An Evaluation of Above- and In-Water Methods for Determining Water-Leaving Radiances

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ABSTRACT

A high-quality dataset collected at an oceanographic tower was used to compare water-leaving radiances derived from simultaneous above- and in-water optical measurements. The former involved two different above-water systems and four different surface glint correction methods, while the latter used three different in-water sampling systems and three different methods (one system made measurements a fixed distance from the tower, 7.5 m; another at variable distances up to 29 m away; and the third was a buoy sited 50 m away). Instruments with a common calibration history were used, and to separate differences in methods from changes in instrument performance, the stability (at the 1% level) and intercalibration of the instruments (at the 2%–3% level) was performed in the field with a second generation Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Quality Monitor (SQM-II). The water-leaving radiances estimated from the methods were compared to establish their performance during the field campaign, which included clear and overcast skies, Case-1 and Case-2 conditions, calm and roughened sea surface, etc. Three different analytical approaches, based on unbiased percent differences (UPDs) between the methods, were used to compare the various methods. The first used spectral averages across the 412–555-nm SeaWiFS bands (the part of the spectrum used for ocean color algorithms), the second used the ratio of the 490- and 555-nm bands, and the third used the individual (discrete) wavelengths. There were eight primary conclusions of the comparisons, which were considered within the context of the SeaWiFS 5% radiometric objectives. 1) The 5% radiometric objective was achieved for some in-water methods in Case-1 waters for all analytical approaches. 2) The 5% radiometric objective was achieved for some above-water methods in Case-2 waters for all analytical approaches, and achieved in both water types for band ratios and some discrete wavelengths. 3) The largest uncertainties were in the blue domain (412 and 443 nm). 4) A best-to-worst ranking of the in-water methods based on minimal comparison differences did not depend on the analytical approach, but a similar ranking of the above-water methods did. 5) Above- and in-water methods not specifically designed for Case-2 conditions were capable of results in keeping with those formulated for the Case-2 environment or in keeping with results achieved in Case-1 waters. 6) There was a significant difference between two above-water instruments oriented perpendicular with respect to the sun, but pointed in the same direction (best agreement) versus the opposite direction (worst agreement). 7) The overall intercomparison of all methods across Case-1 and Case-2 conditions was at the 9.1% level for the spectral averages, and at the 3.1% level for the band ratios (uncertainties other than those associated with implementing the individual methods account for 2%–4% and 1%–3% of these values, respectively). 8) A comparison with traditional regression analyses confirms the UPD conclusions.

1. Introduction and background

Spectral water-leaving radiance, $L_W(\lambda)$, is the central physical quantity for bio-optical studies in the upper ocean; whether determined from above- or in-water data, $\hat{L}_W(\lambda)$ and $\tilde{L}_W(\lambda)$, respectively, it must be accurately measured. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project, for example, requires $L_W(\lambda)$ uncertainties within 5% (Hooker et al. 1993b). This was shown to be achievable for in-water measurements in Case-1 waters using primarily a single methodology (Hooker and Maritorena 2000), but the uncertainty associated with multiple methods has not been well quantified. The SeaWiFS calibration and validation plan (Hooker and McClain 2000) has emphasized in-water field work because when the plan was conceived, the above-water protocols were not as mature as the in-water protocols (Mueller and Austin 1992). Although there has been steady progress in defining the proper metrology for above-water measurements, intracomparisons within a group of accepted techniques have not occurred. More importantly, intercomparisons between above- and in-water methods have also not been thoroughly investigated, although individual comparisons are available in the literature (e.g., Pinkerton et al. 1999; Toole et al. 2000).

6. Conclusions

This study used data from three different environmental conditions that covered much of the dynamic range of in situ optical measurements, but, nonetheless, it was based on a small dataset collected during three days of measurements in the near-coastal environment. One of the three days (SDY 194) was within the parameter range established by the NRSR Workshop; the other two were not, but they were typical of the kinds of environmental conditions that can be encountered during above- and in-water radiometric field campaigns. Three in-water methods for determining water-leaving radiances from profiling (S84) and fixed-depth (P94 and P97) sampling systems were combined with four above-water methods to quantify the performance of all the methods. The removal of glint contamination from the surface measurement distinguished the above-water methods from one another and included four correction schemes: near-infrared radiance ratio (M80), Fresnel reflectance plus residual reflection (C85), modified Fresnel reflectance (S95), and near-infrared irradiance ratio (L98).

The seven methods, three different days of environmental conditions, and five sampling platforms produced a large number of performance comparisons, which were separated according to UPD analyses based on spectral averages, band ratios, and discrete wavelengths. Although each method was usually found superior to the others at some stage in the performance evaluation process, the most suitable point for overall evaluation is at the intercomparison level summarized in Tables 6–9 and Figs. 8–9. Based on these summaries, some general capabilities concerning all the methods can be discerned.

1) In terms of the 5% calibration and validation objective, and the hoped for performance to within 3%, the spectral-average approach (Table 7d) produced larger average differences (and standard deviations) than the band-ratio approach (Table 8d), which were 9.1% (5.6%) and 3.7% (1.1%), respectively. Using band ratios, the S84, P94, C85, and S95 methods produced ranges of expected differences (average plus and minus 1 standard deviation) within the 5% level, and frequently to within 3%.
2) The best results were not restricted to Case-1 or clear-sky conditions; water type was seen to be important, although other environmental parameters agreed well with the UPD levels (considered in more detail below). Consider, for example, the difficult circumstance of overcast conditions, which can be highly variable in terms of sky radiance distribution and relative (percent) variations in illumination conditions during a deployment interval. Because of the low signal levels, small absolute differences represent large relative discrepancies, but all the methods agreed very well for overcast conditions when using the data from the same instrument.
3) Above- and in-water methods not formulated for Case-2 conditions were capable of results in keeping with those achieved in Case-1 waters (e.g., Table 6). Agreement to within 5% was achieved with in-water methods in Case-1 waters for all three analytical approaches. Agreement within 5% was achieved with above-water methods in Case-2 waters for all analytical approaches, and was achieved in both water types for the band-ratio and discrete wavelength analyses (spectral averages were elevated due to large uncertainties in the blue domain).
4) For both above- and in-water methods, the largest uncertainties were usually associated with the blue part of the spectrum (412–443 nm), with the blue-green transition (490–510 nm) a local minimum, which was followed by a small increase at 555 nm (Table 9). The above-water methods that calculated the surface reflectance by assuming $\lambda_r = 0$ (M80 and L98) were spectrally dependent during Case-2, clear-sky conditions, with very large uncertainties at 412 nm (as much as 38%) and minimum uncertainties at 555 nm (less than 5%).

Note that all of the analytical approaches yielded average uncertainties across all three days and all methods below the 10% level, so for applications where this level of agreement is acceptable—for example, perhaps with large-scale bio-optical models, any of the methods are probably acceptable. It is also important to remember the regression analysis results confirm these overall conclusions (although there are small shifts in the magnitude of the uncertainties).

For the in-water methods alone, the specific details of the capabilities of the methods are as follows.

5) P94 and P97 grouped together, but S84 performed the best. Consequently, an in-water method making use of vertical profiles of the water column should be considered superior than those using sensors at a fixed depth, although good results were obtained for the latter during Case-1 conditions and for band-ratio analyses.
6) The best-to-worst ranking of the in-water methods (using the minimal range in average differences) did not depend on the analytical approach (S84, P94, and P97), but the ranking of the above-water methods did (S95, L98, C85, and M80 for the spectrally averaged approach; and C85, S95, M80, and L98 for the band-ratio approach).
7) The in-water spectral averages intracompared best during Case-1 conditions and worst during Case-2 conditions (Table 7c), which is consistent with the higher variability associated with the latter; however, the opposite result was seen with the band-ratio analysis (Table 8c).

Before considering the above-water methods separately, it is important to remember proper data filtering to remove glint spikes is an essential part of above-water methods that permit it (the C85 method does not). Although many schemes were considered in this study (section 3c), the adopted filter retained only the lowest 5% of the data, based on the reddest (780-nm) band. Similarly, data averaging was shown to needlessly and significantly degrade the quality of the above-water data because it artificially elevated the $L_T(\lambda)$ values by contaminating them with glint. Subsampling did not degrade the above-water data as significantly as averaging, but it showed that above-water sampling rates should be equal to, or greater than, 1 Hz (Fig. 7). The conclusion to be derived here is the glint field must be adequately discretized, so it can be removed by filtering.