Reflectance-based calibration of SeaWiFS. II. Conversion to radiance

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For instruments that carry onboard solar diffusers to orbit, such as the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), it is possible to convert the instrument's reflectance measurements to radiance measurements by knowledge of the solar irradiance. This process, which generally requires the application of a solar irradiance model, is described. The application of the irradiance model is separate from the measurements by the instrument and from the instrument's reflectance calibration. In addition, SeaWiFS was calibrated twice before launch for radiance response by use of radiance sources with calibrations traceable to the National Institute of Standards and Technology. With the inclusion of the at-launch diffuser-based radiance calibration, SeaWiFS has three possible radiance calibrations for the start of on-orbit operations. The combination of these three into a single calibration requires changes of 4% or less for the current at-launch radiance calibration of the instrument. Finally, this process requires changes of 4% or less for the reflectance calibration coefficients to provide consistency among the radiance calibration, the reflectance calibration, and the solar irradiance.

OCIS codes: 120.0120, 120.0280, 120.5700, 120.5630.

1. Introduction

In a companion paper[1] we developed a reflectance-based calibration of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). When this calibration is applied, SeaWiFS operates as a reflectometer, viewing the reflected solar flux from both the Earth and the onboard diffuser. Because the Sun is the common source of irradiance for both diffuse reflectors, the ratio of the two SeaWiFS measurements is also the ratio of the two reflectances. The reflectance-based calibration of SeaWiFS allows the direct determination of the remote sensing reflectance of the Earth, relative to the reflectance of the SeaWiFS onboard diffuser. It does not require knowledge of the absolute value of the flux from either the Sun or an integrating sphere in the laboratory. However, the reflectance-based calibration does require the solar flux to be constant during the time between the two measurements in the ratio. In addition, the reflectance-based calibration does not require knowledge of the calibrated radiances for the SeaWiFS measurements because the measurements are applied as a ratio. It is sufficient to know that the instrument output, in digital numbers (DNs), is a linear function of the input radiance, as shown in Barnes *et al.*[2]

Here, that calibration is combined with a solar irradiance model to provide an on-orbit radiance-based calibration for SeaWiFS. Such a calibration is used for other satellite instruments, such as the moderate-resolution imaging spectroradiometer (MODIS)[3] and the Global Imager.[4] For SeaWiFS, this calibration requires knowledge of the absolute value of the solar spectral irradiance at the instrument's input aperture plus knowledge of the reflecting properties of the instrument's diffuser. The reflectance-based calibration of SeaWiFS is summarized in Section 2, the properties of the solar irradiance model used in the conversion to radiance is discussed in Section 3, and the on-orbit radiance calibration is presented in Section 4.

In 1993, at the facility of the instrument manufacturer, Hughes Santa Barbara Research Center (now Raytheon Santa Barbara Remote Sensing), a prelaunch solar radiation-based calibration (SRBC) was performed.[5,6] That calibration duplicates the on-orbit radiance calibration in Section 4, except that it was performed prior to launch and performed at a site below the Earth's atmosphere. The prelaunch SRBC of SeaWiFS is described in Section 5, including

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Received 30 August 2002; revised manuscript received 23 December 2002.
0003-6935/03/091648-13$15.00/0

a comparison with the results of the on-orbit radiance calibration in Section 4.

For SeaWiFS, there were two prelaunch laboratory radiance calibrations that used integrating spheres as radiance sources. These calibrations are described in Section 6. In Section 7 these calibrations are combined with the on-orbit calibration from Section 4 to provide revised radiance calibration coefficients for the instrument. The revised coefficients are an unweighted mean of the values from these calibrations. For all eight SeaWiFS bands, the revised coefficients agree with those currently in use at better than the 4% level and fall within the estimated uncertainty ($k = 1$) for the top-of-the-atmosphere radiances from the instrument.

2. Reflectance-Based Calibration

In the companion paper[1] we developed the calibration equation for the Earth bidirectional reflectance factor (BRF) $R_E(t)$ using the SeaWiFS diffuser as an on-orbit reflectance standard. The BRF is defined as the ratio of the radiant flux from a sample surface to that of an ideal diffuse standard surface irradiated in the same way as the sample.[7,8] For an ideal diffuse surface, the bidirectional reflectance distribution function (BRDF)[7,8] has a value of $1/\pi\ \mathrm{sr}^{-1}$, and its BRF, by definition, is unity (dimensionless). Thus, for an ideal diffuse surface and for other surfaces as well, the conversion constant between BRDF and BRF has a value of π steradians.

For each SeaWiFS band, our calibration equation[1] has the form

$$\begin{aligned} R_E(t) &= \pi F_E(t) \\ &= [\mathrm{DN}(t) - \mathrm{DN}_0(t)]_E \frac{D_{\mathrm{ES}}^2(t)}{\cos(\theta_I)} [\pi k_F(t_0)]\alpha(t_0) \\ &\quad \times [\Delta_G(t)]^{-1}[\Delta_F(t)]^{-1}, \end{aligned} \tag{1}$$

where $R_E(t)$ is the Earth BRF (dimensionless) at time t in days after launch. In Eq. (1), $F_E(t)$ is the Earth BRDF in units of inverse steradians and π is the conversion constant in units of steradians. The term $[\mathrm{DN}(t) - \mathrm{DN}_0(t)]_E$ gives the DNs measured by SeaWiFS, $\mathrm{DN}(t)$, after correction for the instrument's zero offset, $\mathrm{DN}_0(t)$. The terms $D_{\mathrm{ES}}^2(t)$ and $\cos(\theta_I)$ are corrections for the Earth–Sun distance and the cosine of the solar zenith angle at the time of the measurement, respectively, and both of these corrections are dimensionless. The term $\cos(\theta_I)$ is a geometric correction for the projection of the incident solar radiation when it is not normal to the Earth's surface. This type of correction applies whenever the illuminated area on a surface overfills the field of view of the instrument measuring the reflected radiation and is not related to the nature of the reflecting surface. It is also possible to provide an Earth reflectance product without this geometric correction, allowing the correction to be applied by the user, as is the case for MODIS.[3]

In Eq. (1) the reflectance calibration coefficient $k_F(t_0)$ has units of BRDF per DN ($\mathrm{sr}^{-1}\ \mathrm{DN}^{-1}$). It is a constant that is given for the time of the instrument's launch, t_0. It has no time dependence. The coefficient is composed of three terms: the BRDF of the diffuser $F_D(t_0)$, the net DNs for the diffuser measurement $\mathrm{DN}_D(t_0)$, and the gain ratio for the diffuser measurement $G_R(t_0)$ all at time t_0 (Ref. 1):

$$k_F(t_0) = \frac{F_D(t_0)}{\mathrm{DN}_D(t_0)[G_R(t_0)]^{-1}}. \tag{2}$$

In Eq. (2), the net DNs are corrected for the instrument's zero offset, and the gain ratio accounts for the difference of the band's electronic gain used during the diffuser measurement from that used during Earth measurements.[1] The gain ratio is dimensionless. In addition, the values of $\mathrm{DN}_D(t_0)$ have been corrected for the Earth–Sun distance and the cosine of the solar zenith angle at time t_0.[1]

The term $\alpha(t_0)$ in Eq. (1) is applied as an initialization constant determined from surface-truth measurements by the Marine Optical Buoy (MOBY).[9,10] It has no time dependence, and it is dimensionless. The term is used in the standard processing stream for ocean color measurements, which are the primary products for SeaWiFS measurements. The $\alpha(t_0)$ initialization constant is required for the particular characteristics of ocean measurements, where the ocean is relatively dark and most of the top-of-the-atmosphere radiance comes from the atmosphere.[10] For land and atmosphere applications and for the top-of-the-atmosphere BRF, $\alpha(t_0)$ is set to unity.[11] It is important to emphasize that $\alpha(t_0)$ is provided by a vicarious calibration[10] in a process that is separate from the determination of the other coefficients in Eq. (1). It is not part of the on-orbit reflectance-based calibration of the instrument, and it is used only in the production of the ocean color data products.

There are two time-dependent correction terms in Eq. (1) that account for changes in the gain ratio $\Delta_G(t)$ and for changes in the BRDF of the diffuser $\Delta_F(t)$. Both of these terms are dimensionless and are normalized to unity at time t_0, and both are smoothly changing functions of time, easily calculated at the time of each Earth measurement.[1]

SeaWiFS does not carry an independent device, such as a ratioing radiometer,[12] to determine long-term changes in the onboard diffuser. As a result, changes in the diffuser are determined from the solar measurements themselves, and these measurements involve two parts, that is, the instrument–diffuser system. For SeaWiFS, the long-term changes in the diffuser are determined by removal of the long-term changes in the instrument from the solar measurements.[1] And for SeaWiFS, light from the Moon is used as a reference to determine instrument changes.[11] As a result, the knowledge of the changes in the diffuser can never be as good as the knowledge of the changes in the instrument itself. Thus it is possible to modify Eq. (1) when we substitute the lunar-based instrument changes for $\Delta_G(t)$ and $\Delta_F(t)$:

$$R_E(t) = \pi F_E(t) = [\mathrm{DN}(t) - \mathrm{DN}_0(t)]_E \frac{D_{\mathrm{ES}}^2(t)}{\cos(\theta_I)} [\pi k_F(t_0)]\alpha(t_0) \times \{1 - \beta[1 - \gamma \exp(-\delta t)]\}^{-1}, \quad (3)$$

where the term $\{1 - \beta[1 - \gamma \exp(-\delta t)]\}$ gives the change in the radiometric sensitivity of the instrument derived from measurements of the Moon.[1,11] In this term, β and γ are dimensionless and δ has units of day^{-1}. In an exponential manner, this lunar-based sensitivity factor decreases fractionally from a value of unity at t_0 to a value of $(1 - \beta)$ for times far into the future. The correction is applied as the reciprocal of the change. As explained above, the instrument change term $\{1 - \beta(1 - \gamma \exp(-\delta t)]\}$ in Eq. (3) is also part of the calculation of $\Delta_F(t)$ in Eq. (1). Thus Eq. (3) provides an improved determination of the Earth BRF to that from Eq. (1) over time.

The reflectance properties of the Earth's surface and the atmosphere above it are complex functions of the incident azimuthal and elevation angles of the solar irradiance (ϕ_I and θ_I) and of the scattered radiance (ϕ_S and θ_S). This is true of all reflecting surfaces.[13] As a result, these surface and atmospheric reflectance properties are contained in the Earth reflectance terms $A_E(t)$ and $F_E(t)$. The angles for these properties can be calculated from knowledge of the positions of the spacecraft, the Earth, and the Sun in a standard frame of reference for each Earth measurement; but the determination of these properties is outside of the calculation of $R_E(t)$ and $F_E(t)$. In addition, because each SeaWiFS band has a finite bandwidth, the measured reflectances must be considered as averages over these bandwidths.[13] The BRDF of the instrument diffuser varies smoothly and slowly with wavelength; however, any wavelength-dependent structure of the effective reflectance of the Earth's surface within each instrument bandwidth is not known from these measurements.

For the reflectance-based calibration of SeaWiFS, the instrument is used as a transfer radiometer between the onboard diffuser and the Earth, with the onboard diffuser as a reference standard. In this calibration, the absolute magnitude of the solar flux is not a contributor because it is applied to both parts of the transfer measurement. This is the reason why the Earth–Sun distance correction is applied to both the measurements of the diffuser and the Earth.[1] However, knowledge of the absolute value of the solar flux is fundamental to the conversion from reflectance to radiance.

3. Solar Irradiance

As with most Earth-imaging satellite instruments, SeaWiFS was not designed to provide calibrated solar irradiances, and an independent solar irradiance model is required to convert SeaWiFS reflectances to radiances. Several solar models are available. Because different models convert the same reflectance into different radiances, it is prudent to examine the model-to-model differences in these irradiances. At the inception of the SeaWiFS Project in 1991, the solar irradiance model of Neckel and Labs[14] was selected as the reference for SeaWiFS. It remains so, as of SeaWiFS reprocessing 4 in July 2002. The Neckel and Labs[14] model is used to create band-averaged solar irradiances $E_{M,B}$ for the eight SeaWiFS bands by the equation

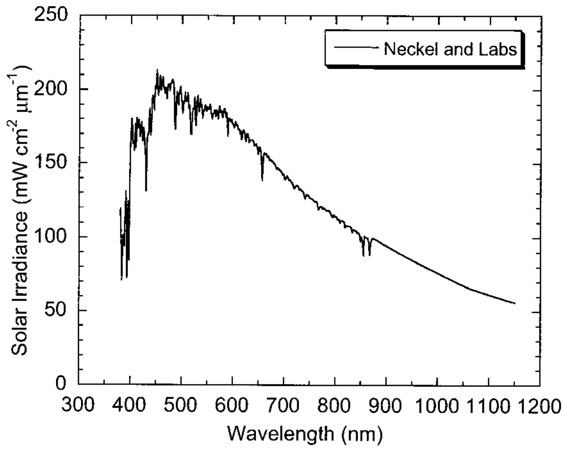

Fig. 1. Solar irradiances from the model of Neckel and Labs.[14] The irradiances are given at 1-nm intervals from 380 to 1150 nm.

$$E_{M,B} = \frac{\int_{\lambda_1}^{\lambda_2} E_{M,\lambda} R_\lambda \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} R_\lambda \mathrm{d}\lambda}, \quad (4)$$

where $E_{M,\lambda}$ is the model irradiance and R_λ is the spectral response of the SeaWiFS band at wavelength λ. Because R_λ is found in both the numerator and the denominator of Eq. (4), the absolute value of the spectral response cancels out of the equation. The spectral responses for the SeaWiFS bands are given at 1-nm intervals from 380 to 1150 nm.[15] The solar irradiances from Neckel and Labs[14] are given at wavelength intervals close to 1 nm, but not at the even nanometer values of the SeaWiFS spectral responses, so the irradiances were calculated at those wavelengths by linear interpolation. The Neckel and Labs solar irradiances, at the SeaWiFS wavelengths, are shown in Fig. 1, and the band-averaged values of $E_{M,B}$ are listed in Table 1.

Wehrli[16,17] compiled a set of solar irradiances, based on previously published results from the literature. For the SeaWiFS wavelength range from 380 to 869 nm, the Wehrli[16,17] irradiances come from Neckel and Labs,[14] with a reduction of approximately 0.15% in each of the irradiances from the literature reference. For the remaining portion of the SeaWiFS radiance range, 870 to 1150 nm, Wehrli[16,17] used the values from Smith and Gottlieb.[21] The values from Wehrli were interpolated to the

Table 1. Irradiances from Four Solar Models Band Averaged with the SeaWiFS Spectral Responses by Eq. (4)[a]

SeaWiFS Band	Wavelength (nm)	Neckel and Labs[b]	Wehrli[c]	MODTRAN[d]	Thuillier *et al.*[e]
1	412	170.79	170.57	176.27	172.81
2	443	189.44	189.17	189.70	190.20
3	490	193.66	193.36	196.00	196.26
4	510	188.34	188.06	188.96	188.02
5	555	185.33	185.03	187.09	183.06
6	670	153.36	153.20	153.88	151.15
7	765	122.24	122.01	122.65	122.29
8	865	98.82	98.05	95.87	96.19

[a]The irradiances are in units of mW cm^{-2} μm^{-1}. The wavelengths are the nominal center wavelengths for each band.
[b]Ref. 14.
[c]Refs. 16 and 17.
[d]Refs. 18 and 19.
[e]Ref. 20.

Table 2. Percent Differences of the Irradiances of Wehrli, MODTRAN, and Thuillier *et al.* from the Irradiances of Neckel and Labs[a]

SeaWiFS Band	Difference from Neckel and Labs[b] (%)		
	Wehrli[c]	MODTRAN[d]	Thuillier *et al.*[e]
1	−0.13	3.21	1.18
2	−0.14	0.14	0.40
3	−0.15	1.21	1.34
4	−0.15	0.33	−0.17
5	−0.16	0.95	−1.22
6	−0.10	0.34	−1.44
7	−0.19	0.34	0.04
8	−0.78	−2.99	−2.66

[a]The differences are calculated with the band-averaged solar irradiances in Table 1.
[b]Ref. 14.
[c]Refs. 16 and 17.
[d]Refs. 18 and 19.
[e]Ref. 20.

SeaWiFS wavelengths in the same manner as Neckel and Labs, and the band-averaged results are listed in Table 1.

MODTRAN[18,19] provides an irradiance data set at a higher wavelength resolution than the SeaWiFS spectral responses. To provide this resolution, the MODTRAN spectrum includes computations of the detailed structure in the solar irradiance in addition to measured results.[19] To obtain values at 1-nm intervals, the MODTRAN solar irradiances were averaged by a triangular slit function with a full width at half-maximum (FWHM) of 1 nm. The MODTRAN solar irradiances are combined with the SeaWiFS spectral responses to provide the values of $E_{M,B}$ listed in Table 1. Finally, the solar irradiances of Thuillier *et al.*[20] provide the most recent irradiance set, developed over the past several years with solar measurements from space.[22–25] For wavelengths below 872 nm, the irradiances of Thuillier *et al.*[20] have wavelength intervals close to 1 nm and were interpolated to the wavelengths of the SeaWiFS spectral responses. For wavelengths greater than 872 nm, the Thuillier *et al.* irradiances have a much higher wavelength resolution, and the values at the SeaWiFS wavelengths are calculated by a triangular slit function with a FWHM of 1 nm. The band-averaged solar irradiances from Thuillier *et al.* are also listed in Table 1.

The differences in the set of irradiances from the currently used values of Neckel and Labs[14] are listed in Table 2. Of particular interest are the differences of the solar model from Thuillier *et al.*[20] For Sea WiFS bands 1–7, the differences in the Thuillier *et al.* irradiances from those of Neckel and Labs are less than 1.5%. However, at 2.7%, the difference for SeaWiFS band 8 is significantly greater. Figure 2 shows the passband for SeaWiFS band 8, along with the irradiance values from the four solar models. It covers the wavelength region that dominates the calculation of the band-averaged solar irradiance for band 8.

From 872 to 910 nm, the Neckel and Labs irradiances change smoothly with wavelength. As shown in Fig. 1, this lack of wavelength-dependent structure extends to 1150 nm. This is an indication of an absence of a set of measured solar irradiances over these wavelengths. This may be the reason that Wehrli[16,17] used the irradiances of Smith and Gottlieb[21] above 872 nm in his compilation. The impact of the Neckel and Labs solar values over this range can be calculated when those values are substituted into the other models and the band-averaged solar irradiances are recalculated. This is easily done because the solar irradiances for the models are all given at the same 1-nm intervals. When the substitution is done, the Wehrli band-averaged solar irradiance for band 8 increases by 0.7%. This change accounts for most of the difference from Neckel and Labs for this band. For the models of MODTRAN[18,19] and Thuillier *et al.*[20] the increases are 1.6% in each case. This change accounts for more than half of the difference from Neckel and Labs for these models.

The solar irradiances in Fig. 2 also show absorption features (Fraunhofer lines) from 850 to 870 nm. For the MODTRAN spectra, the lines are deeper and more narrow than the others because of the higher spectral resolution of the data. For the irradiances of Neckel and Labs and Wehrli, the absorption features are identical in shape and depth. It is possible to estimate the effect of these three features when we bridge across them, that is, by when we replace the values in the features with straight lines across each of their bases (see Barnes *et al.*[6]) and recalculate the band-averaged solar irradiance for band 8. These calculations essentially remove the Fraunhofer lines from the solar irradiances. With the Fraunhofer lines removed, the band 8 solar irradiances increase by 1.4% for the models of Neckel and Labs, Wehrli, and Thuillier *et al.* and by 2.4% for the model of MODTRAN. Thus the effect of the Fraunhofer lines in the MODTRAN spectrum accounts for a 1% decrease in

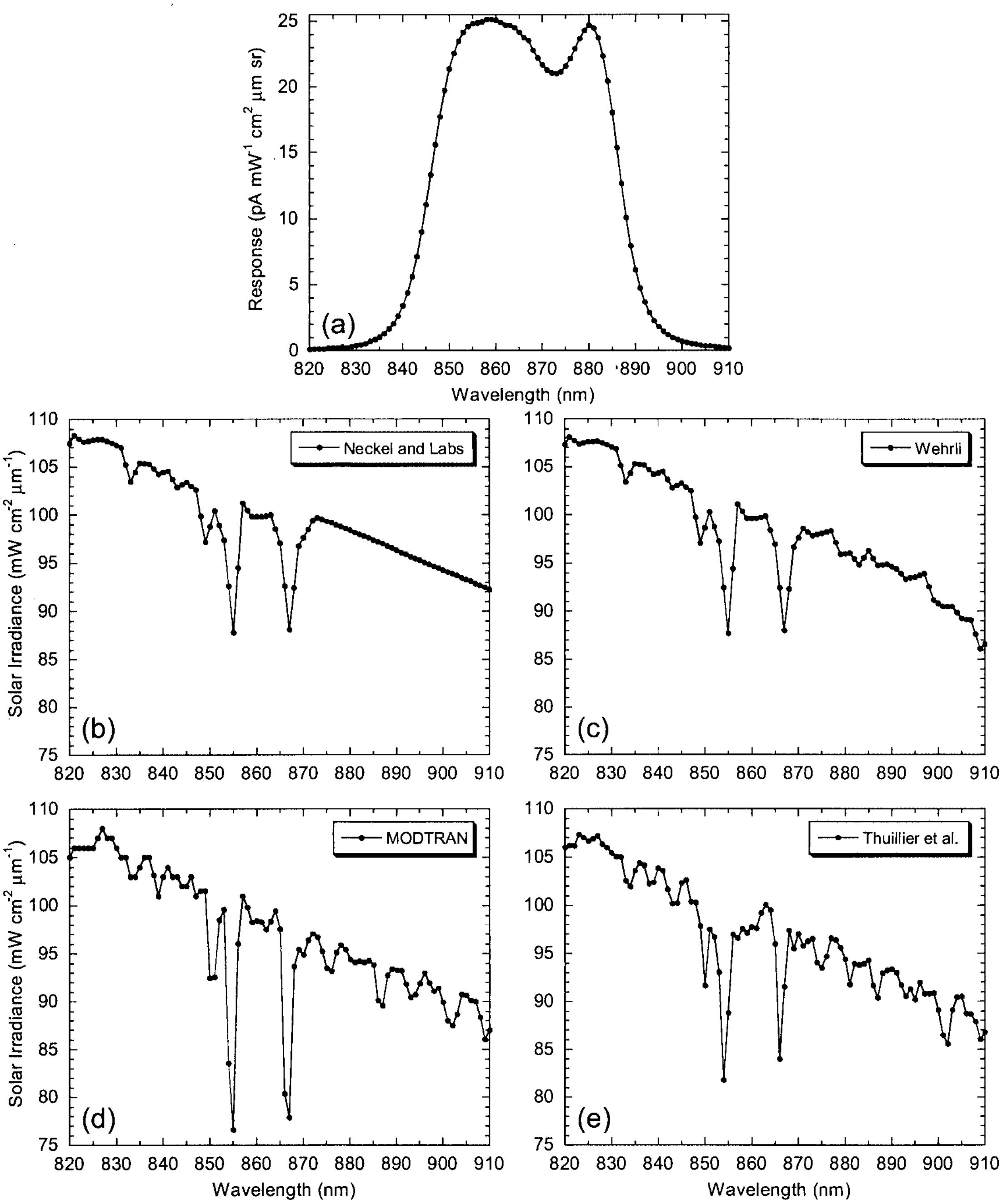

Fig. 2. SeaWiFS band 8 spectral response and irradiances from four solar models. The values in each panel are given at 1-nm intervals from 820 to 910 nm. (a) The band 8 spectral response is in units of picoamperes from the photodiode detector per unit spectral radiance.[15] The solar irradiances come from the models of (b) Neckel and Labs,[14] (c) Wehrli,[16,17] (d) MODTRAN,[18,19] and (e) Thuillier *et al*.[20]

the band 8 band-averaged solar irradiance relative to the other models.

A portion of the difference of the solar irradiance of Thuillier *et al*. from Neckel and Labs can be found in the wavelengths adjacent to the 852-nm absorption feature. For wavelengths from 851 to 852 nm and from 856 to 861 nm, the Thuillier *et al*. irradiances are up to 5 mW lower than those in the other spectra. This accounts for a decrease of more than 0.50% in the band 8 solar irradiance from Thuillier *et al*., relative to Neckel and Labs.

For each remote sensing experimenter, the choice of a solar irradiance model is a value judgment. Here, the differences between Neckel and Labs and Thuillier *et al*. for SeaWiFS bands 1–7 are sufficiently small to be well within the combined uncertainties of the two data sets (see Table 2). For SeaWiFS band 8, we believe that the Thuillier *et al*. results provide an incremental improvement over those from Neckel and Labs, with significantly more irradiance values at wavelengths longer than 872 nm. In addition, the solar irradiance model of

Thuillier *et al*. represents the current state of the art in solar irradiance spectra, and it is the preferred model for the radiance calculations in Sections 4–7.

4. On-Orbit Radiance Calibration

The relationship between the SeaWiFS-measured Earth reflectance and the Earth radiance is given by the equation

$$F_E(t) = \frac{L_E(t)}{E_{M,B}}, \tag{5}$$

where $L_E(t)$ is the Earth radiance (in mW cm^{-2} sr^{-1} μm^{-1}), $F_E(t)$ is the Earth BRDF measured by SeaWiFS (in sr^{-1}), and $E_{M,B}$ is the solar irradiance from the model of Thuillier *et al.*[20] (in mW cm^{-2} μm^{-1}). Equation (5) is a standard definition of the BRDF, except for the omission of the cosine of the angle of incidence for the irradiance.[1] This implies that the irradiance is normal to the Earth's surface. In addition, use of a solar model in Eq. (5) implies an Earth–Sun distance of 1 astronomical unit. Differences from these two conditions require corrections to Eq. (5). For SeaWiFS measurements, the correction for the incidence angle is applied in the calculation of the top-of-the-atmosphere Earth BRDF, $F_E(t)$, in the reflectance-based calibration. The Earth reflectance and the Earth radiance are both functions of the time after the instrument launch. The irradiance from the solar model is a constant and has no time dependence.

For SeaWiFS, the Earth BRDF is converted to radiance by use of the solar irradiance as a conversion coefficient,

$$\begin{aligned} L_E(t) &= E_{M,B}F_E(t) \\ &= [\mathrm{DN}(t) - \mathrm{DN}_0(t)]_E\left[\frac{D_{\mathrm{ES}}{}^2(t)}{\cos(\theta_I)}\right][E_{M,B}k_F(t_0)]\alpha(t_0) \\ &\quad \times \{1 - \beta[1 - \gamma \exp(-\delta t)]\}^{-1}, \end{aligned} \tag{6}$$

in the same manner that the Earth BRDF is converted to BRF in Eq. (3) by π steradians as a conversion coefficient. Except for the conversion coefficients and of course the derived products, Eqs. (3) and (6) are identical. In addition, both the derived reflectances and the radiances from Eqs. (3) and (6) include corrections for the Earth–Sun distance and the cosine of the solar zenith angle.

This differs from the Earth radiance derived from the standard radiance-based calibration of SeaWiFS, where neither correction is applied,[11]

$$\begin{aligned} L_E(t) &= k_2(t_0)[\mathrm{DN}(t) - \mathrm{DN}_0(t)]_E\alpha(t_0) \\ &\quad \times \{1 - \beta[1 - \gamma \exp(-\delta t)]\}^{-1}, \end{aligned} \tag{7}$$

and where $k_2(t_0)$ is the radiance calibration coefficient (in mW cm^{-2} sr^{-1} μm^{-1} DN^{-1}) determined in the laboratory before launch.[26] This coefficient is independent of the time after launch, and the other terms in Eq. (7) are also found in Eq. (6). As a result, for the standard SeaWiFS radiance calibration with Eq. (7), the Earth–Sun distance and the cosine of the solar zenith angle are applied to the derived geophysical products, such as the water-leaving radiance,[10] and not to the top-of-the-atmosphere radiance as done in Eq. (6). Ultimately, however, these two corrections are applied to the geophysical products from the SeaWiFS measurements. The difference lies in the point in the algorithm at which the corrections are applied.

It is possible to combine the model-based solar irradiance from Section 3 and the reflectance-based calibration coefficient from Eq. (2) to produce a radiance-based calibration coefficient from the diffuser measurements:

$$k_L(t_0) = E_{M,B}k_F(t_0) = \frac{E_{M,B}F_D(t_0)}{\mathrm{DN}_D(t_0)[G_R(t_0)]^{-1}}. \tag{8}$$

The on-orbit radiance calibration coefficient $k_L(t_0)$ in Eq. (8) has the same units as the prelaunch coefficient $k_2(t_0)$ from Eq. (7). The constants used to calculate $k_L(t_0)$ in Eq. (8), except for the solar

Table 3. Coefficients Used to Derive the Reflectance-Based Calibration Coefficient $k_F(t_0)$ in Eq. (2)[a]

SeaWiFS Band	$F_D(t_0)$ (sr^{-1})	$\mathrm{DN}_D(t_0)$ (DN)	$G_R(t_0)$ (dimensionless)
1	0.0269	433.66	1.30318
2	0.0279	398.03	1.00000
3	0.0274	468.62	0.89973
4	0.0279	468.27	0.79427
5	0.0274	451.39	0.65149
6	0.0277	386.64	0.37556
7	0.0281	384.48	0.32273
8	0.0297	370.90	0.27183

[a]From Ref. 1.

Table 4. Derived Values of $k_L(t_0)$ (units of mW cm^{-2} sr^{-1} μm^{-1} DN^{-1})[a]

	Calibration Coefficient $k_L(t_0)$			
SeaWiFS Band	Neckel and Labs[b]	Wehrli[c]	MODTRAN[d]	Thuillier *et al.*[e]
1	0.013806	0.013788	0.014249	0.013969
2	0.013279	0.013260	0.013297	0.013332
3	0.010188	0.010172	0.010311	0.010325
4	0.008913	0.008900	0.008942	0.008898
5	0.007329	0.007317	0.007399	0.007239
6	0.004126	0.004122	0.004140	0.004067
7	0.002883	0.002878	0.002893	0.002884
8	0.002151	0.002134	0.002087	0.002094

[a]The calibration coefficients are calculated with Eq. (8) and the constants in Tables 1 and 3. There is one coefficient for each SeaWiFS band and each solar irradiance model. The preferred calibration coefficients are those derived from the model of Thuillier *et al.*[20]
[b]Ref. 14.
[c]Refs. 16 and 17.
[d]Refs. 18 and 19.
[e]Ref. 20.

irradiances, are listed in Table 3. The four model-based irradiances are listed in Table 1. The combination of these coefficients gives 32 values of $k_L(t_0)$, with four per SeaWiFS band, and these values are listed in Table 4. As stated above, the model of Thuillier *et al.*[20] represents the current state of the art in solar irradiance spectra, and it provides the preferred values for $k_L(t_0)$ in Table 4.

5. Prelaunch Solar Radiation-Based Calibration

The prelaunch SRBC of SeaWiFS[5,6] provides a calibration coefficient that is the functional counterpart of the on-orbit coefficient $k_L(t_0)$ described in Section 4, and the procedures for the SRBC also form the basis for the ground portion of the transfer-to-orbit experiment.[13] On 1 November 1993, SeaWiFS was moved into the courtyard of the instrument manufacturer's facility and aligned to make the direct beam of the solar flux normal to the input aperture of the instrument diffuser.[13] Measurements were made by SeaWiFS of the radiance from its diffuser. However, ancillary measurements were required to account for atmospheric effects on the SRBC. These effects include the atmosphere as an attenuator of the direct beam of the solar flux and as a source of diffuse light (skylight) from outside of the solar beam.

For the skylight correction, the SeaWiFS diffuser assembly was aligned to the Sun and the DNs from the instrument were recorded for each band. Then the diffuser was shadowed by a small occulting disk that blocked the direct beam of the Sun (see Fig. 6 of Barnes *et al.*[13]), and the DNs were again recorded. The difference in these measurements accounts for the amount of diffuse light from the sky that falls on the diffuser. In addition, a correction can be made to account for the small amount of forward-scattered skylight that is blocked by the occulting disk. The correction is wavelength dependent, but in all cases it is small, approximately 0.5 DN for the atmospheric conditions and the size of the disk.[5] This is approximately 0.25% of the measured values or less.

These measured digital numbers can be applied to the basic calibration equation for the SRBC:

$$L_S(t_S) = k_S(t_S)\{[\mathrm{DN}(t_S) - \mathrm{DN}_0(t_S)]_U - [\mathrm{DN}(t_S) - \mathrm{DN}_0(t_S)]_S - 0.5\mathrm{DN}\}[G_R(t_S)]^{-1}, \tag{9}$$

where $L_S(t_S)$ is the SeaWiFS-measured radiance from the diffuser (in mW cm^{-2} sr^{-1} μm^{-1}) at the time of the SRBC, t_S. The SRBC-determined radiance calibration coefficient $k_S(t_S)$ (in mW cm^{-2} sr^{-1} μm^{-1} DN^{-1}) converts the measured DN to radiance. This coefficient is given for the standard electronic gain for SeaWiFS Earth measurements on orbit. However, some of the SRBC measurements were made at different electronic gains because the reflectance of the diffuser differs significantly from Earth scenes, particularly in the blue and the near infrared. The gain ratio term in Eq. (9), $G_R(t_S)$, corrects the SRBC-measured DN to the standard gain, gain 1. The technique for the application of the gain ratio is explained in Ref. 1. The net DNs in Eq. (9) are those from the unshadowed measurement $[\mathrm{DN}(t_S) - \mathrm{DN}_0(t_S)]_U$ minus those from the shadowed measurement $[\mathrm{DN}(t_S) - \mathrm{DN}_0(t_S)]_S$ minus those from the forward-scattered light correction. These net DNs give the skylight-corrected results for the SRBC, $\mathrm{DN}_C(t_S)$, as shown in Eq. (10):

$$L_S(t_S) = k_S(t_S)\mathrm{DN}_C(t_S)[G_R(t_S)]^{-1}. \tag{10}$$

The SeaWiFS-measured radiance for the SRBC, $L_S(t_S)$, can also be calculated from knowledge of the incident irradiance on the instrument and the BRDF of the diffuser. This is a basic rearrangement of Eq. (5). However, $L_S(t_S)$ also includes the effects of a nonnormal incidence angle for the irradiance, of the Earth–Sun distance, and of the transmittance of the atmosphere, none of which are in Eq. (5). In addition, the SeaWiFS bands have finite spectral bandwidths with respect to the spectral structure in the solar irradiance and the atmospheric transmittance. This requires use of band averaging, leading to the equation[13]

$$L_S(t_S) = \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} E_{M,\lambda} \frac{\cos(\theta_I)}{{D_{\mathrm{ES}}}^2(t_S)} T_\lambda(t_S) F_\lambda(t_S) R_\lambda \mathrm{d}\lambda}{\displaystyle\int_{\lambda_1}^{\lambda_2} R_\lambda \mathrm{d}\lambda}. \tag{11}$$

As shown for Eq. (4), the integrals and the spectral response of the band at each wavelength R_λ are the basis for the band average. The band average can be considered as a weighted mean over the spectral response of the band. As with Eq. (4), the limits of integration give the wavelength range over which there is a significant spectral response for the band. Both the atmospheric transmittance T_λ and the diffuser reflectance F_λ have wavelength dependencies. However, this is not the case for the solar zenith angle and the Earth–Sun distance. In addition, for the prelaunch SRBC, the instrument was aligned to make the solar flux normal to the input aperture of the instrument diffuser[13] so that the cosine term is unity. This allows the simplification of Eq. (11) to

$$L_S(t_S) = \frac{1}{{D_{\mathrm{ES}}}^2(t_S)} \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} E_{M,\lambda} T_\lambda(t_S) F_\lambda(t_S) R_\lambda \mathrm{d}\lambda}{\displaystyle\int_{\lambda_1}^{\lambda_2} R_\lambda \mathrm{d}\lambda}. \tag{12}$$

The upper integral in Eq. (12) contains the product of the solar irradiance model, the atmospheric transmittance, and the diffuser BRDF. As shown in Barnes *et al.*,[13] it is possible to calculate the band average for each term in the integral and present the result as

Table 5. Constants and Measured Values Used in Eq. (14)[a]

SeaWiFS Band	$F_D(t_S)$ (sr^{-1})	$DN_C(t_S)$ (DN)	$T_B(t_S)$ (dimensionless)	$D_{ES}^2(t_S)$ (dimensionless)	$G_R(t_S)$ (dimensionless)
1	0.0269	193.5	0.29046	0.98466	1.93438
2	0.0279	235.5	0.35321	0.98466	1.65039
3	0.0274	228.5	0.43582	0.98466	1.00000
4	0.0279	276.5	0.46073	0.98466	1.00000
5	0.0274	360.5	0.51162	0.98466	1.00000
6	0.0277	447.5	0.63005	0.98466	0.67024
7	0.0281	452.5	0.63709	0.98466	0.58360
8	0.0297	532.5	0.74737	0.98466	0.50682

[a]The diffuser BRDF values for the SeaWiFS bands at the time of the SRBC, $F_D(t_S)$, are the same as those at the start of on-orbit operations $F_D(t_0)$ from Table 3. This equality is based on the results of the transfer-to-orbit experiment.[13] The net digital numbers $DN_C(t_S)$ come from Table 3 of Barnes *et al.*[13]

the product of these averages. This allows the simplification of Eq. (12) to

$$L_S(t_S) = \frac{E_{M,B} T_B(t_S) F_D(t_S)}{D_{ES}^2(t_S)}, \qquad (13)$$

where $E_{M,B}$ is the band-averaged solar irradiance, $T_B(t_S)$ is the band-averaged atmospheric transmittance at the time of the SRBC, and $F_D(t_S)$ is the band-averaged diffuser BRDF at the same time. This is the BRDF for the diffuser assembly measured in the laboratory prelaunch.[13] It is also the BRDF value used at the start of on-orbit operations for SeaWiFS.[1] Because Eqs. (10) and (13) both give solutions for $L_S(t_S)$, it is possible to combine them and solve for $k_S(t_S)$, which is the coefficient for the SRBC of SeaWiFS:

$$k_S(t_S) = \frac{E_{M,B} T_B(t_S) F_D(t_S)}{DN_C(t_S)[G_R(t_S)]^{-1} D_{ES}^2(t_S)}. \qquad (14)$$

The terms in Eq. (14), except for the band-averaged solar irradiance, are given in Table 5. The irradiances from the four solar models are given in Table 1. As a result, there are four sets of solutions for $k_S(t_S)$, in the same manner as for $k_L(t_0)$. The results for the prelaunch SRBC of SeaWiFS, that is, the values for $k_S(t_S)$, are listed in Table 6. As with the values of $k_L(t_0)$ in Table 4, the model of Thuillier *et al.*[20] is considered to provide the preferred values for $k_S(t_S)$ in Table 6.

The calculation of $k_S(t_S)$, the prelaunch SRBC coefficient in Eq. (14), is an analog of the calculation of $k_L(t_0)$, the on-orbit radiance calibration coefficient in Eq. (8). For both calculations, the DNs are corrected for the Earth–Sun distance and the cosine of the solar zenith angle. For Eq. (8), these corrections are part of the derivation of $DN_D(t_0)$.[1] For Eq. (14), these corrections are separate from $DN_C(t_S)$. For both sets of DNs, the gain ratio corrections provide the equivalent DN values for electronic gain 1, the electronic gain for Earth observations. Both calculations use the same solar model, and both use the same values for the reflectance of the onboard diffuser, that is, $F_D(t_S)$ is the same as $F_D(t_0)$.

However, the prelaunch SRBC requires a correction for the atmospheric attenuation of the solar flux $T_B(t_S)$, whereas the on-orbit radiance calibration does not. This is the principal difference in the calculation of the two calibration coefficients. The estimated uncertainty for the measurements of $T_B(t_S)$ is 3%.[13] A comparison of the two calibration coefficients is shown in Fig. 3. The differences of the values of $k_S(t_S)$ from $k_L(t_0)$ average -0.6%, and all the differences are well within the 3% estimated uncertainty for the atmospheric attenuation measurements.

6. Prelaunch Laboratory Radiance-Based Calibrations

In 1993, SeaWiFS was calibrated by the instrument manufacturer, Hughes Santa Barbara Research Center (now Raytheon Santa Barbara Remote Sensing). SeaWiFS was calibrated at the instrument manufacturer's facility by use of a large-aperture integrating sphere (the SIS100) with an internal barium sulfate coating that was illuminated by sets of lamps with wattages of 5, 45, and 200 W. Six lamp combina-

Table 6. Derived Values of $k_S(t_S)$ from the Prelaunch SRBC of SeaWiFS (units of $mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}\ DN^{-1}$)[a]

SeaWiFS Band	Calibration Coefficient $k_S(t_S)$: Neckel and Labs[b]	Wehrli[c]	MODTRAN[d]	Thuillier *et al.*[e]
1	0.013548	0.013531	0.013983	0.013708
2	0.013287	0.013268	0.013305	0.013340
3	0.010278	0.010262	0.010403	0.010416
4	0.008892	0.008879	0.008922	0.008877
5	0.007319	0.007307	0.007389	0.007229
6	0.004071	0.004067	0.004085	0.004012
7	0.002866	0.002861	0.002876	0.002868
8	0.002120	0.002104	0.002057	0.002064

[a]The calibration coefficients are calculated by Eq. (14) and the constants in Tables 1 and 5. There is one coefficient for each SeaWiFS band and each solar irradiance model. The preferred calibration coefficients are those derived from the model of Thuillier *et al.*[20]
[b]Ref. 14.
[c]Refs. 16 and 17.
[d]Refs. 18 and 19.
[e]Ref. 20.

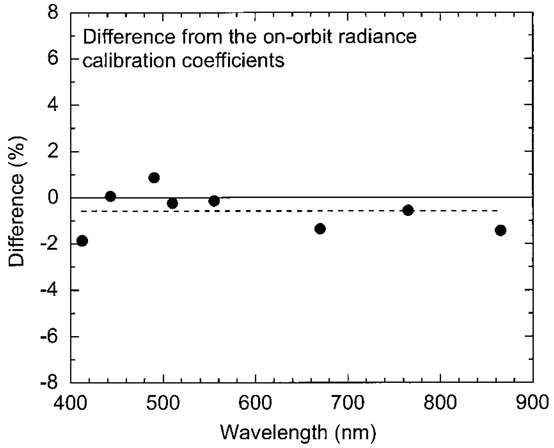

Fig. 3. Percent differences from the on-orbit radiance calibration coefficients for SeaWiFS. The differences of the prelaunch SRBC coefficients are shown as circles. The dashed line gives the average value for the eight differences. Both sets of coefficients use the solar irradiance model of Thuillier *et al.*[20] in their calculation.

tions were used for the calibration of SeaWiFS.[27] The sphere was calibrated for radiance by the manufacturer by use of a quartz–halogen standard irradiance lamp with a calibration traceable to the National Institute of Standards and Technology (NIST) and a halon diffuse reflecting plaque with a known 0°/45° BRF. This combination produces a source of known spectral radiance. A modified Cary-14 spectroradiometer viewed the lamp–diffuser source and compared the measured detector output with that measured while viewing the SIS100. For each band, the net DNs, that is, the numbers after correction for zero offset, were combined with the calculated band-averaged spectral radiances to provide the calibration coefficients. The band-averaged spectral radiances were calculated by use of the spectral responses of the SeaWiFS bands and the spectral radiance curves for the SIS100 lamp levels. This calculation process is explained in detail in a recent measurement comparison by the Earth Observing System Calibration Program.[28]

Table 7. Calibration Coefficients from the Two Prelaunch Laboratory Radiance-Based Calibrations of SeaWiFS (units of mW cm^{-2} sr^{-1} μm^{-1} DN^{-1})[a]

SeaWiFS Band	1993 Laboratory Calibration $k_{1993}(t_0)$	1997 Laboratory Calibration $k_{1997}(t_0)$
1	0.014201	0.013845
2	0.013541	0.013423
3	0.010655	0.010698
4	0.009189	0.009213
5	0.007483	0.007615
6	0.004226	0.004360
7	0.003013	0.003110
8	0.002136	0.002223

[a]Both calibrations were made with integrating spheres as radiance sources. The coefficients from the 1997 calibration, $k_{1997}(t_0)$, are the official prelaunch calibration coefficients for the instrument.[11]

The coefficients from the 1993 SRBC prelaunch calibration of SeaWiFS, $k_{1993}(t_0)$, are listed in Table 7. Uncertainty estimates for these coefficients were not provided by the instrument manufacturer. However, a radiometric accuracy of 5% ($k = 1$) was part of the SeaWiFS performance specifications,[2] and this value is carried as the estimate of the uncertainty in the 1993 calibration.

The 1997 calibration of SeaWiFS[26] was performed by scientists from NIST and from the SeaWiFS Project. A second calibration was considered prudent because of the delay in the completion of the spacecraft bus and in the launch of the instrument. This was performed at the facility of the spacecraft manufacturer, Orbital Sciences Corporation. For this calibration, radiances were provided by an integrating sphere from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC). The calibration and characterization of the GSFC sphere was performed at NIST in 1995.[29] The calibration standard was a gas-filled tungsten ribbon lamp that was itself calibrated for spectral radiance at the Facility for Automated Spectroradiometric Calibrations[30] at NIST. During the 1995 NIST calibration of the sphere, measurements of the sphere spectral radiance were made with the SeaWiFS Transfer Radiometer (SXR), which was designed, fabricated, and characterized for the SeaWiFS Project by NIST.[31] For the 1997 calibration of SeaWiFS, measurements of the sphere spectral radiance were repeated with the SXR. The differences between the 1995 and the 1997 measurements by the SXR were used to determine the changes in the output of the GSFC sphere over that period of time. There is an uncertainty in these changes that comes from use of the SXR as a transfer radiometer for measurements of the same source over time. This is incorporated into the estimated uncertainties for the calibration.[26]

The coefficients from the 1997 NIST prelaunch calibration of SeaWiFS, $k_{1997}(t_0)$, are listed in Table 7. These are the official prelaunch calibration coefficients for the instrument.[11] The uncertainties for these coefficients are 3.0, 2.0, 1.6, 1.3, 1.3, 1.2, 1.4, and 1.8% ($k = 1$) for bands 1–8, respectively.[26]

7. Revised At-Launch Radiance Calibration Coefficients

With the inclusion of the on-orbit radiance calibration coefficients $k_L(t_0)$ from Section 4, SeaWiFS has three possible sets of calibration coefficients for the start of on-orbit operations. The others are the 1993 prelaunch laboratory radiance calibration coefficients $k_{1993}(t_0)$[27] and the 1997 prelaunch laboratory coefficients $k_{1997}(t_0)$.[26] Each of these sets requires use of the transfer-to-orbit experiment[13] to show that the prelaunch calibration of the instrument and diffuser did not change, at the 3% level, during the insertion of the instrument into orbit. The on-orbit radiance calibration coefficient $k_L(t_0)$ also requires

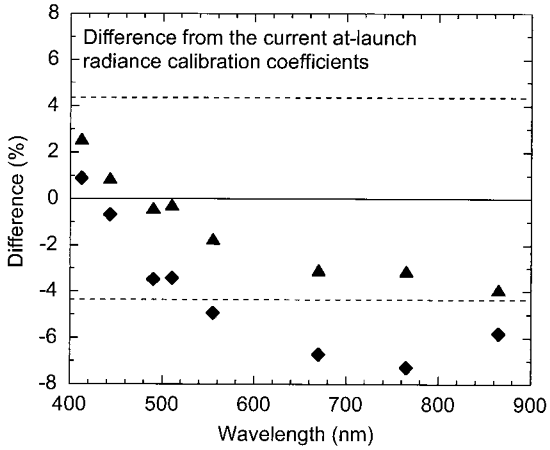

Fig. 4. Percent differences from the 1997 prelaunch calibration coefficients for SeaWiFS. The 1997 prelaunch coefficients are the current at-launch calibration coefficients for the instrument. The dashed lines give the estimated uncertainty ($k = 1$) for the on-orbit calibration of SeaWiFS. The differences of the on-orbit radiance calibration coefficients are shown as diamonds. The differences of the 1993 laboratory calibration coefficients are shown as triangles.

Table 8. Calculation of the Revised At-Launch Radiance Calibration Coefficients $k_{L*}(t_0)$[a]

SeaWiFS Band	$k_L(t_0)$	1993 Laboratory Calibration $k_{1993}(t_0)$	1997 Laboratory Calibration $k_{1997}(t_0)$	$k_{L*}(t_0)$
1	0.013969	0.014201	0.013845	0.014005
2	0.013332	0.013541	0.013423	0.013432
3	0.010325	0.010655	0.010698	0.010559
4	0.008898	0.009189	0.009213	0.009100
5	0.007239	0.007483	0.007615	0.007446
6	0.004067	0.004226	0.004360	0.004218
7	0.002884	0.003013	0.003110	0.003002
8	0.002094	0.002136	0.002223	0.002151

[a]These values are the averages of the on-orbit [$k_L(t_0)$] and the two prelaunch [$k_{1993}(t_0)$ and $k_{1997}(t_0)$] coefficients. The on-orbit coefficients come from Table 4, and the prelaunch coefficients come from Table 7. The units for the coefficients are mW cm^{-2} sr^{-1} μm^{-1} DN^{-1}.

the inclusion of a solar model to convert the reflectance measurements of the instrument into radiance, and the model of Thuillier *et al.*[20] is used here. As of the current reprocessing of the SeaWiFS data set (July 2002), the 1997 prelaunch calibration still provides the official at-launch radiance calibration coefficients for the instrument.

Figure 4 shows the differences of the calibration coefficients $k_L(t_0)$ and $k_{1993}(t_0)$ from the currently used coefficients $k_{1997}(t_0)$ for the eight SeaWiFS bands. Figure 4 also includes the estimated uncertainty ($k = 1$) for the SeaWiFS top-of-the-atmosphere radiances.[11] For the 1993 prelaunch calibration, the differences of all eight coefficients from the $k_{1997}(t_0)$ values fall within the $k = 1$ uncertainty. For the on-orbit radiance calibration, the differences of four coefficients fall within the $k = 1$ uncertainty, and the differences of all eight coefficients fall within the $k = 2$ uncertainty. However, there is a definite wavelength dependence to the differences in Fig. 4, even though all of them fall within the $k = 2$ estimate.

The selection of a calibration coefficient is a matter of individual (or group) discretion. This is one definition of the term arbitrary. When there is no compelling reason to prefer one calibration to the others, it is prudent to combine the results from the three calibrations. This ameliorates the effects of systematic errors in any of the calibrations. Such a combination is provided here as a revised set of at-launch calibration coefficients for the eight SeaWiFS bands. The combination is a simple, unweighted average of the three sets of coefficients $k_{1993}(t_0)$, $k_{1997}(t_0)$, and $k_L(t_0)$. The revised coefficients $k_{L*}(t_0)$ are listed in Table 8. The differences of the revised coefficients from the current (July 2002 reprocessing) coefficients are shown in Fig. 5(a). For all eight bands, the differences of the revised coefficients fall within the $k = 1$ uncertainty for the current the top-of-the-atmosphere values. Also, for all eight bands the revised coefficients are close to those for the 1993 laboratory calibration.

There are measurements that support (validate) the selection of the revised calibration coefficients. The first are the measurements from the vicarious calibration of SeaWiFS.[10] In this calibration, the SeaWiFS top-of-the-atmosphere radiances are adjusted to force agreement with the water-leaving radiances from MOBY. This calibration requires the application of an atmospheric model[10] and provides a calibration of the instrument–atmospheric correction system. The vicarious calibration covers the six SeaWiFS bands from 412 to 670 nm. For SeaWiFS, this is the calibration used in the derivation of the ocean color data products. For SeaWiFS land and atmosphere products, the vicarious calibration is not applied.[11] It is the independence of the vicarious calibration that allows its use to validate the selection of the on-orbit radiance coefficients. The terms from the vicarious calibration are given as fractional correction factors, with values of unity giving no correction. Figure 5(b) shows the vicarious calibration coefficients from the July 2002 SeaWiFS reprocessing converted to percent difference from unity. This gives the percent difference, at each wavelength, of the vicarious calibration from the $k_{1997}(t_0)$ calibration. The wavelength-dependent trends in Figs. 5(a) and 5(b) show strong similarities, albeit with scatter in Fig. 5(b) at 490 and 555 nm. Overall, there is significantly better agreement between the vicarious calibration and the revised coefficients $k_{L*}(t_0)$ than between the vicarious calibration and the $k_{1997}(t_0)$ coefficients.

The second set of measurements comes from the Southern Ocean band 8 gain study.[11] In the near infrared, there is a vicarious calibration of the SeaWiFS 765-nm band (band 7), relative to the 865-nm band (band 8), based on the type of atmospheric aerosol at the MOBY site.[10] However, there is no vicar-

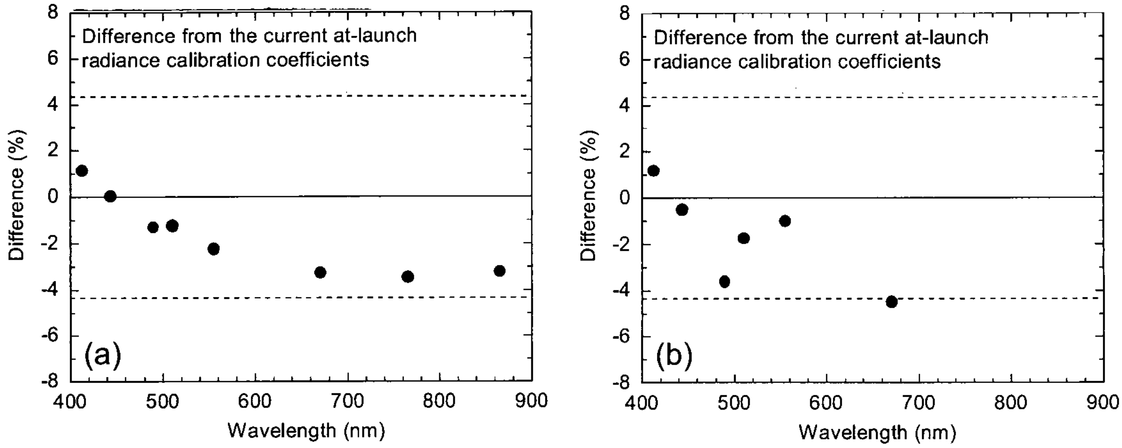

Fig. 5. Percent differences from the 1997 prelaunch calibration coefficients for SeaWiFS. The 1997 prelaunch coefficients are the current at-launch calibration coefficients for the instrument. The dashed lines give the estimated uncertainty ($k = 1$) for the on-orbit calibration of SeaWiFS. (a) Differences of the revised at-launch coefficients. The revised coefficients are the average of the 1993 prelaunch calibration, the 1997 prelaunch calibration, and the on-orbit radiance calibration. (b) Differences of the vicarious calibration coefficients. These coefficients are derived by use of water-leaving radiances from MOBY as surface-truth values (see text for details).

ious calibration of the SeaWiFS 865-nm band. In an effort to investigate the calibration of band 8 (865 nm), the SeaWiFS Project undertook a study of the Southern Ocean,[11] a region where, at times, the atmosphere can be essentially aerosol free. For cloud-free regions of the Southern Ocean with low chlorophyll amounts and no atmospheric aerosols, the top-of-the-atmosphere radiance from SeaWiFS band 8 should equal the radiance from molecular scattering in the atmosphere. When compared with this assumption, the measurements showed the maximum fractional miscalibration of band 8 to be between 5% and 6%, with the instrument producing radiances that are too large.[11] The revised calibration coefficient for SeaWiFS band 8 reduces the top-of-the-atmosphere radiances by 3.2%. These results are consistent with the assumption that the revised calibration coefficients provide an improvement to the current coefficients, even though the changes are within the $k = 1$ uncertainty for the current SeaWiFS-measured radiances.

8. Concluding Remarks

The reflectance-based calibration of SeaWiFS[1] provides the basis for a radiance-based calibration of the instrument in the same manner as other sensors that use onboard diffusers as flight standards, such as MODIS[3] and the Global Imager.[4] For each of these instruments, a solar irradiance model is required to obtain the reference radiances for the calibration coefficients. Here, the model of Thuillier *et al.*[20] is preferred. However, the SeaWiFS Project also has two prelaunch laboratory calibrations of the instrument. One of them, the 1997 prelaunch calibration,[26] provides the current (July 2002 reprocessing) calibration coefficients, and those coefficients have not changed from the launch of SeaWiFS in August 1997 to the current reprocessing of the data set.

A revised at-launch calibration for SeaWiFS is proposed here, based on an unweighted average of the three instrument calibrations now in existence. The revised coefficients are listed in Table 9. They agree

Table 9. Calculation of the Revised At-Launch Reflectance Calibration Coefficients $k_{F*}(t_0)$[a]

SeaWiFS Band	Revised At-Launch Radiance Coefficient $k_{L*}(t_0)$ (mW cm^{-2} sr^{-1} μm^{-1} DN^{-1})	Band-Averaged Solar Irradiance $E_{M,B}$ (mW cm^{-2} μm^{-1})	Revised At-Launch Reflectance Coefficient $k_{F*}(t_0)$ (sr^{-1} DN^{-1})
1	0.014005	172.81	0.0000810
2	0.013432	190.20	0.0000706
3	0.010559	196.26	0.0000538
4	0.009100	188.02	0.0000484
5	0.007446	183.06	0.0000407
6	0.004218	151.15	0.00002791
7	0.003002	122.29	0.00002455
8	0.002151	96.19	0.00002236

[a]These coefficients are calculated as the revised at-launch radiance coefficients $k_{L*}(t_0)$ divided by the solar irradiances $E_{M,B}$. The irradiances come from Thuillier *et al.*[20]

with the current values to within the estimated uncertainty ($k = 1$) for the SeaWiFS top-of-the-atmosphere radiances. The differences range from 1.2% (revised coefficient higher) for SeaWiFS band 1 to 3.5% (revised coefficient lower) for SeaWiFS band 7. The differences are shown in Fig. 5(a).

The creation of the revised SeaWiFS radiance-based calibration coefficients has an impact on the reflectance-based coefficients for the instrument because the radiance and reflectance calibrations are connected by the solar irradiance, as shown in Eq. (8). This connection is applied in Table 9, where the revised radiance calibration coefficients $k_{L^*}(t_0)$ are combined with the band-averaged solar irradiances from Thuillier *et al.*[20] to calculate the revised reflectance coefficients for SeaWiFS, $k_{F^*}(t_0)$. This step is necessary to provide a consistency in the radiance and reflectance calibrations of the instrument. Overall, the revised reflectance-based calibration coefficients $k_{F^*}(t_0)$ are larger than the corresponding coefficients from Ref. 1. However, they differ by less than the uncertainty for the measured top-of-the-atmosphere reflectances, which is estimated to be between 4 and 5% ($k = 1$).[1] The increases in the reflectance calibration coefficients are 0.2, 0.7, 2.3, 2.3, 3.0, 3.7, 4.1, and 2.7% for bands 1–8, respectively. They propagate directly into revised values for the instrument's at-launch diffuser BRDFs.

This research was supported by the SeaWiFS Project under NASA contract NAS5-00141 (R. A. Barnes) and by the SIMBIOS (Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies) Project under NASA contract NAS5-00197 (E. F. Zalewski).

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