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# Increased spectral resolution enhances coral detection under varying water conditions

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ABSTRACT

Earth observation offers effective spatial and temporal coverage to monitor coral reefs in addition to in situ monitoring. Effective monitoring requires that significant substratum features are detectable by a sensor. This detectability is a function of the sensor spectral resolution, the depth and composition of the water column and the spectral characteristics of the substratum. Most broadband multispectral satellite sensors are ineffective in resolving reef substrata at depth due to a lack of spectral specificity. The aim of this simulation study was to quantify the level to which substrata can be classified by sensors with variable spectral resolutions over a range of depths and water qualities and also to improve and quantify the definition of substratum detectability (the measure to which a substratum can be resolved from the water column) and substratum separability (the measure to which a substratum pair can be resolved from each other and from the water column). Three sensors were selected, representing hyperspectral data (CASI with 30 spectral bands) and multispectral data (WorldView-2 with 8 bands, and QuickBird with 4 bands). Spectral separability of substratum reflectance spectra (convolved to the spectral resolution of the three sensors) were compared within two contrasting water columns (reef-oceanic and coastal) over a range of water column depths. Metrics for substratum detectability and substratum separability were determined. As spectral resolution increases from QB to WV2 to CASI, end-members can be resolved to greater depths (e.g. from two to six meters in a coastal water column). The additional three spectral bands in the visible part of the spectrum of the WV2 sensor, as compared to QB, increase the applicability of multispectral sensors to systematic coral reef remote sensing. Increase in water column attenuation, due to higher concentrations of water column constituents, causes loss of substratum detectability and substratum separability. This effect can be partly compensated for by increased spectral resolution. For example, although the CASI and WV2 sensor performed comparably in a very shallow coastal water column (e.g. at 2 m depth), the higher spectral resolution of the CASI sensor enhanced spectral separability, resulting in higher substratum separability in deeper water than WV2. With more spectral bands, more substratum end-member reflectances are distinct from the water column signal to greater depth. This implies that higher spectral resolution will enhance bathymetry retrieval, especially within coastal waters. The quantitative framework of this study extends findings of previous contextual coral reef substratum mapping studies. It confirms that higher spectral resolution (i.e. WV2 and CASI) earth observation data significantly enhances coral reef classification capability to increased depths or to the same depth in a more turbid water column. The conclusions of this study can also be extended to coastal ecosystems.

## 1. Introduction

Coral reefs are widely recognized as an important resource for tourism, fisheries and local economies but are susceptible to large-scale processes, such as rising ocean temperatures (Hoegh-Guldberg, 1999), changes in ocean water biogeochemistry (LeDrew et al., 2000), anthropogenic effects (Riegl et al., 2009) and competition by invasive species (Riegl et al., 2009). Effective management and conservation of coral reefs requires periodic monitoring to detect environmental changes, however, in situ monitoring of protected coral reef habitats is often constrained by their remote location and often vast extents.

Satellite remote sensing offers effective spatial and temporal coverage to monitor coral reefs in the periods between routine in situ monitoring campaigns and after catastrophic events (e.g. Bahuguna et al., 2008). However, consistent mapping of coral reef systems from satellite sources is often hampered by unknown water quality parameters (Lubin et al., 2001) and lack of accurate information on the substratum types present at the time of image acquisition (Holden & LeDrew, 1998a). Hochberg and Atkinson (2003) identified two fundamental requirements for remote sensing of coral reefs, namely that each coral reef substratum-type should have characteristic spectral features and that

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those spectral features can be detected by a specific sensor. Most historical multispectral satellite sensors are incapable of effectively resolving reef substrata, such as living, dead and bleached corals and functional forms of algae, due to the limited number (usually four) and lack of specificity of their spectral bands (Andréfouët et al., 2001; Hedley et al., 2004; Hochberg et al., 2003). However, a new generation of satellite sensors with higher spectral and spatial resolution, such as the WorldView-2 sensor, even with broad spectral bands, may contribute to the solution of this problem.

Efforts to classify coral reef systems, as well as other marine systems such as coastal seagrass meadows and macroalgae, from satellite data traditionally included implementing supervised classification techniques, for example, Spectral Angle Mapping (SAM) (Casal et al., 2011; Kutser & Jupp, 2006), spectral clustering (Casal et al., 2011; Kutser & Jupp, 2006; Vahtmaë & Kutser, 2007), derivative analysis (Holden & LeDrew, 1998b; Karpouzli et al., 2004; Kutser & Jupp, 2006), and spectral mixture analysis (Goodman & Ustin, 2007; Hedley et al., 2004; Van der Meer, 1999).

These empirical classification approaches are often confounded by the effect of varying water depth and water quality across the image (Green et al., 1996; Holden & LeDrew, 1998a; Holden et al., 2001; Kutser et al., 2003). Water depth and water quality influence light attenuation across the water column, impacting on the ability to detect subsurface species, density of cover and/or color of substrata from image data.

Subsurface irradiance reflectance, measured above a water column where part of the reflectance at the surface is composed of a bottom signal (optically shallow), is a combination of the downwelling light and two upwelling light-streams: one from the substratum and one from the backscattered light in the water column itself (Maritorena et al., 1994) and can be expressed as:

$$r_{rs} = r_{rs}^{dp} + \exp(-K_d z)\left[R_{sub}\exp(-\kappa_B z) - r_{rs}^{dp}\exp(\kappa_C z)\right] \quad (1)$$

where the subsurface irradiance reflectance ($r_{rs}$), measured over an optically shallow water body with a given depth ($z$) is equal to the subsurface irradiance reflectance of an infinitely deep water column ($r_{rs}^{dp}$) plus the difference between the product of bottom irradiance reflectance ($R_{sub}$), attenuated vertically upward ($\kappa_B$), and the product of the vertically upward attenuated ($\kappa_C$) infinitely deep water column irradiance reflectance ($r_{rs}^{dp}$) times the vertical downward attenuation of the downwelling light stream ($K_d$) (Brando et al., 2009; Dekker et al., 2006; Maritorena et al., 1994).

The quantities describing the underwater lightfield (i.e. $r_{rs}^{dp}$, $K_d$, $\kappa_B$, $\kappa_C$) are influenced by concentrations of the bio-optical constituents within the water column, including phytoplankton, suspended material and colored dissolved organic material. To circumvent light attenuation variations in water bodies, various image-based techniques were developed. These include exploring statistics within the image, such as creating linear models across known benthos at various depths (e.g. Mishra et al., 2006; Vahtmaë & Kutser, 2007), developing band ratios and indices (e.g. Lyzenga, 1981; Mishra et al., 2006) and contextual editing (Mumby et al., 1998). As most of these techniques are image-based, they can often be site specific, sensor specific and/or time specific (Kutser et al., 2003).

Analytical and semi-analytical approaches are based on radiative transfer theory and employ algorithms to map substratum type and benthic cover from imagery which incorporate the effects of water column constituents and substratum spectral reflectance (Holden & LeDrew, 2002). This enables a per-pixel analysis of images of submerged habitats, accounting for the confounding effects of water column depth and water quality parameters (Lee et al., 1998, 1999, 2001). Lee et al. (2001) proposed a semi-analytical implementation of Eq. (1) (Maritorena et al., 1994), incorporating a series of semi-analytical relationships based on the Mobley (1994) radiative transfer model to relate the four quantities $r_{rs}^{dp}$, $K_d$, $\kappa_B$, and $\kappa_C$ to absorption and backscattering.

When substratum irradiance reflectance ($R_{sub}$, Eq. 1) is considered in an optically shallow system, it is generally described by a series of representative reflectance spectra (spectral libraries) of the substratum-types present. As differential attenuation by the water column will modify the spectral signature of an object at depth (Lyzenga, 1981; Maritorena et al., 1994), the selection of representative substratum spectra that will remain distinct at known depths or optical water quality ranges, is an important consideration. Although Hochberg and Atkinson (2000) and Phinn et al. (2008), for example, have shown that the three most elementary biotic reef classes (sand, coral and algae) are spectrally distinct and can be accurately classified to a depth of at least 3.5 m within a complex coastal water column in a hyperspectral image, applying the same spectral libraries to the limited spectral resolution of multispectral data may not yield the same accuracies. Due to the increased spectral width of each multispectral band, the sharpness of the spectral features of the data may be diminished (Dekker et al., 1992) and, consequently, the ability to resolve distinct spectral features in the substratum spectra may be compromised with increasing water depth.

This study aims to quantify the level to which substrata can be resolved by sensor platforms with variable spectral resolutions within a water column over a range of depths and optical water qualities. The ability to detect a spectral signal from the substratum is dependent on the spectral optical depth of the water column, the brightness and spectral contrast of the substratum and the sensor design (Dekker et al., 2001). In this study, the ability to resolve distinct spectral features by sensors with different spectral resolutions will be based on a two-stage procedure, derived from measures of spectral difference. Firstly the substratum detectability is quantified to determine whether a substratum type is distinguishable from the optically deep water column, then the substratum separability will determine if variability between a pair of different substratum spectra was sufficient to be successfully distinguished from each other at a range of depths and water properties.

Studies of substratum spectral separability have shown that careful placement of hyperspectral bands (Fyfe, 2003; Holden & LeDrew, 1998a), and reduction of end-member variability in spectral mixture analysis (Somers et al., 2011), can improve retrieval of subpixel fractions and enable better species differentiation. Hedley et al. (2012) presented a systematic sensitivity analysis, outlining the environmental and sensor limitations for benthic mapping objectives in coral reefs with airborne hyperspectral sensors. They concluded that spectral variation of benthic types and sub-pixel mixing is the primary limiting factor for benthic mapping objectives. To our knowledge no similar study has been published on end-member separability of spaceborne multispectral sensors based on sensor characteristics, water quality and water column depth. This study will therefore compare the spectral separability of selected substratum reflectance spectra in coral reef systems within the East Marine Bioregion of Australia (Australian Government – Department of Environment, Water, Heritage & the Arts, 2009).

The bio-optical properties of natural water bodies are a continuum of bio-optical conditions between clear, oceanic waters, predominantly influenced by phytoplankton, and coastal waters characterized by a large variability in particulate and dissolved matter (D'Alimonte et al., 2007). Therefore, to quantify the effect of water column properties on substratum separability, in this study the overlying water column will be parameterized with two sets of water quality parameters, representative of reef-oceanic and coastal water types within the Australian East Marine Bioregion, over a range of water column depths. The aim is to quantify the depth to which substrata can be identified and mapped from sensor platforms with variable spectral resolutions (CASI, programmed with 30 aquatic ecosystem specific spectral bands, WorldView-2 with eight spectral bands and QuickBird-2 with four spectral bands).