Alternative on-orbit vicarious calibration schemes for ocean color satellites

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http://oceancolor.gsfc.nasa.gov

Recent advances in global climate and productivity research demonstrate a critical need for long-term ocean color satellite data records of consistent high quality. Currently, NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imagine Spectroradiometer (MODIS), and ESA's Medium Resolution Imaging Spectrometer (MERIS) provide the oceanographic community continuous, global marine bio-optical data sets. The community relies heavily on their data products, the concentration of the phytoplankton pigment chlorophyll *a*, C_a, in particular, to support studies ranging from management of regional ecosystems to development of decadal climate records. The successes of SeaWiFS and MODIS result, in part, from their rigorous, mission-long on-orbit vicarious calibration, executed by the NASA Ocean Biology Processing Group (OBPG) to fine-tune the instrument-atmospheric correction system. In this calibration, top-of-atmosphere visible radiances are adjusted using *in situ* normalized water-leaving radiances, $L_{wn}(\lambda)$, which are currently acquired using the Marine Optical Buoy (MOBY; Clark et al. 1997). Here, we execute a survey of three alternative sources of calibration quality $L_{wn}(\lambda)$, all of which exploit only commercially available, off-the-shelf (COTS) hardware. For each, SeaWiFS vicarious gains, *g*, are calculated (Eplee et al. 2001) and Level-2 validation results for deep water (> 1000 meters) are presented (Bailey and Werdell 2006).

SEA SURFACE REFLECTANCE MODEL

Recently developed sea surface reflectance models (SSRM) accurately reproduce radiance spectra observed in the field, at least for clear, marine waters. Simplifications to the radiative transfer equation permit the estimation of $L_{wn}(\lambda)$ via a single input parameter, C_a, a measurement for which long-term, seasonal *in situ* time series exist. The OBPG recently explored the efficacy of an SSRM in the calibration of the NASA Coastal Zone Color Scanner and the JAXA Ocean Color and Temperature Scanner, both of which pre-date MOBY (Werdell et al. 2006).

The general form of the L_{wn} model is:

$$L_{wn} = \frac{t_u\, t_d}{n^2}\, F_0\, \frac{f}{Q}\, \frac{b_b}{a}$$

Table 1 provides parameter definitions and units and spectral dependence is implied. The SSRM of Morel and Maritorena (2001), with several modifications, and the bidirectional reflectance parameterizations of Morel et al. (2002) permit the estimation of the unknown spectrally dependent variables in this equation, *a*, b_b, *f*, and *Q*, via a single geophysical input, C_a. Following, knowledge of C_a in a given *Case-1* location (phytoplankton being the only optically significant constituent) provides sufficient information to estimate L_{wn} at that location..

a	absorption coefficient (m^{-1})	L_u	upwelling radiance ($\mu W\ cm^{-1}\ nm^{-1}\ sr^{-1}$)
b_b	backscattering coefficient (m^{-1})	L_{wn}	normalized water-leaving radiance ($\mu W\ cm^{-1}\ nm^{-1}\ sr^{-1}$)
E_d, E_u	downwelling & upwelling irradiance ($\mu W\ cm^{-1}\ nm^{-1}$)	n	refractive index of seawater (unitless)
E_s	surface irradiance ($\mu W\ cm^{-1}\ nm^{-1}$)	Q	bi-directional reflectance function (= E_u/L_u; sr^{-1})
f	term relating R to b_b and a via $R = f\, b_b\, a^{-1}$ (unitless)	R	subsurface reflectance (= E_u/E_d; unitless)
F_0	mean extraterrestrial solar irradiance ($\mu W\ cm^{-1}\ nm^{-1}$)	t_d	downward irradiance air-sea transmittance (unitless)
		t_u	upward radiance air-sea transmittance (unitless)

Table 1. Parameter definitions and units.

For vicarious calibration using the SSRM, we require candidate study sites to:

(1) be in a location where SeaWiFS acquires regular LAC (1-km^2) coverage
(2) be considered *Case-1*
(3) have a well-characterized, annual *in situ* C_a time series

The Hawaiian Ocean Time-series (HOT) Station ALOHA and Bermuda Atlantic Time-series Study (BATS) programs provide fluorometrically and HPLC-derived C_a data sets that satisfy all of these criteria.

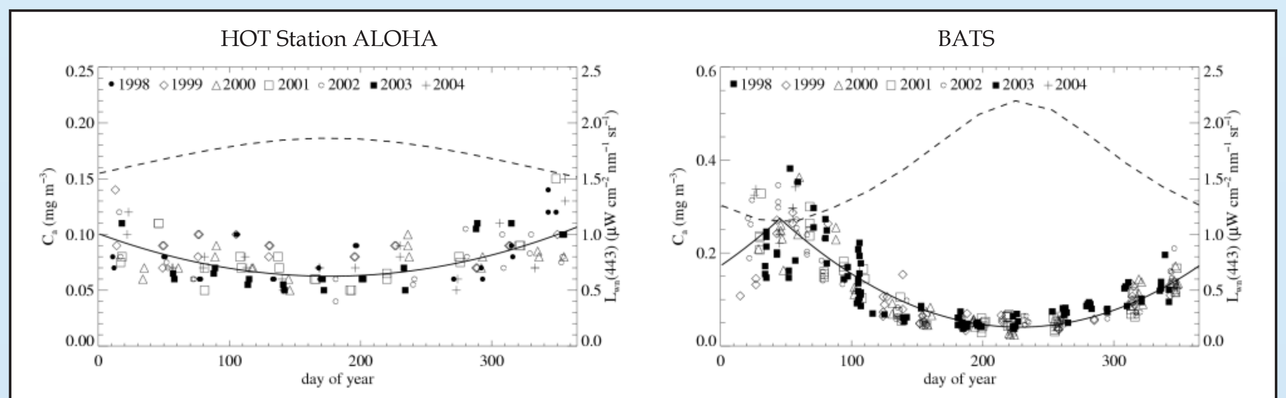

Figure 1. The statistically-derived C_a climatologies (solid), *in situ* C_a (symbols), and resultant SSRM $L_{wn}(443)$ (dashed).

Only 6% of input *in situ* stations result in valid vicarious calibration match-ups. To increase the sample size, we generated climatological expressions for the C_a data. A quadratic fit was calculated to express C_a as a function of day of year. Using this expression and the SSRM, we estimated SeaWiFS-specific L_{wn} for every day of 1998 - 2004 at both the Station ALOHA and BATS sites. These spectra were subsequently input into the calibration system. With the exception of 510-nm, the SSRM and MOBY gains agree to within 0.33% (Table 2). The g_{ssrm} validation results are excellent for a considerable dynamic range of clear water conditions, and are statistically equivalent to those for g_{moby} (Figure 2).

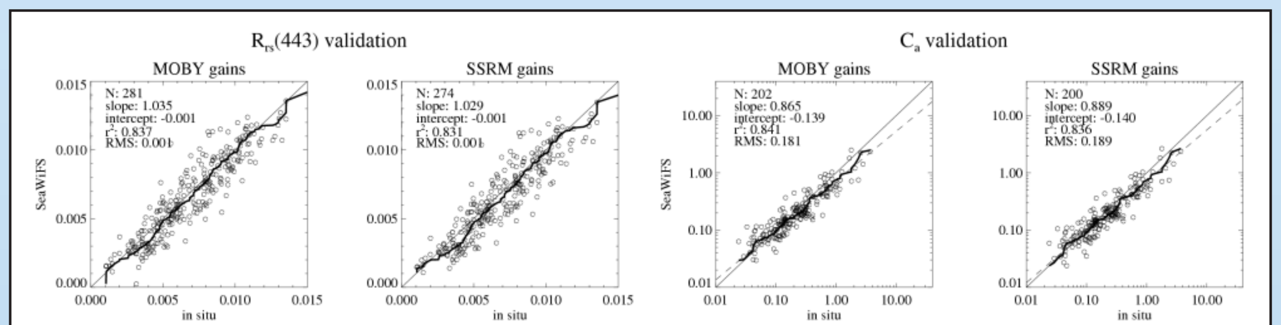

Figure 2. Comparisons of *in situ* and satellite-derived products for SeaWiFS data processed using g_{moby} and g_{ssrm}. The bold solid lines show quantile-quantile comparisons, where sorted (ascending) data are compared.

AUTONOMOUS ABOVE-WATER RADIOMETRY

Recent innovations in autonomous above-water radiometers, particularly those continuously deployed at fixed sites, have fortified their potential for ocean color satellite calibration and validation. The European Commission Joint Research Centre (JRC; Ispra, Italy), in collaboration with the OBPG and the NASA Aerosol Robotic Network (AERONET) group, recently developed such instrumentation, the SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), a modified CIMEL Electronique CE-318 (Hooker et al. 2000). AERONET's ocean color component (AERONET-OC; Zibordi et al. 2006) recently completed a four year testing phase of SeaPRISMs deployed at five offshore locations. In the forthcoming operational phase, AERONET-OC will routinely acquire, process, and publicly distribute SeaPRISM marine and atmospheric products in support of international ocean color research efforts.

We highlight data from the Acqua Alta Oceanographic Tower (AAOT), located 8 nautical miles outside the Venice Lagoon, Italy (Figure 3). This frontal region is predominantly characterized by oceanic conditions, modulated by *Case-2* riverine influences, and continental aerosols originating from the Po River valley.

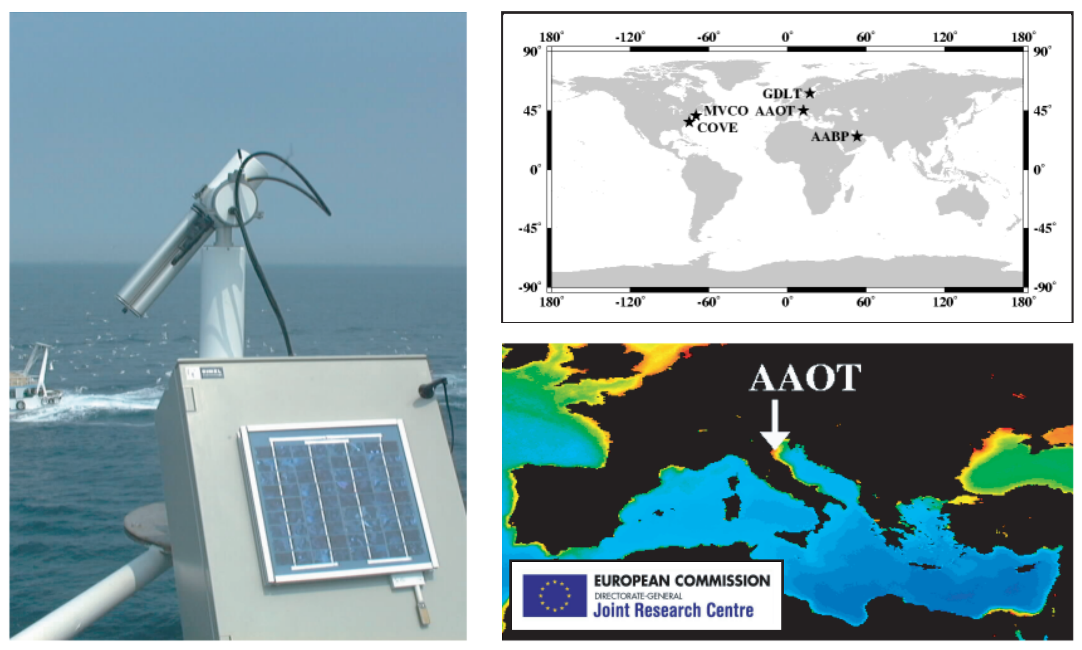

Figure 3. Clockwise from left: a SeaPRISM in operation; locations of the network testing phase AERONET-OC stations (2001 - 2005; see http://aeronet.gsfc.nasa.gov for acronym definitions and an updated list of SeaPRISM stations); and, a detailed view of the location of the AAOT.

The standard operation of a CE-318 sun photometer consists of measurements of sky radiance at multiple instrument viewing angles and direct solar irradiance at routine intervals throughout the day. The extended capability of a SeaPRISM is a sea-viewing scenario to retrieve L_{wn}. While the AERONET-OC recently updated the wavelength suite to better conform with ocean color research, the prototype SeaPRISM used in this analysis has channels at 413, 440, 501, 555, and 674-nm.

After the application of quality control metrics to the data, the JRC sent SeaPRISM L_{wn} spectra (collected mid-2002 through mid-2003) to the OBPG for inclusion in their calibration system. The SeaPRISM and MOBY gains all agree to within 2.5%, including $g(490)$ and $g(510)$, which were calculated using $L_{wn}(501)$ (Table 2). The remaining differences may stem from geographically-induced atmospheric correction issues (e.g., failure of the black pixel assumption or presence of absorbing aerosols). Given the form of the C_a algorithm, the gain offsets result in a increased slope in the $g_{seaprism}$ results (Figure 6). The results for the mesotrophic regime ($0.1 < C_a < 1$ mg m^{-3}), however, and for the full dynamic range of $R_{rs}(443)$, indicate excellent agreement and endorse the SeaPRISM as a viable ocean color calibration source.

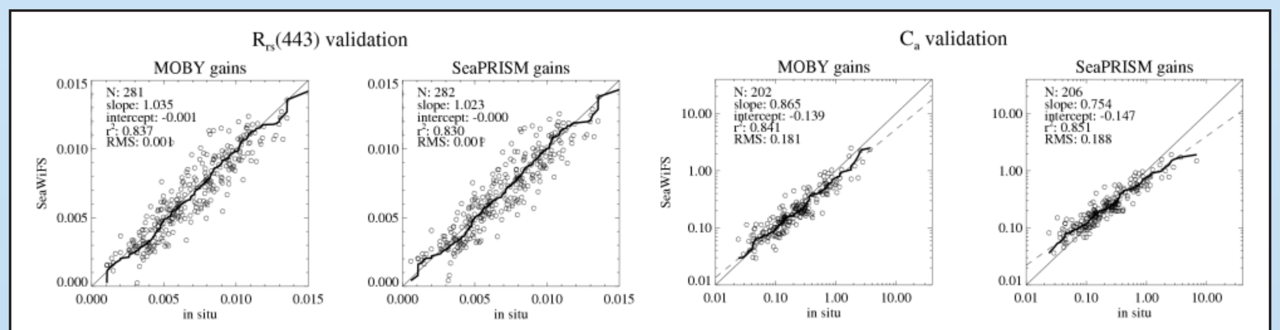

Figure 4. Comparisons of *in situ* and satellite-derived products for SeaWiFS data processed using g_{moby} and $g_{seaprism}$. The bold solid lines show quantile-quantile comparisons, where sorted (ascending) data are compared.

ALTERNATIVE IN-WATER BUOYS

The Laboratoire d'Océanographie de Villefrance (LOV; Villefranche-sur-Mer, France) initiated the Bouée pour l'acquisition de Séries Optiques à Long Terme (BOUSSOLE) project to facilitate the development of a long term *in situ* bio-optical time series to support their ocean color satellite calibration and validation activities (Antoine et al. 2006). While BOUSSOLE includes both a regular field program and a coastal AERONET station, its centerpiece is a permanent optics mooring located in the Ligurian Sea approximately 32 miles from Nice, France (Figure 5). This low current site is predominantly oligotrophic, however, C_a on occasion approaches 5 mg m^{-3} during the spring blooms of March and April.

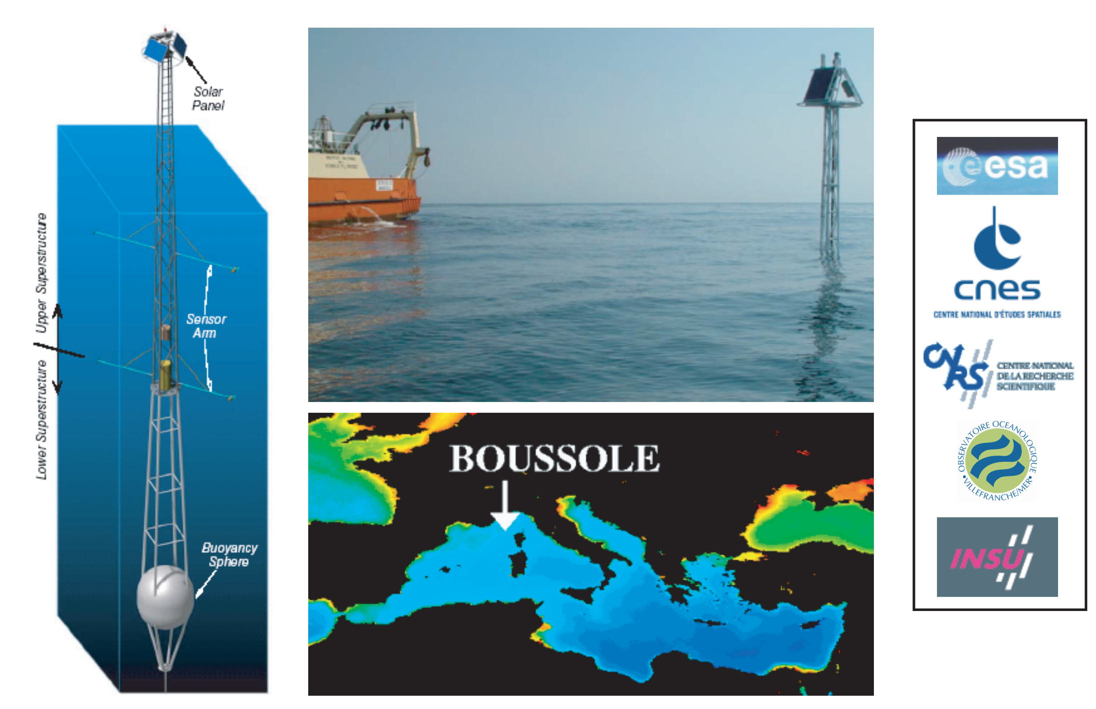

Figure 5. Design and location of the BOUSSOLE permanent optical mooring.

The most notable physical feature of the mooring is its latticed structure. This novel design minimizes perturbation of the in-water light field (and, therefore, instrument shading), while ensuring platform stability by minimizing wave interaction.

The COTS mooring instrumentation provides:

(1) E_s at 7 wavelengths (Satlantic Inc.)
(2) L_u, E_u, and E_d at 7 wavelengths at 4 and 9 meters (Satlantic Inc.)
(3) $b_b(443)$ and $b_b(560)$ at 9 meters (HOBI Labs)
(4) beam attenuation coefficient at 660-nm at 4 and 9 meters (WET Labs)
(5) C_a fluorescence at 4 and 9 meters (Chelsea Technologies Group)
(6) temperature, pressure, and salinity at 9 meters (Sea-Bird Electronics, Inc.)

Radiances are collected at SeaWiFS, MODIS, and MERIS visible wavelengths. Data are acquired every 15 minutes during the day and hourly at night. The full data collection sequence lasts one minute. Data are stored locally, with a subset transmitted to LOV via ARGOS for monitoring general system health. All data are downloaded from the buoy during the regular monthly field campaigns.

After applying quality control metrics to the data, the LOV calculated L_{wn} from the mooring radiances (collected late-2003 through late-2004) and sent these data to the OBPG for inclusion in their calibration system. With the exception of 412-nm, the BOUSSOLE and MOBY gains agree to within 0.6% (Table 2). Excluding 412-nm, the $g_{boussole}$ validation results are excellent for the deep water subset and statistically parallel those for g_{moby} (Figure 6). As for SeaPRISM, the spectrally varying gain offsets result in a increased slope in the $g_{boussole}$ C_a results.

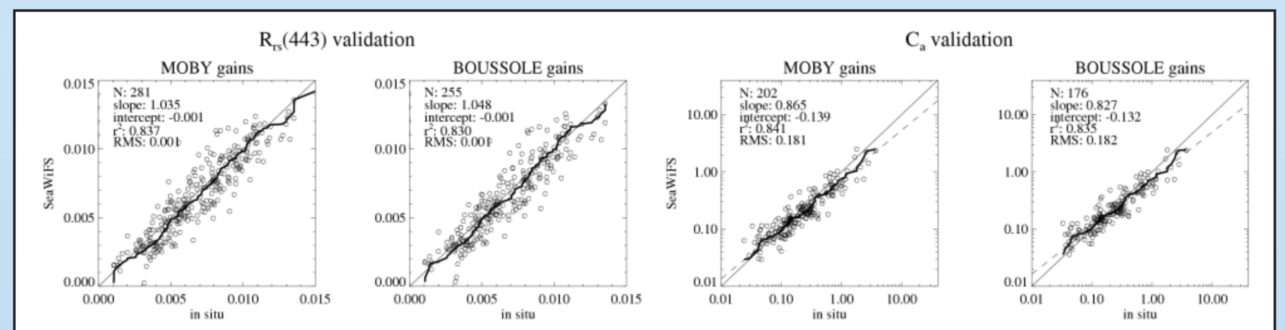

Figure 6. Comparisons of *in situ* and satellite-derived products for SeaWiFS data processed using g_{moby} and $g_{boussole}$. The bold solid lines show quantile-quantile comparisons, where sorted (ascending) data are compared.

For over a decade, MOBY has endured as the premier source of *in situ* radiometry for the on-orbit calibration of ocean color satellites (Clark et al. 1997). Pioneering in design and operation, the community continues to acknowledge its value, both historical and modern, and currently relies on its data for the vicarious calibration of both SeaWiFS and MODIS (Eplee et al. 2001). After a decade of technological advances and accumulated experience, however, there now appear to be maturing, credible alternatives to MOBY with potential for a greater geographic distribution of calibration sites within current budget constraints. While all approaches to vicarious calibration possess inherent weaknesses, those outlined in this poster enjoy a significant economical advantage in their use of COTS hardware and techniques. Further, their scientific potential is evident as indicated by the derived vicarious gains (Table 2) and resulting validation statistics (Figures 2, 4, and 6), all of which approach, and occasionally exceed, those of MOBY.

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	n	412	443	490	510	555	670
MOBY	32	1.0360	1.0126	0.9910	0.9956	0.9939	0.9627
SSRM	28	**1.0395** (0.34)	**1.0108** (-0.18)	**0.9883** (-0.27)	0.9864 (-0.92)	**0.9907** (-0.32)	0.9659 (0.33)
SeaPRISM	8	1.0487 (1.23)	1.0163 (0.37)	**1.0013 (1.04)**	**1.0198 (2.43)**	1.0068 (1.30)	0.9838 (2.19)
BOUSSOLE	18	1.0008 (-3.40)	1.0149 (0.23)	0.9968 (0.59)	**1.0010** (0.54)	0.9998 (0.59)	**0.9623** (-0.04)

Table 2. SeaWiFS vicarious gains for MOBY and the three alternate L_{wn} sources. Relative differences (%) in parentheses. Gains with the lowest absolute differences are **highlighted in red**. For SeaPRISM, **$g(490)$ and $g(510)$ were calculated using $L_{wn}(501)$**, which impacts its C_a validation results in Figure 4.

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