Method: Surface Hyperspectral Radiometry

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Brief description of protocol and relation to export pathways: Hyperspectral remote sensing reflectance was obtained within 1 hour of local overflight each day (1100-1300 local time and in concert with C-OPS profiling) using a Satlantic Hyper Tethered Spectral Radiometer Buoy (H-TSRB). Downwelling irradiance was measured with a cosine sensor in air at 123 wavebands from 398 nm to 800 nm with approximately 3 nm resolution. Upwelling radiance was measured 63 cm below the air-sea interface with a nadir-viewing radiance sensor with 8½ º FOV.

Remote sensing reflectance measured at the sea surface provides the ground truth observation for top-of-the atmosphere remote sensing reflectance obtained from ocean color sensors such as the currently in orbit multi-spectral MODIS and the propose hyperspectral PACE sensors. Semi-analytic inversions of ocean color reflectance yield estimates of inherent optical properties such as component absorption and backscattering coefficients and carbon-based optical proxies such as POC and DOC.

Deployment methodologies: The H-TSRB was deployed by hand off the back deck of the ship and allowed to float >100m (>3 optical depths) from the vessel to minimize ship shadow and reflectance. Approximately 15-30 minutes of 1-Hz observations were collected while sea and sky conditions characterized. The radiometer was retrieved and capped in order to obtain temperature and stability dark readings for correction of sample observations.

Data processing, uncertainties and quality control concerns:

A 15minute-to-30minute sampling interval is impacted significantly by wave, wind and solar conditions. A balance between increasing the number of observations in the sample median versus increasing the natural variations was assessed. The standard deviation of natural variations decreased with increasing sampling interval until 60s to 120s. After 120s standard deviations increased substantially. Daily files were processed such that a representative 60s-to-120s bin median, with minimal standard deviation spectrum, was computed. Instrument uncertainty was assessed by mean and standard deviation of the burst sample of dark readings collected with capped sensors at in situ temperature. The sample median dark spectrum was subtracted from the sample median light spectrum.

The median dark-corrected incident downwelling solar spectra were interpolated to the wavelengths associated with the upwelling radiance spectra.

Following the approach of Morel et al. (2007), modified for hyperspectral radiometry, upwelling radiance measured at 63-cm depth below the surface, $L_u(\lambda, 0.63)$, was propagated to the surface, $L_u(\lambda, 0^-)$, assuming: (1) the diffuse attenuation for the upwelling radiance is equivalent to that for the downwelling radiance, $K_d(\lambda)$, and (2) the diffuse attenuation is

equivalent to the sum of the spectral absorption and backscattering for pure seawater, corrected for in situ temperature and salinity (Morel 1974; Pope and Fry 1997):

$$L_u(\lambda, 0^-) = \frac{L_u(\lambda, 0.63)}{\exp(-K_d(\lambda) \times 0.63)}$$

The upwelling subsurface radiance was propagated through the interface to retrieve water leaving radiance, $L_w(\lambda)$:

$$L_w(\lambda) = \frac{L_u(\lambda, 0^-) \times (1-\rho)}{\eta^2}$$

Where $\rho$is the Fresnel reflectance (0.021) and η is the refractive index for seawater (1.345). Remote sensing reflectance, $R_{RS}(\lambda)$, is computed from the ratio of hyperspectral water leaving radiance to incident downwelling irradiance:

$$R_{RS}(\lambda) = \frac{L_w(\lambda)}{E_S(\lambda)}$$

The uncertainties are arithmetically propagated (Jcgm 2008)from radiance and irradiance to remote sensing reflectance computations, and all are spectrally dependent.

$$\sigma_{Lu_{dark-corr}} = \sqrt{(\sigma_{Lu})^2 + (\sigma_{Lu-dark})^2}$$

$$\sigma_{Es_{dark-corr}} = \sqrt{(\sigma_{Es})^2 + (\sigma_{Es-dark})^2}$$

$$\sigma_{Lw} = \sigma_{Lu_{dark-corr}} \times \frac{(1-\rho)}{\eta^2 \times \exp(-K_d(\lambda) \times 0.63)}$$

$$\sigma_{RRS} = R_{RS}(\lambda) \times \sqrt{\left(\frac{\sigma_{Lw}}{Lw}\right)^2 + \left(\frac{\sigma_{Es_{dark-corr}}}{Es_{dark-corr}}\right)^2}$$

Data products originating with this method and order in submitted file:

Parameter	Symbol	Units
Wavelength	λ	nm
Median dark-corrected upward radiance measured at 63 cm depth	$L_u(\lambda, 0.63)$	μW cm^{-1} nm^{-1} sr^{-1}
Median dark-corrected downward irradiance measured above the surface	$E_d(\lambda, 0^+)$	μW cm^{-1} nm^{-1}
Water leaving radiance	$L_w(\lambda)$	μW cm^{-1} nm^{-1} sr^{-1}
Remote sensing reflectance	$R_{RS}(\lambda)$	sr^{-1}
Measure radiance uncertainty	$\sigma_{Lu_{dark-corr}}(\lambda)$	μW cm^{-1} nm^{-1} sr^{-1}
Measured irradiance uncertainty	$\sigma_{Es_{dark-corr}}(\lambda)$	μW cm^{-1} nm^{-1}
Computed water leaving radiance uncertainty	$\sigma_{Lw}(\lambda)$	μW cm^{-1} nm^{-1} sr^{-1}
Computed remote sensing reflectance uncertainty	$\sigma_{RRS}(\lambda)$	sr^{-1}

References:

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