HYPERSPECTRAL MONITORING OF CORAL REEFS A CASE STUDY: FORDATE, TANIMBAR, INDONESIA*

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ABSTRACT

The overall aim of this study is to monitor coral reefs and associated ecosystems by integrating different remote sensing data with spectral libraries and field measurements. To assess and verify the technical feasibility of a spaceborne hyperspectral sensor, a preliminary bottom-type classification was made based on hyperspectral data from the CHRIS/PROBA sensor. The atmospheric correction was performed with in-house atmospheric correction software, WATCOR, which takes into account atmospheric and air/water-interface effects. Due to the lack of bathymetric information, a water column correction could not be performed. As ground-truth data was available neither, the classification was based on automatic endmember selection using data-inherent spectral and spatial information. After the endmember selection, a Spectral Angle Mapper (SAM) procedure was followed to classify the dataset. Although some problems remain to be solved, the preliminary result presented, shows the potential of spaceborne hyperspectral data for detail coral reef studies.

1. INTRODUCTION

Coral reefs are considered to be one of the most spectacular marine ecosystems on earth displaying an extremely rich biodiversity. They also represent valuable socio-economic resources. Despite this natural wealth and socio-economic significance, many threats are posing stress on coral reefs. According to Bryant et al. (1998) 58% of the coral reefs in the world are potentially endangered by devastating human activities. The most important worldwide threats generated by human activities are pollution, sedimentation and unsustainable fishing activities (Bryant et al., 1998; Spalding et al., 2001). In reaction, several international organisations include the study of coral reefs in their programme and support the conservation and sustainable use of coral reefs. UNEP (United Nations Environment Programme), for example, established its Coral Reef Unit in 2000 and IGOS (Integrated Global Observing Strategy Partnership) adopted a coral reef sub-theme in 2001. Likewise, the 2002 Johannesburg World Summit on

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Sustainable Development recognised that the maintenance of healthy environments, such as coral reefs, is essential to reduce poverty and improve human health.

Current coral reef monitoring techniques range from underwater transect monitoring to remote sensing data analysis (Bryant et al., 1998). Remote sensing data offer the opportunity to gather information over vaster areas compared to traditional 'on-the-spot' survey methods where only limited spatially distributed information can be collected. The ideal approach would be 'multilevel sampling' (Bryant et al., 1998) whereby detailed, locally sampled information is extrapolated to wider, unsurveyed areas using satellite data. Remote sensing makes it also possible to follow up the situation in a multi-temporal manner. In this way remotely sensed observations can help to monitor changes in coral reefs and to differentiate between anthropogenic and natural effects on coral reef health (Kutser et al., 2003). Consequently, remote sensing is a useful tool for setting up monitoring programmes for distant or intensively "used" coral reef areas and offers a more cost-effective methodology than detailed labour-intensive field surveys (Mumby et al., 1999).

Most satellite data are well suited for coarse-level mapping of the geomorphology and bottom-type composition of the coral reefs. However, today, they are often lacking the spatial and/or the spectral resolution which are required to create detailed bottom-type maps and to detect and monitor the health status and vitality of coral reefs (Joyce et al., 1995). Hyperspectral airborne sensors, on the other hand, have a high potential for not only mapping small coral reef ecosystems but also for identifying areas with bleached or stressed corals. Kutser et al. (2003) recognise three main advantages of hyperspectral sensors: they possess a large number of narrowband channels capable of discriminating bottom-types in more detail (Mumby and Edwards, 2002), their large number of bands increase the capacity to unmix spectral signatures (Hedley and Mumby, 2003), and they can also distinguish bottom-types in deeper waters. However, even with these enhanced technical characteristics, the accuracy of the result will still be limited by the spatial heterogeneity of the study object and the effects of the atmosphere and the water column on the signal received by the air- or spaceborne sensor.

The major drawbacks to the use of hyperspectral information (HSI[1]) as a routine methodology are its limited areal coverage and the relatively high costs involved (Mumby and Edwards, 2002). This approach also needs an ancillary spectral library of coral reef bottom-type reflectances which is still not widely available (Hochberg et al., 2003). Airborne hyperspectral remote sensing is however a powerful tool for application and algorithm development given the versatility it offers. The intention of a study proposed by the authors is to develop a HSI-based monitoring methodology for a small area based on in situ spectral measurements, which are used to supplement the existing library of spectral signatures of coral-reef bottom-types (Hochberg et al., 2003) and to model simulations to see how the water column and atmosphere change the benthic spectral signature. The algorithms developed will then be generalised so that they can be implemented on UAVs[2], micro-satellite and satellite platforms. These systems, equipped with sensors with programmable narrow spectral bands (e.g. Goeke, 2004), will have the ability to revisit the sites at regular time intervals at high spatial resolution and at highly reduced costs.

A preliminary study was undertaken by the research groups involved to assess and verify the technical feasibility of a future-generation, spaceborne hyperspectral sensor. This preliminary study was based on the analysis and interpretation of experimental CHRIS/PROBA satellite imagery. The first results of bottom-type classification are discussed below.

[1] HSI: hyperspectral information
[2] UAV: unmanned airborne vehicle

2. STUDY AREA

As test site for the utility of CHRIS/PROBA data in coral reef studies, Fordate, a small island to the northeast of the Tanimbar archipelago (South-East Moluccas, Eastern Indonesia), has been chosen (Figure 1). The Tanimbar archipelago is part of one of the top ten coral reef hotspots identified by UNEP's World Conservation Monitoring Centre (WCMC) as exceptionally rich in endemic marine species but facing extreme threat (Roberts et al., 2002).

Figure 1. Localisation of the Study Area (green) (left: CIA, 2005; right: ReefBase, 2005)

3. TEST DATA

The PROBA (Project for Onboard Autonomy) satellite was launched in October 2001. It is an experimental, technology driven mission and was intended to be one of the first so-called *smallsats* whose design follows the principles of the "smaller, faster and cheaper" initiative (Barnsley et al., 2004). PROBA carries several scientific payloads of which the principal instrument is the Compact High Resolution Imaging Spectrometer (CHRIS). CHRIS acquires spatial high resolution data in up to 62 narrow bands in the visible and near-infrared part of the spectrum.

CHRIS/PROBA is nowadays as close as we can get to a spaceborne operational system. It has several interesting technological features that make the sensor a suitable instrument for a feasibility study on coral reef monitoring. The relatively high spectral resolution of CHRIS is almost comparable to what a hyperspectral airborne sensor, like CASI, can offer and is much higher then what is available for most other satellite sensors. The CHRIS spectral band setting is programmable for marine applications with (amongst other bands) three bands in the blue and five bands in the green wavelength range. The moderate spatial resolution of CHRIS, i.e. 20m at nadir, gives the potential to map individual reef components. Furthermore, images from the target area are taken at five different angles (nadir, ±36°, ±55°). This pointability of the platform enables the construction of different stereo-pairs in water-penetrating blue and green bands which allows the generation of a bathymetric map. This bathymetric information can be used as input data for the water column correction algorithm

A CHRIS/PROBA dataset was acquired over Fordate on January 27th, 2004. The CHRIS instrument was programmed in its mode 2 (optimized for water applications) setting (Table 1), which has an 18 band spectral

resolution and a full spatial resolution of 20m at nadir. While Fordate Island is mainly covered by clouds, the coral reef areas are mostly cloud-free (Figure 2).

Table 1. CHRIS/PROBA Mode 2 Spectral Band Setting

Band	Central λ (nm)	Band Width (nm)	Band	Central λ (nm)	Band Width (nm)
1	409.90	9.66	10	648.76	14.98
2	441.33	12.05	11	666.78	10.68
3	489.71	11.51	12	677.68	11.06
4	509.05	12.74	13	686.10	5.70
5	529.23	11.39	14	703.64	18.11
6	560.17	13.48	15	752.13	13.83
7	572.33	10.74	16	777.17	22.26
8	589.14	15.59	17	867.21	27.10
9	620.40	13.40	18	1012.34	43.40

Figure 2. CHRIS/PROBA Nadir Image (TCC) over the Study Area

4. METHODOLOGY

4.1 PRE-PROCESSING

Due to sensor calibration constraints, vertical stripes were present in the images which complicated the spectral analysis. Some lines and columns were missing as well. The missing information was filled in by averaging the adjacent lines. To minimize the vertical stripes, a one-dimensional convolution filter (kernel size 9 x 1) was applied to all spectral bands in the dataset. This filter placed more weight on the central pixel and lessened the importance of pixels further away from the centre. Besides, a land and cloud mask was applied in order to maximize contrast over the coral reef areas.

4.2 ATMOSPHERIC CORRECTION

The radiance received by the sensor L_{rs} consists of atmospheric path radiance $L_{atm\text{-}path}$, background path radiance $L_{rs,b}$ created by the adjacency effect, and target reflected radiation L_{target} or:

$$L_{rs} = L_{atm-path} + L_{rs,b} + L_{target} \tag{1}$$

with

$$L_{target} = \frac{d^{*}_{direct}(\tau,\theta_V) R_{app} E_d(a)}{\pi} \quad \text{and} \quad L_{rs,b} = \frac{d^{*}_{diffuse}(\tau,\theta_V) A_{app} E_d(a)}{\pi} \qquad (2)\,(3)$$

where $E_d(a)$ is the downwelling irradiance above the water surface, $d^{*}_{diffuse}$ and d^{*}_{direct} are the diffuse and direct ground-to-sensor transmittance respectively, R_{app} is the target apparent reflectance, and A_{app} is the average or background apparent reflectance.

The atmospheric correction was performed with the in-house software WATCOR. WATCOR uses the radiative transfer code MODTRAN-4 and follows the formulas given in De Haan and Kokke (1996). The at-sensor radiance is converted to apparent reflectance R_{app}. The apparent reflectance R_{app} can be estimated from the at-sensor radiance L_{rs} and the background radiance $L_{rs,b}$ (average radiance of surrounding pixels, calculated with a moving window technique) according to:

$$R_{app} = \frac{c_1 + c_2 L_{rs} + c_3 L_{rs,b}}{c_4 + c_5 L_{rs,b}} \tag{4}$$

where $c_1,\ldots,c_5$ are the atmospheric correction parameters.

The calculation of the atmospheric correction function required three Modtran-4 runs. The Modtran-4 tropical atmospheric profile and a navy maritime aerosol model were used for atmosphere characterization. An adapted dark-target approach was applied to estimate the visibility used as input to Modtran-4. This method assumes that somewhere in the scene there will be a dark water pixel for which the water-leaving radiance is negligible. This is a common assumption for deep, optically clear case 1 (Jerlov, 1976) water types. Deep, optically clear water is almost totally attenuating wavelengths in the near-infrared region of the spectrum. Thus, the at-satellite radiance detected in the near-infrared results mainly from atmospheric scattering, and it can therefore be used to estimate the visibility. The visibility was set by running WATCOR with a variety of reasonable visibility values until a reflectance value of near 0, but not negative, corresponded to this dark target pixel for the near-infrared band 17, centred around 867 nm.

4.3 WATER-COLUMN CORRECTION

For marine, coastal applications, the effect of the water column on the radiance reflected by the seabed is as important as the atmospheric effects. Light travelling through seawater is scattered and absorbed by both the water molecules and the suspended matter in the water column. The attenuation of the water column is wavelength dependent, i.e. longer wavelengths are more attenuated than shorter wavelengths, and the effect on the signal increases with the height of the water column. Knowledge of the depth variations in the study area is therefore essential input data to the water column correction algorithm. Before bathymetric information could be derived from

the stereoscopic CHRIS images, a minimum of six absolute orientation points (X, Y and Z) were needed. Unfortunately, these were not available to this moment and a water column correction was not yet performed.

4.4 CLASSIFICATION

Since no actual field survey has been undertaken, the classification was based on image inherent information. Both spectral and spatial image information was used to automatically select a set of endmembers out of the hyperspectral data. Depending on the number of bottom-type classes desired, a coarse or a more detailed classification can be achieved. After the endmember selection, all image pixels were compared to the endmembers using a SAM-procedure. SAM computes a spectral angle between each pixel spectrum and each endmember spectrum. The smaller the spectral angle, the more similarity between the pixel and target spectra is assumed. In this way a map of the occurring bottom-types was created using the CHRIS/PROBA data.

5. RESULT AND DISCUSSION

A SAM-classification algorithm based on 18 endmembers was performed on the CHRIS/PROBA dataset. The result of the bottom-type classification is shown in figure 3. An attempt was made to assign names to the endmember classes. As no ground-truth information was available, this was based on the visual examination of the endmember reflectance spectra and *a priori* knowledge of the reef geomorphology. Mixed pixels containing different habitat types, particularly near the shoreline of Fordate, complicated this task. The lack of a water column correction also truncated the result. Different bottom-type classes may be the result of spectral differences due to changes in depth over a similar substrate, hence for example the differentiation between three classes of “deep sand”.

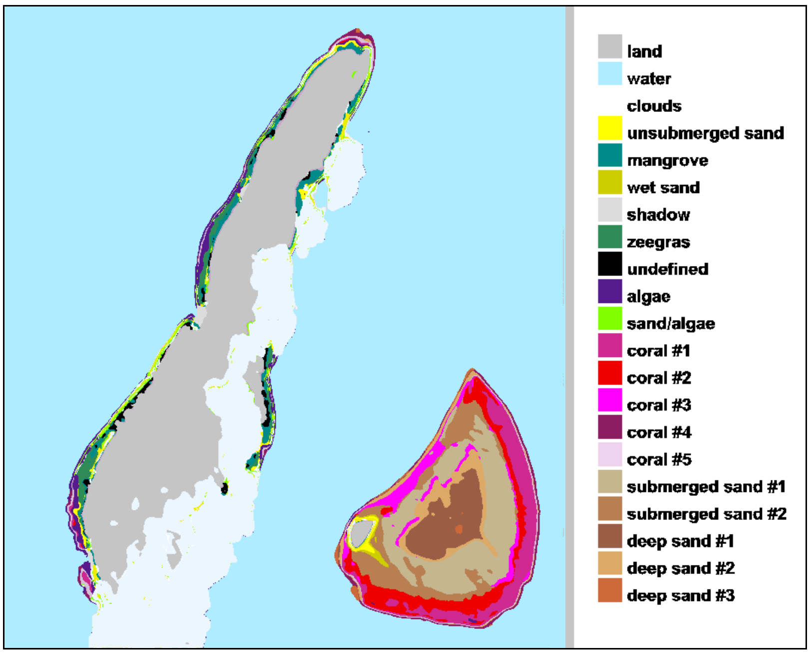

Figure 3. Preliminary Bottom-Type Classification Result based on CHRIS/PROBA Data over Fordate

Figure 3 should therefore not be considered as a highly accurate bottom-type classification. However, it shows that, based on the spectral information contained in the CHRIS/PROBA dataset, different bottom-types could be automatically distinguished. Besides, the patterns detected are not random noise, but show clear structures consistent with the morphology of the reefs. With the availability of ground-truth data or a spectral library of the bottom-types occurring in the study area and a thorough water column correction, an accurate and detailed bottom-type classification is likely to be achieved based on spaceborne HSI.

Finally, remark that the CHRIS/PROBA is not considered as the operational tool for future coral reef monitoring programmes. Since the CHRIS is an experimental sensor, some radiometer errors occur in the data which limit the full potential for coral reef studies. Next to the striping in the images and the missing data, different studies (Guanter et al., 2004; Lavender et al., 2004) have shown the poor calibration of the blue wavelength bands which are vital for subaquatic studies. The spectral, Mode 2 band setting might, therefore, prove to be suboptimal for the detection and monitoring of such detailed information as the health status and vitality of coral reefs. Other reasons for this decision are its limited on board capacity, its limited projected operational lifetime and its relatively low spatial resolution.

6. CONCLUSIONS

CHRIS/PROBA data were used to demonstrate the capability of spaceborne hyperspectral remote sensing for a cost-effective monitoring of remote coral reef regions, such as surrounding Fordate. The noisy CHRIS/PROBA data were successfully analysed through different image processing steps (noise reduction, atmospheric and air-interface correction, automatic endmember selection and classification) to maximize the information content of the data. This preliminary result, however, lacked a water column correction. For this reason one bottom-type at different depths might represent different endmembers and, as a result, more classes might have been distinguished than actually present. Nevertheless, the potential use of spaceborne HSI, supplemented with field measurements, in detailed and accurate coral reef studies has been shown.

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