HYPERSPECTRAL DATA FOR CORAL REEF MONITORING. A CASE STUDY: FORDATE, TANIMBAR, INDONESIA

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ABSTRACT

Coral reefs are endangered world-wide by devastating fishing methods (overfishing, dynamite and cyanide fishery), pollution, tourism, environmental changes and bleaching. The aim of this project is to monitor coral reefs and associated ecosystems (mangroves, sea-grass beds) by integrating different remote sensing data with spectral libraries and field measurements. The study area is Fordate, a small island to the northeast of Tanimbar, Indonesia. The monitoring system under development will enable not only the mapping of the coral reefs but also the localisation of those parts of the reefs that are most affected by degradation. A first test with hyperspectral data from the CHRIS/PROBA sensor shows promising results for the discrimination of different bottom-types on the Pulau Nukaha patch reef east of Fordate. Further field sampling and spectral measurements are needed to validate this preliminary classification.

KEYWORDS: coral reefs, health monitoring, CHRIS/PROBA, Indonesia

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 put stress on coral reefs. According to Bryant et al. (1) 58% of the coral reefs in the world are potentially endangered. The most important worldwide threats generated by human activities are pollution, sedimentation and unsustainable fishing activities (1,2). As a result of this, several international organisations include the study of coral reefs in their programme and support the conservation and sustainable use of coral reefs, e.g. UNEP (United Nations Environment Programme) 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 Sustainable Development recognised that the maintenance of healthy environments such as coral reefs, was essential to reduce poverty and improve human health.

Current coral reef monitoring techniques range from satellite data to underwater transect monitoring (1). The ideal approach would be 'multilevel sampling' (1) where detailed, locally sampled information would be extrapolated to wider areas using satellite data. Remote sensing data offer the opportunity to gather information over vast areas compared to traditional 'on-the-spot' survey methods where only limited spatially distributed information can be collected. Remote sensing also makes it possible to follow up the situation in a cost-effective 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 (3). 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.

Satellite data in general are well suited for coarse-level mapping of the geomorphology and bottom-type composition of the coral reefs. However, today, they are lacking either the spatial and/or the spectral resolution (4) that are required to create detailed bottom-type maps and to detect and monitor the health status and vitality of coral reefs. Hyperspectral airborne sensors, on the other hand, offer both high spatial and very high spectral resolution and therefore have great potential not only for mapping small coral reef ecosystems but also for identifying areas with bleached or stressed corals. The major drawbacks to use the technique as a routine methodology are the limited areal coverage and the relatively high costs involved. Airborne hyperspectral remote sensing is however a powerful tool for application and algorithm development given the versatility it offers. In the near future such (automated) algorithms can be implemented on Unmanned Airborne Vehicles (UAVs), micro-satellite and satellite platforms. These systems, equipped with sensors with programmable narrow spectral bands, will have the ability to revisit the sites at regular time intervals at high spatial resolution.

The overall aim of this research project is the development of a monitoring system for coral reef ecosystems based on remote sensing information. This monitoring system should enable not only the efficient mapping of the coral reefs, but also the identification of the reefs that are most endangered. This information will significantly contribute to the progress of protecting and restoring the coral reef environments and will in this way add to the sustainable development of these valuable natural resources.

The project attempts to integrate different (airborne and spaceborne) remote sensing data with field measurements. The coral reef communities are a complex mixture of coral, various algae and carbonate sands. Mapping their distribution is essential for the assessment of the reef status. Assessing the health of the reef requires the capability to distinguish living corals from dead corals and other substrates and to monitor their possible recovery after a bleaching event. Comparison of multi-temporal images allows an accurate assessment of possible ecological degradation of the reefs and the identification of critical areas that require extra protection. Before remote sensing data can be accurately analysed and interpreted, the spectral separability of the different benthic substrates needs to be examined, the extent to which changes in coral health can be detected by the sensor used needs to be analysed, and the problem of water attenuation which alters the optical properties of the various substrates needs to be solved. Bathymetric information is an essential ancillary data source required for water column corrections prior to image classification.

To assess and verify the technical feasibility of the proposed project objectives, a preliminary study was undertaken by the research groups involved. This preliminary study was based on an extensive literature review as well as on the analysis and interpretation of CHRIS/PROBA satellite imagery; data which were available at marginal cost over the intended study site. The results of this study are presented below.

STUDY SITE

As study area the coral reefs near Fordate, a small island to the northeast of the Tanimbar archipelago (South-East Moluccas, Eastern Indonesia) was 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 (5).

Local people are heavily dependent on the coral reefs for the fish found there for local consumption and export. Because of their unique diversity, the reefs could potentially support the development of sustainable tourism in the future. The biodiversity of the reefs, however, is seriously threatened by poison fishing, dynamite fishing, irresponsible coral mining, and over-fishing carried out by non-local and foreign fishermen. These destructive methods are spurred by short-term economic profits. The main concern of the inhabitants, who recognise the problems, is their wish to maintain a sustainable economy in harmony with the natural resources on land and in the surrounding seas.

To realize this, the first necessary step is to map the reefs with respect to type, health and depth. As this is not feasible by conventional in situ methods alone - considering the remoteness of the reefs and the expense of sending an expedition - a remote sensing based approach is required.

Figure 1: Map of Indonesia with the Tanimbar archipelago and Fordate Island indicated

Table 1: CHRIS/PROBA water mode band setting

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

METHODS

The test data

A CHRIS/PROBA dataset was acquired over Fordate on 27 January 2004. The CHRIS instrument was programmed in its mode 2 (optimized for water applications) setting (Table 1), which has a 18 band spectral resolution and a full spatial resolution of 20 m at nadir. The PROBA (Project for On-board Autonomy) satellite was launched in October 2001. It is an experimental, technology driven mission and is intended to be one of the first so called *smallsats* whose design follows the principles of the “smaller, faster and cheaper“ initiative (6). PROBA carries several scientific instruments of which the principal instrument is the Compact High Resolution Imaging Spectrometer (CHRIS).

CHRIS acquires spatial high resolution images in up to 62 narrow bands in the visible and near-infrared part of the spectrum.

While Fordate Island was mainly covered with clouds, the coral reef area was cloud-free (Figure 2).

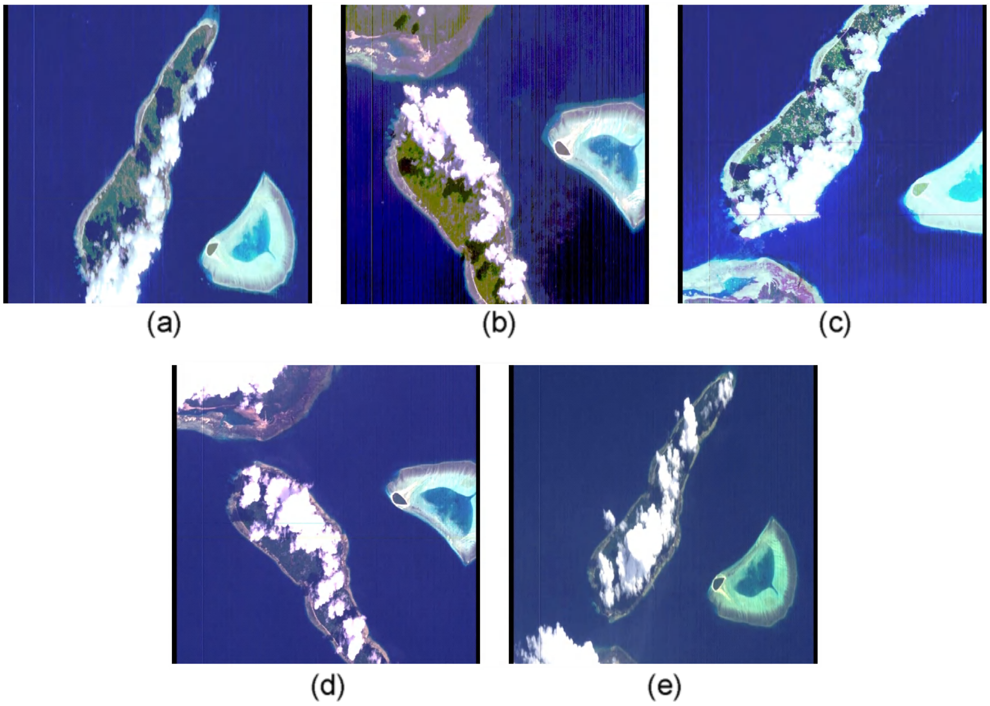


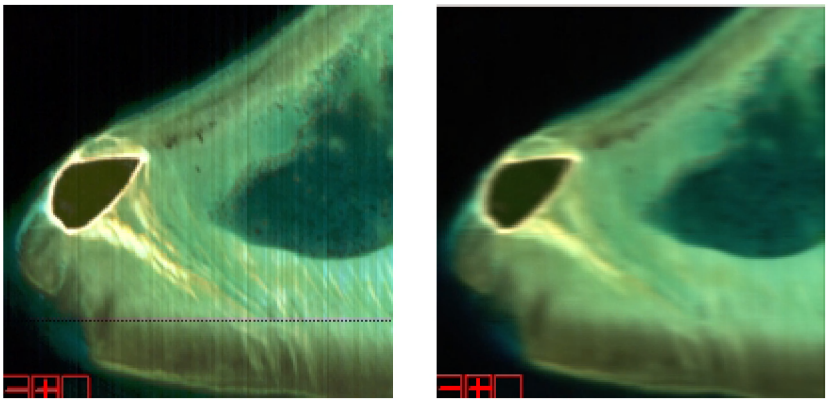
Figure 2: Multi-angle hyperspectral CHRIS/PROBA dataset (RGB colour composite, R: 651.3 nm, G: 562 nm and B: 442.5 nm) acquired from Fordate and coral reef environment. CHRIS/PROBA zenith angles are (a) 55°, (b) 36°, (c) 0°, (d) -36°, (e) -55°.

CHRIS/PROBA, which may be considered a relatively low budget mission, has several interesting technological features that make the sensor a suitable instrument for a feasibility study on reef monitoring via hyperspectral remote sensing combined with bathymetry. Images from the target area are taken at five different angles. This *pointability* of the platform enables the construction of different stereo-pairs which allows the generation of a bathymetric map. This bathymetric map can then be used to remove the effect of the water column on the recorded signal at the sensor. 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 on most other satellite sensors. The CHRIS bands are programmable for marine applications with (amongst other bands) three bands in the blue and five bands in the green wavelength range. CHRIS/PROBA data gives therefore the opportunity to obtain stereoscopic information in water-penetrating blue and green bands. The high spectral resolution is necessary to differentiate various coral reef types based on often subtle spectral differences. Furthermore, CHRIS offers a moderate spatial resolution (20 m) that gives the potential to map individual reef components.

In brief, CHRIS is nowadays as close as we can get to a spaceborne operational system. However, CHRIS is not considered as the operational tool for future coral reef monitoring programmes. The reasons for this decision are its limited on board capacity, its limited projected operational lifetime and the fact that the spatial resolution and the spectral, Mode 2 band setting might prove to be suboptimal for the detection and monitoring of such detailed information as the health status and vitality of coral reefs, which is the primary goal of the project.

Pre-processing

Due to sensor calibration constraints, vertical stripes were present in the images which complicated the spectral analysis. Moreover, some lines are missing as well. Therefore, some pre-processing steps were required. The missing lines were 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 of the image. This filter placed more weight on the central pixel and lessened the importance of pixels further away from the centre. The result of these two pre-processing steps is illustrated in Figure 3.



(a) (b)

Figure 3: Removal of the vertical and horizontal errors present in the raw CHRIS/PROBA data. Subset on Pulau Nukaha, (a) before pre-processing (RGB colours), (b) after pre-processing

Atmospheric correction

The radiance received by the sensor L_{rs} consists of atmospheric path radiance $L_{atm-path}$, background path radiance $L_{rs,b}$ and ground reflected radiation L_{target} or

$$L_{rs} = L_{atm-path} + L_{rs,b} + L_{target} \quad (1)$$

with
$$L_{target} = \frac{d^{*}_{direct}(\tau,\theta_V)\, R_{app} E_d(a)}{\pi}$$

and
$$L_{rs,b} = \frac{d^{*}_{diffuse}(\tau,\theta_V)\, A_{app} E_d(a)}{\pi},$$

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, R_{app} is the target apparent reflectance and A_{app} is the average 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 (7). 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:

$$R_{app} = \frac{c_1 + c_2 L_{rs} + c_3 L_{rs,b}}{c_4 + c_5 L_{rs,b}} \quad (2)$$

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 (8) 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.

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 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. As no field survey has been conducted to this moment, this part of the research was omitted from the test study.

Classification procedure

Prior to the classification, a land mask was applied to the data. 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 select the endmembers automatically. After the endmember selection, all image pixels were compared to the endmembers using a Spectral Angle Mapper (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.

RESULTS

Atmospheric correction result

Resulting apparent reflectance outputs for different bottom-types are given in Figure 4.

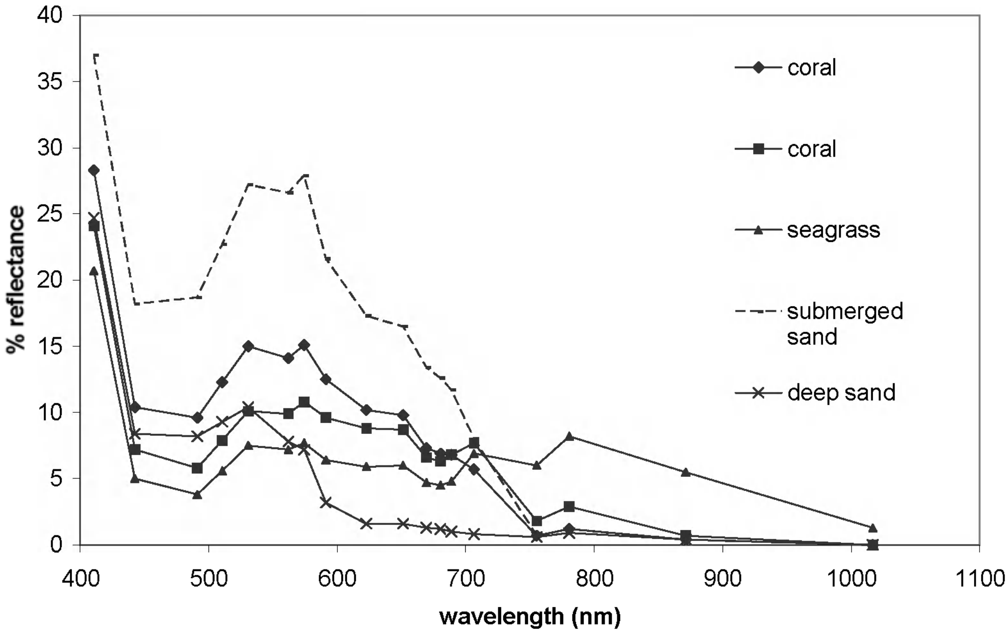


Figure 4: Derived apparent reflectance values for different bottom-types.

The reflectance in the first wavelength bands (410 and 441 nm) is extremely high. This sharp increase in reflectance values may be caused by (a) inaccuracies in the atmospheric correction due to the lack of in-situ atmospheric measurement or (b) by poor radiometric calibration of the sensor in the blue wavelength region. Since the same artefacts have also been reported by others (9,10) it is believed that it is mainly due to a calibration problem of the CHRIS/PROBA sensor. Guanter et al. (9) explained the problem as follows "because the focal plane array is designed to have the best radiometric quality in the central wavelengths, it is getting worse as the wavelength approaches the extremes".

Classification result

The result of the classification is shown in Figure 5. Depending on the number of habitat classes desired, a coarse or a more detailed classification can be achieved. A first attempt is made to assign names to the retrieved classes based on visual examination of the endmember reflectance spectra. Mixed pixels containing different habitat types, particularly near the shoreline of Fordate, complicated this task. The result has still to be checked in the field, therefore the overall accuracy of the classification result is unknown.

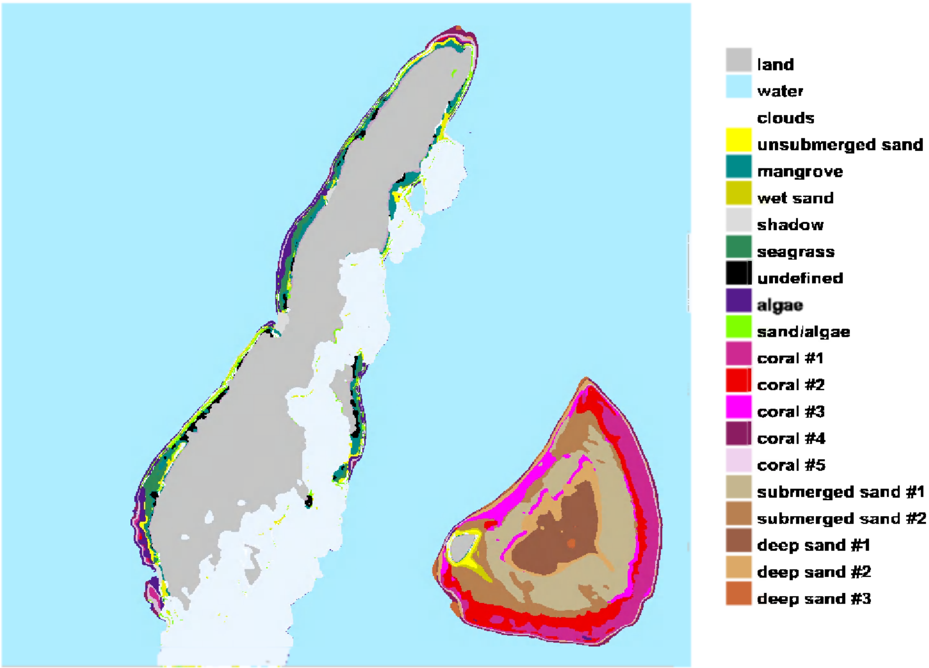


Figure 5: Classification result of the coral reef environment.

CONCLUSIONS

CHRIS/PROBA data were used to demonstrate the capability of remote sensing for a cost-effective monitoring of remote coral reef regions, such as those 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. Furthermore, a ground truth campaign is required to verify the accuracy of the benthic habitat map and to assign appropriate class names to each class.

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