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Quantifying coral substratum detectability from earth observation sensors

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Abstract. Earth observation offers effective spatial and temporal coverage to monitor coral reefs, enhancing *in situ* monitoring. Effective monitoring requires that significant substratum features be detectable by a sensor. This is affected by the sensor spectral resolution and the depth and composition of the water column. Most historical multispectral satellite sensors are incapable of effectively resolving reef substrata at depth. We quantified the level to which substrata can be resolved by sensors with variable spectral resolution over a range of water depths and water qualities. Three sensors were selected, representing hyperspectral data (CASI with 30 spectral bands) and multispectral data (WorldView-2 (WV2) with 8 bands, and QuickBird (QB) with 4 bands). Spectral separability of substratum reflectance spectra (convolved to the spectral resolution of the three sensors) were compared for oceanic and coastal water over incremental water depths. Metrics for substratum detectability and substratum separability were determined. The increased spectral resolution of the WV2 and CASI sensors, permits brighter substratum-types, such as abiotic reef material, bleached coral and light corals to be resolved at greater depths, compared to QB. In a coastal water column, a higher number of substratum-types were indistinguishable at shallower depths than in the oceanic waters. Increased spectral resolution leads to more substratum types being separable from each other (substratum separability) at greater depth. This simulation study shows that higher spectral resolution (i.e. WV2 and CASI) earth observation data significantly enhances coral reef classification to increased depths thereby increasing the management relevance of this method.

Key words: substratum classification, earth observation sensors, water column constituents

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, changes in ocean water biogeochemistry, anthropogenic effects and competition by invasive species (LeDrew et al. 2000; 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. 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 (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, may contribute to the solution of this problem. This study will therefore compare the spectral separability of representative substratum reflectance spectra in coral reef systems, convolved to the spectral resolution of different sensor platforms (CASI, programmed with 30 aquatic ecosystem specific spectral bands, WorldView-2 (WV2) with eight spectral bands and QuickBird-2 (QB) with four spectral bands) in an attempt to quantify the effect of additional spectral bands on spectral separability of substratum types at depth.

Water depth and water quality influence the manner in which light is attenuated across the water column, ultimately impacting the ability to detect subsurface species, density of cover and/or colour of substrata from image data. Therefore, to quantify the effect of water column properties on substratum separability, the overlying water column will be parameterized with two sets of water quality parameters, representative of oceanic and coastal water types, over a range of water column depths. The aim is to quantify the depth to which substrata can be resolved from the different sensor platforms.

Material and Methods

Data collection

Substratum irradiance reflectance spectra (R_{sub}), representative of a coral reef benthic environment were collected during field campaigns in the Lihou Reef National Marine Park (Coral Sea Territory, Australia, representative of a tropical coral reef system) and the Lord Howe Island Marine Park (NSW, Australia, representative of a more subtropical coral reef system). Sample biotic and abiotic benthic types were sourced *in situ* in the intertidal- (exposed, above water) and the near-shore subtidal (submerged) zone. Benthic types sampled included consolidated and unconsolidated coral reef material, bleached coral, colored corals and coralline algae, seagrasses (if present) and macroalgae.

During both field campaigns, representative spectral data was collected with an ASD FieldSpec Pro HandHeld spectroradiometer (www.asdi.com). This instrument is designed for portability and measures over the range 325 to 1075 nm with a sampling interval of 1.4nm and a Full Width at Half Maximum (FWHM) resolution of 3nm.

To increase the database for the selection of representative spectra, the two coral reef spectral datasets collected at different locations were merged, as both Holden and LeDrew (1998) and Hochberg et al. (2003) found that coral reef substratum spectra measured at multiple locations were statistically consistent

Data processing

A three stage procedure was followed to prepare the substratum reflectance data for analysis:

- A set of representative spectra were identified from the dataset.
- A radiative transfer model was implemented to simulate the effects of variable water depths on the separability of the substratum spectral reflectance signatures.
- The resultant dataset was transformed to match the spectral resolution provided by the CASI, WorldView-2 and QuickBird sensors.

Selection of representative substratum spectra

Representative spectra of dominant elements in the coral reef environment were selected from the combined coral reef dataset for comparison. Nine classes (Fig. 1) were selected, based on two criteria: (1) Australia's National Intertidal/Subtidal Benthic (NISB) Habitat Classification Scheme (Mount et al. 2007) and (2) dominant substratum colour.

To select the representative spectra, each spectrum in the combined coral reef dataset were initially classified into a dominant substratum type based on field documentation. For each dominant substratum type, spectra were selected within two standard deviations of the mean of all available spectra within that class. From this reduced dataset, a synthetic median spectrum was calculated to account for possible non-normal distributions within the available spectra (Schmidt and Skidmore 2003). For each individual spectrum in a given substratum type the Least Square Difference (ΔLS) to the synthetic median spectrum was computed. The spectrum with the lowest ΔLS value within the class was selected as the representative spectrum for that class.

Radiative transfer modeling

For this study, an enhanced implementation of the (Lee et al. 1999; 2001) semi-analytical model was applied to simulate the reflectance expected at the top of the water column given the benthic substratum reflectance at the bottom of the water column (Brando et al. 2009; Dekker et al. 2011).). The water column properties used in this study to simulate vertical attenuation coefficients and reflectances were adapted from two contrasting water type data sets: a clear oceanic water column representative of Heron Reef, located in the southern portion of the Great Barrier Reef, Australia (Wettle et al. 2005) and a coastal water column, representative of Moreton Bay, Australia (Brando et al. 2009).

Subsurface remote sensing reflectance spectra were simulated for each of the nine representative substratum types at incremental depths to 20m for both water columns. These subsurface remote sensing reflectance spectra will be identified in this manuscript as $r_{rs\,(i,z,w,s)}$ where i is the substratum class (unconsolidated, consolidated, dead, yellow, orange, purple, red, brown, green), z is the depth of the water column, w is the water type (oceanic, coastal) and s is the sensor (ASD, CASI, WV2, QB).

Data transformation

The hyperspectral $r_{rs(i,z,w,\,ASD)}$ spectra, generated by the radiative transfer model were transformed to the equivalent CASI, WorldView-2 and QuickBird spectral bands using the appropriate spectral response filter functions (CASI: Brando et al. 2009; WV2 and QB: (Scott 2011)).

Data analysis

To determine the separability of the simulated $r_{rs(i,z,w,s)}$ from each other at depth, $r_{rs(i,z,w,s)}$ were compared with each other to determine if the spectral difference was sufficient between the substratum pairs to be successfully distinguished from each other at a range of depths and water properties.

In this study, differences in both the spectral magnitude and the spectral shape of the modelled spectra were considered to objectively quantify spectral separability of these representative spectra at depth. For this purpose, we implemented a modification of the Spectral Similarity Scale (SSS, (Granahan and Sweet 2001)), proposed by (Nidamanuri and Zbell 2010) which combines the spectral angle between two spectra (SAM, (Kruse et al. 1993)), to account for differences in spectral shape, and euclidian distance (ED) between the spectra, to account for differences in albedo

$$SSS = \sqrt{ED^2 + SAM^2} \qquad (1)$$

Where,

ED is the euclidian distances between the two spectra, modified to take the number of spectral bands (n) into account:

$$ED = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(r_{rs(s1)i} - r_{rs(s2)i}\right)^2} \qquad (2)$$

and SAM is the spectral angle between the two spectra as defined by:

$$SAM = \cos^{-1}\frac{\sum_{i=1}^{n}\left(r_{rs(s1)i}r_{rs(s2)i}\right)}{\left[\sum_{i=1}^{n}\left(r_{rs(s1)i}\right)^2\right]^{1/2}\left[\sum_{i=1}^{n}\left(r_{rs(s2)i}\right)^2\right]^{1/2}} \qquad (3)$$

The SSS varies between zero (identical spectra) and square root of two (dissimilar spectra). A value of 0.07 was selected as a threshold for spectral discrimination for this study based on published depths at which light and dark substratum types could be distinguished from the water column in CASI, QB and IKONOS images (Table 1, data not presented). Substratum reflectances resulting in SSS < 0.07, when compared to each other, were considered indistinguishable from each other.

Bands	Type	Sensor	Subs. type	Max. depth	Ref.
4	O	QB	sand	18m	Mishra et al. (2006)
		IKONOS	sand	>15m	Stumpf et al. (2003)
	C	IKONOS	sand	3m	Kutser et al. (2006)
		QB	seagrass	3m	Phinn et al. (2008)
		IKONOS	seagrass	1.5m	Kutser et al. (2006)
28+	O	CASI	coral	15m	Bertels et al. (2008)
	C	CASI	seagrass	12m	Brando et al. (2009)

Table 1: Selected case studies, showing the depths at which light (sand) and dark (seagrass/coral) substratum types can be discriminated by four band multispectral (QuickBird and IKONOS) and airborne hyperspectral (CASI) data in coastal (C) and clear oceanic (O) water types.

Results

Model output

Figure 1 shows the full simulated spectrum model output, at incremental depths of the oceanic water column, for the nine representative substratum-types depths ($r_{rs\ (i,z,\ coastal,\ ASD)}$ were also simulated but are not shown). Some reflectance features are common for all substratum types. This includes lower reflectance values in the blue and green wavelengths and higher reflectance values in the red wavelengths. Between 500nm and 600nm, $r_{rs(i,z,w,s)}$ for all substratum types decreases strongly with increasing water column depth as the water column increasingly attenuates the substratum component of the remote sensing signal. Brighter colored substratum-types, such as unconsolidated material, consolidated material, dead coral and yellow coral have higher subsurface reflectance values at depth than darker coral or coralline algae and green substratum types (seagrass and/or green macroalgae) in the 500 nm to 600 nm portion of the spectrum. The brighter substratum-types, with higher r_{rs}, would potentially be detected over a greater range of water column depths than substratum types with lower albedo values as the lower albedo values will cause these r_{rs} to be completely attenuated by the water column at shallower depths.

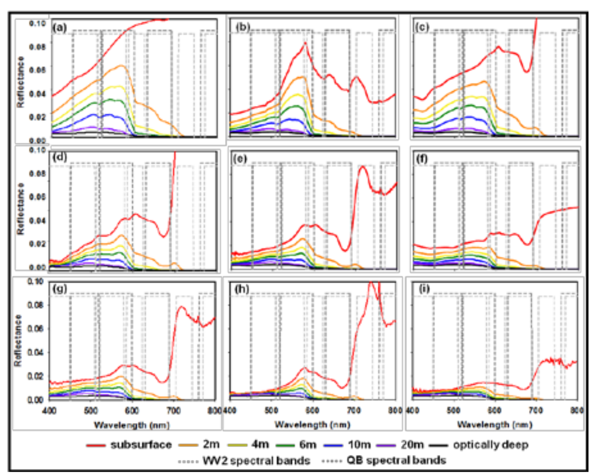

Figure 1: Modelled $r_{rs\ (i,z,\ oceanic,\ ASD)}$, based on the full spectrum measurements of (a) unconsolidated-, (b) consolidated-, (c) dead coral, (d) yellow-, (e) orange-, (f) purple-, (g) red-, (h) brown- and (i) green representative substratum types in a range of oceanic water column depths ($r_{rs\ (i,z,\ coastal,\ ASD)}$ were simulated but not shown). The band widths of the two multispectral sensor platforms (WorldView-2 and QuickBird) are included to demonstrate the extent to which spectral features may potentially be diminished with limited spectral resolution.

Yellow, orange, red and brown coral/coralline algae exhibits a triple-peaked reflectance pattern between 550nm and 670nm with a prominent reflectance peak near 570nm while purple coral have a plateau-like shape between 600nm and 650nm. Dead coral is spectrally similar to abiotic unconsolidated and consolidated reef substratum material while the green substratum-type has a single broad reflectance feature centred between 550nm and 650nm.

Substratum separability

Figure 2 represents substratum-types that are spectrally separable from each other (SSS >0.07) in four water column depths for the oceanic and coastal water types by the CASI, WV2 and QB sensors, respectively.

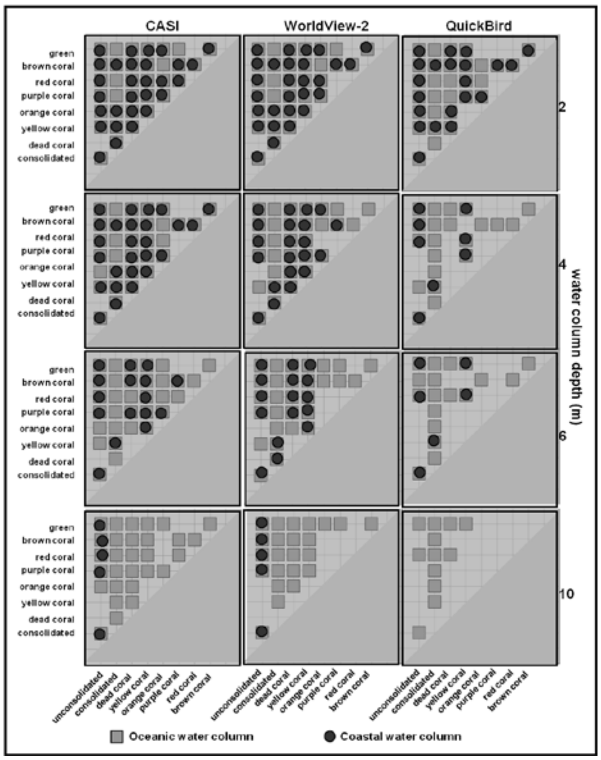

Figure 2: Substratum-types that were spectrally separable from each other (SSS > 0.07) by the CASI, WorldView-2 and QuickBird sensors in four different coastal and oceanic water column depths

Increased spectral resolution leads to more substratum types being separable from each other at greater depth. Additionally, the oceanic water type leads to better spectral separability compared to the coastal water column due to lower attenuation coefficients.

In oceanic waters, $r_{rs\ (unconsolidated,\ z,\ oceanic,\ s)}$ and $r_{rs\ (consolidated,\ z,\ oceanic,\ s)}$ can be separated from each other across all sensor-types to a depth of at least ten meters (Figure 2). Abiotic substratum-types are more readily separable from live reef material (corals and green substatum) than from each other to a depth of at least ten meters by the CASI and WV2 sensors. $r_{rs\ (red,\ z,\ oceanic,\ s)}$ is more separable from the other dark coral substratum types but not from $r_{rs\ (green,\ z,\ oceanic,\ s)}$, suggesting that it is distinguished by its lower albedo from the other coral substrata and not by a distinct spectral feature.

Higher spectral resolution enhances spectral separability. Due to the stronger water column attenuation in coastal waters, subtle spectral absorption features becomes less distinct at shallower depths than in clearer oceanic waters. The WV2 sensor, with its higher number of spectral bands, performed similar to the hyperspectral airborne CASI sensor while the QB sensor, with a more limited number of spectral bands was unable to resolve any substratum from each other at depths beyond six meters in the coastal water column.

Discussion

The aim of this study was to quantify the level to which coral reef substrata can be resolved by earth observation sensors with variable spectral resolutions within a water column over a range of depths and water qualities. Three sensors were selected, representing hyperspectral data (CASI) and multispectral data (WV2 and QB).

Fine-scale spectral features, that can potentially separate substrata from each other, become lost when data is collected in broad multispectral bands. The WV2 sensor consistently outperformed the QB sensor for detecting and differentiating substrata at depth. This suggests that the additional spectral of the WV2 sensor increase its applicability to systematic coral reef remote sensing. This enhanced performance is particularly important in more turbid coastal waters where the additional spectral bands leads to better discrimination of substratum types at depths beyond which the QB sensor is capable of.

Mapping coral reef ecosystems with remotely sensed data is challenging due to the optical-, spatial- and temporal complexity of coral reef communities (Mumby et al. 1997; Holden and LeDrew 1998). In addition to water column and substratum albedo effects, factors such as the texture, structure and degree of homogeneity of the substratum, atmospheric attenuation and water surface state can also affect spectral reflectance discrimination of the substratum signal.

Reef substrata are known for their spatial heterogeneity and it is often impossible to match the sensor spatial resolution, to the reef patch size (Mumby et al. 1997). This leads to multiple substratum-types contributing to the reflectance value of a single pixel (Hedley et al. 2004). Several authors have recently extended the semi-analytical model, developed by Lee et al. (1999; 2001), to incorporate linear un-mixing of combined substratum spectra (e.g.; Brando et al. 2009). Much of this work focused on high spectral resolution data. Lee (2009) found that applying semi-analytical models, developed for narrow-band hyperspectral data, to wideband multispectral data introduces uncertainties in the retrieval of model components. Future operationalization of benthic substratum mapping from satellite data will depend on the refinement of these models to optimize the data-retrieval from multispectral imagery. This simulation study focused only on spectral resolution. However, the spatial-, spectral- and radiometric resolution of a sensor will impact on substratum spectral separability. For example, in the case of identical sensors, a sensor with a finer spatial resolution requires a smaller instantaneous field of view (IFOV) in order to record fine spatial detail. A smaller IFOV will yield less signal, compared to the background electronic noise associated with the sensor system (Lillesand and Kiefer 1994). To increase the amount of photons detected (increase the signal) without reducing spatial resolution, the width of the wavelength range for a particular channel is often increased. However, this, in turn, will reduce the spectral resolution of the sensor. Future work should thus focus on whether the trade-off between improved spatial and spectral resolution compromises the ability of, for example, the WV2 sensor to discriminate coral reef substratum types from space at depths greater than that of the QB sensor.

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