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Enhanced satellite remote sensing of coastal waters using spatially improved bio-optical products from SNPP–VIIRS

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ABSTRACT

The spatial dynamics of coastal and inland regions are highly variable and monitoring these waters with ocean color remote sensors requires increased spatial resolution capabilities. A procedure for the spatial enhancement of ocean color products, including chlorophyll and inherent optical properties (IOPs), is developed using a sharpened visible water-leaving radiance spectrum for the visible infrared imaging radiometer suite (VIIRS). A new approach for spectral sharpening is developed by utilizing the spatial covariance of the spectral bands for sharpening the M bands (412, 443, 486, 551, 671 nm; 750-m resolution) with the I-1 band (645 nm; 375-m resolution). The spectral shape remains consistent by the use of a dynamic, wavelength-specific spatial resolution ratio that is weighted as a function of the relationship between proximate I- and M-band variance at each pixel. A comparison of bio-optical satellite products at 375-m and 750-m spatial resolution with in situ measurements of water leaving radiance and bio-optical properties show an improved capability of the VIIRS 375-m products in turbid and optically complex waters, such as the Chesapeake Bay and Mississippi River Plume. We demonstrate that the increased spatial resolution improves the ability for VIIRS to characterize bio-optical properties in coastal waters.

1. Introduction

Characterizing the dynamics of coastal optical water properties is a challenge due to the high spatial and temporal variability of optically active water constituents. These constituents include phytoplankton cells, suspended particulate material (SPM; both inorganic and organic), and chromophoric dissolved organic matter (CDOM), each of which have distinct optical signatures that affect the absorption and scattering of light in water, defining the water's inherent optical properties (IOPs; Kirk, 1992). Numerous coastal processes can drive the spatial distribution of optical water properties, such as fluvial input, tidal activity, eddy circulation, upwelling, and wind-driven mixing, thereby increasing the optical variability of these waters at scales of micrometers to kilometers (Dickey, 1991). As a result, major spatial limitations exist when attempting to characterize these complex waters with a shipboard sampling regime (Hu et al., 2004a; Miller, Twardowski, Moore, & Casagrande, 2003).

The spatial extent of these surface bio-optical properties can be determined from changes in satellite-detected water leaving radiance (L_w), enabling a more synoptic, albeit two-dimensional view of various ocean parameters on a global basis (Lewis, 1992). When using remote measurements to resolve ocean processes, two things must be considered: 1) the resolution capabilities of the remote detector, and 2) the spatial coherence of the process(es) to be studied. Spatial coherence describes the scales of variability within a system and helps determine the optimal pixel size for a satellite detector, or the ground sampling distance, to fully characterize the variability of a system. Semi-variogram analyses have shown that these spatial coherence scales are smaller in coastal and shelf waters and increase to larger scales in open ocean waters. Previous studies suggest a minimum ground sampling distance of 100-m for turbid estuaries (Bissett et al., 2004), while dominant scales of patchiness typical of coastal waters are resolved at 300 to 500-m spatial scales (Aurin, Mannino, & Franz, 2013; Davis, Kavanaugh, Letelier, Bissett, & Kohler, 2007).

The spatial resolution of many polar-orbiting sensors (~1 km) is often too coarse to fully unravel the variability associated with fine-scale coastal processes (IOCCG, 2012). Some sensors, such as the moderate/medium resolution imaging spectroradiometers (MODIS and MERIS, respectively) are equipped with higher spatial resolution bands (250–300 m), which have been successfully used to monitor

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coastal and inland waters for various parameters such as suspended solids (Miller & McKee, 2004), cyanobacterial blooms (Matthews, Bernard, & Winter, 2010), chlorophyll-a (Giardino, Candiani, & Zilioli, 2005; Moses, Gitelson, Berdnikov, & Povazhnyy, 2009), IOPs (Ladner et al., 2007), and general water quality (Floricioiu, Rott, Rott, Dokulil, & Defrancesco, 2004; Hu, Nababan, Biggs, & Muller-Karger, 2004b). While satellite systems with even higher spatial resolution capabilities do exist, such as the Hyperspectral Imager for the Coastal Ocean (HICO; 100-m spatial resolution), the Landsat series (30-m spatial resolution), or WorldView-2 (3-m spatial resolution), the temporal revisit time (1+ week) is not sufficient to resolve the temporal variability of coastal processes. These optically complex waters require the use of satellite sensors with sub-kilometer spatial resolution at all visible bands as well as a revisit time of at least once per day to capture the rapidly changing dynamics of coastal waters (Matthews, 2011).

The Suomi National Polar-orbiting Partnership (SNPP) satellite with the Visual Infrared Imaging Radiometer Suite (VIIRS) offers daily coverage of the world, with some limited regional coverage of more than once per day (Arnone et al., 2013). VIIRS has 7 visible/near infrared moderate resolution (M)-bands ($\lambda = 410, 443, 486, 551, 671, 745, 865$ nm) at a spatial resolution of 750-m at nadir, and two visible/near infrared imaging (I)-bands ($\lambda = 640, 865$ nm) at a spatial resolution of 375-m at nadir (Fig. 1). The 750-m bands offer spatial improvement compared to the analogous 1-km MODIS bands at nadir, in conjunction with a unique along-scan aggregation scheme that enables the retrieval of higher resolution data retrievals at high zenith angles (Baker, 2011). The utilization of the visible 375-m I1 band enables great potential to resolve the spatial variability present in complex coastal waters as the spatial scale offers four times more data than 750-m resolution M-bands, and approximately seven times more data than 1-km scales.

The higher resolution of the broad spectral I1 band (600–680 nm) may be used to spectrally enhance the spatial variability at other (lower resolution) visible wavelengths. In a previous study, Gumley, Descloitres, and Schmaltz (2010) used the 250-m high resolution MODIS band 1 (with similar spectral characteristics to VIIRS I1 band) to sharpen 500-m moderate resolution MODIS bands in order to produce true color imagery at a spatial resolution of 250-m. The Gumley et al. computation for MODIS sharpening is given as a ratio of high to low resolution top of the atmosphere (TOA) radiances:

$$R = \frac{B_{640}}{B^*_{640}} \tag{1}$$

where

R spatial resolution ratio
B_{640} band 1 (640 nm) at 250-m resolution
$B_{640}{}^*$ band 1 (640 nm) at 500-m resolution, projected to 250-m resolution (duplicated pixels)

The lower resolution spectral bands (in this case, the 500-m spatial resolution bands centered at $\lambda = 470$ and 555 nm) are subsequently sharpened by:

$$B_\lambda = RB^*_\lambda \tag{2}$$

where

B_λ band (λ) at 250-m resolution
$B_\lambda{}^*$ band (λ) at 500-m resolution, interpolated to 250-m resolution

In short, the "spatial resolution ratio" empirically determines how each high resolution (MODIS band 1) pixel spatially differs from its neighboring pixel and applies that information about Band 1 variability to sharpen the lower resolution bands at other wavelengths. This sharpening technique works well for producing enhanced true color imagery, but it has the potential to introduce some spectral artifacts and cannot be applied to retrieve quantitative L_w measurements directly, as it centrally relies on the assumption that ocean color variability is unchanging across the visible spectrum. In other words, the approach assumes that the same spatial resolution differences that exist at 250-m in the red portion of the spectrum (645 nm) are also the same for the green and blue portions of the spectrum (410–555 nm). However, each optically active constituent in natural waters imparts its own unique spectral signature based on differing absorption and scattering coefficients, as well as its relative abundance. For example, high concentrations of suspended particles close to shore increase the backscattering coefficient relative to the absorption coefficient, which will be amplified in the red regions of the spectrum (600–700 nm) where there is lower absorption by particles (Miller & McKee, 2004). Meanwhile, wavelengths in the blue region of the spectrum, while also backscattered in the presence of suspended particles, are heavily influenced by absorption of phytoplankton cells, CDOM, and detrital material (Kirk, 1994). Therefore, what bio-optical variation is present in the red band (I1) is not strictly translatable to the bio-optical variability in the other visible bands.

Nevertheless, for spatially dynamic waters, such as those found in coastal regions, the high resolution I1 band can potentially yield useful information about ocean color variability. But in order to apply a spatial resolution ratio approach to sharpen other spectral bands, one must account for the dependence of spatial variability on spectral wavelength in waters of differing composition. In order to fully maximize the use of the VIIRS I1 band, we propose an adaptive image sampling technique that utilizes the relative covariance or divergence in radiance patterns occurring across the visible range of the light spectrum to spatially sharpen the visible spectral M(λ) bands. The objectives of this paper are to 1) demonstrate an enhanced spatial resolution in VIIRS by applying a spectrally weighted band-sharpening based on spatial coherence,

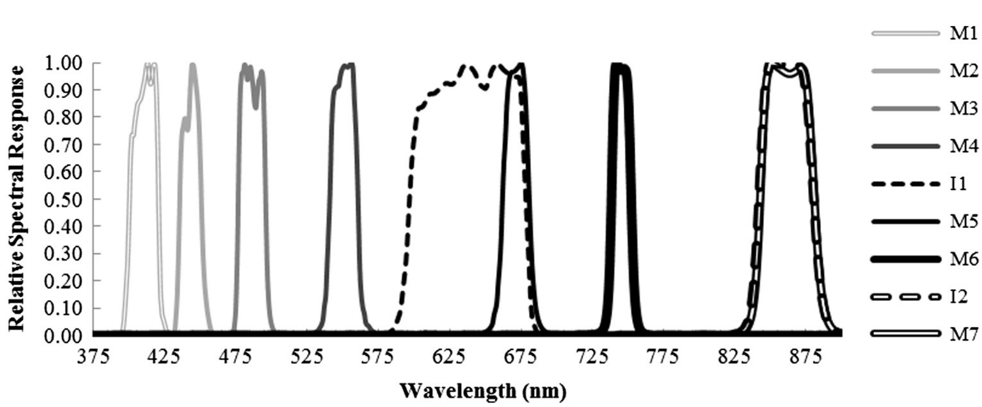

Fig. 1. The relative spectral response of the SNPP–VIIRS ocean color/NIR bands. Bands M1–M7 are at a resolution of 750-m, while the I1 and I2 bands have a higher spatial resolution (375-m).