A novel spaceborne proxy for mapping coral cover

Antoine Collin[1], James L. Hench[2], Serge Planes[1]

[1]Centre of Insular Research and Observatory of Environment, CNRS, Papetoai BP 1013 French Polynesia
[2]Nicholas School of the Environment, Duke University, 135 Marine Lab Road Beaufort, NC 28516, USA
Corresponding author: antoinecollin1@gmail.com

Abstract. Spaceborne remote sensing has resolved critical issues for mapping coral reef structure that human- and ship-based surveys could not have overcome, namely the spatial continuity regardless of the water depth. With the emergence of very high spatial resolution sensors, the spatial capabilities of satellites have outperformed those of aircraft, providing spectral information at the dominant benthos scale but over large areas. With the launch of the WorldView-2 (WV2) sensor, coral reefs can now be surveyed using eight bands at ~2 m spatial resolution, somewhat bridging the gap with high spatial resolution, hyperspectral airborne sensors. The WV2 spectral capabilities were utilized for modeling an *in situ* gradient of Live Coral Cover (LCC). Georeferenced underwater photoquadrats were collected to discern among ten benthic classes, ranging from coralligeneous sand to live *Synarea rus* bommie or *Acropora pulchra* thicket, and to compute the LCC. From the benthic images of the five WV2 visible bands (purple, blue, green, yellow, red), 20 pairwise combinations were tested in the form of a Normalized Difference Ratio (NDR). Four spectral combinations were revealed with high correlations (>0.8) with *in situ* ground-truthing. Associating the common green band with the innovative purple band, the NDR green-purple showed a strong linear relationship with the LCC ($R^2=0.96$, $p<0.001$). The successful combination was mapped over the entire scene, reliably highlighting live corals while being less sensitive to dead corals and sediment. Discussed to be a proxy for the amount of zooxanthellate-borne pigments such as perdinin, the green-purple NDR holds great promise to map, detect and predict change in coral reefs at the dominant benthos scale regionally, aiding their management and conservation.

Key words: Coral Detection Proxy, Very High Resolution, WorldView-2 Satellite.

Introduction

Coral reefs host 25% of the marine species diversity and provide valuable ecological and economic services such as disturbance regulation, food production and recreation (Costanza *et al.* 1997). However, severe impacts from current anthropogenic pressures may cause the degradation of more than half of global coral reefs before 2050 (McGinley and McClary 2008). Understanding the dynamics of their responses to threats requires the ability to rapidly and reliably map coral reefs' spatial patterns across time at the dominant benthos scale over regional extents.

Even if worldwide coral reefs occupy less than 0.1% of the oceanic surface, human-based *in situ* observation can only provide discrete and isolated data. Likewise, waterborne surveys are not suitable for collecting data on reef flats in the extremely shallow areas. Spaceborne coral reef remote sensing has overcome those critical issues in mapping habitats of the seamless reefscape (Collin and Planes 2011). Through the development and the commercialization of Very High Resolution (VHR) sensors, spatial capabilities of satellite have joined those of aircraft, providing information at the dominant benthos scale but over large areas. With the launch of the WorldView-2 (WV2), using eight spectral bands at 2 m resolution, the fineness and the number of spectral bands available are turning out to be less and less the privilege of the airborne sensors. Complementary to the commonly used blue, green and red bands (*e.g.*, QuickBird-2 (QB2), Geoeye-1 (GE1)), the WV2 purple (called "coastal") and yellow bands have allowed the visible spectrum to be quasi-fully detected in five different bands spanning averagely 56 nm per band (1: purple, 2: blue, 3: green, 4: yellow, 5: red). Those technical advancements have resulted in better discrimination among coral reef features over local areas (Collin and Planes 2011).

In this study, we evaluated which combinations of WV2 bands are capable of discriminating live corals while being insensitive to various other features. The assessment is supported by *in situ* photographs from which the live coral cover can be quantified. We then examined whether the mapping using the select WV2 band combination is consistent with empirical knowledge over an entire scene.

Material and Methods

Study site and fieldwork

The study site is located in the northern lagoon of Moorea, Archipelago of the Society Islands, French

Polynesia (17°28’36’’S, 149°48’18’’W). The site has the typical coral reef structure of a volcanic island in South Pacific, including fringing reef, channel, barrier reef, reef crest and outer reef (Fig. 1). Covering an area of ~1.35 km², the site exhibits a complex bathymetric structure ranging from 0 to 23.07 m with an average depth of 5.07 m.

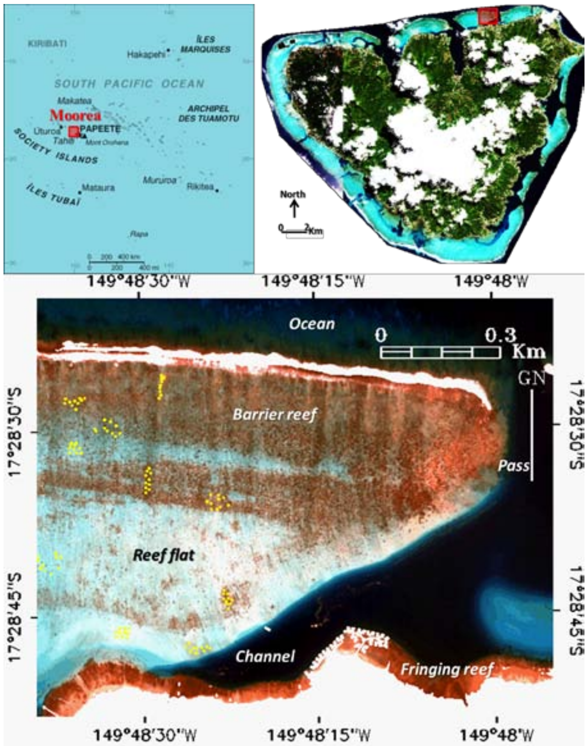

Figure 1: Natural colour image (Red: 5th WV2 bands, Green: 3rd WV2 band, Blue: 2nd WV2 band) of the study site (North Moorea, Archipelago of the Society Islands, French Polynesia). The sampling points are showed in yellow dots.

A ground-truth survey was first conducted to collect 100 high resolution underwater photographs taken over a 0.5 m x 0.5 m quadrat. Each quadrat was geolocated using a 0.5 m horizontal accuracy Trimble GPS Geo XH, and was evaluated to determine the dominant benthic cover variable, among 10 benthic classes (Table 1), within a 10 x 10 superimposed grid. While the variable showing the highest cover percent defined the class assignment of the quadrat, the live coral cover (LCC) percent was calculated as the sum of the quadrat cases exhibiting live coral cover. Three primary benthic features were identified, namely algae, essentially represented by *Padina* spp., consolidated and clastic sediment, and a gradient of live coral cover, from the highest cover with *Acropora* thickets, to habitat dominated by large *Synarea rus* and *Porites* bommies, to sparser cover dominated by colonies of *Pocillopora* spp. (Table 1). Secondly, an acoustic survey was carried out over the northern lagoon of Moorea during 4-18 January 2011 (cf. bathymetric measurements in Fig. 2) so that imagery-derived bathymetry could be calibrated and validated. Depth measurements (n = 10330) were made from a small boat equipped with a dual frequency (50/200 kHz) digital sonar and 12 channel GPS receiver (Garmin GPSMAP 546s).

Spaceborne imagery

Satellite multispectral dataset was acquired on 17 March 2010 over Moorea with the WV2 sensor. Launched in October 2009 by DigitalGlobe, WV2 leverages an eight-band multispectral dataset with a 2 m spatial resolution. Prior to further investigation, we orthorectified and radiometrically corrected the eight-band imagery. Delivered information of the sun-scene-sensor geometry and 15 ground control points (GCP) allowed the subset scene to be reliably orthorectified (RMSE < 1.9 m). The first step of the radiometric correction consisted in the conversion of the 11-bit Digital Number (DN) into the at-sensor radiance (μW cm^{-2} nm^{-1} st^{-1}). The second step called upon the MODerate resolution TRANsmittance (MODTRAN)-cored Fast Line-of-site Atmospheric Analysis of Spectral Hypercubes (FLAASH) package (Research Systems), providing a robust procedure to correct for atmospheric attenuation and adjacency effects, thus outputting the water-leaving radiance (in optical units) or water-leaving reflectance (unitless). Even if a pansharpening algorithm is liable to enhance the eight-band dataset at the panchromatic resolution, namely 0.5 m, the original 2 m dataset was examined so that the initially measured radiance was processed, since the purpose of the work did not target the sub-meter scale.

Benthic class	**Class description**
Algae seabed	*Padina* spp.
Sand	Clastic coralligeneous sediment (0.06 - 2 mm)
Reef flat	Consolidated coralligeneous debris
Gravel	Clastic coralligeneous sediment (2 - 64 mm)
Reef 1	Dead coral colonies covered by encrustine algae
Reef 2	Dead coral colonies with sparse young live colonies
Reef 3	Sparse young live coral colonies over dead reef/rubble
Reef 4	Sparse adult live coral colonies over dead reef
Synarea rus	Live *S. rus* bommie
Acropora pulchra	Live *A. pulchra* thicket

Table 1: Description of the ten classes investigated *in situ*.

Given the specificity of underwater remote sensing, a required third step is to include underwater radiometric correction. While the atmospheric correction accounts for air column attenuation, the hydrospheric correction compensates for the water column attenuation, thus providing the benthic reflectance. The reflectance, at a specific waveband, is exponentially attenuated (scattering and absorption mechanisms) with water depth (Lyzenga 1978):

$$R = \left(R_b - R_\infty\right)e^{-2kz} + R_\infty \qquad (1)$$

where R is the sea surface radiance at a pixel, R_b corresponds to the benthic reflectance, R_∞ refers to the radiance over a putative optically deep bottom (> 40 m), k is the diffuse attenuation coefficient, and z is the water depth.

The water column depth, *z*, was mapped across the scene by applying a band ratio transformation (Stumpf *et al.* 2003) to the purple, green and yellow bands (Collin and Hench 2012) and then calibrating the ratio with hydrographic soundings ($R^2 = 0.74$, Fig. 2). The diffuse attenuation coefficient, *k*, was assessed for each visible band (purple, blue, green, yellow, red) by using the values measured in a study of the optical properties of Moorea's waters (Maritorena *et al.* 1994). Knowing *z* and *k* at each pixel, the underwater radiative transfer model can be inverted so that the benthic reflectance can be retrieved, as follows:

$$R_b = \left(R - R_\infty\right)e^{2kz} + R_\infty \qquad (2)$$

Data from water depths of 0-2.5 m were used for spectral analysis, because the data from deeper water column are likely to skew spectral analysis given attenuation of the lower wavelengths within the water column (Maritorena *et al.* 1994). A Digital Depth Model (DDM) was used to identify the locations where water depth was shallower than 2.5 m.

We used an exploratory approach based on the Normalized Difference Vegetation Index (NDVI), that focuses on the high and low reflectances of photosynthetic vegetation in near infrared and red wavebands, respectively, to define a Normalized Difference Ratio (NDR) as:

$$NDR = \frac{(Wi - Wj)}{(Wi + Wj)} \qquad (3)$$

to synthetize a pairwise combination of wavebands *i* and *j* (W*i* and W*j*) with $i, j \in$ {purple, blue, green, yellow, red} and $i \neq j$. A total of 20 NDR was computed, generating 20 NDR Models. From the 10 quadrats of the 10 differentiated benthic classes, 10 pixels per class were used to compare the associated values of LCC and NDR per model. The Pearson product-moment correlation coefficient was employed to compare performances among models.

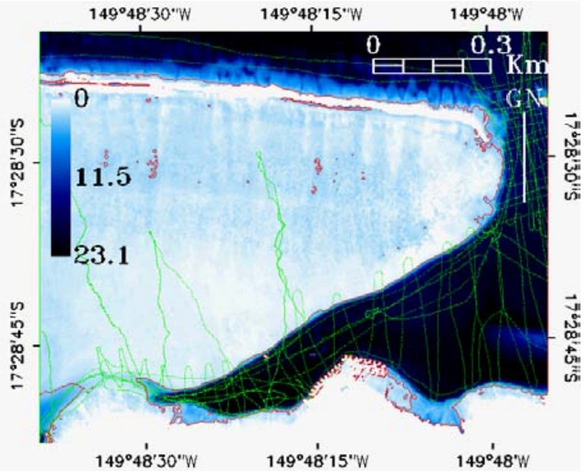

Figure 2: Digital Depth Model of the study site resulting from the band ratio transformation and calibration to field data. The 2.5 m contour line is displayed in red. The bathymetric measurements are showed in green dots.

Results

Correlations computed between *in situ* LCC and modeled NDR varied considerably, ranging from 0.04 to 0.98 (Fig. 3). Four combinations exhibited high correlations (> 0.8), namely, green-red, blue-purple, green-yellow and green-purple, *i.e.*, 35, 21, 34 and 31, respectively. A symmetry centered on 0 logically occurred, resulting from the switch between the two bands involved in the NDR combination.

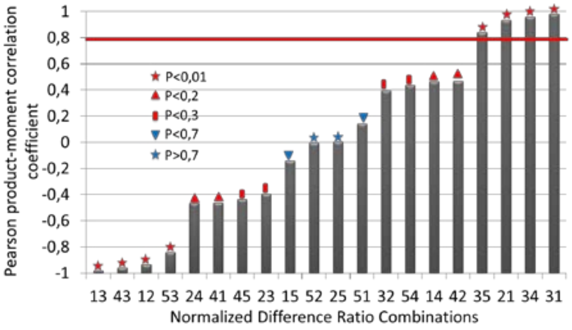

Figure 3: Clustered column plot showing the Pearson product-moment correlation coefficient between the measured Live Coral Cover (LCC) and the various Normalized Difference Ratio (NDR) combinations.

We selected the band ratio with the highest positive correlation (0.98, green-purple or 31 combination) for further investigation. A linear model strongly described the relationships between the NDR 31 and the LCC (Fig. 4). Linked with the 10 LCC averages, 10 photographs were selected to represent the benthic class based on their dominant percent cover. While the NDR 31 displayed values close to 0.35 for algae

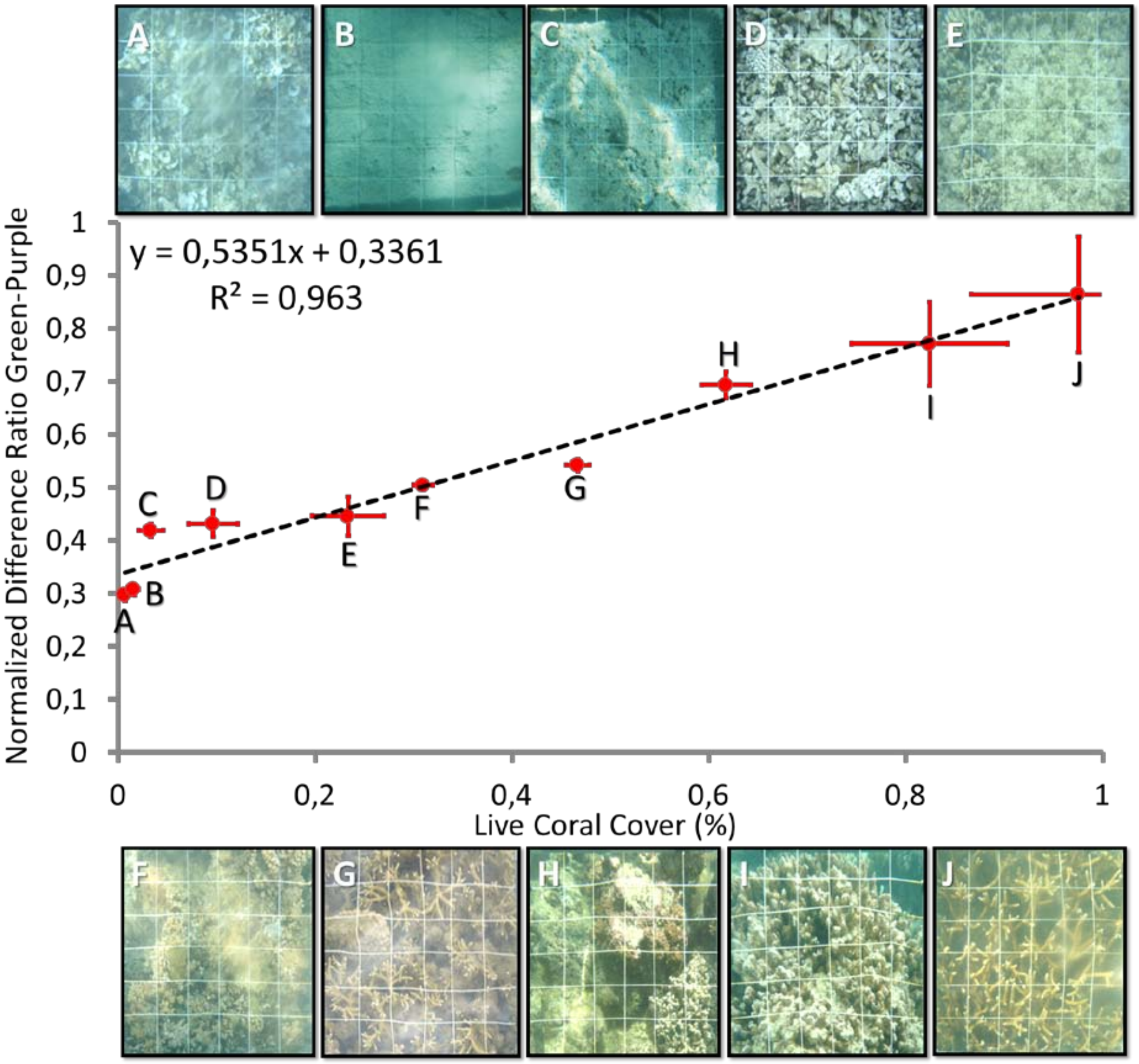

Figure 4: Scatterplot of the Live Coral Cover (LCC), visually defined by photographs, and the Green-Purple Normalized Difference Ratio (NDR 31). Vertical bars represent standard errors associated with the variability of spectral values and horizontal bars show standard errors inherent to the photograph analysis.

seabed and bare benthos, either clastic or consolidated, it ranged from 0.5 to 0.7 with increasingly live coral colonies, and it topped around 0.8 for totally live colonies. The gradient of the percent cover of live coral corals was revealed from examining 9 out of the 10 photographs attendant with LCC.

Discussion

The novel spectral capabilities of the spaceborne WV2 sensor were analyzed for modeling the gradient of the Live Coral Cover (LCC) index in shallow waters. Correlations between pairwise combinations of spectral bands and *in situ* ground-truthing revealed four useful spectral combinations as proxy measures of LCC. Three out of these four best combinations contained the green band, which is also found into other sensors (QB2 and GE1). However, the two best combinations solicited two novel bands paired with the green band, exclusively operated by WV2, namely the yellow and purple bands. The combination linking the green and purple bands exhibited the highest linear relationship with the LCC index. Sensitive to the difference of reflectance between the green and purple bands, the NDR green-purple is likely to embody a robust proxy for detecting coral pigments in live corals that exhibit higher reflectance in the purple band and a lower reflectance in the green band. A potential pigment characterized by such a spectral signature is peridinin (Collin and Planes 2012). This assumption corroborates findings by Clark *et al.* (2000), attesting a salient discrimination between live and dead corals in the green spectrum (515-596 nm). The strong agreement between the NDR green-yellow and green-red (2nd and 4th best correlations), involving the green band, and the LCC also suggests that the pigment peridinin may contribute to the spectra of pixels dominated by live corals. On the other hand, the high correlation attributed to the NDR blue-purple (3rd best correlation) suitably matched a spectroscopic study showing that the spectral region between 430 and 490 nm displayed the highest differentiation among various health states of corals (Leiper *et al.* 2009).

The successful green-purple NDR was mapped to verify the consistency of this novel index over the entire scene (Fig. 5). Within the scene, sandy plains appeared blueish, barrier and fringing reef with moderate cover of live coral colonies appeared greenish and hotspots of live colonies were reddish-coloured.

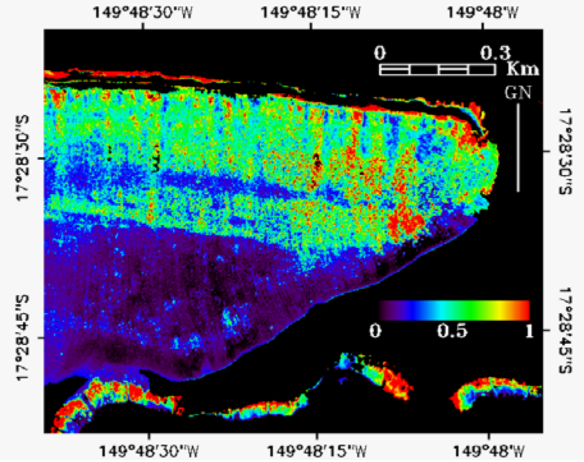

Figure 5: Digital Normalized Difference Ratio Model 31 (NDR 31) involving the green and purple bands. While purple-blue colours indicate low Coral Pigment Cover, yellow-red colours demonstrate high Live Coral Cover (LCC).

In situ spectral signatures of reef habitats are currently being analyzed so that the peridinin assumption can be robustly confirmed. Ongoing analyses aim to characterize the specificity of the index against different coral genera. Nevertheless, based on the findings of this work, this novel index holds great promise to detect and predict change in coral reefs, aiding their management and conservation.

Acknowledgements

Authors gratefully acknowledge the French Agency of Marine Protected Areas and CRIOBE technical staff. Partial support for the field measurements came from the U.S. National Science Foundation through the Moorea Coral Reef LTER program (OCE-1026851). The four anonymous reviewers who allowed the manuscript to be strongly improved are also deeply thanked.

References

Clark C, Mumby P, Chrisholm J, Jaubert J, Andréfouët S (2000) Spectral discrimination of coral mortality states following a severe bleaching event. Int J of Rem Sens 21: 2321-2327

Collin A, Hench J (2012) Towards deeper measurements of tropical reefscape structure using the WorldView-2 spaceborne sensor. Rem Sens, submitted

Collin A, Planes S (2011) What is the value added of 4 bands within the submetric remote sensing of tropical coastscape? Quickbird-2 vs WorldView-2. In Proc of the 31st IGARSS, Vancouver, Canada

Collin A, Planes S (2012) Highlighting three reef-building coral communities' health state using spectral diversity indices from WorldView-2 imagery. Rem Sens of Env, submitted

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, *et al.* (1997) The value of the world's ecosystem services and natural capital. Nature 387: 253-260

Leiper IA, Siebeck UE, Marshall NJ, Phinn SR (2009) Coral health monitoring: linking coral colour and remote sensing techniques. Canadian Journal of Remote Sensing 35: 276-286.

Lyzenga DR (1978) Passive remote sensing techniques for mapping water depth and bottom features. Appl. Opt. 17: 379-283

Maritorena S, Morel A, Gentili B (1994) Diffuse Reflectance of Oceanic Shallow Waters: Influence of Water Depth and Bottom Albedo. Limnol and Oceanogr 39(7): 1689-1703

McGinley M, McClary M (2008) Threats to coral reefs. In: CJ Cleveland (ed) Encyclopedia of Earth

Stumpf RP, Holderied K, Sinclair M (2003) Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnol. and Oceanogr. 48:547-556