DISCLAIMER

This draft chapter is a work in progress and is being provided to the public for information purposes only. Because it is a work in progress, there are parts that are either missing or will be revised, and the page numbers will change. Permission to cite any part of this work must be obtained from the prime author. The final version of this chapter will be published in Volume 9 of the *SeaWiFS Postlaunch Technical Report Series*.

Chapter 6

MOBY Data Analysis for the Vicarious Calibration of SeaWiFS Bands 1–6

Robert E. Eplee, Jr.
SAIC General Sciences Corporation, Beltsville, Maryland
Charles R. McClain
NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract

The SeaWiFS CVT performs the vicarious calibration of SeaWiFS by comparing normalized water-leaving radiances retrieved by SeaWiFS with contemporaneous measurements of normalized water-leaving radiances from the Marine Optical Buoy (MOBY). The procedures and results of the vicarious calibration are described in this chapter.

6.1 INTRODUCTION

Variations in the radiometric response of the eight SeaWiFS bands with time, and uncertainties in the atmospheric correction algorithm, require a mission-long vicarious calibration program to monitor the performance of the sensor system [instrument plus atmospheric correction algorithm, Evans and Gordon (1994)] to meet the radiometric constraints on the ocean color data set (McClain et al. 1992 and 1998). The CVT of the SeaWiFS Project is monitoring the temporal stability of the on-orbit calibration of the instrument with a time series of lunar calibration data (Eplee and Barnes 2000a). The CVT is using data from the NASA/NOAA Marine Optical Buoy (MOBY) (Clark et al. 1997), deployed off of Lanai, Hawaii, for the vicarious calibration of SeaWiFS bands 1–6.

The CVT has performed the vicarious calibration of SeaWiFS by comparing normalized water-leaving radiances, L_{WN}, (Gordon and Clark 1981) measured by MOBY with L_{WN} retrieved by SeaWiFS from contemporaneous overflight images of the buoy site. The vicarious calibration adjusts the prelaunch calibration gains to minimize the difference between SeaWiFS and MOBY L_{WN} in bands 1–6. Because no methodology has been developed to vicariously calibrate bands 7 and 8, the gains for these bands are adjusted to optimize the atmospheric correction in the vicinity of MOBY (Robinson and Wang 2000). The vicarious calibration is independent of the time correction derived from the lunar calibrations (Eplee and Barnes 2000). The CVT has derived a set of system gains which, when applied to the SeaWiFS calibration, yields values for L_{WN} measured by SeaWiFS and MOBY that agree to better than 1%. These gains are defined in a simplified version of the SeaWiFS level-1b calibration equation:

$$\begin{aligned} L_S(\lambda) \; = \; & \big(C_{\text{out}}(\lambda) - C_{\text{dark}}(\lambda)\big)\, K_1(g,d,\lambda) \\ & \times \; K_2(\lambda)\,\alpha(\lambda)\,\big[\beta(\lambda) \; + \; \gamma(\lambda) \\ & \times \; (t \; - \; t_o) \; + \; \delta(\lambda)\,(t - t_o)^2\big] \end{aligned} \quad , \qquad (1)$$

where:

- λ is the wavelength of measurement;
- L_S is the calibrated at-sensor radiance;
- C_{out} is the counts from sensor output data;
- C_{dark} is the median value of dark count from sensor output data;
- K_1 is the counts to radiance conversion factor (calibration coefficient);
- g is the gain;
- d is the detector;
- K_2 is the additional calibration factors;
- α is the vicarious gain;
- β is the constant term in temporal correction;
- γ is the linear (in time) term in temporal correction;
- δ is the quadratic (in time) term in temporal correction;
- t is the time tag of sensor output data; and
- t_o is the reference time for temporal correction.

The reference time for the temporal correction is the time tag of the first SeaWiFS on-orbit image, which was obtained on 4 September 1997 at 16:26:30 UT. The full level-1b calibration equation is presented in Eplee and Barnes (2000).

In some of the SeaWiFS level-1a data sets, the dark count for particular scan lines may have spuriously high values. In addition, the dark count radiance for some bands is midway between two digitization levels. These two effects can give rise to striping in the level-2 products. To avoid this striping, for each band, the median value of the dark counts over each scene is computed and subtracted from each scan line in that scene.

The determination of the temporal correction factors is presented in Eplee and Barnes (2000) and discussed in Barnes et al. (1999a). The vicarious calibration strategy employed by the CVT assumes that the temporal corrections to the instrument calibration yield stable top-of-the-atmosphere radiances from SeaWiFS. This paper discusses the current strategy employed by the CVT to determine the vicarious gains, α, for each band.

6.2 NEAR-INFRARED CALIBRATION

Beacause open ocean reflectances are low (≈2%), approximately 90% of the top-of-the-atmosphere signal observed by SeaWiFS over the oceans is due to Rayleigh scattering of sunlight and to aerosol radiance within the atmosphere. The SeaWiFS atmospheric correction algorithm must remove this atmospheric signal to yield the water-leaving radiances. The algorithm estimates the aerosol radiance (L_A) for bands 7 and 8 and extrapolates to L_A in the other SeaWiFS bands using the ratio of L_A in band 7 to that in band 8 (Gordon and Wang 1994). This ratio is called ϵ [$\epsilon(765, 865)$]. Currently, the vicarious gain for band 8 is defined to be unity. The calibration of band 7 is accomplished by adjusting the gain for band 7 so that the ϵ value has the expected value for a set of open-ocean scenes in the vicinity of MOBY. This procedure is discussed in Robinson and Wang (2000). The gain for band 7 derived for the vicarious calibration discussed in this paper is 0.946.

6.3 VISIBLE BAND CALIBRATION

In performing the vicarious calibration, the CVT has produced a matchup data set of simultaneous observations of L_{WN} from SeaWiFS and MOBY. The current vicarious calibration data set contains 125 matchups spanning an 862 day time range from 19 September 1997 through 13 March 2000.

6.3.1 SeaWiFS Data Selection

The SeaWiFS observations are mean water-leaving radiances (L_W) computed for 3×3 pixel regions centered on the pixel containing MOBY, where at least five pixels in the region pass the exclusion criteria:

a) Land;
b) Clouds and ice;
c) Sun glint;
d) Stray light;
e) Total radiance above the knee of the bilinear gain;
f) Low water-leaving radiance in band 5;
g) Atmospheric correction algorithm failure;
h) Scan angle greater than 45°;
i) Satellite zenith angle greater than 56°;
j) Solar zenith angle greater than 70°;
k) Turbid water;
l) Coccolithophore; and
m) Aerosol optical depth in band 8 greater than 0.1.

These criteria are based on standard quality control masks and flags, computed on a pixel-by-pixel basis. It should be noted that some of these criteria are not directly applicable to observations obtained around MOBY, such as turbid water and coccolithophores, but are included to maintain consistency with other SeaWiFS matchup analyses such as Bailey et al. (2000). Sun glint in the SeaWiFS scenes can be interpreted by the atmospheric correction algorithm as aerosol radiance. To avoid sun glint contamination of the matchup data, an upper limit of 0.1 is set on the aerosol optical depth in band 8 for valid SeaWiFS retrievals. The imposition of this limit results in the loss of several matchup scenes during the summer.

Alternative statistical measures to the mean value, which have been considered for determining the optimum value of L_W in a scene, include the median value of the pixels, the value of the central pixel, and the mode of the pixels. The median value can be affected by outliers. Because the standard deviation of the mean is typically small, the central pixel does not provide a better value than the mean. The mode may provide the best estimate of L_W, but it is difficult to compute for nine pixels. Consequently, the mean value is used in the vicarious calibration.

The mean L_W are converted to L_{WN} for the matchup comparison as discussed in Sect. 6.3.3. The time series of mean SeaWiFS L_{WN} for the matchup scenes are plotted in Fig. 1. The primary source of noise in the plots is the variation in the atmospheric correction of the SeaWiFS data.

6.3.2 MOBY Data Selection

MOBY measures downwelling irradiances and upwelling radiances over the wavelength range of 340–900 nm at a subnanometer resolution with two spectrometers coupled by a dichroic beamsplitter. The beamsplitter gives the blue spectrometer a bandpass of 340–600 nm and the red spectrometer a bandpass of 630–900 nm. The potential for stray light is greatly reduced by splitting the visible spectrum at the beginning of the water absorption region, because most of the short wavelength energy is diverted from the entrance slit of the long wavelength spectrometer. The splitting also allows the spectrometers to be optimized, in terms of free spectral range and integration times, for the two distinctive spectral domains.

The MOBY observations are mean water-leaving radiances measured over 30 min intervals centered on local noon, the satellite overpass time. In-water measurements are made at depths of 2, 5, and 9 m. These measurements are used to compute diffuse attenuation coefficients at each depth and thus, to derive L_W at the surface. Surface irradiance (E_S) measurements are also made. In order for the MOBY spectra to be considered valid, the diffuse attenuation coefficients computed for each depth must be consistent with each other. The calibrated MOBY spectra are convolved with the SeaWiFS relative spectral response functions for use in the matchup analysis. The processed MOBY data for a given day includes L_W for bands 1–6 and E_S for bands 1–8. Estimates of E_S from the subsurface data are currently not provided.

High calibration accuracy for the MOBY data requires that the buoy in the water is swapped out for refurbishment and recalibration approximately every three months. To ensure continuous data, the MOBY Project maintains two buoys, one in the water and one undergoing refurbishment. The current vicarious calibration uses matchup data from seven MOBY deployments. The mean L_W is converted to L_{WN} for the matchup comparison as discussed in Sect. 6.3.3. The time series of MOBY L_{WN} are plotted in Fig. 2. The plots show that the MOBY data are stable from one deployment to the next.

Shortly after the launch of SeaWiFS, the above-water E_S detector on MOBY failed. The E_S measurements from MOBY for October and November of 1997 are invalid. This failure is one of the reasons that the CVT uses computed E_S rather than measured E_S for estimating MOBY L_{WN} values in the matchup comparisons of the vicarious calibration.

6.3.3 Match-up Analysis

In performing the vicarious calibration, the CVT evaluated matchups of L_{WN} between SeaWiFS and MOBY. Initially, SeaWiFS retrievals of L_{WN} were compared with L_{WN} computed from MOBY measurements of L_W and E_S:

$$L_{WN}(\lambda) \; = \; \frac{L_W(\lambda,\theta_0)}{E_S(\lambda,\theta_0)} F_0(\lambda), \tag{2}$$

where F_0 is the solar constant and θ_0 is the solar zenith angle. Because of problems with the E_S measurements, such as the detector failure mentioned above, this approach was not used in the matchup analysis.

For the match-up analysis, L_{WN} were computed from the SeaWiFS retrievals of L_W and from the MOBY measurements of L_W by using the atmospheric diffuse transmittance, $t(\lambda,\theta_0)$:

$$L_{WN}(\lambda) \; = \; \frac{L_W(\lambda,\theta_0)}{\cos(\theta_0)\, t(\lambda,\theta_0)}, \tag{3}$$

where $t(\lambda,\theta_0)$ is defined as:

$$t(\lambda,\theta_0) \; = \; \exp\left[\frac{-\big(0.5\tau_r(\lambda) \; + \; \tau_{\rm oz}(\lambda) \; + \; K\big)}{\cos(\theta_0)}\right], \tag{4}$$

where:

- τ_r is the computed Rayleigh optical thickness;
- $\tau_{\rm oz}$ is the ozone optical thickness from the SeaWiFS ancillary data; and
- K is the aerosol effects (0.0054) estimated for an aerosol optical thickness of 0.1 and the maritime aerosol model for 90% relative humidity.

The approximation of the aerosol effects with a value independent of wavelength is made because L_A has only a weak dependence on wavelength for the maritime aerosol model. SeaWiFS retrievals of L_{WN} can be compared directly with the L_{WN} computed from the MOBY data using (3). However, the vicarious calibration is based on the computation of L_{WN} from L_W using (3) for both SeaWiFS and MOBY to minimize the uncertainties due to the approximations made in (3).

As a check on the L_{WN} matchup analysis, the comparisons were also performed for L_W. Because the MOBY observations are centered on the satellite overpass times, the L_W matchups yielded essentially the same results at the L_{WN} matchups, with equivalent levels of noise in the data.

In performing the vicarious calibration, the CVT adjusted the vicarious gains [$\alpha(\lambda)$ in (1)] to optimize the agreement between the L_{WN} retrieved by SeaWiFS with the L_{WN} measured by MOBY in each band. To avoid any residual seasonal variations in solar illumination, the ratios of the SeaWiFS values to the MOBY values were computed in each band for each scene. Because the distribution of the ratios of L_{WN} ($L_{WN}^{S:M}$) is more log-normal than normal, the vicarious gains were adjusted until the geometric mean of the ratios for each band was essentially unity. The results of the vicarious calibration shown in Table 1 and plotted in Fig. 3 as functions of time, were derived using an atmospheric correction algorithm which incorporates the near-infrared reflectance correction of Siegel et al. (2000). Other estimators of the $L_{WN}^{S:M}$ over the matchup scenes were considered, (the arithmetic mean, the median, and the mean of the center quartiles), but the use of these other estimators had negligible effect (<0.1%) on the vicarious gains.

The vicarious calibration of band 6 is difficult because of the low values of L_{WN} in this band. Several of the SeaWiFS scenes yield negative L_{WN} for band 6. Additionally, the calibration of MOBY over this band pass is problematic because of the crossover between the two spectrometers (D. Clark, pers. comm.). As a result, the matchups where negative L_{WN} occurred for band 6 were excluded from the vicarious calibration.

Figure 3 shows a number of matchups that are *outliers*. These outliers are defined to be individual matchup data points for any of bands 1–5 that deviate from the mean ratio in that band by more than two standard deviations. The CVT has attempted to determine why the outlier matchups plotted in these figures deviate so far from the mean $L_{WN}^{S:M}$ ratios. The CVT has looked for correlations

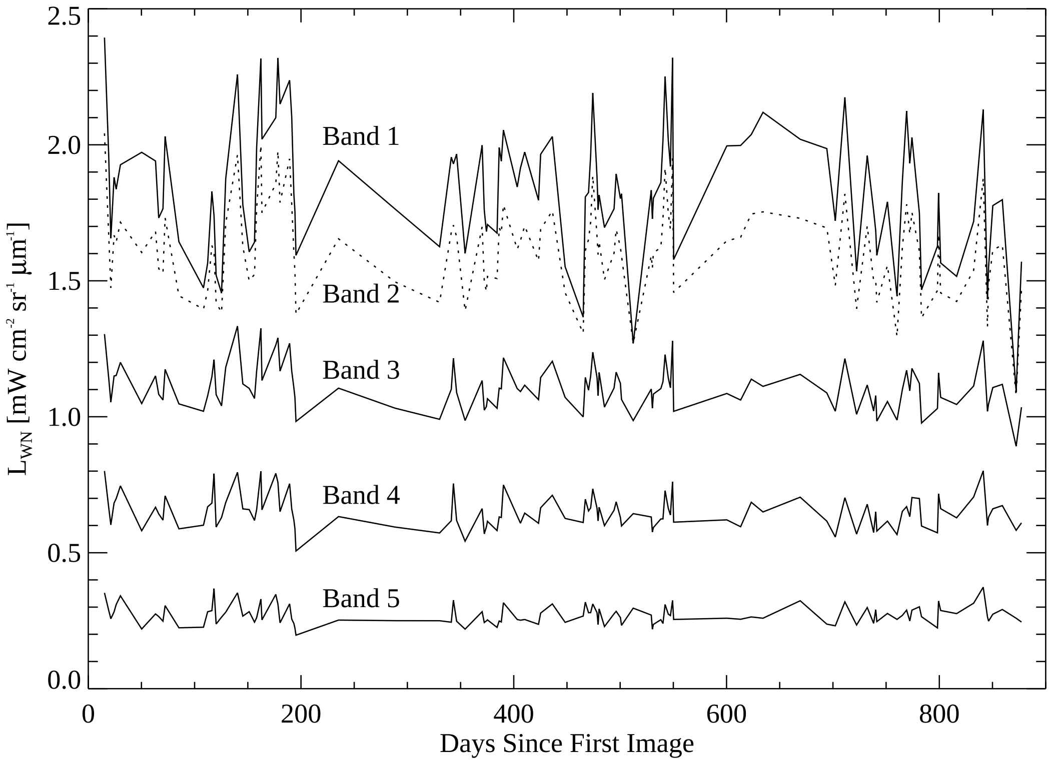


Fig. 1. SeaWiFS normalized water-leaving radiances for match-up scenes.

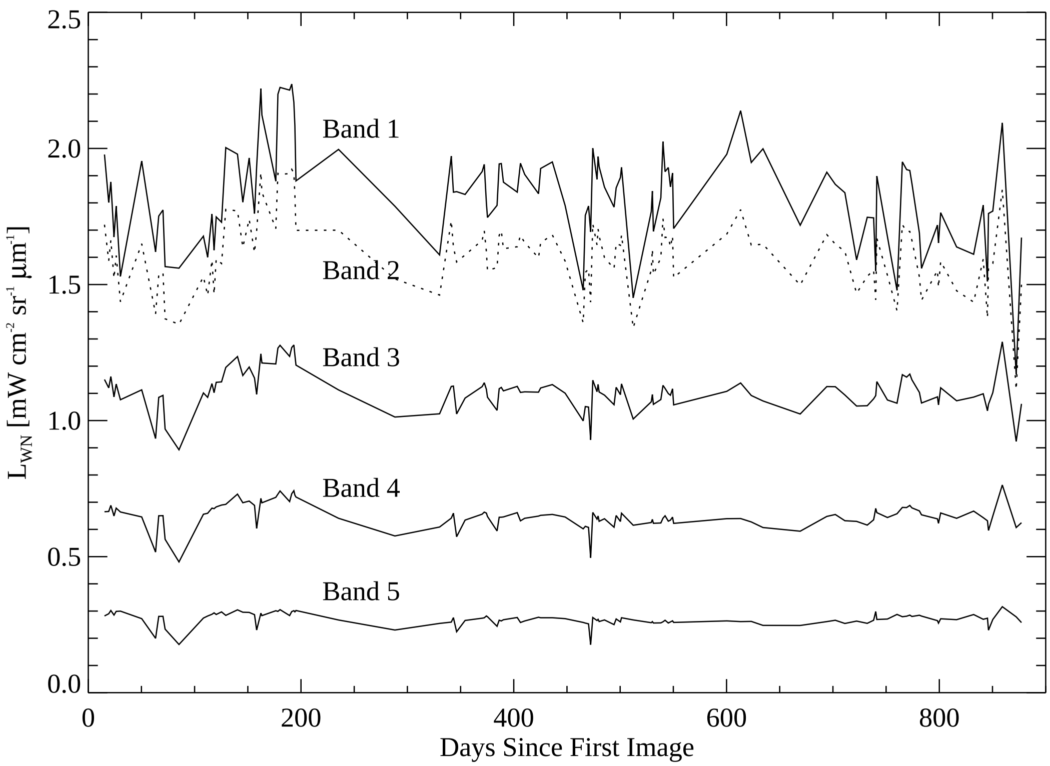
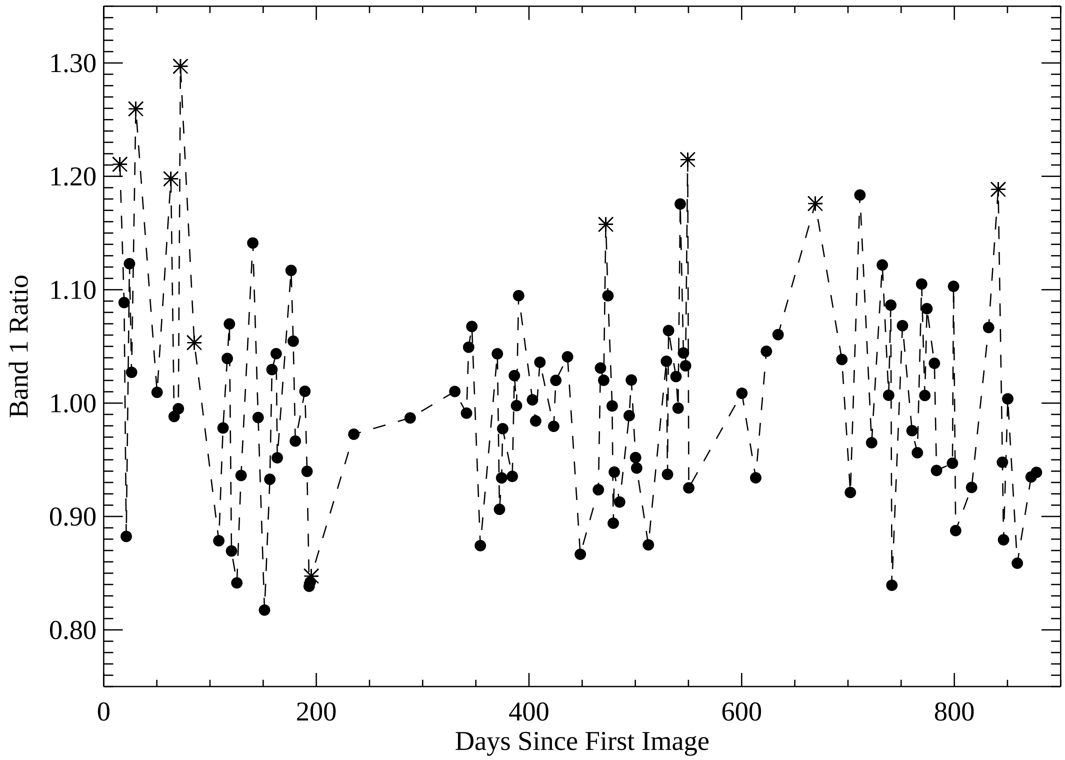


Fig. 2. MOBY normalized water-leaving radiances for match-up scenes.



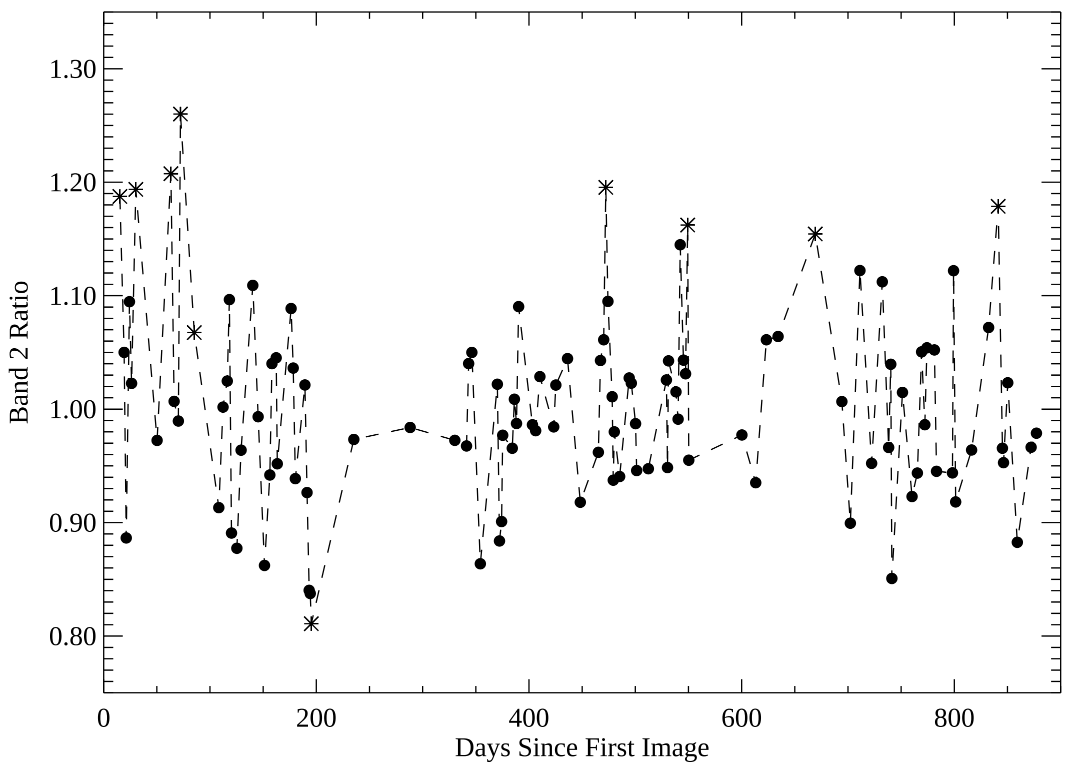
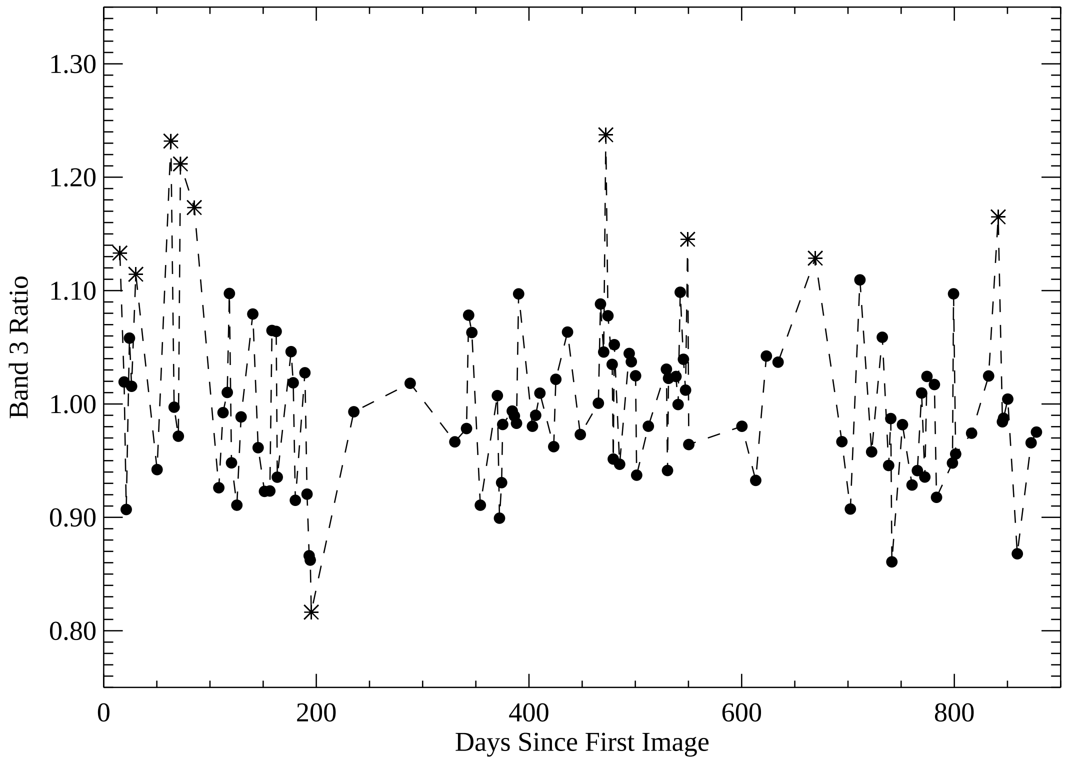


Fig. 3. Vicarious calibration matchups versus time.



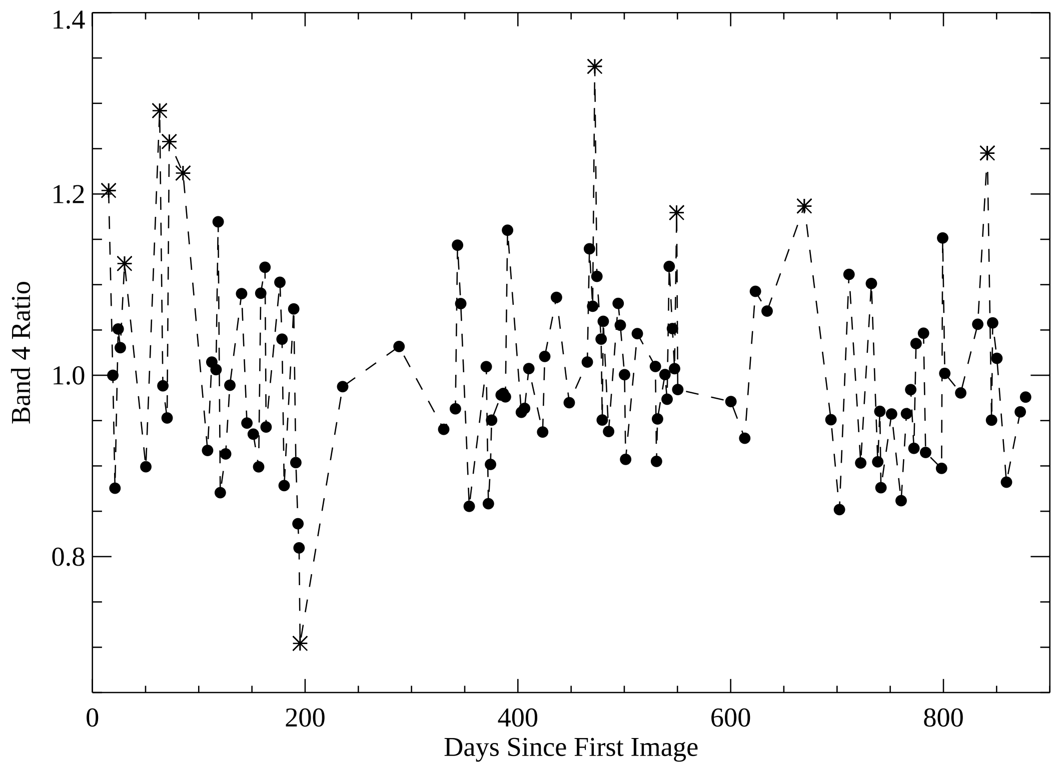


Fig. 3. (cont.) Vicarious calibration matchups versus time.

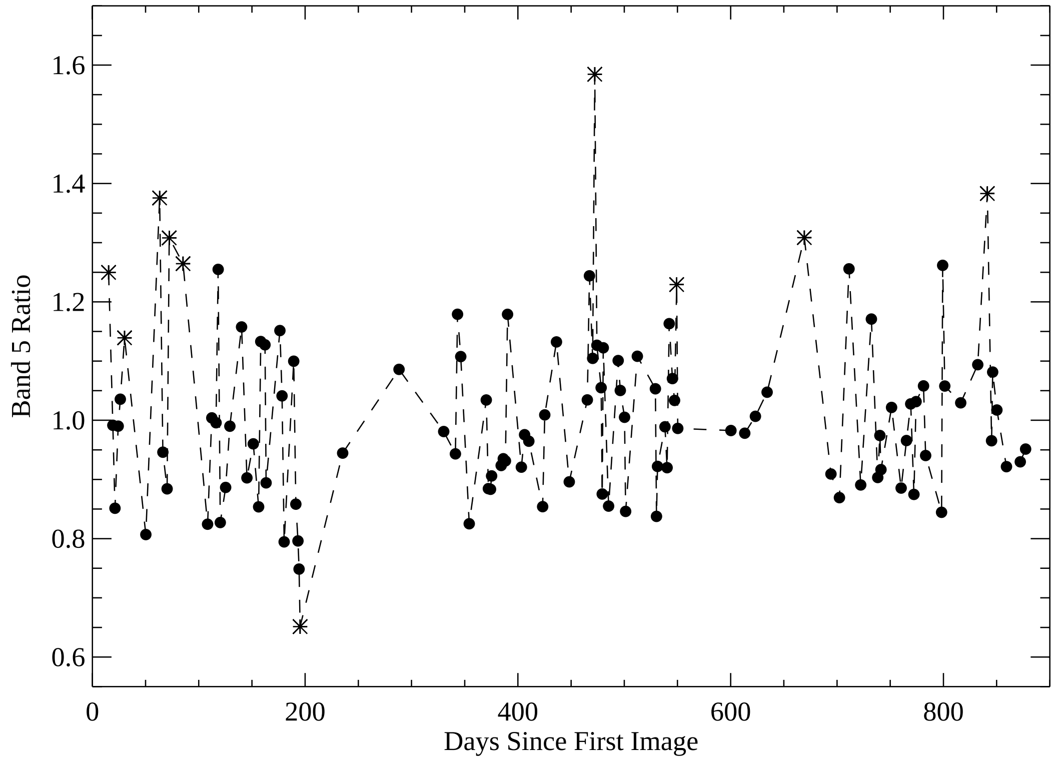


Fig. 3. (cont.) Vicarious calibration matchups versus time.

Table 1. Results of SeaWiFS vicarious calibration. The MOBY and SeaWiFS radiances are in units of $\mathrm{mW\,cm^{-2}\,sr^{-1}\,m^{-1}}$.

λ [nm]	*MOBY* *Radiance*	*SeaWiFS* Radiance	*Mean Ratio* (SeaWiFS/MOBY)	*Vicarious* Gain
412	1.8263525	1.8263380	0.9999204	1.00310
443	1.6133271	1.6133275	1.0000002	0.991158
490	1.1106925	1.1106931	1.0000005	0.959938
510	0.65016730	0.65016802	1.0000012	0.985839
555	0.27024732	0.27024714	0.99999934	0.993857
670	0.014412810	0.014454512	1.0069607	0.959650
765				0.946
865				1.000

between the outliers and solar zenith angles, spacecraft zenith angles, aerosol optical depth, ϵ value, chlorophyll concentration, local wind speed, and ozone concentration without success. The use of the geometric mean in estimating the $L_{WN}^{S:M}$ ratios allows the outlier matchups to be included in the vicarious calibration.

The matchup time series plotted in Fig. 3, excluding the outlier matchups, do not show any trends with time, which indicate the time corrections applied to bands 1, 2, 5, 6, 7, and 8 do not have any significant residual errors. Earlier during the mission, an error in the ratio of band 7:band 8 of 0.5% gave rise to a discernable error in the matchup time series. The matchups will be discussed as functions of scan angle in Eplee and McClain (2000).

6.4 DISCUSSION

The departure of the vicarious gains for bands 1–6 from unity are the result of uncertainties in the atmospheric correction algorithm, uncertainties in the laboratory calibration of SeaWiFS, and uncertainties in the laboratory calibration of MOBY. The uncertainty in the SeaWiFS calibration, as estimated by the vicarious gains, ranges from 1–4% depending on the band. This result is consistent with the uncertainty derived from the prelaunch recalibration of SeaWiFS (Johnson et al. 1999) and with the uncertainty derived from the calibration transfer-to-orbit experiment (Barnes et al. 1999b).

The time series of $L_{WN}^{S:M}$ matchups provides the CVT with a check on the time corrections applied to the individual bands. Currently, the time series show no significant residual errors. As the number of matchups increases with time, the accuracy of these checks will increase accordingly.

The latest set of vicarious gains should be applied to the SeaWiFS data in conjunction with the current SeaWiFS calibration table, which contains the temporal corrections for the instrument. The CVT will periodically update the vicarious calibration coefficients over the five-year SeaWiFS mission, e.g., at each reprocessing, as additional matchups become available.

REFERENCES

Barnes, R.A., A.W. Holmes, W.L. Barnes, W.E. Esaias, C.R. McClain, and T. Svitek, 1994: SeaWiFS Prelaunch Radiometric Calibration and Spectral Characterization. *NASA Tech. Memo. 104566, Vol. 23,* S.B. Hooker, E.R. Firestone, and J.G. Acker, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 55 pp.

Barnes, R.A., R.E. Eplee, Jr., F.S. Patt, and C.R. McClain, 1999a: Changes on the radiometric sensitivity of SeaWiFS. *Appl. Opt.,* **38,** 4,649–4,664.

Barnes, R.A., R.E. Eplee, Jr., S.F. Biggar, K.J. Thome E.F. Zalewski, P.N. Slater, and A.W. Holmes, 1999b: The SeaWiFS Solar Radiation-Based Calibration and the Transfer-to-Orbit Experiment. *NASA Tech. Memo. 1999–206892, Vol. 5,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 28 pp.

Clark, D.K., H.R. Gordon, K.J. Voss, Y. Ge, W. Broenkow, and C. Trees, 1997: Validation of atmospheric correction over the oceans. *J. Geophys. Res.,* **102,** 17,209–17,217.

Eplee, R.E., Jr., and R.A. Barnes, 2000: "Lunar data analyses for SeaWiFS calibration." In: McClain, C.R., E.J. Ainsworth, R.A. Barnes, R.E. Eplee, Jr., F.S. Patt, W.D. Robinson, M. Wang, and S.W. Bailey, SeaWiFS Postlaunch Calibration and Validation Analyses, Part 1. *NASA Tech. Memo. 2000–206892, Vol. 9,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, ???–???.

Eplee, R.E., Jr., and C.R. McClain, 2000b: "Along-scan effects in SeaWiFS data." In: McClain, C.R., R.A. Barnes, R.E. Eplee, Jr., B.A. Franz, N.C. Hsu, F.S. Patt, C.M. Pietras, W.D. Robinson, B.D. Schieber, G.M. Schmidt, M. Wang, S.W. Bailey, and P.J. Werdell, 2000: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 2. *NASA Tech. Memo. 2000–206892, Vol. 10,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, ???–??? pp.

Evans, R.H., and H.R. Gordon, 1994: Coastal zone color scanner "system calibration": A retrospective examination. *J. Geophys. Res.,* **99,** 7,293–7,307.

Gordon, H.R., and D.K. Clark, 1981: Clear water radiances for atmospheric correction of coastal zone color scanner imagery. *Appl. Opt.,* **20,** 4,175–4,180.

Gordon, H.R., and M. Wang, 1994: Retrieval of water-leaving radiances and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm. *Appl. Opt.,* **33,** 443–452.

Johnson, B.C., E.E. Early, R.E. Eplee, Jr., R.A. Barnes, and R.T. Caffrey, 1999: The 1997 Prelaunch Radiometric Calibration of SeaWiFS. *NASA Tech. Memo. 1999–206892, Vol. 4,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 51 pp.

McClain, C.R., W.E. Esaias, W. Barnes, B. Guenther, D. Endres, S.B. Hooker, G. Mitchell, and R. Barnes, 1992: Calibration and Validation Plan for SeaWiFS. *NASA Tech. Memo. 104566, Vol. 3,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 41 pp.

McClain, C.R., M.L. Cleave, G.C. Feldman, W.W. Gregg, S.B. Hooker, and N. Kuring, 1998: Science quality SeaWiFS data for global biospheric research. *Sea Technol.,* **39,** 10–16.

Robinson, W.D., and M. Wang, 2000: "Vicarious calibration of SeaWiFS band 7." In: McClain, C.R., E.J. Ainsworth, R.A. Barnes, R.E. Eplee, Jr., F.S. Patt, W.D. Robinson, M. Wang, and S.W. Bailey, SeaWiFS Postlaunch Calibration and Validation Analyses, Part 1. *NASA Tech. Memo. 2000–206892, Vol. 9,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, ???–???.

Bailey, S.W., C.R. McClain, P.J. Werdell, and B.D. Schieber, 2000: "Normalized water-leaving radiance and chlorophyll *a* match-up analyses." In: McClain, C.R., R.A. Barnes, R.E. Eplee, Jr., B.A. Franz, N.C. Hsu, F.S. Patt, C.M. Pietras, W.D. Robinson, B.D. Schieber, G.M. Schmidt, M. Wang, S.W. Bailey, and P.J. Werdell, 2000: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 2. *NASA Tech. Memo. 2000–206892, Vol. 10,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, ???–??? pp.

Siegel, D.A., M. Wang, S. Maritorena, and W. Robinson, 2000: Atmospheric correction of satellite ocean color imagery: the black pixel assumption. *Appl. Opt.,* **39,** 3,582–3,591.