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SeaWiFS Technical Report Series

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Abstract

The final acceptance, or rejection, of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) will be determined by the instrument's on-orbit operation. There is, however, an extensive set of laboratory measurements describing the operating characteristics of the radiometer. Many of the requirements in the Ocean Color Data Mission (OCDM) specifications can be checked only by laboratory measurements. Here, the calibration review panel (composed of the authors of this technical memorandum) examines the laboratory characterization and calibration of SeaWiFS in the light of the OCDM performance specifications. Overall, the performance of the SeaWiFS instrument meets or exceeds the requirements of the OCDM Contract in all but a few unimportant details. The detailed results of this examination are presented here by following the outline of the specifications, as found in the Contract. The results are presented in the form of requirement and compliance pairs. These results give conclusions on many, but not all, of the performance specifications. The acceptance by this panel of the performance of SeaWiFS must only be considered as an intermediate conclusion. The ultimate acceptance (or rejection) of the SeaWiFS data set will rely on the measurements made by the instrument on orbit.

1. INTRODUCTION

In addition to its role as an ocean color experiment, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) serves as a satellite procurement experiment for the National Aeronautics and Space Administration (NASA). For the SeaWiFS Project, NASA is procuring *data*, not an instrument designed by the agency. NASA has entered into a contractual agreement, the Ocean Color Data Mission (OCDM) contract, (hereinafter referred to as the Contract, unless otherwise stated) with Orbital Sciences Corporation (OSC) to obtain, at a fixed price, an ocean color data set. OSC has, in turn, entered into an agreement with the Hughes Santa Barbara Research Center (SBRC) for which SBRC, as a subcontractor, has built the satellite sensor required to provide these data. In this arrangement, SBRC has had the freedom to design an instrument which meets the predetermined set of specifications. The design of the testing procedures for the instrument has also been left to SBRC.

Although not written in the specifications, it is the responsibility of the Project to understand the design, the operation, and the calibration of the satellite sensor. The Project also has the responsibility of transferring this understanding to the community of scientists who will use the ocean color data set. Without a specific requirement in the Contract, SBRC, OSC, and the Project set up an unofficial program of visits to the instrument builder by a Project representative during the construction and calibration of SeaWiFS. From the outset, these visits developed into a collaboration between SBRC and the Project, rather than strict supervision by NASA, over the instrument development.

This arrangement has been non-standard in another way, since the Contract remains an agreement between NASA and OSC. Care has been taken to ensure no interference from the Project in the contractual obligations between OSC and SBRC. It should be noted that adherence to the OCDM performance specifications is the responsibility of OSC. The contract between OSC and SBRC has incorporated the OCDM performance specifications almost completely. There have been a few instances in which the deliverables in the subcontract between OSC and SBRC have not provided the information needed by the Project to assure compliance with the OCDM specifications. In those instances, the informal arrangement has given a mechanism for the Project to obtain the necessary information.

The major events in the construction and testing of the SeaWiFS instrument are given in Table 1. Throughout this period, the Project has worked as an active partner with SBRC. This partnership has been of great advantage to the Project. The Project representative has been given access to all of the technical information about SeaWiFS, plus access to the engineers and technicians working on the instrument. Technical problems that arose during construction were openly discussed by SBRC and the Project. In addition, test procedures were developed, in part, through informal talks between SBRC engineers and the Project representative. The representative was an active participant in several of the tests.

Again, this active participation has been of great advantage to the Project. In this review of the SeaWiFS specifications, the review panel can base its conclusions on a set of tests and calibrations with results and procedures that the panel understands. More importantly, the active participation has provided a greater understanding of the operation of SeaWiFS. This includes an understanding of some of the characteristics that are particular to the instrument—characteristics that the SBRC engineers have called its *personality*. These include the instrument's along-track modulation transfer function (MTF), discussed below, and its stray light characteristics, which will be discussed at length in a future volume within the SeaWiFS Technical Report Series. Such understanding will be crucial as the Project works to interpret the data that the radiometer will transmit from orbit.

Table 1. Major events in the construction and testing of the SeaWiFS instrument.

Date	*Noteworthy Event*
16 May 1991	Letter Contract Signed between OSC and SBRC
6 July 1991	Preliminary Design Review
16 December 1991	Critical Design Review
16 September 1992	Engineering Design Unit Completed
27 October 1992	SBRC and GSFC† Integrating Sphere Comparison
8 December 1992	First *Field Test* (lunar and solar measurements)
15 January 1993	Vibration and Thermal-vacuum Testing
7 March 1993	Second *Field Test*
27 April 1993	Initial Pre-Ship Review
27 May 1993	Stray Light Paths Review (at GSFC)
3 August 1993	Performance Specification Modification (at OSC)
26 October 1993	Vibration Testing of Modification Workmanship
1 November 1993	Third *Field Test*
22 November 1993	Completion of Instrument
2 December 1993	Post-Modification Pre-Ship Review

†Goddard Space Flight Center

It is the opinion of the review group that in light of the instrument design and testing program, the prelaunch performance of the SeaWiFS radiometer meets, or exceeds, the requirements of the Contract in all but a few small details, which are considered to be minor. In addition, it is the opinion of the review group that the testing of the instrument has also been adequate to allow these conclusions.

In Sections 2 through 22, individual parts of the performance specifications are addressed. Some of these sections include requirements that do not involve the radiometer's performance. One such section is Section 20, which concerns satellite pointing data. These additional requirements are discussed in the compliance section for those specifications. Section 23 gives a short summary of the conclusions.

2. FIELD-OF-VIEW

2.1 Requirement

The instantaneous field-of-view (IFOV) at nadir and 0° tilt shall be between 1 and 1.21 km. Sampling shall be done once per nominal (square) IFOV.

2.2 Compliance

The field-of-view of the instrument is determined from data measured by scanning a narrow slit across the nadir pixel, both along-scan and along-track. The narrow slit is 0.16 mrad wide (about 0.1 of the width of a pixel), and the slit is scanned in 0.1 mrad increments. The slit overfills the pixel in the direction perpendicular to its narrow opening. The term for the results from this type of measurement is a *line spread function.*

The along-scan and along-track line spread functions for the eight SeaWiFS bands are shown in Fig. 1. The along-scan values are given in the direction of scan, i.e., the values are representative of the instrument scanning from left to right. In the same manner, the along-track values are given in the direction of flight, i.e, for an instrument moving left to right. For the purposes of Fig. 1, the offsets have been removed from the data, and the data have been normalized to unity. As shown in Fig. 1, the right-most data points in both scans have been set to zero. The scans in Fig. 1 also provide the basis for the MTF calculations and for the band-to-band registration calculations.

The basic method for determining the field-of-view is to calculate the full-width at half-maximum (FWHM) for the along-scan and along-track measurements. These results are presented in Table 2. In addition, the results are presented in terms of the length of an arc that subtends the angle at a distance of 705 km. Such an arc represents the width of the footprint of the SeaWiFS measurement, assuming that the instrument is 705 km above the Earth. The values calculated here are in agreement with the calculations found in the SeaWiFS Calibration and Acceptance Data Package (SCADP). The SCADP was generated by A. Holmes of SBRC in the course of constructing, calibrating, and testing the SeaWiFS instrument. Many of the conclusions made by the review panel are based on information found in the SCADP.

However, these calculations do not adequately represent the two-dimensional nature of the field-of-view. The shape of a SeaWiFS footprint is not a perfect rectangle, since the line spread functions are not perfect square waves. To better represent the SeaWiFS footprint, the along-scan and along-track values for each band have been combined into two-dimensional arrays. Each element in the array is the product of the value at the ordinate (the along-scan

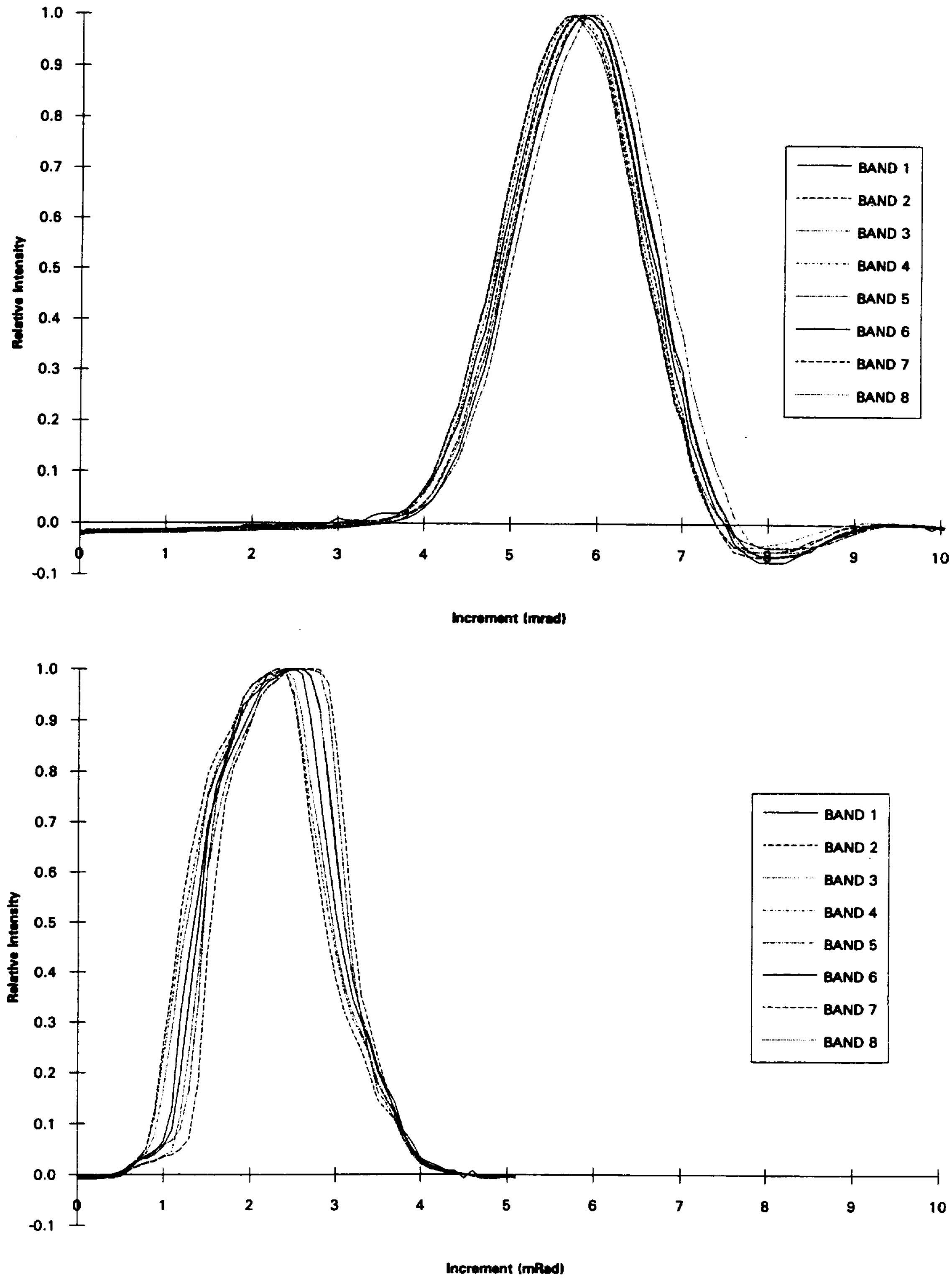

Fig. 1. The along-scan and along-track line spread functions. The top figure shows the along-scan line spread function. In this figure, the zero offsets have been removed from the data, and the results have been scaled to unity. The bottom figure shows the along-track line spread function. As in the top figure, the zero offsets have been removed from the data, and the results have been scaled to unity.

Table 2. Field-of-view calculations. All measurements given are the FWHM of the line spread function.

Band No.	*Along-Scan Values* These Results [mrad]	[km]	SCADP [mrad]	[km]	*Along-Track Values* These Results [mrad]	[km]	SCADP [mrad]	[km]
1	1.84	1.30			1.70	1.20		
2	1.78	1.26			1.69	1.19		
3	1.82	1.28			1.68	1.19		
4	1.78	1.25			1.70	1.20		
5	1.82	1.28			1.69	1.19		
6	1.80	1.27			1.67	1.18		
7	1.76	1.24			1.66	1.17		
8	1.77	1.2			1.65	1.16		
Mean	1.80	1.27	1.8	1.27	1.68	1.18	1.7	1.20
Std. Dev.	0.03	0.02			0.02	0.01		

relative response) and the value of the abscissa (the along-track relative response). This result can be represented as a three-dimensional figure (Fig. 2), with the base given as the ordinate and abscissa locations, and the height as the product of the ordinate and abscissa values.

Figure 3 shows the 50% cross section of the instrument response for band 7. It gives the edge of the three-dimensional figure at the half maximum of the response for the band in Fig. 2. Figure 3 also shows the values for the major axes, i.e., for the axis with an along-scan value of unity and for the axis with an along-track value of unity. Each of the two axes gives the widest possible distance across the cross section in each direction. When these widest possible distances are multiplied together, they give an area that is larger than the actual footprint in Fig. 3.

Figure 4 shows the 50% cross section without the added axes. This footprint for band 7 is nominally, i.e., roughly, square. For the purposes of this review, it seems preferable to define the field-of-view of the SeaWiFS measurements in terms of the area of the (nominally) square footprint. For the eight SeaWiFS bands, the area within the 50% cross sections was calculated, and the length for the side of a square that would enclose those areas was subsequently determined. Table 3 gives the results of the calculations. The lengths of the sides in Table 3 then give the best representation of the fields-of-view of the eight bands in the instrument, as determined by this review.

The average side length for SeaWiFS is 1.60 mrad, or 1.13 km, at an altitude of 705 km. The actual values range from 1.10–1.16 km. All values conform to the requirement of the specifications for an IFOV between 1 and 1.21 km.

3. CROSS-TRACK SCAN

3.1 Requirement

The active portion of the cross-track scan shall not be less than 90° (±45° about nadir) nor greater than 116.6° (±58.3° about nadir). The swath width shall not be less than 1500 km for tilts of ±20° to enable two-day global coverage from the nominal altitude. All scan data shall be transmitted in the local area coverage (LAC) broadcast. Global area coverage (GAC) data subsampled from the cross-track scan need not include data taken at greater than ±45°.

Table 3. Field-of-view, calculated from the footprint area.

Band No.	*Cross-Section*†	*Side Length*‡	*Side Length*§
1	2.67	1.64	1.15
2	2.51	1.58	1.12
3	2.55	1.60	1.12
4	2.44	1.56	1.10
5	2.73	1.65	1.16
6	2.48	1.57	1.11
7	2.53	1.59	1.12
8	2.50	1.58	1.11
Mean		1.60	1.13
Std. Dev.		0.03	0.02

†mrad² ‡mrad §km

3.2 Compliance

The angular portion of the SeaWiFS measurements is determined by the rotation rate of the optics within the instrument, the sampling frequency of the instrument, and the number of samples in a scan line. The optics within the SeaWiFS instrument rotate 6 times per second $6\times360°\,\mathrm{s}^{-1}$). The time period between pixels is 42 μs. There are 1,285 pixels per scan line. The calculation is shown in (1):

$$6 \times 360°\,\mathrm{s}^{-1} \cdot \frac{42\times10^{-6}\,\mathrm{s}}{\mathrm{pixel}} \cdot \frac{1{,}285\,\mathrm{pixels}}{\mathrm{scan\ line}} = \frac{116.58°}{\mathrm{scan\ line}}. \quad (1)$$

The specifications call for this angle to be between 90° and 116.6°. It should be noted that the distance from the

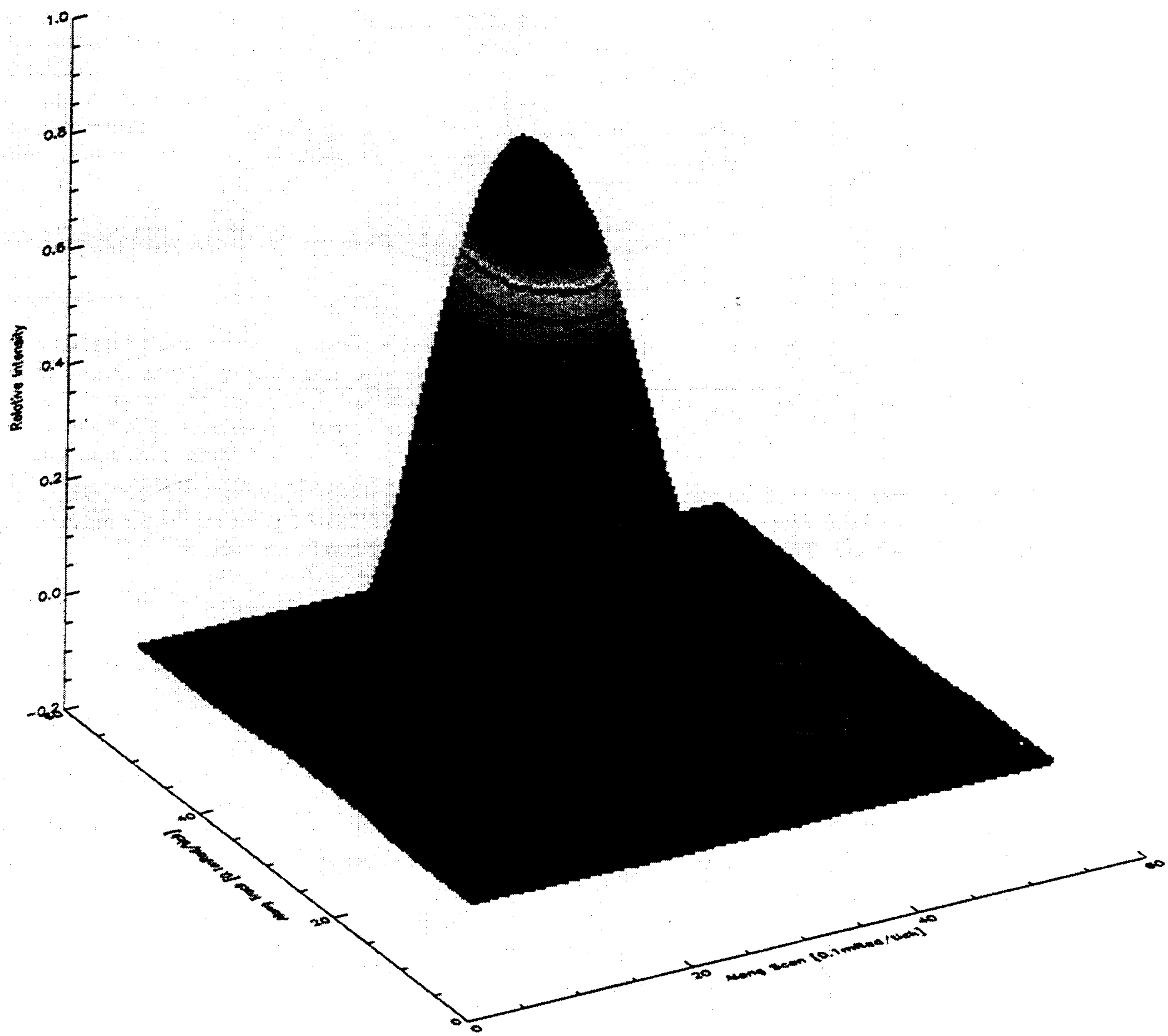

Fig. 2. The response (field-of-view) for SeaWiFS band 7 in three dimensions. The axes for the base are in the along-scan and along-track directions. The height shows the response of the band normalized to unity.

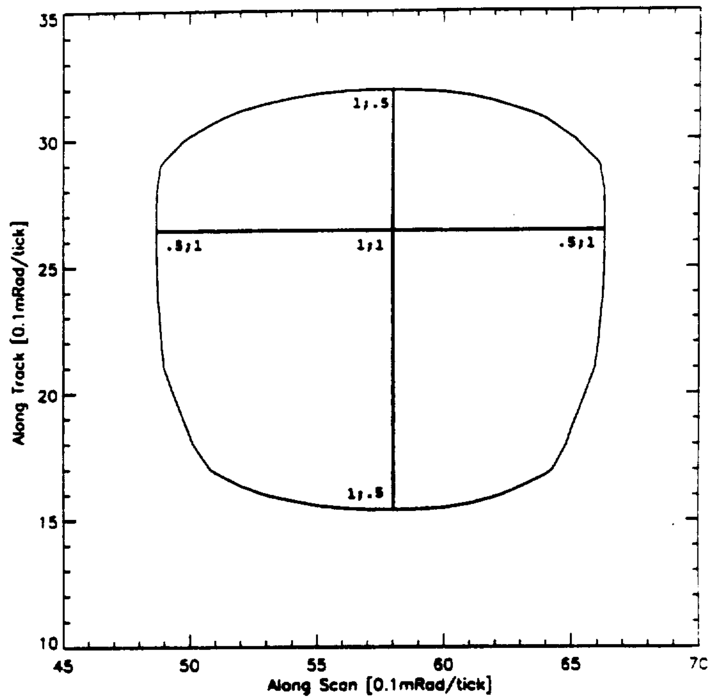

Fig. 3. The cross section of the response of SeaWiFS band 7 at the 50% response level. The two axes within the cross section correspond to the FWHM values in Table 1. The 1:1 point marks the maximum response for the band. The other four points are located on the half maximum contour.

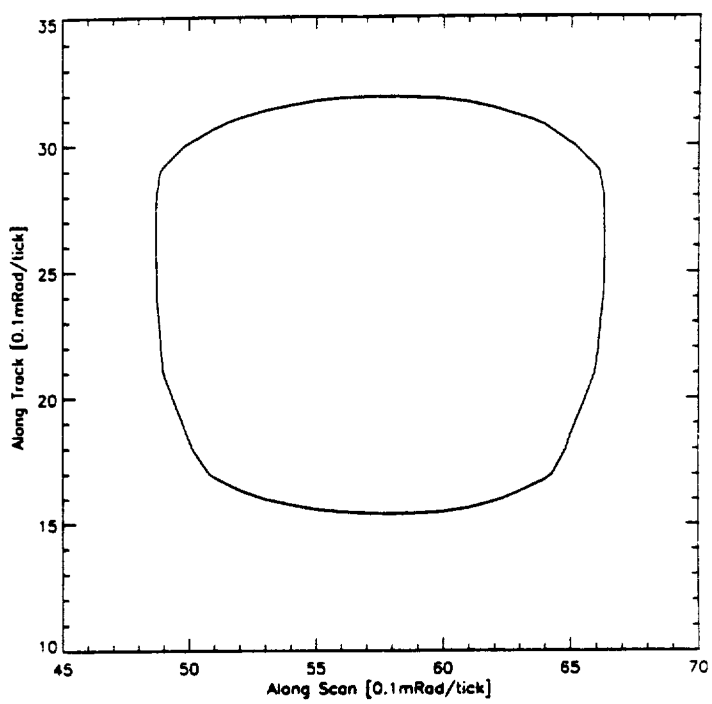

Fig. 4. The measurement footprint for SeaWiFS band 7. The best estimate of the field-of-view for this band is calculated as the side of a square with an area equal to this footprint.

start to the end of the first pixel is one pixel. Thus, the distance from the start of the first pixel to the end of the 1,285th pixel is 1,285 pixels. The distance from the center of the first pixel to the center of the 1,285th pixel is 1,284 pixels. As a result, the angular distance from the center of pixel 1 to the center of pixel 1,284 is 116.48°.

A figure in the SCADP gives a clock rate of 1.905 MHz ±1%. It also shows that there are 80 bits per pixel, or 41.99 microseconds (±1%) per pixel. The rotation rate and the number of pixels per scan line are also described in the SCADP.

Subsampling of each scan line for GAC will be performed by the SeaStar bus. This subsampling will give the 90° angular range (centered about nadir), which is required in the specification.

4. FORE-AND-AFT POINTING

4.1 Requirement

The data shall be taken with a sensor capable of pointing the swath fore and aft (positive and negative with respect to the velocity vector, respectively) to avoid specular solar reflectance from the ocean's surface. The sensor scan must be capable of tilts of 0.0°, +20.0°, and −20.0° from nadir. Changes in the tilt angle from −20° to +20° shall take less than 30 seconds. Data describing the tilt angle shall be accurate to within 0.01°.

4.2 Compliance

The nadir direction for SeaWiFS is given as the $+x$ axis. The instrument scans in the (x,z) plane, and the solar diffuser points in the $+y$ direction. The diffuser points at the sun after the instrument has completed its Earth views and is passing over the South Pole. The diffuser is at the back of the instrument. SeaWiFS flies in the $-y$ direction. A forward tilt has a $-y$ direction and a backward tilt has a $+y$ direction; the values here are from the SCADP. The fore and aft angles have been measured relative to nadir. The angles for nadir direction were measured with respect to the alignment mirrors mounted on the instrument.

Here is a brief description of the procedure that was used to measure the fore and aft tilt angles relative to nadir. With the instrument at zero tilt, a collimated light source was aligned with pixel 643 of the SeaWiFS scan. The entire instrument was then rotated in a specially designed cradle fore and aft 20°, and the scanner was tilted in the other direction. The cradle was designed to rotate the instrument to these 20° locations with great accuracy. The instrument tilt realigned the nadir pixel of the instrument with the collimated light source. The collimated light source was moved in the y direction to determine the difference in the tilt angle from 20°.

Since the tilt angles used in this procedure were determined by SeaWiFS measurements of the source, these angles include the optical paths through the instrument. Thus, the values in Table 4 include measurements with both sides of the half angle mirror. All of the values in this table are given with respect to the alignment mirrors. The SCADP gives the uncertainty for the aft tilt as ±0.003°, and for the nadir and forward tilt the error is given as ±0.006°. The specifications call for tilt knowledge to be within 0.01°.

The SeaWiFS scanner tilts from −20 to +20° in about 13 seconds. The speed profile for the tilt is Gaussian, with a maximum speed of about $6°\,s^{-1}$.

Table 4. SeaWiFS tilt angles.

Tilt	*Mirror Side*	*Angle*	*Uncertainty*
Aft	A	19.896°	±0.003°
Aft	B	19.888°	±0.003°
Aft	Average	19.892°	±0.003°
Nadir	A	0.075°	±0.006°
Nadir	B	0.068°	±0.006°
Nadir	Average	0.072°	±0.006°
Fore	A	−19.850°	±0.006°
Fore	B	−19.857°	±0.006°
Fore	Average	−19.853°	±0.006°

5. DARK LEVEL

5.1 Requirement

A portion of every scan shall contain sensor output data while the field-of-view is obscured and the input radiance is less than the Noise Equivalent Differential Spectral Radiance (NEdL).

5.2 Compliance

The SeaWiFS instrument incorporates a zero offset, or dark restore value, for each scan of the instrument. This value is provided in accordance with the dark level measurements specification. For details on the design and positioning of the dark restore, the reader is referred to Fig. 1 of Woodward et al. (1993), which shows dark direct current (DC) restore at the angular range between 140° and 220° from nadir for each SeaWiFS scan. SeaWiFS provides the dark level measurements required by the specifications.

6. BAND TOLERANCES

6.1 Requirement

The location of the band edges shall be ±2 nm (3σ) of the values in Table 1, and shall be stable to less than ±1 nm over the duration of the ground test program. The edge range shall not exceed 50% of the bandwidth in any spectral band.

6.2 Compliance

6.2.1 Band Edges

The band edge calculations are described in Barnes et al. (1994). The results presented here have been taken from that manuscript, and are summarized in Tables 5–7. These tables include the 5%, 50%, and 80% response levels that are required to calculate the band edges and the edge ranges. The specifications call for the band edges to be within ±2 nm of the values in the specifications. The right (upper) band edge for band 8 falls at the 2.0 nm limit, and the remaining band edges are within the specification limits. The band edge and edge range results in Barnes et al. (1994) are in agreement with the results in found in the SCADP.

6.2.2 Edge Ranges

The specifications require that the edge range for each band shall not exceed 50% of the bandwidth. The edge range is the wavelength interval between 5% of peak response and 80% of peak response. The edge range values are given in Tables 6 and 7. These values were also taken from the calculated results in Barnes et al. (1994). The edge range for band 2, left edge, is 54% of the bandwidth. The edge range for band 6, right edge, is 51%. The remaining ratios fall within the 50% limits.

7. OUT-OF-BAND RESPONSE

7.1 Requirement

The out-of-band response shall be less that 5% of the within-band value. Each 1% point shall be within 1.5 times the bandpass from the corresponding band edge. Compliance with this specification shall be determined for a source with spectral shape equivalent to L_{cloud} (the spectral radiance of a Lambertian surface of 100% reflectance illuminated by the sun at 22.5° zenith angle). Note: The L_{cloud} radiances can be found in Table 18, below. They are also called the SeaWiFS maximum cloud radiances.

7.2 Compliance

7.2.1 Out-of-Band Response.

The in-band response is defined as the integrated response of each band between the 1% transmission points. The out-of-band response is defined as the integrated response at all other wavelengths. The ratio of out-of-band response to in-band response is used to give the percent out-of-band response. These values have been calculated by Barnes et al. (1994). Tables 8 and 9 have been adapted from Table 12 of Barnes et al. (1994) and are based on measurements using a 5,900 K blackbody source, as required in the specifications. A 5,900 K blackbody duplicates the spectral shape of the solar output over the wavelength range of the SeaWiFS measurements (Barnes et al. 1994). All of the calculated out-of-band values are well within the specifications. Table 9 contains a compari from Barnes et al. (1994) with those from ectral data provided as part of the SCAD of calculations show reasonable agreement.

7.2.2 Point

The sp that each 1% response point shall be wi e bandwidth from the corresponding b alculated results are given in Tables 10 a lts are also derived from calculations in B). The calculations have been made using dy source, in accordance with the specific 1% response points are well within the s s.

In gener the SeaWiFS bands are a significant imp shapes required by the specifications.

8. SPEC FERENCES

8.1 Requ

If multipl nts are used within a band, the spectral letector elements in a band shall be comp on and shape, by use of normalized spec ves. The central wavelength of any elemen ±0.5 nm of the average central waveleng nts of the band. The integrated spectr en the 10% response points shall not diffe .0% for any two elements in the band.

8.2 Compl

8.2.1 Ce... ...gth

No spectral measurements have been specifically designed for the SeaWiFS instrument to confirm this specification. However, there is evidence to indicate that the central wavelength for each of the four channels in each SeaWiFS band is well within 0.5 nm of the average central wavelength for that band, as called for in the specifications.

The design of SeaWiFS has the four channels for each band located below a single interference filter for that band. As shown in Barnes et al. (1994), the shape of the spectral response of the filter dominates the determination of the central wavelength. Barnes et al. (1994) also shows that the quantum efficiency of the type of silicon photodiode used in SeaWiFS is roughly constant over the 10–20 nm half-widths of the interference filters. This spectral flatness implies a very minor effect from the detectors on the central wavelength of the band.

Table 5. Reference wavelengths for band edge and edge range calculations. All measurements are in nanometers.

Band	*Left*			*Right*		
No.	5% Point	50% Point	80% Point	80% Point	50% Point	5% Point
1	398.4	403.2	407.4	421.1	423.4	428.9
2	427.8	434.1	438.3	451.0	453.7	459.5
3	474.6	480.8	483.3	499.4	501.4	507.1
4	492.8	498.9	501.1	518.9	521.2	527.2
5	540.4	545.5	547.6	561.4	563.8	570.4
6	653.4	658.3	660.1	675.6	678.2	685.8
7	734.5	744.7	748.9	780.8	785.0	798.3
8	835.8	845.7	849.2	884.1	887.0	896.8

Table 6. Band edge calculations. All measurements and calculated quantities are in units of nanometers.

Band	*Left Band Edge Results*			*Right Band Edge Results*		
No.	Specified	Measured	Difference	Specified	Measured	Difference
1	402	403.2	1.2	422	423.4	1.4
2	433	434.1	1.1	453	453.7	0.7
3	480	480.8	0.8	500	501.4	1.4
4	500	498.9	−1.1	520	521.3	1.3
5	545	545.5	0.5	565	563.8	−1.2
6	660	658.3	−1.7	680	678.2	−1.8
7	745	744.7	−0.3	785	785.0	0.0
8	845	845.7	0.7	885	887.0	2.0

Table 7. Edge range calculations. All measurements are in nanometers.

Band No.	Bandwidth	Left Edge Range	Percent of Bandwidth	Right Edge Range	Percent of Bandwidth
1	20.2	9.0	45	7.8	39
2	19.6	10.5	54	8.5	43
3	20.6	8.7	42	7.7	37
4	22.4	8.3	37	8.3	37
5	18.3	7.2	39	9.0	49
6	19.9	6.7	34	10.2	51
7	40.3	14.4	36	17.5	43
8	41.3	13.4	32	12.7	31

Table 8. Calculated out-of-band responses for the eight SeaWiFS bands. The instrument responses are given as the output of the photodiode in picoamperes (pA). The 5,900 K radiances in the calculations are normalized to the expected saturation radiance for each band at the nominal center wavelength for each band. The upper and lower extended band edges come from Tables 7 and 8 of Barnes et al. (1994). These results are calculated over the wavelength range from 380–1,150 nm.

Band No.	Lower Out-of-Band Response [pA]	Lower Extended Band Edge [nm]	In-Band Response [pA]	Upper Extended Band Edge [nm]	Upper Out-of-Band Response [pA]	Out-of-Band Response [%]
1	3.38	395.2	2175.34	433.6	11.77	0.70
2	9.59	424.1	3418.80	463.7	1.56	0.33
3	6.48	470.7	4301.14	511.7	28.08	0.80
4	17.32	488.1	4586.23	530.7	8.96	0.58
5	39.14	536.3	3631.84	577.2	46.14	2.35
6	12.66	646.7	2071.19	692.5	7.84	0.99
7	10.17	727.3	2818.97	813.4	29.58	1.41
8	66.36	826.4	2191.97	907.5	15.43	3.73

Table 9. A comparison of the calculated instrument out-of-band response results found in Barnes et al. (1994) with SCADP results for the same parameter. Both sets of calculations show the instrument's out-of-band response to be within the 5% value in the specifications.

Band No.	Barnes et al. (1994) [%]	SCADP [%]
1	0.70	0.65
2	0.33	0.40
3	0.80	0.80
4	0.58	0.57
5	2.35	2.35
6	0.99	0.98
7	1.41	1.41
8	3.73	3.73

The detectors in each band are etched from a single piece of silicon. The overall dimensions for the set of four detectors are approximately 0.05 in × 0.01 in. Assuming reasonable uniformity in the manufacture of the silicon material, the four detectors in each band should have nearly identical spectral response over the half-width of the interference filter. It is the response of the interference filter, not the detectors, that dominates the determination of the central wavelength for each SeaWiFS band. The estimate of the within-band spectral differences is based primarily on an assumption of uniformity in the manufacture of the interference filter. This estimate of uniformity covers an area of 0.05 in × 0.01 in.

8.2.2 Integrated Spectral Response

The within-band spectral response specification also requires an integrated spectral response, between the 10% response points for the individual elements, to be within 10%, i.e., the range from greatest to least integrated response for the elements can be no more than 10% of the value of the average integrated response. Measurements of individual SeaWiFS channels with the SBRC integrating sphere have shown that the output from the individual detectors in each band corresponds at the 1% level. That is, the integrated response of the detectors agrees at the 1% level. Of course, the output from each channel has been adjusted (or rather, the values of the resistors in the operational amplifiers have been adjusted) to give uniformity at the 1% level.

In general, switching from detector to detector in a SeaWiFS band will give a change in output from the instrument on the order of 1%—considerably better than the 10% limit in the specification. This 10% specification was included in the SeaWiFS specification, in case the design of the flight instrument included area arrays with many individual detectors.

9. BAND CO-REGISTRATION

9.1 Requirement

The IFOVs from all spectral bands shall be co-registered to within 0.3 pixel (1σ).

9.2 Compliance

The specification requires that the IFOVs from all spectral bands be co-registered within 0.3 pixel. From the field-of-view calculations in Section 2 above, it was determined that the IFOV for the instrument is 1.6 mrad on a side. The band-to-band registration results presented here are based on the along-scan and along-track line spread functions in Section 2. The line spread measurements were made by moving a narrow slit across the field-of-view of the nadir SeaWiFS pixel. The slit was part of a collimated light source, and the slit was moved in increments

Table 10. Reference wavelengths for one percent response point calculations. All values are in nanometers.

Band No.	*Left* 1% Point	*Left* 50% Point	Center Wavelength	*Right* 50% Point	*Right* 1% Point
1	395.2	403.4	413.4	423.4	433.6
2	424.1	434.2	444.0	453.8	463.7
3	470.7	480.8	491.1	501.4	511.7
4	488.1	498.9	510.1	521.3	530.7
5	536.3	545.4	554.6	563.8	577.2
6	646.7	658.3	668.2	678.1	692.5
7	727.3	744.4	764.6	784.9	813.4
8	826.4	845.5	866.1	886.7	907.5

Table 11. One percent response point calculations. The specifications call for a ratio to the bandwidth that is less than 150%. The bandwidths were previously given in Table 7.

Band No.	Bandwidth [nm]	Left 1% from Left 50% [nm]	Percent of Bandwidth	Right 1% from Right 50% [nm]	Percent of Bandwidth
1	20.0	8.2	41	10.2	51
2	19.6	10.1	52	9.9	50
3	20.6	10.1	49	10.3	50
4	22.4	10.8	48	9.4	42
5	18.4	9.1	50	13.4	73
6	19.8	11.6	59	14.4	73
7	40.5	17.1	42	28.5	70
8	41.2	20.1	49	20.8	50

(ticks) equal to a 0.1 mrad angular displacement as seen by the instrument. The center for each pixel (in ticks) was calculated as the average of the positions of the two half maximum points for each band. The along-scan and along-track centers were calculated independently. The absolute values for the central positions (in ticks) are not important in these results—it is the relative locations of the central points that are relevant here. Table 12 gives the along-scan results. Table 13 gives the along-track results. Figure 5 shows the results relative to the average for the set of band centers, and also shows the locations of the eight band centers in two dimensions. Figure 5 also includes a square 0.1 pixel wide, centered on the average band center. The maximum distance between band centers in the along-scan direction is 0.15 pixels, and the maximum distance along-track is 0.21 pixels. The instrument's spectral band-to-band registration is significantly better than the requirements of the specifications.

10. SENSITIVITY

10.1 Requirement

Table 14 provides the signal-to-noise ratio (SNR) specifications for all bands at a gain value of unity. The required SNR shall be achieved at the typical spectral radiance levels (L_{typical}). NEdL may be calculated from the expression: NEdL= L_{typical}/SNR.

10.2 Compliance

The noise in the SeaWiFS instrument was measured by viewing the SBRC integrating sphere. The SNR was calculated by determining the mean and the standard deviation in a 21 pixel-long section of the scan of the sphere's center. These measured results are listed in Table 14. The measurements were made close to, but not at, the exact typical radiance levels required by the specifications. The results have been scaled to the typical levels by changing the SNRs, assuming that the noise in the measurement varies as the square root of the change in signal level over this small range. These measured SNRs exceed the requirements of the specifications. However, the SNR measurements include the non-uniformity in the output of the sphere. This additional variation makes the measured values lower than the actual SNRs.

SBRC has provided a calculation of the SNRs, based on the noise in the dark output from the instrument. These calculated values are also listed in Table 14. For purposes of evaluation, it seems reasonable to assume that the actual SNRs for SeaWiFS fall between the measured and calculated SNRs in Table 14. In all cases, however, the measured values (the lower limits for the actual SNRs) are better than the requirements in the specifications. Section 19 describes the model for instrument noise devised by the Project. The SNRs from this model fall between the measured and calculated values in Table 14. For the review

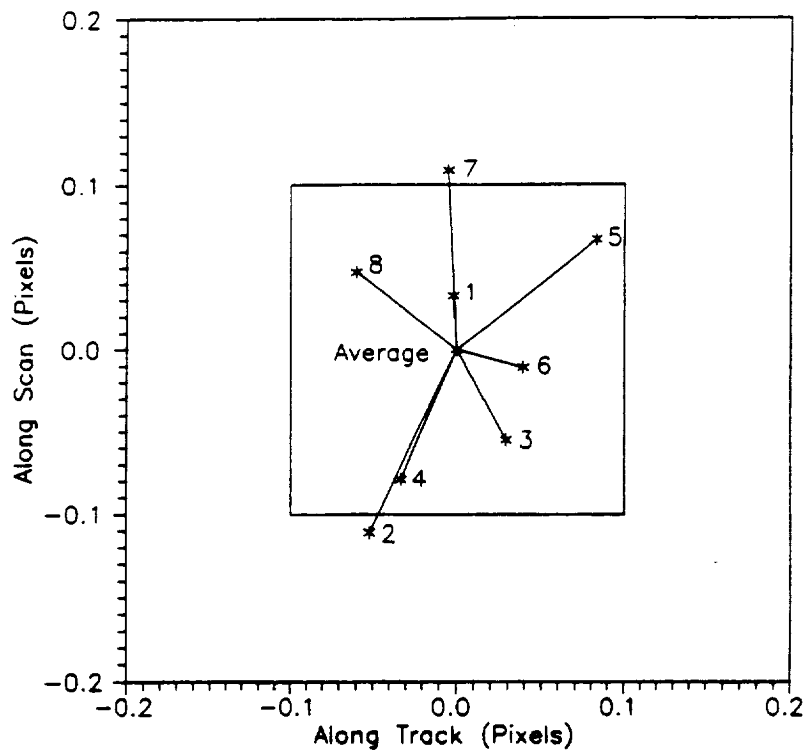

Fig. 5. Band-to-band registration of SeaWiFS. The locations of the individual band centers are given relative to the average for the eight bands. The distances are given in "pixels," where 1 pixel equals 1.6 mrad. The figure also includes a square that is 0.1 pixel on each side and which is centered on the average center location for the eight bands.

panel, the results in Section 19 give the best prelaunch estimates of the SNRs for the instrument at the L_{typical} radiances. However, those values remain prelaunch estimates. An extensive set of on-orbit measurements (McClain et al. 1992 and Woodward et al. 1993) will be used to obtain an improved set of SNRs.

Table 12. Along-scan band center measurements. The measurements were made in ticks, with each tick equal to 0.1 mrad. The results are also given in mrad and in pixels, where one pixel is 1.6 mrad. The range gives the distance between the two bands that are farthest apart.

Band No.	Center Position [ticks]	Distance from center [mrad]	Distance from center [pixel]
1	57.56	−0.003	−0.002
2	56.71	−0.088	−0.055
3	58.08	0.049	0.031
4	57.03	−0.056	−0.035
5	59.00	0.141	0.088
6	58.26	0.066	0.041
7	57.52	−0.008	−0.005
8	56.58	−0.101	−0.063
Range	2.42	0.242	0.151

Table 13. Along-track band center measurements. The same procedure used to obtain the measured values in Table 12 was employed here.

Band No.	Center Position [ticks]	Distance from center [mrad]	Distance from center [pixel]
1	22.50	0.050	0.031
2	20.29	−0.170	−0.106
3	21.15	−0.085	−0.053
4	20.78	−0.121	−0.076
5	23.02	0.103	0.064
6	21.83	−0.016	−0.010
7	23.67	0.167	0.104
8	22.73	0.073	0.046
Range	3.37	0.337	0.210

11. POLARIZATION

11.1 Requirement

The radiometric data shall be nominally insensitive to linear polarization. The polarization factor (PF) as defined below, shall be no greater than 2% over scan angles from +45° to −45° for all bands and tilt angles between −20° and +20°. $I_{\max}$ and $I_{\min}$ are the recorded maximum and minimum output when the plane of incoming 100% linearly polarized light is rotated through 180°.

$$PF = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} < 0.020 \qquad (2)$$

Table 14. SNRs for the SeaWiFS Bands.

Band No.	Specified SNR	Measured SNR	Calculated SNR
1	499	940	1107
2	674	950	1269
3	667	1156	1402
4	640	1055	1373
5	596	690	1242
6	442	798	846
7	455	860	971
8	467	670	796

11.2 Compliance

Polarization is defined in this requirement in terms of the difference from the average for the output range. This definition then gives a polarization value that is half of the difference between the maximum output and the minimum output. The polarization sensitivity of SeaWiFS was checked using two linear sheet polarizers, at different times, between the light source and the instrument. The first polarizer (Polaroid HR) checked bands 1–6, and the second (Polaroid HN) checked the two near infrared (IR) bands—bands 7 and 8. Changes in the output of the instrument during these tests included variations in the light through the polarizers as well as polarization dependent changes in the output of the instrument itself. The variation in light through the polarizer is an artifact of the measurement procedure, since the rotation axis for the polarizer is not located at the center of the input aperture of the instrument. Crossed polarizers showed good extinction for each band, indicating that the polarizers were creating polarized light.

Using knowledge of the expected angular dependence of the polarization effect, an effort was made to separate the instrument's portion of the polarization pattern. The polarization measurements were made by rotating each polarizer through 360° in 22.5° increments. Since polarization changes from a minimum to a maximum in 90°, the response of the instrument should show two cycles, i.e., two maxima and two minima, in the 360° rotation. Fourier analysis was used to look for the expected two cycle sinusoidal function in the polarization results.

The data were taken at 16 angles, from an arbitrarily determined zero, through 360°, back to the original angular zero. The two measurements at 0° were averaged to give a data set with 15 points from 0 to 337.5°. From the Fourier transform of these data, sinusoidal waveforms with 1–9 cycles per 360° were extracted for analysis. The data for band 1 are shown in Fig. 6. These data are representative of the results for bands 1–6. The input data show a dominant signal of 1 cycle per 360° and show an average value of 100. This allows a direct conversion of the average-to-peak values from the Fourier analyses into percentages.

The results of the Fourier analysis are summarized in Table 15. They are given in terms of the average-to-peak values for the input to the Fourier transforms, for the one-cycle component, and for the two-cycle component. It is the two-cycle component that contains the information about the polarization of the instrument. Since the average value for the measurements is 100, the average-to-peak values translate directly into percentages.

As shown in Table 15, the one-cycle Fourier component accounts for almost half of the average-to-peak signal in the data from bands 1–6. In the judgement of the review panel, the majority of the observed variation in the measurements of these bands does not come from polarization sensitivity in the SeaWiFS instrument. Presumably, the bulk of the variability derives from a non-uniformity in the polarizer plate used in the measurements. The effects of the polarizer plate repeat for each of the 6 bands for which the polarizer plate was used. The polarization in the SeaWiFS instrument for these bands is less than 0.25%.

Table 15. Summary of polarization results. The values in columns 3–5 are average-to-peak values, expressed as percentages.

Band No.	Input to Transform	One-Cycle Output	Two-Cycle Output
1	1.90	0.96	0.15
2	1.10	0.53	0.09
3	0.90	0.30	0.11
4	0.60	0.22	0.08
5	1.10	0.39	0.20
6	1.00	0.43	0.14
7	0.90	0.01	0.26
8	1.10	0.05	0.35

The test results for bands 7 and 8 show a pattern that is similar for the two bands (see Fig. 7 for band 7). However, the pattern is noticeably different from the pattern for bands 1–6. Of course, bands 7 and 8 used the same polarizer plate, a different polarizer plate than the one used for measurements on bands 1–6. The patterns for bands 7 and 8 show essentially no one-cycle component. In addition, the two-cycle component in the pattern is somewhat larger than for bands 1–6, falling between 0.25% and 0.35%. No instrument based explanation can explain why the polarization in SeaWiFS for bands 7 and 8 should be different from that for the other 6 bands. For this reason, a large part of the two-cycle Fourier component for bands 7 and 8 appears to be an artifact caused by variations in the polarizer plate for these bands. This assumption explains the similarity in the angular pattern for the measurements on bands 7 and 8, in the same manner that it explains the similarity in the patterns for bands 1–6.

Thus, for all eight SeaWiFS bands, the polarization in the instrument is estimated to be less than 0.25%.

12. DYNAMIC RANGE

12.1 Requirement

The sensor shall be designed to operate over a dynamic range that extends from the noise floor (NEdL) in each spectral band to the maximum levels (L_{cloud}) given in Table 18. (There is an amendment to the Contract. With this addition, there are 3 radiance levels in the specifications: saturation radiance, maximum ocean radiance, and maximum cloud radiance. The specification radiances are given in Tables 16, 17, and 18, respectively.)

12.2 Compliance

The specification, which gives the saturation levels for the eight SeaWiFS band, was supplemented by an amendment to the contract in August 1993. The amendment provides the maximum ocean radiances and the maximum cloud radiances for the instrument. These changes to the specifications were required due to the use of bilinear gains in SeaWiFS. However, the saturation values from the original specification remain an important part of the SeaWiFS measurements. The saturation values are the maximum radiances that the SeaWiFS bands would provide if the *knees* the point where the radiance vs. counts slope changes) in the bilinear gains are ignored. The saturation values *define the sensitivity of SeaWiFS*, in counts per unit radiance, for the instrument's ocean measurements.

In summary, the saturation radiances define the sensitivities of the SeaWiFS bands for ocean measurements, i.e., for measurements below the knees of the bilinear gains. The maximum ocean radiances are the radiances at the knees for the eight bands. The maximum cloud radiances are the greatest values that the SeaWiFS bands will measure. With the addition of the "maximum ocean" and the "maximum cloud" radiances to the specifications in the contract amendment, the term "saturation" radiance has become a misnomer. However, the term has been retained here.

Table 16 gives the saturation radiances from the SeaWiFS calibration (ignoring the bilinear gain knees). Table 17 gives the maximum ocean radiances, and Table 18 gives the maximum cloud radiances. All radiances are calculated in terms of milliwatts per square centimeter per micrometer per steradian ($\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$). The differences from the specifications are also calculated. They are small, and present no problem with regard to specification compliance.

13. QUANTIZATION

13.1 Requirement

Data shall be quantized at 10 bits. The differential linearity of the quantizer(s) shall be better than one-half a least significant bit.

13.2 Compliance

The data from SeaWiFS are quantized at 10 bits. The data from each detector in each band are digitized with 12-bit analog-to-digital (A/D) converters. For 4-to-1 Time Delay and Integration (TDI), the 12-bit values from each detector are summed to give a 14-bit value. The bottom four bits from this output are removed, with the upper 10 bits sent to SeaStar. Measurements by the instrument manufacturer (SBRC), using a voltage ramp, show linearity at better than one-half of the least significant bit of the output 10 bits. This procedure was relatively easy, since the least significant bit for each detector corresponds to four times the least significant bit in the A/D converters, themselves.

14. MTF

14.1 Requirement

The MTF of the data shall equal or exceed the values tabulated in Table 19 below, in both the along-track and cross-track directions for a sine wave input. The Nyquist frequency† has a spatial period equal to two IFOVs on the ground.

The MTF specifications shall be satisfied for modulations between dark and L_{typical} and between dark and L_{max}, for every detector element in each spectral band. Data describing the MTF shall be provided from prelaunch testing to verify that the specification is met. Data from lunar views and/or internal stabilized sources will also be provided for analysis of the MTF on orbit.

14.2 Compliance

The SeaWiFS MTFs are calculated from the line spread functions in Fig. 1. They consist of the Fourier transforms of the line spread functions. The results in Table 20, below, use the MTF calculation program provided by SBRC. The values in the specification give minimum amplitudes for several low frequency sinusoidal waves from the Fourier analysis. The waves are given in terms of their wavelengths relative to the width (FWHM) of the field-of-view, i.e., in cycles per pixel.

† The Nyquist frequency is the minimum sampling frequency of a digital system sufficient to reconstruct the original information. For SeaWiFS, the original information is the input sequence of radiances.

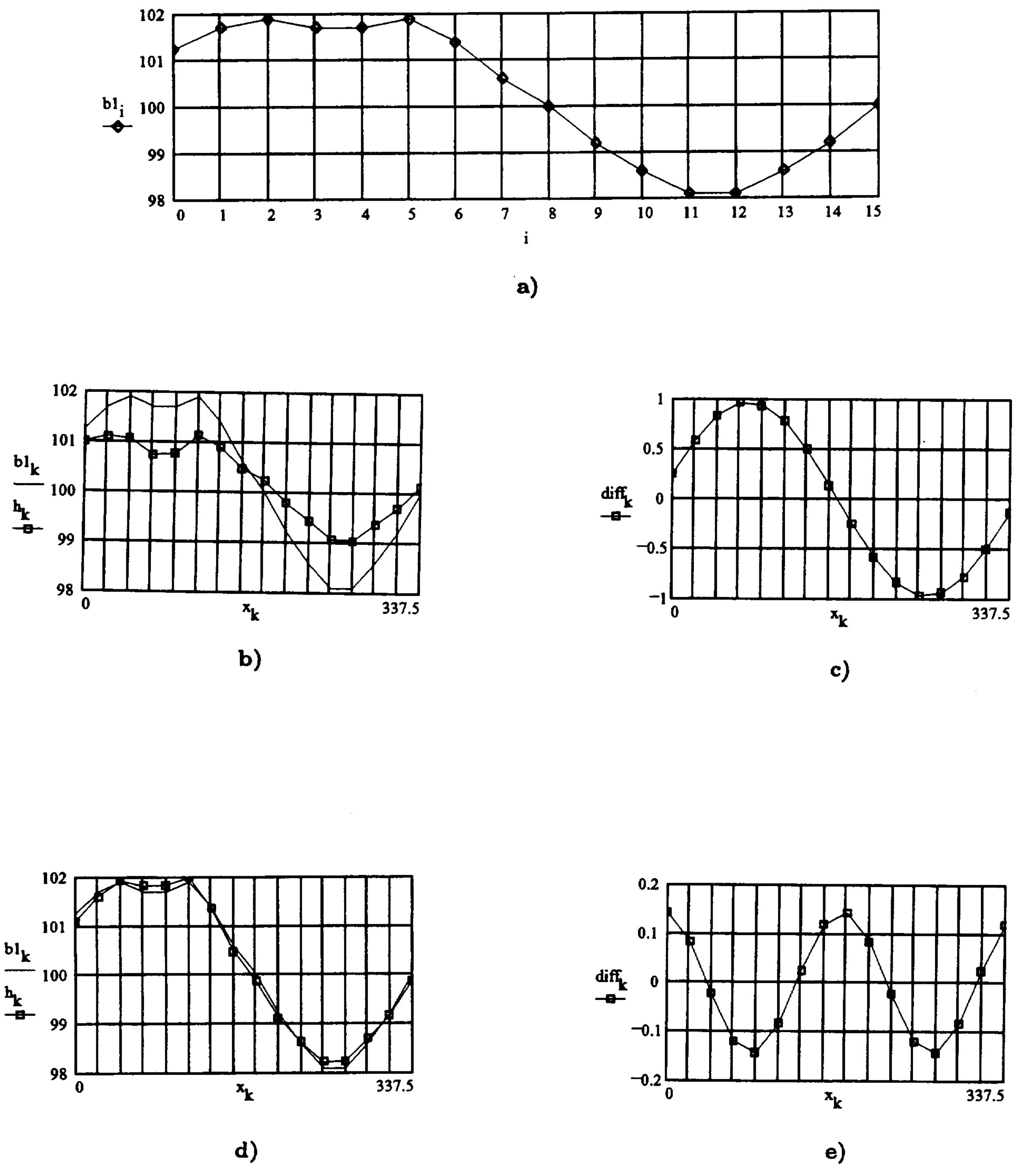

Fig. 6. Polarization measurements for SeaWiFS band 1. **a)** The instrument response measured at 22.5° increments of polarizer rotation. These values are the input values for Fourier analysis. **b)** The polarization values with and without the one-cycle component $b1(k)$ equal the measured values, and $h(k)$ equal the measured values without the one-cycle component. **c)** The one-cycle polarization component generated by Fourier analysis. **d)** The polarization values with and without the two-cycle component $b1(k)$ equal the measured values and $h(k)$ equal the measured values without the two-cycle component. **e)** The two-cycle polarization component generated by Fourier analysis.

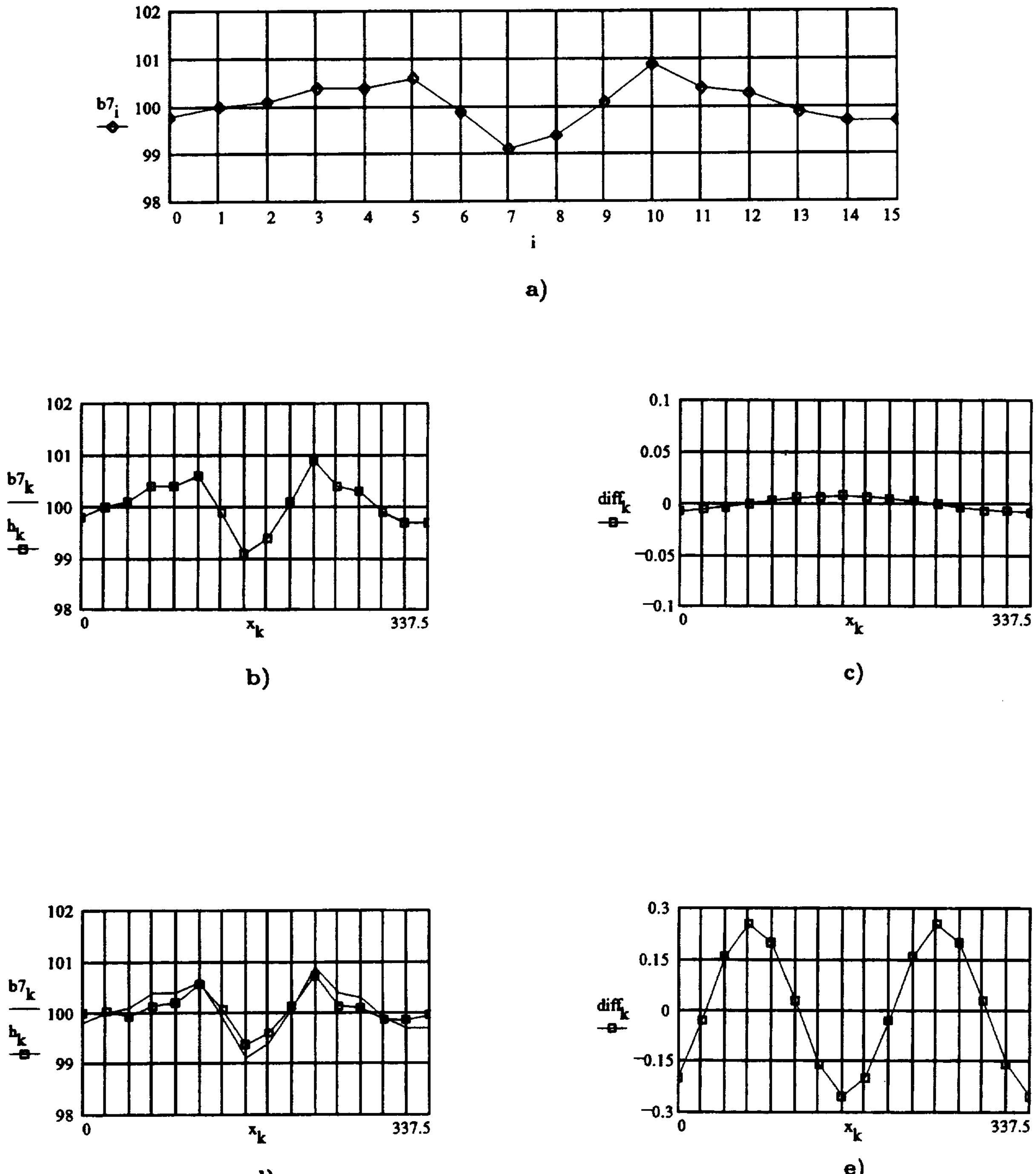

Fig. 7. Polarization measurements for SeaWiFS band 7. **a)** The instrument response measured at 22.5° increments of polarizer rotation. These values are the input values for Fourier analysis. **b)** The polarization values with and without the one-cycle component $b7(k)$ equal the measured values, and $h(k)$ equal the measured values without the one-cycle component. **c)** The one-cycle polarization component generated by Fourier analysis. **d)** The polarization values with and without the two-cycle component $b7(k)$ equal the measured values and $h(k)$ equal the measured values without the two-cycle component. **e)** The two-cycle polarization component generated by Fourier analysis.

Table 16. SeaWiFS saturation radiances (in $\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$). The measured and specified saturation radiances appear in columns 3 and 4, respectively.

Band No.	Gain	Measured Radiance	Specified Radiance	Percent Difference
1	1	13.76	13.63	1.0
2	1	13.44	13.25	1.4
3	1	10.52	10.50	0.2
4	1	9.22	9.08	1.5
5	1	7.47	7.44	0.4
6	1	4.25	4.20	1.3
7	1	3.02	3.00	0.5
8	1	2.15	2.13	1.0
			Average % Difference	0.9
			Greatest % Difference	1.5
			Least % Difference	0.2

Table 17. SeaWiFS maximum ocean radiances (in $\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$). The measured and specified ocean radiances appear in columns 3 and 4, respectively.

Band No.	Gain	Measured Radiance	Specified Radiance	Percent Difference
1	1	10.90	10.84	0.5
2	1	10.56	10.46	0.9
3	1	8.18	8.19	−0.1
4	1	7.16	7.05	1.6
5	1	5.74	5.74	0.0
6	1	3.25	3.21	1.2
7	1	2.29	2.29	0.0
8	1	1.64	1.62	1.0
			Average % Difference	0.6
			Greatest % Difference	1.6
			Least % Difference	−0.1

Table 18. SeaWiFS maximum cloud radiances (in $\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$). The measured and specified cloud radiances appear in columns 3 and 4, respectively.

Band No.	Gain	Measured Radiance	Specified Radiance	Percent Difference
1	1	60.16	60.02	0.2
2	1	67.91	66.24	2.5
3	1	68.21	68.17	0.1
4	1	66.47	65.62	1.3
5	1	64.97	65.16	−0.3
6	1	54.93	53.78	2.1
7	1	42.98	42.95	0.1
8	1	34.38	34.05	1.0
			Average % Difference	0.9
			Greatest % Difference	2.5
			Least % Difference	−0.3

The MTF gives an idea of the response of the instrument to variations in the input radiance, both along-scan and along-track. For example, consider a case in which the instrument scans across a scene with a variation of the input radiance having a sinusoidal shape and a spatial period of two pixels per period. In this case, the scene varies at the Nyquist frequency. According to the specification, the output from the sensor should show a variation (from pixel to pixel) across the scene that is greater than 30% of the amplitude of input sinusoidal radiance variation.

Table 19. MTF requirements for spatial resolution.

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

15. GAINS

15.1 Requirement

Band independent gains shall be provided, which are commandable band by band, and which will increase or decrease sensitivity according to the following:

$$S_n = G_n \times S_i \qquad (3)$$

where S_i and S_n are the initial detector signal and the signal with gain, respectively, and G_n is the gain factor at gain setting n. The nominal G_n values for gain settings of n equal to 2, 3, and 4 shall be based on the values in Table 21. These G values include those required for on-board solar and lunar capabilities. The values of G will be within 5% of the specifications in Table 21, and shall be known relative to $G_1 = 1$ with an accuracy of greater than 99.5%. The nominal G_n value for $n = 2$ is 2.

15.2 Compliance

Gain values for gain settings 3 and 4 were re-evaluated in the summer of 1993 during a meeting at OSC. Gains 3 and 4 are used for solar and lunar measurements. The SCADP contains the predicted on-orbit lunar and solar diffuser radiances. They have been derived from ground based solar and lunar measurements at SBRC (Biggar et al. 1993). The values presented in Table 21, below, are appropriate for those radiances. The gains are given for a 4:1 TDI.

These relative gain values can be measured on orbit. Current plans will have these values checked twice a day at the start of the mission.

16. TRANSIENT RESPONSE

16.1 Requirement

Radiometric data should be relatively free of effects of overshoot and ringing when the IFOV scans across a steep gradient in radiance, from a maximum radiance of L_{cloud} to a minimum radiance of L_{typical}. For this radiance step change, the output signal shall settle to within 0.5% of its final value within 10 IFOVs.

16.2 Compliance

16.2.1 Original Specification

The original SeaWiFS specification describes the required response of the instrument when it scans across a steep gradient in radiance. The specification describes a gradient that is expected be found on orbit, i.e., from the radiance level for a cloud (L_{cloud}) to the typical radiance level for ocean measurements (L_{typical}). The original specification requires that the output from the instrument settles to within 0.5% of its final value (L_{typical}) within 10 pixels. This limit, calculated in counts using values from the specifications, is given in Table 22. Since the values are small, the limit is given to 0.1 count relative to the quantization of the data.

During the April 1993 SeaWiFS Pre-Ship Review, it was determined that the instrument did not meet the original bright target recovery (BTR) specification. At that time, it was decided that the instrument manufacturer would rework SeaWiFS to improve its stray light characteristics. The series of modifications included the tilting of filters, incorporation of bilinear responses and corresponding changes to gains, refiguring the polarization scrambler, and testing. The modifications did not include changes to the instrument's focal planes. A description of the revised BTR specification is given in the following section. The discussion presented here centers on the performance of the reworked SeaWiFS radiometer only with respect to the original specifications.

The results in Table 23 were derived from laboratory measurements using the output of the SBRC integrating sphere. The measurements were made in four sets—one for each focal plane in the instrument. Color glass filters were placed over the output from the sphere in order to give a spectral shape which approximated the sun over the wavelength range of the bands on each of the four focal planes. Cross-talk between bands on a focal plane is a significant factor in the recovery of the instrument from bright targets. The measurements were made for a three pixel wide slit.

The results in Table 23 give the distance, in pixels, required for the instrument to settle to less than 0.5% of L_{typical}, using the counts given in Table 22. For bands 1–5, the results give the pixels required to settle to 3 counts

Table 20. MTF calculations for SeaWiFS. The amplitude is shown for each band at four different wavelengths: 0.500, 0.375, 0.250, and 0.125 cycles per pixel.

Band	*Along-Scan MTF Amplitude*				*Along-Track MTF Amplitude*			
No.	0.500	0.375	0.250	0.125	0.500	0.375	0.250	0.125
1	0.35	0.57	0.76	0.93	0.44	0.65	0.84	0.96
2	0.36	0.58	0.76	0.92	0.41	0.62	0.81	0.95
3	0.36	0.58	0.77	0.93	0.41	0.62	0.82	0.95
4	0.36	0.58	0.77	0.93	0.40	0.61	0.81	0.95
5	0.35	0.57	0.76	0.93	0.48	0.67	0.84	0.96
6	0.37	0.59	0.78	0.93	0.43	0.63	0.82	0.95
7	0.39	0.61	0.79	0.94	0.49	0.68	0.85	0.96
8	0.34	0.55	0.74	0.91	0.47	0.66	0.83	0.96
Minimum Amplitude	0.30	0.50	0.70	0.90	0.30	0.50	0.70	0.90

above background. For bands 6–8, the results give the pixels required to settle to 2 counts. Table 23 also gives the number of pixels required for the instrument to settle to zero counts after illumination by the slit. All eight bands settle to less than the specification limit within 10 pixels.

Table 21. SeaWiFS gain values. These values are given relative to gain 1. The nominal value for gain setting 2 is 2.

Band No.	G_1	G_2	G_3	G_4
1	1	1.931	1.302	1.642
2	1	1.940	1.303	1.648
3	1	1.951	0.900	1.655
4	1	1.955	0.796	1.658
5	1	1.961	0.652	1.579
6	1	1.969	0.376	0.671
7	1	1.969	0.323	0.583
8	1	1.975	0.272	0.507

16.2.2 Revised BTR Specification

In the summer of 1993, there was a meeting at OSC in Chantilly, Virginia. At that meeting, a set of improvements to ameliorate stray light in SeaWiFS was discussed. Each proposed improvement was presented, accompanied by a corresponding estimate of the resulting improvement to performance of the instrument. A final and accepted set of instrument improvements from that meeting was incorporated into a Contract modification. As demonstrated by SBRC testing, this set of modifications has created the anticipated improvements to the performance of the sensor. However, as described above, the reworked SeaWiFS radiometer also meets the original BTR specifications.

17. ABSOLUTE ACCURACY

17.1 Requirement

An absolute radiometric accuracy of 5% ($1\,\sigma$) shall be achieved at the typical spectral radiance levels. At spectral radiances between 0.2 L_{typical} and 0.9 L_{max}, the absolute radiometric accuracy shall be within ±6%. Measurements of the accuracy shall be made, as a minimum, at scan angles centered at 0°, −40°, and +40°; tilt angles of 0°, −20°, and +20°; special tilt angles, should they be required, used to view the moon; and at all gains.

17.2 Compliance

17.2.1 Accuracy at Nadir

This specification calls for an absolute radiometric calibration at the 5% level. The SeaWiFS instrument was calibrated radiometrically by the manufacturer (SBRC) using an integrating sphere that was calibrated with standards that are traceable to the National Institute of Standards and Technology (NIST). In addition, the SBRC sphere has been compared with the GSFC sphere, which has also been calibrated using standards traceable to NIST. The comparison of the GSFC and SBRC spheres showed agreement at the 2% level.

Fundamentally, the accuracy of the radiometric calibration of SeaWiFS reduces to the accuracy of the calibration of the integrating sphere. The absolute uncertainty in the radiances from the sphere is the largest of the set of uncertainties in the instrument calibration. In addition, many uncertainties in the radiometric calibration of SeaWiFS, such as the alignment of the sphere and the instrument, duplicate uncertainties in the calibration of the sphere, such as the alignment of the sphere, the radiance standard, and the transfer instrument.

The current understanding of the uncertainties in the calibration of the GSFC sphere is reported by Walker et al. (1991). Two of the authors specialize in radiometric calibrations at NIST, and the third author is the principal investigator for the GSFC sphere. In the abstract, Walker et al. (1991) states: "Recent measurements performed at NIST and NASA Goddard Space Flight Center have demonstrated that the uncertainty of sphere-source radiance measurements can be improved from the present

Table 22. Constants used in the calculation of the specification count limit. The L_{cloud} and $L_{typical}$ values come from the performance specifications. The slopes (or sensitivities for each band) come from the SBRC calibration data.

Band No.	L_{cloud} [$mW\,cm^{-2}\mu m^{-1}sr^{-1}$]	$L_{typical}$ [$mW\,cm^{-2}\mu m^{-1}sr^{-1}$]	$\frac{L_{cloud}}{L_{typical}}$	Radiance per Count	0.5% of $L_{typical}$ [counts]
1	60.0	9.10	6.59	0.0137	3.3
2	66.2	8.41	7.87	0.0134	3.1
3	68.2	6.56	10.4	0.0105	3.1
4	65.6	5.64	11.6	0.00920	3.1
5	65.2	4.57	14.3	0.00746	3.1
6	53.8	2.46	21.9	0.00425	2.9
7	43.0	1.61	26.7	0.00301	2.7
8	34.0	1.09	31.2	0.00215	2.5

5–10% level to a 1–2% level." This is a general statement about the technique for calibrating sphere sources. However, it does not describe the actual uncertainty in radiances from the GSFC sphere.

Table 23. This table shows the SeaWiFS BTR characteristics. Column 2 gives the value of 0.5% of $L_{typical}$, in counts, for each band. The instrument response must settle below this level of residual counts after scanning a bright target. Column 3 shows the number of pixels after the slit required for the instrument to settle to the level of the specified residual counts. Column 4 provides the number of pixels the instrument requires to settle to a level of zero residual counts.

Band No.	Residual Cnts. (0.5% $L_{typical}$)	Pixels to Spec.	Pixels to Zero Cnts.
1	3.3	6	10
2	3.1	5	9
3	3.1	7	10
4	3.1	5	15
5	3.1	9	15
6	2.9	7	9
7	2.7	9	11
8	2.5	7	10

At the conclusion of the report, Walker et al. (1991) states: "The normal stated uncertainty for the NASA calibration of their large-area sphere source is presently 5–10%. The repeatability of the calibration from month to month is about 1 percent. The major contributors to NASA's large overall uncertainty are the uncertainties associated with the standard lamp, the dimensions of the apertures, the distance measurement, the alignment, and the lamp current of the sphere source lamps. The results of our measurements confirmed the accuracy of the spectral irradiance method employed by NASA, and in the future it will permit them to state uncertainties in the range of 1–2%. The reason for the difference in NASA's independent check method has not been determined. More work will have to be done if this problem is to be resolved."

Recent discussions indicate that error propagation in NASA's independent check method has not changed. The discrepancy between the NASA 5–10% error estimate and the 1–2% estimate in Walker et al. (1991) remains unresolved. This assessment has led to the conclusion that the uncertainty in the radiances from the GSFC sphere is in the range of 2–5%. This conclusion is nothing more than an educated guess. If the 2–5% uncertainty in the GSFC sphere is correct, and if the GSFC and SBRC spheres agree at the 2% level, then the estimate of the uncertainty in the SBRC sphere is 2–5%. This is also the review panel's estimate for the uncertainty in the calibration of SeaWiFS.

17.2.2 Accuracy Over a Scan Line

These measurements were made at nadir. The specifications also call for a 5% accuracy at scan angles of +40° and −40°. SBRC has made measurements to check the output of the instrument at scan angles 20°, 40°, and 58° on both sides of nadir. The results of the measurements at these angles give the instrument output relative to the output at nadir; this effect is called *scan modulation*. A fitted curve to the scan modulation gives a correction that is good to 0.5% at all scan angles. This correction has been incorporated into the data reduction procedures for SeaWiFS. The absolute radiometric calibration of the instrument remains within 5% over its entire scan range.

17.2.3 Accuracy Over Tilt Angles

The specification calls for the radiometric calibration to be known at all tilt angles. For SeaWiFS, the entire scanner tilts, including all components from the optical inlet to the focal planes. The optical path through the instrument does not change as a function of tilt angle. Tilt angle is not considered a factor in the radiometric accuracy of SeaWiFS.

18. RELATIVE ACCURACY

18.1 Requirement

The design shall be capable of achieving an accuracy within 2% (1σ) relative to the sun. The calibrated data shall be linear to within ±1% over the full range of input signals.

18.2 Compliance

18.2.1 Accuracy Relative to the Sun

The instrument shall be capable of achieving an accuracy, within 2%, relative to the sun. SBRC has made field measurements of the solar flux in March 1993 and in October 1993. Atmospheric transmission measurements for these two field measurements were made by the University of Arizona (Biggar et al. 1993). The differences in the predicted on-orbit solar measurements from these two field tests averaged 1.5%. The greatest difference was 3.6% in band 8. These field measurements include uncertainties in the measurement of the atmospheric transmission that may amount to 2 or 3%. The field test results also show a consistency in the SeaWiFS solar measurements at the 2-3% level. However, with the error source of atmospheric transmission, ground based measurements cannot confirm an accuracy of 2% in the SeaWiFS solar measurements. They do, however, give some confidence that the instrument is capable of that accuracy.

18.2.2 Linearity

18.2.2.1 February 1993 Measurements

The measurements presented here were made in February 1993. They were taken during the radiometric calibration of the instrument. The radiance measurements were made at eight light levels to cover the radiance ranges of the SeaWiFS bands. The results from those measurements are given as the averages of 25 individual measurements for each band (see Table 24). Due to the spectral shape of the light from the integrating sphere, only SeaWiFS band 1, at 412 nm, produced output that did not saturate at any of the radiance levels. For SeaWiFS band 2, light level 1 caused the output to saturate. For that band and that light level, the band produced only its maximum digital output. For band 3, two of the radiance levels caused the band to saturate. This sequence continued up to band 8, which saturated for seven of the eight light levels. However, this final light level was sufficient for the radiometric calibration of band 8.

Table 24 gives the sensitivity for SeaWiFS bands 1–4 at each light level. It is the consistency of the instrument's sensitivity with light level that is required by the specifications. To check this sensitivity, the difference (in percent) of the sensitivity at each light level from the average sensitivity for the band was calculated. These differences should be less than 1%. Except for one outlier in each band, all differences are observed to be less than 1%. For light level 7, each band shows the sensitivity to be between 1.4% and 1.9% higher than the other levels. The review panel feels that this discrepancy does not come from the instrument, but from the calibration of the integrating sphere. It occurs at one light level, and it is present in all bands.

With the knowledge of this discrepancy, the average values for the bands in Table 24 have been calculated without the sensitivity for light level 7. The inclusion of this light level skews the results for the remaining measurements. In addition, it is interesting to note that the linearity of the SeaWiFS measurements is sufficiently good to reveal a 1.5–2.0% inconsistency in the calibration of the integrating sphere. It should also be noted that the consistency of the calibration of the sphere is an integral part of the linearity measurement.

18.2.2.2 November 1993 Measurements

Although not reported in the SCADP, a set of linearity measurements was made by SBRC for the eight SeaWiFS bands in November 1993. The results of these measurements are given in Table 25. The sensitivity of each band is presented in the table at three radiance levels, approximating L_{typical}, two-thirds L_{typical}, and one-third L_{typical}. The least linear of the bands in Table 25 is band 2, with differences of 1.2% and 1.3% from the average sensitivity. As discussed above, the consistency in the calibration of the sphere is a fundamental part of these results. The review panel feels that imprecision in the repeatability of the SBRC integrating sphere output has created a substantial portion of these differences. The repeatability of band 2 from the February 1993 measurements in Table 24 is significantly better than that in Table 25. As a result, the review panel concludes that the linearities of the eight SeaWiFS bands meet specification.

The results in Table 24 also indicate that the response of the SeaWiFS bands are linear at low radiance levels. As shown for bands 1 and 2 in Table 24, the response of the instrument is linear for radiance levels corresponding to output from 15–50 counts.

Table 24 lists only the results for SeaWiFS bands 1–4. The results for the other four bands are consistent with those presented here, at least to the extend that they can be checked. For band 8 in particular, it is difficult to check linearity using one point only.

19.0 SYSTEM NOISE

19.1 Requirement

The SNR shall be determined for all bands at a sufficient number of spectral radiance levels between 0.2 L_{typical}

Table 24. SeaWiFS radiometric measurements given for four SeaWiFS bands at eight light levels. The sensitivity for each band is calculated for each light level. The differences are the percent differences for the average sensitivity for each band. See text for details.

Band No.	Light Level	Counts	Offset	Net Counts	Radiance [$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	Sensitivity [radiance/count]	Difference [%]
1	1	842.77	21.76	821.01	11.80	0.014373	−0.1
	2	435.54	21.76	413.78	5.97	0.014428	0.3
	3	257.50	21.76	235.74	3.40	0.014423	0.3
	4	194.59	21.76	172.83	2.49	0.014407	0.2
	5	111.85	21.76	90.09	1.29	0.014319	−0.4
	6	54.03	21.76	32.27	0.46	0.014255	−0.9
	7	39.60	21.76	17.84	0.26	0.014574	1.4
	8	36.98	21.76	15.22	0.22	0.014455	0.5
					Average sensitivity	0.014380	
2	1	Band output saturates					
	2	710.43	19.46	690.97	9.56	0.013836	0.2
	3	413.26	19.46	393.80	5.45	0.013840	0.2
	4	308.19	19.46	288.73	3.99	0.013819	0.0
	5	170.34	19.46	150.88	2.08	0.013786	−0.2
	6	73.63	19.46	54.17	0.75	0.013845	0.2
	7	49.35	19.46	29.89	0.42	0.014052	1.7
	8	44.90	19.46	25.44	0.35	0.013758	−0.4
					Average sensitivity	0.013814	
3	1	Band output saturates					
	2	Band output saturates					
	3	872.75	21.05	851.70	9.28	0.010896	0.2
	4	646.69	21.05	625.64	6.80	0.010869	−0.0
	5	349.98	21.05	328.93	3.56	0.010823	−0.5
	6	139.07	21.05	118.02	1.28	0.010846	−0.3
	7	86.97	21.05	65.92	0.73	0.011074	1.8
	8	75.92	21.05	54.87	0.60	0.010935	0.6
					Average sensitivity	0.010874	
4	1	Band output saturates					
	2	Band output saturates					
	3	Band output saturates					
	4	897.99	20.80	877.19	8.19	0.009337	−0.3
	5	482.88	20.80	462.08	4.30	0.009306	−0.6
	6	186.47	20.80	165.67	1.55	0.009356	−0.1
	7	113.04	20.80	92.24	0.88	0.009540	1.9
	8	97.02	20.80	76.22	0.72	0.009446	0.9
					Average sensitivity	0.009361	

and 0.9 L_{max} to characterize the signal dependence of the system noise.

19.2 Compliance

The SNRs for the eight SeaWiFS bands have been measured near L_{typical}. These measurements were made using the SBRC integrating sphere. Uncertainties in the output of the sphere, both over the area of the output aperture and over short intervals of time, have caused a small (but significant) decrease in the SNRs from these measurements. SBRC has created a model of their instrument noise, based on dark noise measurements and on the electronic design of the instrument. These model-based SNRs are slightly higher than the measured values at L_{typical}, which is in agreement with the review panel's understanding of the measurements.

The SeaWiFS SNR model gives the calculated results

Table 25. SeaWiFS radiometric measurements given for all bands at three light levels. The differences are the percent differences from the average sensitivity for each band. These measurements were made in November 1993.

Band No.	Counts	Offset	Net Counts	Radiance [$\mathrm{mW\,cm^{-2}\mu\,m^{-1}sr^{-1}}$]	Sensitivity [radiance/count]	Difference [%]
1	695.60	20.84	674.76	9.246	0.013703	−0.5
	516.70	20.84	495.86	6.817	0.013748	−0.1
	268.60	20.84	247.76	3.432	0.013852	0.6
				Average sensitivity	0.013768	
2	701.30	18.00	683.30	9.122	0.013350	−1.3
	491.60	18.00	473.60	6.485	0.013693	1.2
	258.30	18.00	240.30	3.257	0.013554	0.2
				Average sensitivity	0.013532	
3	709.00	20.45	688.55	7.216	0.010480	−0.4
	503.80	20.45	483.35	5.076	0.010502	−0.2
	248.50	20.45	228.05	2.414	0.010585	0.6
				Average sensitivity	0.010522	
4	699.50	20.12	679.38	6.212	0.009144	−0.8
	480.30	20.12	460.18	4.223	0.009177	−0.5
	248.60	20.12	228.48	2.134	0.009340	1.3
				Average sensitivity	0.009220	
5	703.30	22.00	681.30	5.073	0.007446	−0.4
	527.60	22.00	505.60	3.791	0.007498	0.3
	281.40	22.00	259.40	1.940	0.007479	0.1
				Average sensitivity	0.007474	
6	590.60	23.10	567.50	2.427	0.004277	0.4
	450.90	23.10	427.80	1.835	0.004289	0.7
	195.70	23.10	172.60	0.727	0.004212	−1.1
				Average sensitivity	0.004259	
7	706.50	22.73	683.77	2.057	0.003008	0.8
	347.10	22.73	324.37	0.966	0.002978	−0.2
	209.60	22.73	186.87	0.555	0.002970	−0.5
				Average sensitivity	0.002985	
8	526.40	20.14	506.26	1.075	0.002123	−0.4
	365.50	20.14	345.36	0.734	0.002125	−0.3
	210.30	20.14	190.16	0.408	0.002146	0.7
				Average sensitivity	0.002131	

from the SBRC generated values for instrument noise. The SBRC results give the SNRs for the eight SeaWiFS bands at three radiance levels: L_{typical}, one-half L_{typical}, and one-quarter L_{typical}. The L_{typical} radiance levels are listed in Barnes and Holmes (1993). They are also given as part of Table 26. The prelaunch calibration coefficients used to convert the counts from the instrument into the measured radiance and vice versa are found in Table 6 of Barnes et al. (1994).

The model presented here gives the noise from each band, in counts, as a function of the number of counts in the measurement by that band. The noise values that form the basis for the model have been calculated from the counts and from their associated SNRs in the SCADP data. The counts of noise for one-quarter L_{typical} in bands 3 and 4 in the SBRC data were smaller than the accepted value for digitization noise (0.289 count). As a result, it was concluded that digitization noise had not been incorporated into the SBRC data. Digitization noise is included in the SeaWiFS noise model presented in Table 26. The addition of digitization noise to the model lowers the SNRs in the model's results. However, the model SNRs remain slightly higher than the measured results.

Noise values from the calibration data show a strong linear dependence with the measured counts. Based on this linear dependence, a noise value for each band has

Table 26. SNRs calculated from the SeaWiFS noise model. The noise model is a linear function of the counts from each SeaWiFS band. This model is given for the standard gain (gain 1) and the standard detector configuration (TDI 4) for the SeaWiFS ocean measurements. The noise values in the model incorporate digitization noise.

Band No.	$L_{typical}$ [$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	$L_{typical}$ [counts]	Noise Intercept [counts]	Noise Slope [counts/count]	Noise† [counts]	SNR at $L_{typical}$
1	9.10	638.4	0.420	0.0003528	0.645	990
2	8.41	618.2	0.372	0.0003141	0.566	1,091
3	6.56	613.0	0.348	0.0002875	0.524	1,170
4	5.64	612.2	0.352	0.0002928	0.531	1,152
5	4.57	607.1	0.375	0.0003178	0.568	1,069
6	2.46	584.9	0.510	0.0004083	0.749	781
7	1.61	531.6	0.424	0.0003674	0.619	859
8	1.09	513.5	0.494	0.0004144	0.707	726

† Noise at $L_{typical}$

been calculated for zero radiance. The noise model for SeaWiFS band 7 is shown in Fig. 8. The linear noise model for the eight SeaWiFS bands (intercepts and slopes) are given in Table 26. For the review panel, the SNRs in Table 26 give the best prelaunch estimates of the SNRs for the instrument at the $L_{typical}$ levels.

As part of the SCADP data, there is a complete scan line of data from the third outdoor field test on 1 November 1993. A description of the components of a solar scan line are given in Woodward et al. (1993). For three of the SeaWiFS bands, the solar diffuser measurements are made using gain 1. The results for these bands from the field test are given in Table 27. They are based on the average counts from 25 consecutive measurements across the diffuser. The noise values in Table 27 represent one standard deviation about each average. The linear model in Table 26 is used to convert those noise counts into the noise values at $L_{typical}$. The SNRs for bands 3, 4, and 5 in Table 27 compare favorably with those in Table 26.

Table 27. Measured SNRs from a SeaWiFS solar scan. For bands 3, 4, and 5, the solar diffuser measurements are made using gain 1. The noise model in Table 26 is used to convert the noise values from the measured count levels to those at $L_{typical}$. These SNRs compare favorably with those in Table 26.

Band No.	Average Counts	Noise [counts]	Noise† [counts]	SNR†
3	282.0	0.400	0.495	1,238
4	331.2	0.431	0.513	1,193
5	421.5	0.571	0.630	963

† At $L_{typical}$

For the review panel, the results from the solar scan indicate that there has been a problem with SBRC SNR measurements for band 5 (Section 10), the cause of which is undetermined. The SBRC measurements for the calibration data book (SNR of 690 for band 5) show the instrument to meet the specifications for that band. However, the measured results for band 5 in the SCADP data are also substantially lower than those from previous laboratory measurements by SBRC. The review panel feels that the value of 1,069 from Table 26 gives a more proper value for the SNR for band 5. This value, along with those for the other seven bands, remains a prelaunch estimate. An extensive series of on-orbit measurements (McClain et al. 1992 and Woodward et al. 1993) will be used to obtain an improved set of SNRs. A summary of the prelaunch SNR model for SeaWiFS bands 1–4 is presented in Table 28. A similar summary for bands 5–8 is presented in Table 29.

20. POINTING KNOWLEDGE

Pointing knowledge is a system level requirement. It includes knowledge of the nadir vector and scan plane of the instrument relative to the spacecraft; of the location of the spacecraft on orbit; and of the yaw, pitch, and roll angles of the spacecraft relative to the Earth.

20.1 Requirement

The contractor shall provide in the downlinked data stream, data describing the spacecraft attitude and location and sensor pointing angles required for calculation of the location (in latitude and longitude) of each ocean IFOV to within one IFOV at all scan and tilt angles.

20.2 Compliance

SBRC has provided OSC with the pointing coordinates for the SeaWiFS radiometer, information also found in the SCADP. These coordinates are given with respect to a set of transfer mirrors mounted on the radiometer. These values, from the instrument, are only part of the information required for pointing knowledge, since OSC must transfer these coordinates into their own system for the spacecraft

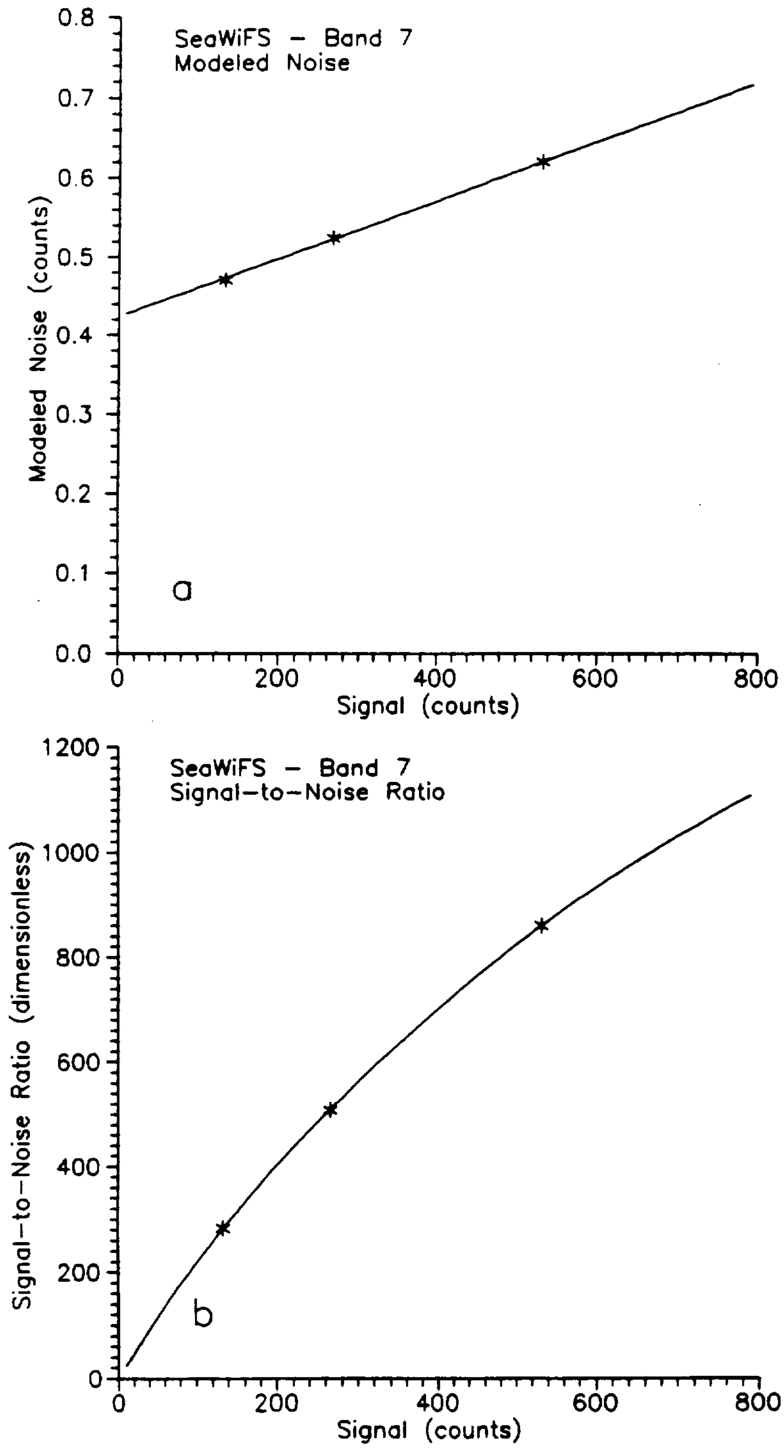

Fig. 8. Results of the noise model for SeaWiFS band 7. The input values for the model come from the SBRC calibration data book. The top figure shows the noise model for SeaWiFS. The curve gives the results of the noise model. The symbols give the input noise values at L_{typical}, one-half L_{typical}, and one-quarter L_{typical}. These three values include digitization noise. The bottom figure displays the calculated SNRs for SeaWiFS. The curve gives the calculated results from the model. The symbols give the input values from SBRC, with digitization noise added.

Table 28. SNR model for SeaWiFS bands 1–4. The counts at each reference level are calculated using Table 6 of Barnes et al. (1994). The noise values are calculated using Table 20.

Radiance	*Band 1*		*Band 2*		*Band 3*		*Band 4*	
[$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	Counts	SNR	Counts	SNR	Counts	SNR	Counts	SNR
11.30	793	1,133						
11.10	779	1,121						
10.90	765	1,109						
10.70	751	1,096	787	1,271				
10.50	737	1,083	772	1,256				
10.30	723	1,071	757	1,242				
10.10	709	1,058	742	1,227				
9.90	695	1,044	728	1,212				
9.70	680	1,031	713	1,196				
9.50	666	1,017	698	1,181				
9.30	652	1,003	684	1,165				
9.10	638	989	669	1,149				
8.90	624	975	654	1,133				
8.70	610	961	640	1,116				
8.50	596	946	625	1,100				
8.30	582	931	610	1,083	776	1,358		
8.10	568	916	595	1,065	757	1,338		
7.90	554	900	581	1,048	738	1,318		
7.70	540	885	566	1,030	719	1,297		
7.50	526	869	551	1,011	701	1,275		
7.30	512	853	537	993	682	1,254		
7.10	498	836	522	974	663	1,231	771	1,334
6.90	484	819	507	955	645	1,209	749	1,311
6.70	470	802	493	935	626	1,186	727	1,287
6.50	456	785	478	915	607	1,162	706	1,263
6.30	442	767	463	895	589	1,138	684	1,238
6.10	428	749	448	874	570	1,114	662	1,213
5.90	414	731	434	853	551	1,088	640	1,187
5.70	400	713	419	832	533	1,063	619	1,160
5.50	386	694	404	810	514	1,037	597	1,133
5.30	372	675	390	788	495	1,010	575	1,105
5.10	358	655	375	766	477	983	554	1,077
4.90	344	635	360	742	458	955	532	1,048
4.70	330	615	346	719	439	926	510	1,018
4.50	316	594	331	695	420	897	488	987
4.30	302	573	316	671	402	867	467	955
4.10	288	552	301	646	383	836	445	923
3.90	274	530	287	621	364	805	423	889
3.70	260	507	272	595	346	773	402	855
3.50	246	485	257	568	327	740	380	820
3.30	232	461	243	541	308	706	358	784
3.10	217	438	228	514	290	672	336	747
2.90	203	414	213	486	271	636	315	709
2.70	189	389	198	457	252	600	293	669
2.50	175	364	184	428	234	563	271	629
2.30	161	338	169	398	215	524	250	587
2.10	147	312	154	367	196	485	228	544

Table 28. (cont.) SNR model for SeaWiFS bands 1–4. The counts at each reference level are calculated using Table 6 of Barnes et al. (1994). The noise values are calculated using Table 20.

Radiance	*Band 1*		*Band 2*		*Band 3*		*Band 4*	
[$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	Counts	SNR	Counts	SNR	Counts	SNR	Counts	SNR
1.90	133	285	140	336	178	445	206	500
1.70	119	258	125	304	159	403	185	454
1.50	105	230	110	271	140	361	163	407
1.30	91	202	96	238	121	317	141	359
1.10	77	173	81	203	103	272	119	309
0.90	63	143	66	168	84	226	98	257
0.70	49	112	51	133	65	178	76	203
0.50	35	81	37	96	47	129	54	148
0.30	21	49	22	58	28	79	33	90
0.10	7	17	7	20	9	27	11	31

Table 29. SNR model for SeaWiFS bands 5–8. The counts at each reference level are calculated using Table 6 of Barnes et al. (1994). The noise values are calculated using Table 20.

Radiance	*Band 5*		*Band 6*		*Band 7*		*Band 8*	
[$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	Counts	SNR	Counts	SNR	Counts	SNR	Counts	SNR
5.75	764	1,237						
5.65	751	1,223						
5.55	737	1,210						
5.45	724	1,197						
5.35	711	1,183						
5.25	697	1,169						
5.15	684	1,155						
5.05	671	1,141						
4.95	658	1,126						
4.85	644	1,111						
4.75	631	1,096						
4.65	618	1,081						
4.55	604	1,066						
4.45	591	1,050						
4.35	578	1,034						
4.25	565	1,018						
4.15	551	1,002						
4.05	538	985						
3.95	525	969						
3.85	511	951						
3.75	498	934						
3.65	485	916						
3.55	472	899						
3.45	458	880						
3.35	445	862						
3.25	432	843						
3.15	418	824	749	918				
3.05	405	804	725	900				
2.95	392	785	701	881				
2.85	379	764	678	861				
2.75	365	744	654	842				
2.65	352	723	630	821				

Table 29. (cont.) SNR model for SeaWiFS bands 5–8. The counts at each reference level are calculated using Table 6 of Barnes et al. (1994). The noise values are calculated using Table 20.

Radiance	*Band 5*		*Band 6*		*Band 7*		*Band 8*	
[$\mathrm{mW\,cm^{-2}\mu m^{-1}sr^{-1}}$]	Counts	SNR	Counts	SNR	Counts	SNR	Counts	SNR
2.55	339	702	606	800				
2.45	325	680	582	779				
2.35	312	658	559	757				
2.25	299	636	535	734	743	1,066		
2.15	286	613	511	711	710	1,037		
2.05	272	590	487	687	677	1,006		
1.95	259	566	464	663	644	975		
1.85	246	542	440	638	611	942		
1.75	232	518	416	612	578	908		
1.65	219	493	392	585	545	873		
1.55	206	468	369	558	512	836	730	917
1.45	193	442	345	530	479	798	683	879
1.35	179	415	321	501	446	758	636	840
1.25	166	388	297	471	413	717	589	798
1.15	153	361	273	440	380	674	542	754
1.05	139	333	250	408	347	629	495	708
0.95	126	304	226	375	314	582	448	659
0.85	113	275	202	341	281	532	400	607
0.75	100	245	178	306	248	481	353	552
0.65	86	215	155	270	215	427	306	493
0.55	73	183	131	232	182	370	259	431
0.45	60	152	107	193	149	310	212	364
0.35	46	119	83	153	116	248	165	293
0.25	33	86	59	111	83	182	118	217
0.15	20	52	36	68	50	112	71	135
0.05	7	18	12	23	17	38	24	47

to provide on-orbit pointing vectors for SeaWiFS and SeaStar. Pointing knowledge is a system level function. Verification of pointing knowledge will be made using measurements of land targets on orbit. Verification of a sufficient set of downlinked data must wait for the Pre-Ship Review of the SeaStar spacecraft.

21. STABILITY & REPEATABILITY

Bias errors will be removed from the data during ground processing in order to improve radiometric accuracy. To accomplish this, the sensor data must be stable over time, as defined below.

21.1 Short-Term Stability Requirement

Short-term stability applies to time intervals less than two weeks. This stability also applies to radiometric responses corrected on the ground using calibration data. The mean radiometric response of each spectral band, shall not differ by more than ±1% from another response measurement made while viewing the same source operating at equal radiance levels, but separated by any time period up to two weeks. This includes the effects of perturbations at the orbital period. This stability requirement shall also be met for short-term temperature excursions that may be expected to occur during sunlit portions of the orbit. Data from lunar views, corrected for secular changes in lunar radiance exitance, collected on several consecutive orbits while the moon is near full phase, shall be provided with sufficient frequency to assess short term and long term stability.

21.2 Compliance

Due to the short period between the completion of instrument modification and the Pre-Ship Review, it was not possible to test this specification before launch. The requirements will require examination of measurements on orbit. However, the radiometric calibration equations for the SeaWiFS bands (Barnes et al. 1994) contain factors, such as the temperature dependences for their radiometric sensitivities, which will be applied on orbit. Lunar measurements (Woodward et al. 1993) are also planned for each measurement opportunity. These measurements are planned for twice each month, as the moon reaches 96% of full before and after each full phase. The correction for temperature dependence will also be applied to lunar measurements.

21.3 Long-Term Stability Requirement

Long-term stability applies to time intervals between two weeks and 5 years. The mean corrected and calibrated radiometric response of each spectral band shall not change by more than ±2% over these time intervals. Compliance will be demonstrated by an estimate based upon short-term tests plus analysis.

21.4 Compliance

As shown in Table 1, the SeaWiFS instrument was completed (after stray light modifications) on 22 November 1993. The post modification Pre-Ship Review was held ten days later on 2 December, which was an insufficient interval of time to test long-term stability. However, measurements by the instrument before its modification to ameliorate the effects of stray light indicated radiometric stability from the instrument at the 1% level over a few months. In addition, solar measurements during "field tests" of the instrument (Section 18) have shown a consistency in the instrument's measurements at the 2-3% level from March to November 1993. These tests suggest, but do not guarantee, long term stability on orbit. Long-term stability during the SeaWiFS mission will be monitored, and instrument changes will be corrected, through a series of lunar, solar, and ground based measurements (McClain et al. 1992 and Woodward et al. 1993)

21.5 Band-to-Band Stability Requirement

The relative amplitude stability between all pairs of spectral bands shall be better than ±0.5% measured at full-scale, and ±1% at half-scale. Each band shall be exposed to a source, and the mean calibrated responses determined. To compare outputs between bands, the ratio of the means shall be calculated for each band with respect to a common band. In addition, ratios shall be calculated for selected pairs of bands, which will be used in common retrieval algorithms. These ratios shall remain constant, within ±0.5% at full-scale and ±1% at half scale, over times separated by any interval up to two weeks.

21.6 Compliance

As discussed in Sections 21.2 and 21.4 above, the time period between the completion of the SeaWiFS instrument and the Pre-Ship Review was less than two weeks. This short time period was instituted in an effort to help ensure the launch of SeaWiFS and SeaStar at the earliest possible date. The practical requirements for an early launch have eliminated the period of time for extended testing by the manufacturer. However, the anecdotal information in Section 21.4 indicates that the performance of the instrument is at the level required by this specification.

22. IN-FLIGHT DATA

22.1 Requirement

Data for calibration and stability monitoring shall be obtained from direct lunar views when the moon is greater than 80% full phase, and either an onboard stabilized source viewed by all optical elements *or* a solar diffuser. The sources shall fill the optical aperture of the sensor. These data shall be obtained for all channels with a SNR no less than 10% of the SNR values specified in Section 10, and shall measure changes in gain or throughput of the optical, focal plane, and electronic subsystems, using either onboard, lunar, or solar sources. In-flight radiometric characterization, i.e., output digital value versus input spectral radiance, shall be made with sufficient accuracy to assure that the calibration and stability requirements delineated in this specification are achieved.

22.1.1 Lunar Calibration

Provision shall be made to use the moon at near full phase as a target source for monitoring stability. The lowest (least sensitive) gain shall accommodate direct viewing at near full lunar phase without saturation in any band.

22.1.2 Solar Diffuser

If a solar illuminated diffuser is selected, data on the diffuser characteristics shall be provided which, when combined with data from other calibration systems, will be adequate to maintain knowledge of the calibration and stability of the radiometric data to within stated specifications throughout the five-year mission lifetime.

22.1.3 Internal Source

In-flight data on characteristics of onboard sources, to show performance within the specifications, are required (should that approach be taken).

22.2 Compliance

The SeaWiFS radiometer has been specifically designed to make both lunar and solar diffuser measurements. There are no internal sources within the instrument. As discussed in Section 15.2, there are gains for each SeaWiFS band specifically set for the expected on-orbit solar and lunar radiances. Also, as discussed extensively in the SeaWiFS Technical Report Series (McClain et al. 1992, Woodward et al. 1993, and Barnes et al. 1994) and Biggar et al. 1993, lunar and solar diffuser measurements form a fundamental part of SeaWiFS on-orbit calibrations.

23. SUMMARY

This technical memorandum contains only a portion of the information from the prelaunch characterization and calibration of the SeaWiFS radiometer. The SCADP is much more extensive. However, as discussed in this acceptance report, the requirements of the SeaWiFS specifications have determined the design of the instrument. Compliance with these specifications has defined the fundamental operation of SeaWiFS.

This report summarizes prelaunch analyses that have been made by the review group, who are the co-authors of this technical memorandum. The review group concludes that, in the period between the delivery and the launch of the instrument, the SeaWiFS radiometer meets or exceeds all applicable specifications. Within the restriction that the instrument has not yet flown, SeaWiFS is found to be acceptable. However, the complete set of the information necessary for the acceptance, or rejection, of SeaWiFS and SeaStar is not yet available. There must be an extensive analysis of the on-orbit operational characteristics of SeaWiFS before a final judgement about the acceptability of the ocean color data set obtained by SeaWiFS can be made. The completion of this work will require information from 60 days of on-orbit operation by the satellite and its instrument.

Glossary

A/D Analog-to-Digital

BTR Bright Target Recovery

DC Direct Current

FWHM Full-Width at Half-Maximum

GAC Global Area Coverage

GSFC Goddard Space Flight Center

HN (Polaroid) Not an acronym; a linear sheet polarizer used to check the polarization sensitivity of bands 7 and 8.

HR (Polaroid) Not an acronym; a linear sheet polarizer used to check the polarization sensitivity of bands 1–6.

IFOV Instantaneous Field-Of-View

IR Infrared.

LAC Local Area Coverage

MTF Modulation Transfer Function

NASA National Aeronautics and Space Administration

NEdL Noise Equivalent Differential Spectral Radiance

NIST National Institute of Standards and Technology

OCDM Ocean Color Data Mission

OSC Orbital Sciences Corporation

SBRC Santa Barbara Research Center

SCADP SeaWiFS Calibration and Acceptance Data Package

SeaWiFS Sea-viewing Wide Field-of-view Sensor

SNR Signal-to-Noise Ratio

TDI Time Delay and Integration

Symbols

$b1(k)$ Input data for polarization calculations for SeaWiFS band 1.

$b7(k)$ Input data for polarization calculations for SeaWiFS band 7.

G Gain factor.

G_n Gain factor at gain setting n.

$h(k)$ Residual values without the calculated sinusoidal response.

$I_{\max}$ Recorded maximum instrument output in response to linearly polarized light.

$I_{\min}$ Recorded minimum instrument output in response to linearly polarized light.

L_{cloud} Maximum radiance from reflected light off of clouds.

$L_{\max}$ Maximum saturation radiance.

L_{typical} Expected radiance from the ocean measured on orbit.

n Gain setting.

PF Polarization factor.

S_i Initial detector signal.

S_n Detector signal with gain.

x Abscissa or longitudinal coordinate, or the pixel number within a scan line depending on usage.

y Ordinate or meridional coordinate.

z Mantissa coordinate.

σ One standard deviation.

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13. ABSTRACT *(Maximum 200 words)*

The final acceptance, or rejection, of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) will be determined by the instrument's on-orbit operation. There is, however, an extensive set of laboratory measurements describing the operating characteristics of the radiometer. Many of the requirements in the Ocean Color Data Mission (OCDM) specifications can be checked only by laboratory measurements. Here, the calibration review panel (composed of the authors of this technical memorandum) examines the laboratory characterization and calibration of SeaWiFS in the light of the OCDM performance specification. Overall, the performance of the SeaWiFS instrument meets or exceeds the requirements of the OCDM contract in all but a few unimportant details. The detailed results of this examination are presented here by following the outline of the specifications, as found in the Contract. The results are presented in the form of requirements and compliance pairs. These results give conclusions on many, but not all, of the performance specifications. The acceptance by this panel of the performance of SeaWiFS must only be considered as an intermediate conclusion. The ultimate acceptance (or rejection) of the SeaWiFS data set will rely on the measurements made by the instrument on orbit.

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