS/Terra and probably the CZCS). Then corrections such as described by Gordon et al. (1997) would not work as well.

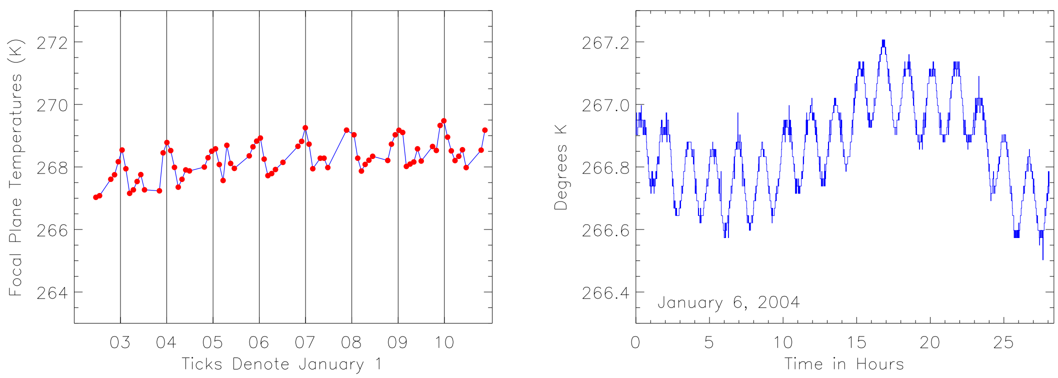

Figure 3.3: The plot on the left shows the temperature variation of the MODIS Aqua VIS focal plane during lunar calibrations throughout the mission. The plot on the right shows the temperature variation of the MODIS Aqua VIS focal plane for a full day. The radiometric response of MODIS Aqua band 8 (412nm) varies by 0.3% per degree Kelvin.

3.1.7 Radiometric Temperature Sensitivity

For a constant radiance source, the variation with temperature of the measured dn shall be less than 0.5% (minimum to maximum) for the whole expected temperature range encountered on-orbit. It is assumed that the focal planes are kept at a constant temperature. During testing, the instrument shall be exposed to simulated on-orbit heating and cooling mechanisms in order to create realistic temperature gradients on the instrument. The accuracy of the sensor temperature sensitivity measurements shall be 0.1% (square summation limit) or better. The sensor shall have a sufficient number of temperature sensors to allow a correction of its temperature sensitivity to within 0.1% (square summation limit).

As an example, Figure 3.3 shows the on-orbit focal plane temperature variations for MODIS Aqua. The variation of 2K during the lunar measurements (plot on the left) results in a correction of about 0.6% for MODIS Aqua band 8.

3.1.8 High Contrast Resolution

Accurate resolution of high contrast in TOA radiance images is important to estimate stray light contamination due to clouds, and for studying small scale features like ocean fronts and for working in coastal and estuarine areas where the scales are ≈1km. The NASA ocean color processing masks MODIS data around clouds. Fig. 3.4 shows the effect of the size of the mask on the vicarious gain calculation for the VIIRS sensor (a larger mask leads to less global coverage, which reduces the occurence of matchups of satellite and in-situ data).

The data loss due to stray light from clouds can be estimated from Fig.3.5, where the number of pixels as a function of 'Distance to cloud' is presented for 6 cases (3 MODIS Aqua granules

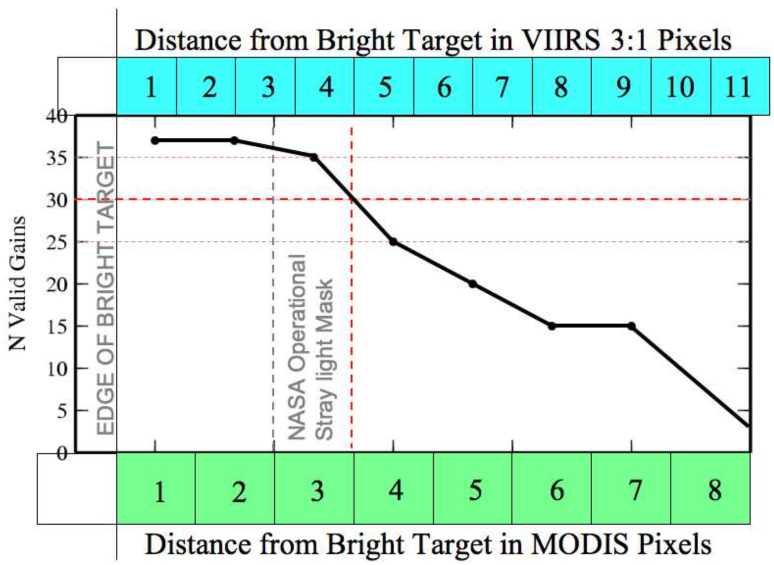

Figure 3.4: The broken line indicates the number of valid match-up pairs of satellite and calibration site (MOBY) data that were acquired for MODIS Aqua when the number of 1km pixels given by the green boxes (numbered 1-8) along the bottom of the plot were masked around cloud edges. (The blue boxes (numbered 1-11) give the equivalent in VIIRS 3:1 aggregation pixels; not relevant in this context.) The dashed vertical black line indicates a mask size comparable to the 5x7 cloud pixel mask applied in the NASA ocean color processing. The dashed horizontal lines indicate the number of match-up data pairs (25-35) needed to achieve convergence of the gain corrections to stable quantities. The amount of available satellite data drop rapidly beyond seven MODIS pixels and are not shown here.

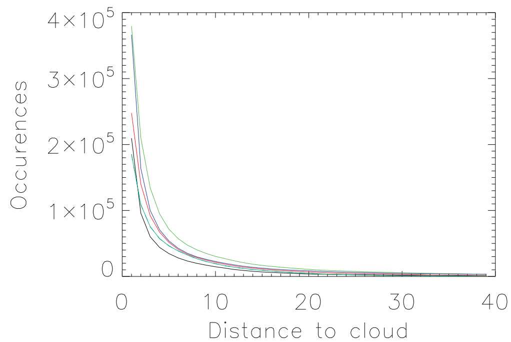

Figure 3.5: Histogram of 'Distance to Cloud' for MODIS (from 3 granules: red, blue and black line) and SeaWiFS ocean pixels (from 3 subsetted MLAC files: green lines). 'Distance to cloud' is an approximation for the distance to the nearest cloud, see Meister and McClain[18] for further details.

and 3 SeaWiFS scenes). The MODIS Aqua stray light mask eliminates about half of all ocean pixels from the NASA ocean color processing[18]. The MODIS mask extends 2km in both track directions, therefore the most stringent requirement of this section evaluates the stray light at a distance of 3km from the scattering source[4]. This ensures that all the data included in MODIS-like coverage is of sufficient radiometric quality.

The sensor high contrast resolution requirement shall be evaluated by two tests: the first with a doughnut-shaped lightfield (scene 1, Fig. 3.6), the second with a square-shaped lightfield (scene 2, Fig. 3.7). The characterization measurements shall be conducted with the instrument in imaging mode (e.g. rotating telescope in the case of a scanning radiometer). This specification limits the impact of several potential instrument artifacts such as internal scattering (stray light), ghosting, and bright target recovery. A separate specification is provided below for cases where detectors saturate.

Scene 1 to assess high contrast resolution is defined as follows:

- The target region is defined as a circular region having a radius of 4 pixels (approximately 4km ground coverage) and having a uniform radiance of L_{target}, with $L_{\text{target}} \leq L_{\text{typ}}$.
- The target region is surrounded by an annular sender region having an inner radius of 4km and an outer radius of 25degrees and having a uniform radiance of L_{sender}.

Scene 2 to assess high contrast resolution is defined as follows:

[4] Scene 2 contains a more realistic cloud than scene 1; scene 1 is useful because the cloud of scene 1 ensures that all straylight effects of the instrument are captured; the second requirement for scene 2 (evaluated at 2 pixels from the cloud) is an attempt to limit straylight for coastal applications, where it is critical to get as close to the coast as possible (since land is usually much less bright than a cloud, the limit of 1% for cloud radiances should result in a contamination of much less than 1% for coastal scenes).

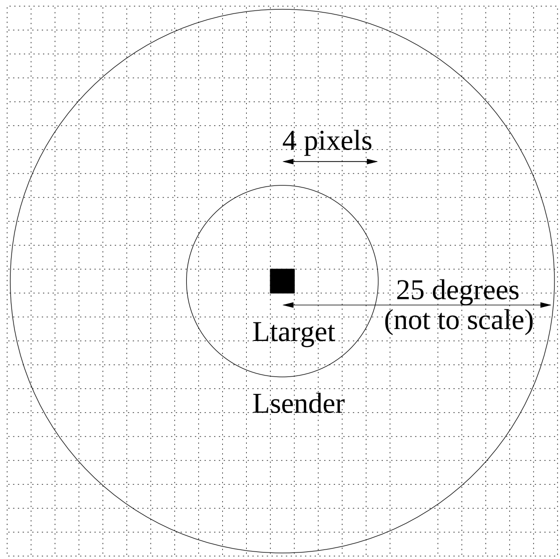

Figure 3.6: Scene 1 described in section 3.1.8. The black square in the center is the central pixel of specification 3.1.8.1 where the radiance change is to be measured.

- The sender region is defined as a square region of 11x11 pixels (approximately 11km x 11km ground coverage) and having a uniform radiance of L_{sender}.
- The sender region is surrounded by a region having an outer radius of 25degrees and having a uniform radiance of L_{target}, with $L_{\text{target}} \leq L_{\text{typ}}$.

There are three specifications in the high contrast resolution requirement 3.1.8:

1. Scene 1: If the radiance L_{sender} is increased from L_{target} to L_{max} in all bands simultaneously, the measured radiance at the central pixel of the target region shall change by no more than 0.2% of L_{typ} for any band.
2. Scene 2: If the radiance L_{sender} is increased from L_{target} to L_{max} in all bands simultaneously, the measured radiances 3 or more pixels away from the sender region in both track directions (i.e. above and below the sender region) and both scan directions (i.e. left and right of the sender region) shall change by no more than 0.2% of L_{typ} for any band.
3. Scene 2: If the radiance L_{sender} is increased from L_{target} to L_{max} in all bands simultaneously, the measured radiances 2 pixels away from the sender region in both track directions (i.e. above and below the sender region) and both scan directions (i.e. left and right of the sender region) shall change by no more than 1.0% of L_{typ} for any band.

The specifications shall be verified using illumination sources as close to scenes 1 and 2 as possible. In case the illumination sources deviate from the desired scenes, corrections shall be

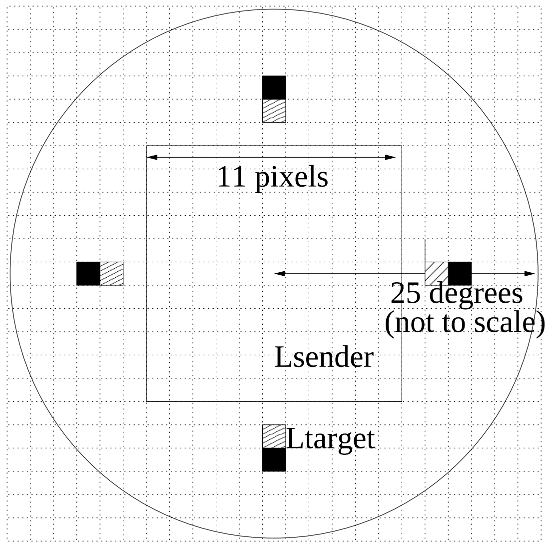

Figure 3.7: Scene 2 described in section 3.1.8. The black squares are the pixels of specification 3.1.8.2 where the radiance change is to be measured. The squares with the diagonal line pattern are the pixels of specification 3.1.8.3 where the radiance change is to be measured.

used to adjust the test results. (For example, if the real illumination source for test 1 extends only for 10 degrees (instead of 25 degrees) and contains a square dark center of 8x8 pixels (instead of a circular dark center with a radius of 4 pixels, the results of the measurement of the real illumination source shall be adjusted using the (independently measured) point spread function.)

In case the measurements do not pass this test without a stray light correction, this specification shall be met after a stray light correction has been applied (thereby converting this instrument performance specification into a specification on the accuracy of the stray light correction).

For bands 21-26 of table 3.1 (wavelengths 765nm to 2130nm), the ratio of L_{max} to L_{typ} is larger than 50 (e.g. 275 for band 26). It is unrealistic to expect the performance called for in this requirement for such high contrast ratios. Therefore, for bands 21-26, L_{sender} shall be defined as 50 times L_{typ}. This provides a similar or better absolute (i.e. not relative to L_{max}) stray light performance for bands 21-26 compared to bands 1-20 and does not make the SWIR stray light performance an optics design driver.

3.1.9 Saturation

The sensor shall not saturate at L_{max} (given in table 3.1) for any multispectral band (ACE requirement[23]). This ensures that a stray light correction algorithm can use the correct data as input from the sending pixels.

3.1.10 Saturation Recovery

Section 3.1.8 defines the dynamic range, but some (very few) pixels in a global data set are expected to be higher than $L_{\max}$, so saturation may occur occasionally. This specification (3.1.10) is meant to limit the impact of saturated pixels on neighboring pixels[5].

The sensor shall be in imaging mode. The same illumination scenario as in scene 2 of section 3.1.8 shall be used. L_{sender} shall be 1.2 times $L_{\max}$ for all wavelengths (no TOA radiances above 1.2 times $L_{\max}$ are expected to occur on-orbit). The measured radiances acquired 10 seconds or more after the last pixel of intensity 1.2 times $L_{\max}$ was measured shall be within $\pm 0.2\%$ of L_{typ} for all channels. This requirement limits the data that needs to be excluded in the case of saturation.

3.1.11 Crosstalk

Optical and electronic crosstalk have been a particular concern for VIIRS because of the optical filter strips and the compactness of the focal plane electronics. Designs need to avoid these effects because they are very difficult and time consuming to quantify and require complicated algorithms to correct.

Let λ_0 and (x_0, y_0) be the wavelength and pixel coordinates of a sensor measurement, respectively. Crosstalk is defined as an erroneously measured signal contaminating this measurement that originates neither from the same wavelength λ_0 nor from the same location (x_0, y_0). An erroneously measured signal originating from the same wavelength λ_0, but from a location not equal to (x_0, y_0), is referred to as spatial stray light. Section 3.1.8 deals with these features. An erroneously measured signal originating from the same location (x_0, y_0), but from a wavelength not equal to λ_0, is referred to as out-of-band. Section 3.2.1 deals with these features.

Line-Spread Function (LSF) measurements are defined here as measurements where a light source that illuminates only one pixel (IFOV) is measured at several locations (x, y), where (x, y) are varied in subpixel steps.[6] Throughout this section, x and y have the unit of 1 IFOV (ideal IFOV as defined in section 3.3.1, not the measured IFOV). The step size for measuring the LSF for the sending area A defined below can be integer. For the purpose of defining this specification, the sensor's IFOV is centered on the area defined by $0 \le x \le 1$ and $0 \le y \le 1$, see Fig. 3.8.[7]

[5]Saturation recovery was a serious issue with the CZCS where the preamps had a very uneven response (ringing) coming off bright targets which could contaminate data for tens of pixels down scan (Mueller, 1988)[21]. These data had to be masked (discarded).

[6]This concept is similar to the MODIS LSF measurements, but for MODIS, the light source was a slit, not a point source.

[7]For practical purposes, the sensor can be moved relative to the light source; for simplicity, this specification assumes that the light source is moved relative to the sensor.

The LSF measurements for each band i (see table 3.1) shall be made with in-band only illumination (L_I), so that

- $L_I(\lambda) = L_{\text{typ}}$ for λ within in-band of band i
- $L_I(\lambda) = 0$ for λ outside of in-band of band i

and the resulting LSF shall be called LSF^i.

Note that per definition

$$\int_{0 \leq y \leq 1} \int_{0 \leq x \leq 1} LSF^i(i, x, y) dx dy = L_{\text{typ}}(\lambda_i) \tag{3.4}$$

A receiver is defined as a pixel (at any scan angle, at any wavelength of table 3.1) that receives crosstalk. The receiver bands are referred to by the index j, and their respective center wavelength is λ_j. Similarly, λ_i is the center wavelength of sender i. The LSF measurements can be described by $LSF^i(j, x, y)$, where x and y are the coordinates in scan and track direction. The IFOV of the receiver covers the area $0 \leq x \leq 1, 0 \leq y \leq 1$ (see Fig. 3.8) for the purpose of this specification, but it can be located at any scan angle.

Additionally, the LSF measurements shall be made with an illumination source similar to a TOA radiance (over blue ocean) spectrum, i.e. L_{typ} for all in-band wavelengths and linearly interpolated between bands. The resulting LSF shall be called LSF^T.

The crosstalk shall be evaluated for a sending area (see Fig.3.8) covering 2 pixels (IFOVs) in both scan and track direction starting from the pixel (IFOV) adjacent to the receiver (note: this results in a square of edge length 7 pixels, with a cut-out square in the center of edge length 3 pixels) and over all out-of-band wavelengths.

The spatial integration ranges defined above were chosen considering the difficulty in evaluating directly adjacent pixels (therefore, 2 is the lower limit, not 1), and the radius of the doughnut hole in the High Contrast Resolution Spec (radius is 4, see section 3.1.8), which covers distances beyond 3 pixels.

Each receiver j shall receive total crosstalk from any sender in area A (defined in Fig.3.8) of less than 0.1% (square summation limit) of L_{typ}. Therefore, for each receiver j, the equation below shall be true:

$$\int_{x,y \epsilon A} LSF^T(j, x, y) dx dy - \int_{x,y \epsilon A} LSF^j(j, x, y) dx dy < 0.001 \cdot L_{\text{typ}}(\lambda_j) \tag{3.5}$$

where area A is defined in Fig.3.8.

3.1.12 Radiometric Stability

Radiometric stability is essential for climate missions, particularly long term stability.

The dn measured prelaunch when illuminated with a constant radiance source shall vary by 0.1% or less during the period of one orbit and all shorter time scales.[8] This specification has to be verified by prelaunch measurements with an accuracy of 0.1%.

[8]Rationale: Solar calibrations can only be performed once per orbit, so any variation within an orbit cannot be detected by calibration.

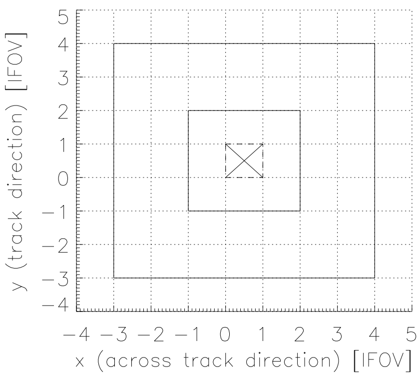

Figure 3.8: Sending area A used in section 3.1.11. The two squares delineated by solid lines are the limits of the sending area. The outer square's corners are at $x = y = -3$ and $x = y = 4$, the inner square's corners are at $x = y = -1$ and $x = y = 2$. The square delineated by a dashed line and marked with a cross is the location of the IFOV of the receiver.

The dn measured prelaunch when illuminated with a constant radiance source shall vary by 0.5% or less during a month and all shorter time scales. This specification has to be verified by prelaunch measurements with an accuracy of 0.1% (ACE requirement[23]). One suggested method of verifying this requirement is weekly measurements for four weeks (e.g. a 1 hour measurement each week) and a continuous measurement for 6 hours. Furthermore, tests are required that demonstrate stability on the same level if the instrument is powered off and on (specifications must be met 30 minutes after power on or earlier). At a minimum, radiometric stability shall be evaluated before and after thermal vacuum testing, and before and after vibration testing.

The Engineering Design Unit (see section 1) shall measure continuously for a period of at least 6 months (e.g. before and during Flight Unit testing) to verify long term radiometric degradation. The illumination source for this test can be used intermittently (e.g. one hour per week). This test will also help to evaluate the quality of any mechanical components (if applicable).

The specifications for long term stability (0.5% per month) and whole mission stability (20% in 5 years) are the on-orbit specifications. In the design phase, these maximum degradation values shall be verified by radiometric modeling (no accuracy requirement). On-orbit, the whole mission stability (i.e. the long term radiometric degradation) shall be determined by lunar measurements with an accuracy of 0.1%[23]. SeaWiFS has demonstrated that this level of accuracy is possible[9]. Monthly stability shall be determined by a combination of lunar and solar diffuser measurements, also with an accuracy of 0.1%. Note that the on-orbit requirements do not apply to the operational radiometric trending (the most recent 6 months of data available) and the first 6 months of the mission. This relaxation of the requirements acknowledges that the uncertainties are highest at the beginning and end of a time series.

3.1.13 Band-to-band Stability

The goal of this spec is to ensure good accuracy of the calibrated radiances relative to each other. This is important for a derivative analysis (especially for adjacent bands), for atmospheric correction (e.g. the ratio of the 748nm band to the 865nm band), and for the standard chlorophyll algorithm (e.g. the ratio of 443nm to 555nm).

For this spec, 'band' refers to any of the 5nm channels in the UV/VIS/NIR, as well as to the standard bands defined in table 3.1. SWIR bands are not covered by this spec.

The ratio of the calibrated radiances of any two bands in the evaluation range shall vary by less than ±0.2% (square summation limit) from its true value over the test period of 4 weeks.

There shall be four short term calibrator measurements during the test period, at approximately weekly intervals. The short term calibration source could be e.g. a solar diffuser. There shall be 5 verification measurements during the test period, including one at the end and one at the beginning of the test period, at approximately weekly intervals. The calibrator measurements and the verification measurements shall be separated by at least 48 hours.

The light source for the verification measurements shall provide radiances at L_{typ} (to within ±30% for each of the standard bands) for at least the two band pairs under test simultaneously (preferably it shall provide the complete spectrum simultaneously at L_{typ}).

The verification measurements shall be made at three earth-view angles (nadir, plus and minus 45deg view angle) with a simulated earth scene. The earth scene shall contain at least one area of size 20 IFOV x 20 IFOV at L_{typ}, and the verification measurement shall be the average of the central 100 pixels of that area.

The calibrator measurements shall use the short term calibration source illuminated/operated similarly to on-orbit conditions.

During the test period (but not necessarily during the calibrator or verification measurements), the short term calibration source shall be exposed to an on-orbit like radiation environment (e.g. in case of a solar diffuser, covering at least UV to NIR wavelengths). In case there is a mechanism for calibrating the short term calibration source (e.g. a separate, protected solar diffuser), such a calibration shall be performed (e.g. using results from measuring the protected solar diffuser at the beginning and end of the test period), and the results shall be applied to the short term calibration source. The instrument shall be calibrated with the corrected short term calibration source, therefore the verification measurements can only be processed after the test period.

3.1.14 Uniform Scene Artifacts

If the sensor is illuminated by a homogeneous light source at a radiance of L_{low}, L_{typ}, or L_{high}, extending over the full scan angle range, there shall be no discontinuities in the measured radiance as a function of scan angle or in track direction. A discontinuity is defined as a change in radiance that is observable in an image, it does not refer to noise. Any discontinuity with a radiance change larger than 0.1% is considered observable. This requirement limits the occurrence of striping in images, which has been an issue in instruments like MODIS (detector or mirror side striping[20]) and MERIS (camera differences, see e.g. Martiny et al.[17], Fig. 3).

3.1.15 White Solar Diffuser Bidirectional Reflectance Distribution Function (BRDF)

The solar diffusers shall be characterized in their final configuration inside the sensor and with on-orbit illumination (from 340nm to 2200nm, considering both the sun and earth as light sources) so that stray light effects are included in the characterization. The specifications described in this section are state of the art as of 2010. The main purpose of the primary solar diffuser is to detect short term (less than 6 months) radiometric gain sensitivity variations. It can also be used to determine SNR on-orbit[10]. Longer term variations are to be detected with lunar measurements. The radiometric gain degradation measured by the combination of the two solar diffusers shall validate the lunar measurements.

1. The absolute BRDF of each of the white solar diffusers shall be known with an accuracy of 1.5% for the sensor-to-diffuser viewing geometry and all solar angles expected on-orbit.

2. The ratio of BRDF values to each other for the sensor-to-diffuser viewing geometry and all solar angles expected on-orbit shall be known with an accuracy of 0.1%. The solar angles vary seasonally, so the change in the BRDF with solar angles needs to be known accurately (square summation limit).

3. The BRDF of the two white solar diffusers relative to each other shall also be known with an accuracy of 0.1%.

4. The radiances measured by the sensor on-orbit from the solar diffuser (or any other calibration source) shall be larger than L_{low} and lower than $L_{\mathrm{max}}/2$ (values for L_{low} and L_{max} are provided in tables 3.1 and 3.2). This ensures that the calibration is performed in the same dynamic range as the ocean measurements.

Table 3.3: Radiometric Calibration Specifications

Type	Performance Specification	Characterization Accuracy	Related sections
Absolute Radiance vs DN	see table 3.1	0.5%	3.1.3
Radiance vs DN: Linearity	0.1%	0.1%	3.1.4
Response vs scan angle	<0.5%	0.1%	3.1.5
Polarization sensitivity	<1.0%	0.2%	3.1.6
Temperature sensitivity	0.5%	0.1%	3.1.7
High contrast resolution	0.2% of L_{typ}		3.1.8
Bright target recovery	0.2% of L_{typ}		3.1.10
Electronic crosstalk	0.1% of L_{typ}		3.1.11
Short term stability	0.1% per day	0.1%	3.1.12
Long term stability	0.5% per month	0.1%	3.1.12
Mission stability	20% in 5 years	0.1%	3.1.12
Solar Diffuser BRDF	5%	0.1%	3.1.15

3.2 Spectral Calibration Specifications

3.2.1 Relative Spectral Response for Multispectral Bands

Spectral specification compliance shall be evaluated for three types of standard radiances: lunar, solar diffuser, and blue ocean TOA. These standard radiance spectra will be published online. Compliance shall be evaluated at nominal focal plane operating temperature.

The band center wavelengths and bandwidths are defined in table 3.1, page 12.

The spectral response of a band (SR(λ)) is defined as the response of the band (measured in *dn*) when illuminated with monochromatic light at wavelength λ. The RSR(λ) is defined as SR(λ) after normalization to the maximum value:

$$RSR(\lambda) = \frac{SR(\lambda)}{\max(SR(\lambda))} \tag{3.6}$$

The band center wavelength shall be calculated as defined in section 3.2.3.

The band edges E_1 and E_2 are defined as those wavelengths with RSR=0.5, with $E_2 > E_1$. There shall be only two wavelengths where RSR=0.5 for each band.

The bandwidth (BW) is defined as the difference between the two band edges: $BW = E_2 - E_1$.

The band limits L_1 and L_2 are defined as those wavelengths with RSR=0.01, with $L_2 > L_1$. There shall be only two wavelengths where RSR=0.01 for each band.

The in-band response (IB) shall be the integrated RSR within the band limits:

$$IB = \int_{\lambda=L_1}^{\lambda=L_2} RSR(\lambda) d\lambda \tag{3.7}$$

The out-of-band (OOB) response shall be the integrated RSR beyond the 0.01 values away from the band center wavelength:

$$OOB = \int_{\lambda=300nm}^{\lambda=L_1} RSR(\lambda) d\lambda + \int_{\lambda=L2}^{\lambda=2500nm} RSR(\lambda) d\lambda \tag{3.8}$$

The integration limits of 300nm and 2500nm where chosen as guidelines, assuming there is no measureable response below 300nm and above 2500nm. If there is a measureable response, the limits need to be extended.

The requirements for the RSR are as follows:

1. All points within the band edges shall have an RSR of more than 0.5.
2. The average of the RSR between the band edges shall be 0.75 or greater.
3. For the UV/VIS/NIR bands, the band edges shall be within ±3nm of the value calculated from table 3.1 using band center wavelength $\pm 0.5 \cdot BW$.
4. Away from the band center, the RSR shall drop to 0.01 within no more than 10nm from the measured band edge for the UV/VIS/NIR bands, i.e.

$$E_1 - L_1 < 10nm \tag{3.9}$$
$$L_2 - E_2 < 10nm$$

For the SWIR bands, the wavelength difference between the band limits shall be less than twice the bandwidth, i.e.

$$L_2 - L_1 < 2 \cdot BW \tag{3.10}$$

5. The ratio of OOB response to IB response shall be 0.01 or less.[9]

6. The RSR of the OOB region shall be measured at 5nm intervals or smaller. The RSR of the IB region shall be measured at 0.1nm intervals. The bandwidth of the source for the IB measurements shall be between 0.1nm and 1nm.

7. Each RSR measurement of the IB region shall have an accuracy of 1e-4 (i.e. 0.1% relative to the peak RSR value). Each measurement of the OOB region shall have an accuracy of 1e-6 or 10% relative to its value, whichever is larger. The wavelengths of the RSR measurements shall be known to within 0.1nm.

8. The radiances calculated for each band with their respective RSR for different sensor elements that produce adjacent pixels in the image data (such as different detectors or different mirror sides) shall not vary by more than ±0.1% for all three types of standard radiances. The radiances calculated for each band with their respective RSR shall not vary by more than ±0.2% for all three types of standard radiances for any scan angle.[10]

The above requirements have been derived from experience with previous ocean color sensors (SeaWiFS, MODIS, and VIIRS).

3.2.2 Relative Spectral Response for Hyperspectral Bands

The requirements for the spectral characteristics of the hyperspectral bands are the following:

1. a wavelength difference of the center wavelengths for adjacent hyperspectral channels of 5nm ±0.5nm

2. a bandwidth of each hyperspectral channel of 5nm ±1.0nm

3. no hyperspectral channel shall have a bandwidth smaller than the wavelength difference of the center wavelengths to its adjacent hyperspectral channels (to avoid gaps in the spectral coverage)

4. the ratio of OOB response to IB response shall be less than 0.05

5. coverage of wavelengths from 345nm to 755nm (for functional group derivative analyses, see Appendix of the ACE Ocean Biology White paper[23]).

[9] While corrections for OOB effects have been made, e.g. SeaWiFS (Gordon, 1995)[12], these effects add uncertainty to the atmospheric correction. VIIRS has a large out-of-band response in some bands, which is a concern.

[10] This requirement reduces radiance variations in images of sensors where different detector elements have slightly different RSRs, such as those caused by the spectral smile within the MERIS cameras[6].

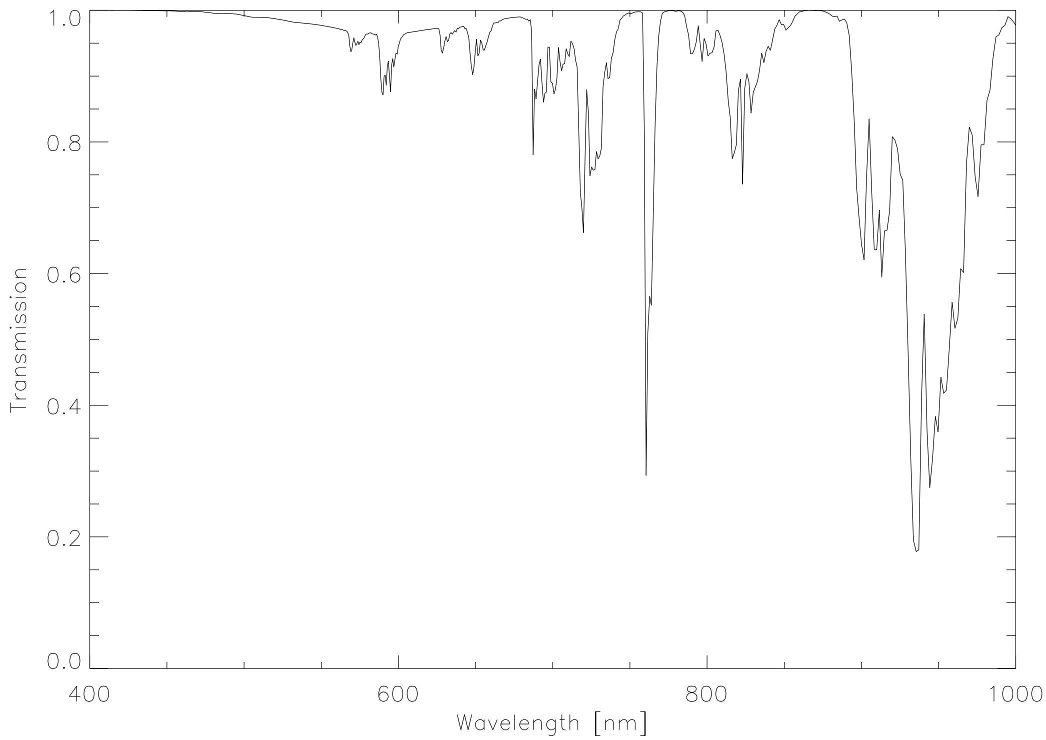

Figure 3.9: Atmospheric transmission due to standard amounts of the following gases: $(H_2O, O_3, CO_2, O_2, NO_2)$, calculated with Lowtran 7.

3.2.3 Center Wavelength

The center wavelength for a hyperspectral or multispectral band shall be calculated with:

$$\lambda_{\mathrm{CW}} = \frac{\int_{300nm}^{2500nm} \lambda RSR(\lambda) d\lambda}{\int_{300nm}^{2500nm} RSR(\lambda) d\lambda} \tag{3.11}$$

where $RSR(\lambda)$ is the relative spectral response of the respective hyperspectral channel at wavelength λ. The RSRs are normalized to 1 at their maximum value.

Each center wavelength shall be determined with an accuracy of 0.1nm.

There may be some hyperspectral channels that need to be placed at certain wavelengths to optimize their position relative to atmospheric absorption lines (see Fig. 3.9. The absolute position of at least one hyperspectral channel shall be selectable with an accuracy of 1nm or better.

3.2.4 On-orbit Monitoring of Spectral Changes

There shall be a mechanism that allows monitoring of on-orbit changes (and changes from prelaunch to on-orbit) in the center wavelengths of the hyperspectral channels. One possibility for such a mechanism is a spectral target (e.g. a doped solar diffuser with absorption lines). No monitoring is necessary for bands that use spectral filters.

The sensor measurements shall allow the determination of the center wavelength of each hyperspectral channel to within 0.5nm, using the assumptions that 1) the shape of the RSR of the hyperspectral channel does not change and 2) the center wavelength of the detectors in between the features of the spectral target can be interpolated from the center wavelengths of those detectors that are affected by the features of the spectral target.

3.2.5 Spectral Temperature Sensitivity

The center wavelengths (derived from the measured RSRs at different temperatures) shall not change by more than 0.2nm per degree Kelvin. These measurements shall be made with an accuracy of 0.1nm per degree Kelvin over the whole range of expected on-orbit instrument temperatures (with focal plane temperatures kept constant). The maximum variation of the center wavelength over the whole range of expected on-orbit temperatures shall be less than 0.5nm.

3.2.6 Spectral Stability

There shall be no measurable variation of the center wavelengths during a day or on shorter time scales. The absolute prelaunch measurement accuracy for the center wavelengths shall be 0.1nm. The longer term stability requirements are 0.5nm per year and 2nm for 5 years. They shall be verified by a radiometric model and be trended for the hyperspectral channels on-orbit with the spectral target with an accuracy of 0.5nm. This specification does not apply to the SWIR bands.

Table 3.4: Spectral Calibration Specifications

Type	Performance Specification	Characterization Accuracy	Related sections
Center wavelength of each channel	1nm (one channel)	0.1nm (all channels)	3.2.3
Spectral monitoring		0.5nm	3.2.4
Temperature sensitivity	0.16nm/degree	0.05nm/degree	3.2.5
Long term stability (center wavelength)	0.5nm per year	0.5nm	3.2.6
Mission stability (center wavelength)	2nm in 5 years	0.5nm	3.2.6

3.3 Spatial Calibration Specifications

3.3.1 Instantaneous Field-Of-View (IFOV)

The IFOV for each band shall be measured such that the shape and size of the area covered by a single pixel is known. The border of the area is defined as the contour line where the sensor response has dropped to 50% of the maximum response.

The instantaneous field-of-view (IFOV) shall measure an area extending over 1km $\pm$ 0.1km in the along-track and along-scan directions, at a tilt angle of 20° at the scan center, for the spacecraft altitude (specified elsewhere). (The ACE requirement for spatial resolution is 1km[23].) This shall be determined as the FWHM of the beam pattern in each direction.

3.3.2 Scan Angle Knowledge

The scan angle per pixel shall vary as a function of scan angle by no more than 0.1% for adjacent pixels. The sensor scan shall be planar to within 2 IFOV. The scan angle and out-of-plane angle for each pixel shall be known to within 0.1 IFOV.

3.3.3 Pointing Knowledge

The pointing accuracy at all three tilt angles $(+20°, 0°, -20°)$ shall be 0.2 degree, and shall be known to 0.01 degree.

3.3.4 Spatial Band-to-band Registration

For each band, the overlap of the area of its IFOV with the area of the IFOV of any other band shall be at least 80% for all scan angles. This requirement is based on heritage sensors.

Note: for sensors like SeaWiFS and MODIS, no scan angle dependency is expected for the band-to-band registration. For such sensors, it is sufficient to evaluate the specification at only one scan angle. However, for sensors like OCTS, a scan angle dependency is expected due to the design. For a sensor where a scan angle dependency is expected, the compliance with this specification shall be evaluated at several scan angles (at a minimum at nadir and the scan edges) to ensure that the specification is met for all scan angles.[11]

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

Table 3.5: MTF requirements

Fraction of Nyquist Frequency	MTF
0.00	1.0
0.25	0.9
0.50	0.7
0.75	0.5
1.00	0.3

3.3.5 Adjacent Scan Lines and Pixels

The IFOVs of adjacent pixels in scan and track direction shall not have gaps in spatial coverage, whereas overlap is acceptable. The spacing of the pixel center ground locations for adjacent scan lines shall be within 10% of the along-track IFOV.

3.3.6 Modulation Transfer Function (MTF)

The sensor Line Spread Function (LSF) in the along-track (cross-track) direction is defined as the response to a line slit test pattern oriented in the cross-track (along-track) direction.

The Modulation Transfer Function (MTF) in the along-track (cross-track) direction is defined as the magnitude of the normalized Fourier Transform of the sensor LSF in the along-track (cross-track) direction. The MTF is a function of spatial frequency, and it is equal to one at the origin by virtue of the normalization condition of the LSF. As used here, MTF applies to the on-orbit sensor performance and includes contributions from diffraction, optical aberrations, detector field-of-view, integration drag, aggregation, TDI, crosstalk, electronic response, jitter disturbances, and charge transfer efficiency.

It is assumed that the instrument will return one sample per IFOV. The MTF specification refers to the MTF measured from super-sampled data and, as a result, assumes optimal phasing of the sampling with the target under examination. The specification shall be verified from super-sampled data obtained from multiple scans of a target with sub-IFOV translations between each scan.

The Nyquist frequency is determined for each band and has a spatial period equal to two IFOVs on the ground. The Nyquist frequency is given by the equation:

$$f_{Nyquist} = \frac{1}{2 \cdot IFOV'} \tag{3.12}$$

where $IFOV'$ is the IFOV as specified in section 3.3.1 converted to distance on the ground.

The MTF in both track and scan direction shall equal or exceed the values specified in table 3.5.

Table 3.6: Spatial Calibration Specifications

Type	Performance Requirement	Characterization Accuracy	Related sections
IFOV (track/scan)	1.464 mrad	0.15mrad	3.3.1
Scan angle knowledge for each pixel (track/scan)	0.1 IFOV		3.3.2
Band-to-band registration	0.2 IFOV	N/A	3.3.4
Pointing knowledge at all three tilt angles	0.2degrees	0.01degrees	3.3.3
MTF	table 3.5	N/A	3.3.6

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14. ABSTRACT
This document suggests requirements for an advanced ocean radiometer, such as e.g. the ACE (Aerosol/Cloud/Ecosystem) ocean radiometer. The ACE ocean biology mission objectives have been defined in the ACE Ocean Biology white paper. The general requirements presented therein were chosen as the basis for the requirements provided in this document, which have been transformed into specific, testable requirements. The overall accuracy goal for the advanced ocean radiometer is that the total radiometric uncertainties are 0.5% or smaller for all bands. Specific mission requirements of SeaWiFS, MODIS, and VIIRS were often used as a model for the requirements presented here, which are in most cases more demanding than the heritage requirements. Experience with on-orbit performance and calibration (from SeaWiFS and MODIS) and prelaunch testing (from SeaWiFS, MODIS, and VIIRS) were important considerations when formulating the requirements.
This document describes requirements in terms of the science data products, with a focus on qualities that can be verified by prelaunch radiometric characterization. It is expected that a more comprehensive requirements document will be developed during mission formulation.

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