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Chapter 5

Vicarious Calibration of SeaWiFS Band 7

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ABSTRACT

A technique for calibrating the gain in the SeaWiFS band 7 is described in this chapter. The basic method for vicariously calibrating band 7 is presented and the details of its implementation are discussed. The technique has been found to provide a consistent estimate of the gain over the life of the SeaWiFS Project.

5.1 INTRODUCTION

This chapter describes the current method used to vicariously determine the gain factor to apply to the band 7 SeaWiFS radiances. Because of their negligible water-leaving radiance components, band 7, at 765 nm, is used in combination with band 8 at 865 nm to determine the aerosol optical properties of the air column (Gordon and Wang 1994b), from which the aerosol radiances in the remainder of the SeaWiFS bands can be deduced. Determining the band 7 gain properly is important so that all the other bands can be calibrated and used properly.

The problem of vicarious calibration of ocean color sensors was discussed by Gordon (1998), who proposed the following requirements for achieving good calibration:

1. The calibration should be made in a cloud-free air mass with a maritime aerosol having an optical thickness of less than 0.1.
2. It must also have uniform water-leaving radiances over the area.

In the case of band 7 (and 8), these requirements should be easily met, as long as highly turbid or high chlorophyll waters are avoided and clear areas are selected. Many of the quantities which need to be measured to properly perform the calibration are available in the form of SeaWiFS radiances and ancillary data. Specific knowledge of the aerosol type is not available, but this uncertainty is reduced in this work by using a region where the aerosol properties are well known.

Section 5.2 looks at the theory behind the calibration of band 7, Sect. 5.3 examines the validity of assuming band 8 has the correct calibration, and Sect. 5.4 discusses the technique for evaluating the gain in more detail, using the measurements available to the SeaWiFS Project. The results and conclusion of this analysis are then presented in Sects. 5.5 and 5.6.

5.2 THEORY

Gordon and Wang (1994b) derived a value, ϵ, as

$$\epsilon(\lambda, 865) = \frac{\rho_{as}(\lambda)}{\rho_{as}(865)}, \qquad (1)$$

which is a constant for any one type of aerosol atmosphere. The single scattering aerosol reflectance is ρ_{as}. Computations of ϵ have been made for a variety of aerosol types including oceanic, maritime, coastal, and tropospheric, and at a variety of relative humidities: 50%, 70%, 90%, and 99%. SeaWiFS bands 7 and 8 were chosen so that the $\epsilon(765, 865)$ could be computed. The equation for upwelling radiance through a clear atmosphere over the ocean is:

$$L_t = L_r + L_a + L_{ra} + TL_g + tL_{wc} + tL_w, \qquad (2)$$

where L_t is the total upwelling radiance, L_r is the Rayleigh radiance, L_a is the radiance arising from aerosol scattering, L_{ra} is the radiance arising from the interaction of molecular and aerosol scattering, TL_g is the glint radiance arising from the specular reflection of the sun off the water surface, tL_{wc} is the whitecap radiance, and tL_w is the water-leaving radiance. Note that T is the direct transmittance and t is the diffuse transmittance of the atmosphere. L_r can be determined accurately with a knowledge of the surface pressure (Gordon et al. 1988). Areas where the sun glint is significant can be predicted and avoided by viewing away from the point of specular reflection. The whitecap radiance can be well estimated at low wind speeds (Gordon and Wang 1994a) and can be avoided at higher wind speeds as the wind field is an available product. L_w at the 765 and 865 nm bands of SeaWiFS can be considered to be zero in nonturbid, low chlorophyll waters; thus, (2) can be simplified for bands 7 and 8 to:

$$L_t - L_r - tL_{wc} = L_a + L_{ra}. \qquad (3)$$

Gordon and Wang (1994b) determined a relationship between the term L_a+L_{ra} and the single scattering radiance, L_{as}, for the above mentioned aerosol models; thus, because L_r and tL_{wc} are known, the total radiance for bands 7 and 8 can be used in (1) to derive ϵ.

Over open ocean areas, it can be assumed that a maritime aerosol is usually present and thus, such a site has a known ϵ value. For sites like this, it is then possible to determine the gain in band 7 through a process of adjusting the gain until (1) produces a maritime ϵ value.

5.3 BAND 8 ACCURACY

The basic method described in Sect. 5.2 can be applied to SeaWiFS observations to determine the gain for band 7. Before this method is described, a tacit assumption was made that the gain in band 8 is already correct and if it is not, the band 7 gain could absorb any small offsets in the band 8 gain. In fact, band 8 does have a laboratory calibration (Johnson et al. 1997) and should be reasonably close to the correct value (Barnes et al. 1999); however, the calibration can change after the stress of launch. Also, the calibration being performed is not strictly an absolute calibration, but a vicarious calibration which includes a calibration of the sensor and the processing algorithms as a whole. Studies of the errors introduced by gain errors (Gordon 1998, Wang and Franz 2000) indicate that this assumption introduces only minor errors. An analysis of the error introduced in the band 7 calibration due to an incorrect band 8 calibration is presented here.

If the single-scattering approximation is used, the ϵ value used in the band 7 gain calculation can be expressed as:

$$\epsilon(765,865) \approx \frac{\big[L_t(765)\,G_7 - L_r(765)\big]\,F_0(865)}{\big[L_t(865)\,G_8 - L_r(865)\big]\,F_0(765)}, \tag{4}$$

where L_t is the total radiance, L_r is the Rayleigh radiance, G_7 and G_8 are the gain factors for bands 7 and 8, and F_0 is the extraterrestrial irradiance. Assuming that the band 7 gain can compensate for any errors in the band 8 gain, then (4) can be rewritten as

$$\epsilon(765,865) \;=\; \frac{\big[L_t(765)\,G_{7:8} - L_r(765)\big]\,F_0(865)}{\big[L_t(865) - L_r(865)\big]\,F_0(765)}. \tag{5}$$

$G_{7:8}$ is the combined gain used as the band 7 gain in this analysis. If the Rayleigh term, L_r is small, then

$$G_{7:8} \;=\; \frac{G_7}{G_8}, \tag{6}$$

and the assumption would work perfectly; however, L_r is significant relative to L_t.

By converting (4) into the form of (5), the actual value of $G_{7:8}$ is seen to be:

$$G_{7:8} \;=\; G_7\,f + \frac{L_r(765)}{L_t(765)}\,(1-f), \tag{7}$$

with

$$f \;=\; \frac{L_t(865) - L_r(865)}{L_t(865)\,G_8 - L_r(865)}. \tag{8}$$

The actual value of $G_{7:8}$ is not of interest, but the amount of variation, specifically, the standard deviation in $G_{7:8}$ [i.e., $\sigma(G_{7:8})$] for the normal range of SeaWiFS data is important. This would indicate the error to be expected in the gain applied to band 7 for an average SeaWiFS pixel.

$G_{7:8}$ was evaluated for a typical GAC pass of data using a nominal band 7 gain (G_7) of 0.95, and values of G_8 ranging from .95–1.05 (i.e., band 8 gain changes of from -5% to $+5\%$). For the 11,778 pixels that could be processed to get L_{WN} data, the $\sigma(G_{7:8})$ is shown in Table 1.

Table 1. Error in the band 7 gain. Column 1 is the actual gain in band 8 for which a gain of 1 is assumed. Column 2 is the error in the band 7 gain expected (i.e., an extra source of noise) and is a result of assuming the band 8 gain is 1.

G_8	$\sigma(G_{7:8})$
0.95	0.00205
0.98	0.00179
0.99	0.00091
1.01	0.00094
1.02	0.00191
1.05	0.00489

The error in the present estimate of band 7 gain is 0.008 (Sect. 5.5), so unless the error in the band 8 gain is large, 5% or more, this error is probably acceptable at this time. If the gain in band 8 needs to be changed, tests indicate that a 3% increase (or decrease) in the band 8 gain requires a corresponding band 7 increase (or decrease) of 2.2% to get the same ϵ value.

5.4 CALIBRATION METHOD

This study is conducted with SeaWiFS data taken at the Marine Optical Buoy (MOBY) site located west of the Hawaiian island of Lanai (Fig. 1). The site is in the open ocean and has a consistent maritime aerosol type. This region was also chosen because it has good coverage by the full, 1 km resolution LAC data throughout the mission and it coincides with the area where the vicarious calibration of the other bands is done (Eplee and McClain 2000).

The choice of the site near Hawaii allowed the use of 724 LAC data sets for the study. The great number of data sets makes it possible to be more selective of the atmospheric conditions in each observation and still retain a large sample of observations. The site was chosen to have a square area of 3×3 LAC pixels, which are averaged together to determine the ϵ value for that observation. The ϵ value found in good pixels is averaged and then matched against the expected maritime ϵ value. The gain in band 7 that produces this ϵ value is the gain determined for that observation.

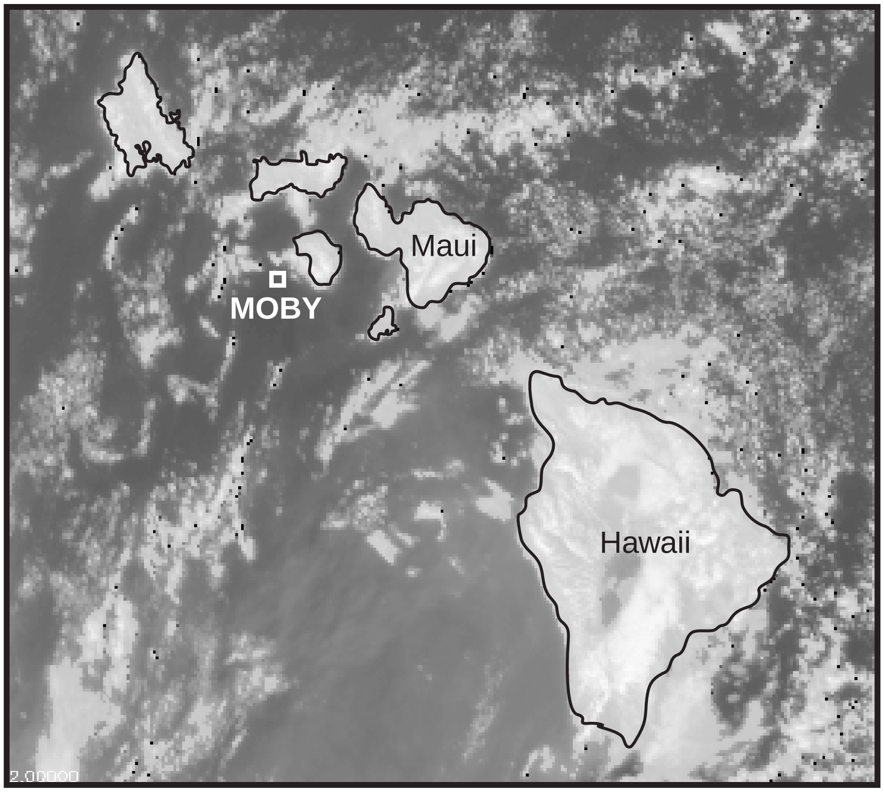

Fig. 1. An image of the Hawaiian Islands showing the location of the MOBY site used to derive the band 7 gain. The islands of Hawaii, Maui, Molokai, Lanai, and Oahu are visible in the image with a black outline of their coasts. The white box shows the 3×3 pixel area centered on the MOBY location at 20.828°N and 157.19°W.

Although the region for this study was selected to have a constant maritime aerosol value, this still leaves four maritime models to choose from with varying humidity conditions. If there was a measure of the aerosol value at the site, the exact maritime model could be determined. The humidity is available in the ancillary data but there may be little correspondence between the actual humidity and the aerosol model based on that humidity. So, in this study, the ϵ value used for the site is the average of the ϵ values from the four maritime models.

The computation of ϵ is performed by running the SeaWiFS operational level-2 program. In order to ensure that only very clear sites are used, some changes are made in the standard flagging controls. First, the cloud albedo threshold is changed from 1.1 to 0.9 so that more stringent cloud screening is used to ensure the selection of cloud-free pixels. The following pixel exclusion conditions are also added: a satellite zenith angle limit of 56°, a solar zenith angle limit of 70°, and a mask of pixels containing excessive stray light. Also note that the calibration table used in the processing has had the time dependence in bands 7 and 8 removed (Eplee and Barnes 2000). The result of the level-2 processing is a 3×3 field of ϵ values and other parameters. The unmasked parameter values are averaged to produce an observation for that site and data set. The averaged ϵ value is used to match the four-model maritime ϵ value.

Additional screening tests are applied to the observations. Observations are considered only if more than five of the points remained unmasked. This screen is designed so that a relatively large clear region is used for each observation and to reduce the effects of noise by averaging a number of LAC pixel values of ϵ. Tests were run to see if a requirement of 100% of the points would reduce the error in the band 7 gain; it did not, instead however, it significantly reduced the number of usable observations.

In the processing, the effect of whitecap radiance is accounted for using a relationship between the wind speed and the whitecap radiance (Gordon and Wang 1994a). The data used to derive this relationship shows a wide variance as the wind speed increases. Also, during some tests, it was found that there may be a weak correlation between wind speed and the band 7 gain. Considering this, another screen is imposed on the observations that keeps only the observations where the wind speed is less than $8\,\mathrm{m\,s^{-1}}$.

The clear air screening was improved using the criteria of Gordon (1998) on the aerosol optical thickness. Only observations having an aerosol optical thickness less than 0.1 are used to determine the band 7 gain. A low limit of 0.03 is also imposed on all of the observations.

A final screen is imposed on the observations to remove any statistically bad observations. The standard deviation of the band 7 gain is derived for the remaining observations

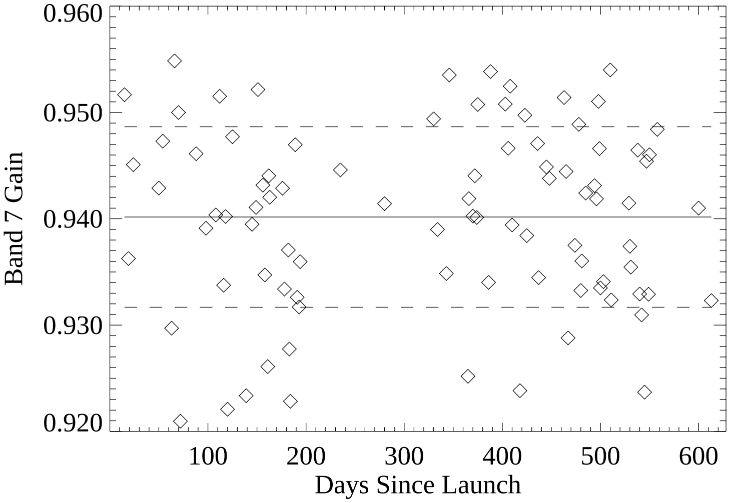

Fig. 2. The gain in band 7 plotted as a function of the number of days since the start of SeaWiFS operations on 4 September 1997. The solid line is at the mean gain 7 value and the dashed lines are $1\,\sigma$ away from the mean.

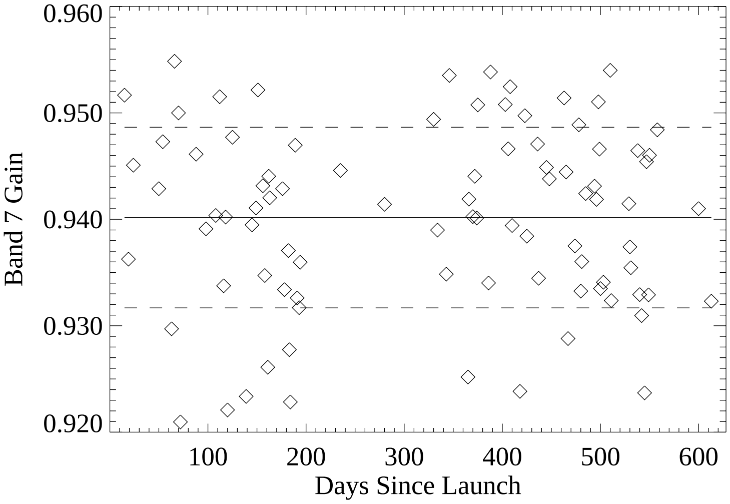

Fig. 3. A histogram of the distribution of band 7 gain at the MOBY site.

and any observations that are more than 2σ away from the mean are discarded.

5.5 RESULTS

The technique described above is applied to available SeaWiFS LAC data using the operational level-2 processing program. Figure 2 is a plot of the band 7 gain determined for the MOBY site as a function of days since SeaWiFS became operational. Out of the 724 LAC data sets covering the Hawaii area, 89 data sets satisfy the screening tests. The mean band 7 gain is 0.940 ±0.008. The error in the band 7 gain of less than 1% translates into errors in L_{WN} (normalized water-leaving radiance) in the other bands of well below 10% (Gordon 1998). This assumes that there is no vicarious calibration of the other bands. The vicarious calibration should compensate for any possible gain 7 errors. Figure 3 shows the histograms of the band 7 gain at the MOBY site.

5.6 CONCLUDING REMARKS

A technique for calibrating the gain in SeaWiFS band 7 has been derived in accordance with the requirements set out by Gordon (1998) and using the resources available to the SeaWiFS Project. A reasonably good estimate of the band 7 gain was made for the current data. This method will be applied as new calibration points and algorithm improvements become available.

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Symbols

F_0	Extraterrestrial irradiance.
G_7	Gain factor for band 7.
G_8	Gain factor for band 8.
$G_{7:8}$	Combined gain for band 7 and 8.
L_a	Radiance arising from aerosol scattering.
L_{as}	Rradiance arising from aerosol single scattering.
L_g	Glint radiance arising from the specular reflection. of the sun off the water surface.
L_r	Rayleigh radiance.
L_{ra}	Rradiance arising from the interaction of molecular and aerosol scattering.
L_t	Total radiance at the TOA.
L_W	Water-leaving radiance.
L_{wc}	Whitecap radiance.
L_{WN}	Normalized water-leaving radiance.
T	Direct transmittance of the atmosphere.
t	Diffuse transmittance of the atmosphere.
$\epsilon(\lambda, 865)$	ϵ value of atmospheric correction for wavelengths λ and 865 nm.
$\rho_{as}(\lambda)$	Single scattering aerosol reflectance for wavelength λ.
$\sigma(X)$	Standard deviation of quantity X.