Spectral Resolution Requirements for Vicarious Calibration of Ocean Color Satellites

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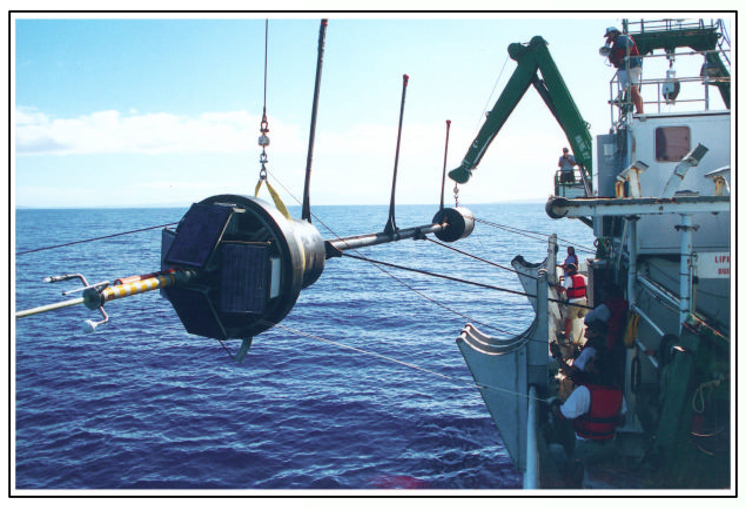
Introduction

Radiometric measurements from ocean color satellite sensors are calibrated by comparison with *in situ* measurements of water-leaving radiances. This vicarious calibration procedure is necessary because the radiance from the ocean is small compared to the total radiance measured from space, which includes the atmospheric component. Laboratory, pre-flight radiometric calibration uncertainty values are about an order of magnitude too large to support the 5% uncertainty requirements for water-leaving radiances.

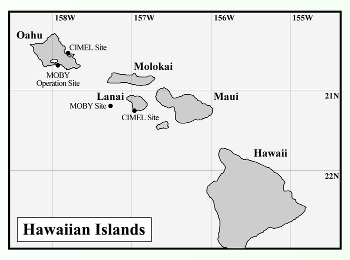
The Marine Optical Buoy (MOBY) (Clark *et al.* 1997) has evolved into the primary calibration site for satellite ocean color sensors based on independent *in situ* measurements. Since late 1996, the suite of radiometric and environmental sensors attached to MOBY has provided a continuous time series of measurements. The radiometric values of the MOBY vicarious calibration reference are traceable to NIST absolute radiometric standards. MOBY functions as the world's primary ocean color vicarious calibration site, serving both US and foreign ocean color missions.



MOBY deployment off Lanai, Hawaii

MOBY spectrograph parameters

System	Coverage (nm)	Bandpass (FWHM) (nm)	λ Step (nm)
Blue	350 - 640	0.91	0.579
Red	550 - 955	1.17	0.808

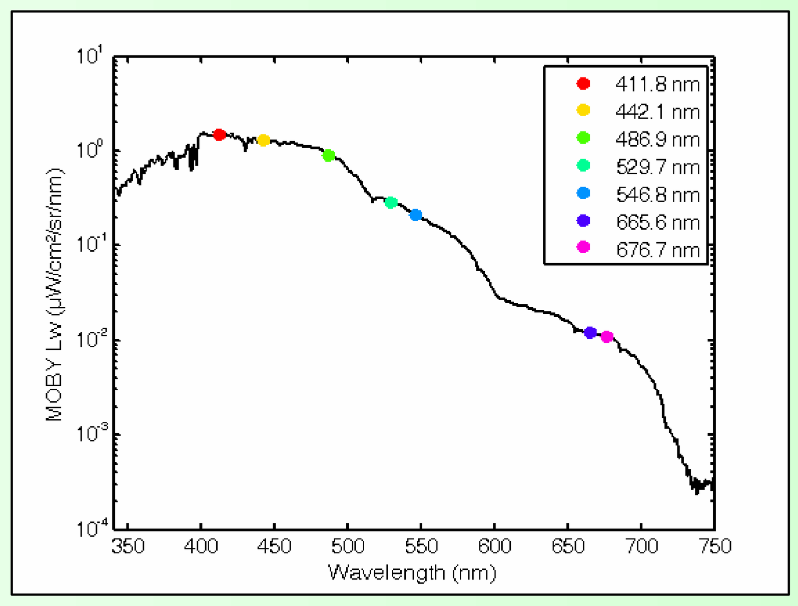


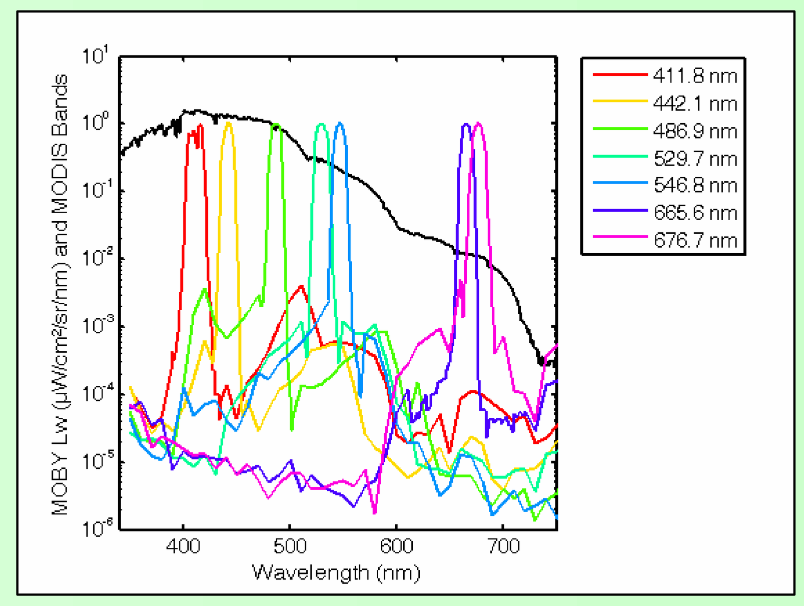
The vicarious calibration facility should supply hyperspectral values in order to serve all sensors. In addition, these needs are met (Mueller 2005): 1) all optical sensors suffer from stray light effects (also termed spectral out of band), and even if fully characterized in the laboratory, full spectral coverage is necessary to execute the stray light correction algorithm; 2) full spectral coverage allows for determination of the "total band" satellite radiance, not just the in-band portion; and 3) the measured spectra can be used to validate sensors algorithms, including design studies.

Band	Center λ (nm)	FWHM (nm)
8	411.8	14.7
9	442.1	9.8
10	486.9	10.5
11	529.7	12.1
12	546.8	10.2
13	665.6	10.2
14	676.7	12.1

To date, US ocean color sensors are filter radiometers—for example, MODIS Terra center wavelengths and full width half maximum (FWHM) values are given in the table. Most bio-optical algorithms used to determine ocean color products are based on ratios of the normalized, water-leaving radiances "band-averaged" for these bands.

MOBY is a full coverage, high resolution, hyperspectral system with two CCD spectrographs. This allows the MOBY measurements to be used for the vicarious calibration site for all ocean color sensors. The wavelength step corresponds to the detector pitch in the CCD.





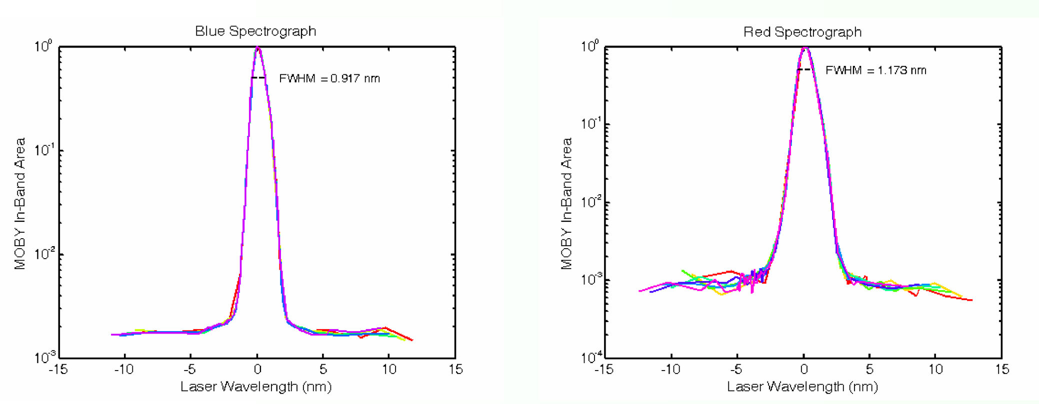
Water-leaving radiance at MOBY site in Lanai, Hawaii and the MODIS Terra bands.

The band-averaged water-leaving radiances, $L_w(\lambda_b)$'s, are determined using the hyperspectral MOBY values, $L_w(\lambda)$, and the relative spectral responsivities (RSRs) for the satellite sensor as provided by its science team:

$$L_w(l_b) = \frac{\int r(l, l_b)\, L_w(l)\, dl}{\int r(l, l_b)\, dl}$$

where $r(\lambda, \lambda_b)$ is the RSR for the band with λ_b (Clark et al. 2003). Prior to the calculation, the RSR values are interpolated to the MOBY wavelength grid.

Given the opportunity to replace the aging MOBY instruments with new technology, we considered the spectral resolution: duplicate MOBY, make it "less" or make it "more"? Note that some existing aircraft and future proposed sensors have spectral resolution of less than 5 nm. Our answer is framed by determining the impact on band averaged radiances, and we used MOBY as the reference in the study.

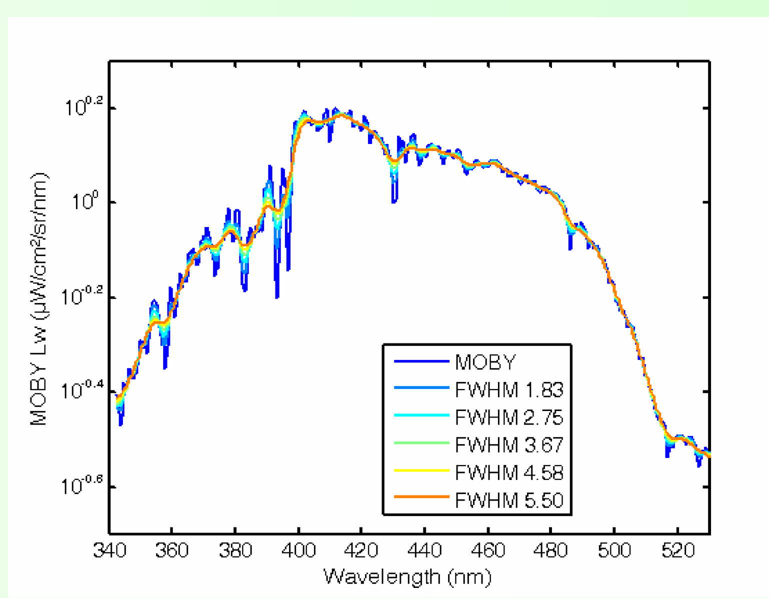


Slit images for MOBY spectrographs

The slit images, or instrument profiles, were measured as part of the stray light characterizations (Feinholz et al. 2007). The BSG and RSG results are shown here. We smoothed the MOBY results by modeling these profiles as Gaussians, varying the corresponding FWHM values and wavelength step. These normalized modeled profiles were truncated at 0.1% because we are not attempting to model spectral out of band. We used the smoothed results to determine "low resolution" satellite band-averaged radiances. The smoothing equation is

$$L_w(l_i) = \frac{\int g(l, l_i)\, L_w(l)\, dl}{\int g(l, l_i)\, dl}$$

The parameters of the smoothed spectra are given in the tables. For simplicity, we continued with the distinction between the BSG and the RSG, and we decreased the resolution by increasing the FWHM and wavelength step by the integral values between 2 and 6. The evaluation was done at the MOBY wavelength grid (λ_i) and then every 2nd, 3rd, … 6th values were discarded to simulate the reduced spectral sampling. We also included a 10 nm FWHM on 3.3 nm spacing case, in order to represent typical commercial instrumentation. This required a final interpolation to produce results at the 3.3 nm spacing.



Smoothed spectra

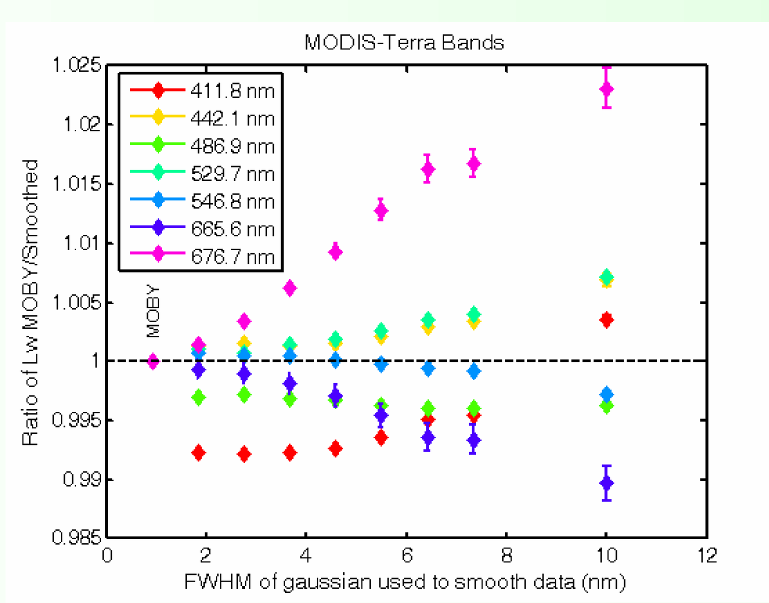
Blue spectrograph

Multiple of MOBY	Model FWHM (nm)	λ Step (nm)
2 & 2	1.83	1.158
3 & 3	2.75	1.737
4 & 4	3.67	2.316
5 & 5	4.58	2.895
6 & 6	5.5	3.475
10.98 & 5.7	10	3.300

Red spectrograph

Multiple of MOBY	Model FWHM (nm)	λ Step (nm)
2 & 2	2.34	1.616
3 & 3	3.51	2.425
4 & 4	4.68	3.233
5 & 5	5.85	4.041
6 & 6	7.02	4.849
8.55 & 4.08	10	3.300

Once the smoothed L_w spectra were obtained, we calculated the satellite band-averaged water-leaving radiances for MODIS Terra. The "good days" of MOBY deployment Buoy230 (4 March 2005 to 20 August 2005) were used for the input data. The results are presented as the ratio of band-averaged radiances using smoothed vicarious calibration data to the MOBY values. As the spectral resolution decreases, biases of up to several percent are introduced.



Impact on band ratios with decreased spectral resolution

Conclusions

The vicarious calibration site must not introduce unnecessary bias in the overall procedure. We have shown that the spectral resolution of the *in situ* measurements can introduce positive or negative bias in the calculation of the band-averaged L_w's that are used to set satellite gain coefficients; with ocean product retrievals based on radiance ratios, the effect can be greater. Also, we have not addressed the impact of such bias on global measurements, where the water type is not comparable to the oligotrophic MOBY waters. We conclude that designing for high spectral resolution with consideration of other constraints (cost, size, etc.) is a rational approach. Selection similar to MOBY (e.g., ~1 nm) provides the additional benefit of *in situ* monitoring of the wavelength calibration using Fraunhofer lines.

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Clark, D. K., M. A. Yarbrough, et al. (2003). MOBY, a radiometric buoy for performance monitoring and vicarious calibration of satellite ocean color sensors: measurement and data analysis protocols. Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 4, Volume 6. J. L. Mueller, G. S. Fargion and C. R. McClain. Greenbelt, MD, NASA Goddard Space Flight Center. **NASA/TM--2003-211621:** 3-34.
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