

Modeling spectral discrimination of Great Barrier Reef benthic communities by remote sensing instruments

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Abstract

Remote sensing can monitor coral reef health, provided the benthic substrates are spectrally resolvable through the water column and surface. We studied the separability of eight substrate types (live coral, dead coral, soft coral, sand, brown algae, green algae, red algae, cyanobacteria) and the influence of the overlying water. A spectral library of coral reef benthic communities was collected from the Great Barrier Reef. Hydrolight 4.1 was used to simulate remote sensing reflectances. One multispectral and two hyperspectral sensors were simulated: the Advanced Land Imager (ALI, space borne), Hyperion (space borne), and HyMap (airborne, at 1.5 km altitude). Spectral radiance differences above different substrates were calculated to estimate what substrates can be separated and to what depth of waters this can be done. The dominant features in reflectance spectra of coral reef substrates are in the wavelength range 550–700 nm. Distinguishing various substrates in this part of the spectrum is limited to water depths of 5–6 m due to attenuation of the water. Below 550 nm some substrates have spectral features that are detectable by hyperspectral instruments even in deeper waters. Broader band instruments (e.g., ALI, Landsat) can provide some information about the substrate type. Sensors with a broad bandwidth provide fewer possibilities for developing analytical remote sensing algorithms for resolving significant numbers of substrate types in waters with variable depth. Hyperspectral sensors increase our capability to detect narrow spectral features that can be used for resolving various benthic communities.

Coral reefs are one of the most diverse ecosystems on the planet, but most of the world's reefs are highly susceptible to degradation either by human activities or climate change. Improved observations of coral reefs and associated ecosystems are desperately needed at all levels of management. They would help to quantify the global extent and distribution of coral reefs, quantify the loss of coral reefs and associated ecosystems over time, and document the health of coral reef ecosystems. Remote sensing observations can monitor changes in coral reefs to determine both anthropogenic and natural effects on coral health. Some of the world reefs are well studied, but the state of most reefs is not known. Remote sensing is the only practical tool to solve this problem.

Multispectral satellite sensors such as Landsat MSS and TM, as well as SPOT, have been used successfully since the

mid-eighties in mapping reef extent and geomorphological zones (Jupp et al. 1985; Bour et al. 1986; Luczkovich et al. 1993; Ahmad and Neil 1994; Maritorena 1996; Morel 1996; Knight et al. 1997; Mumby et al. 1997). Remote sensing sensors have improved over the last three decades, culminating in the currently available airborne hyperspectral sensors (e.g., CASI, AISA, AVIRIS, Hymap) and the first civilian hyperspectral satellite sensor Hyperion, which was launched in November 2000. These improved sensors have vastly increased the number of geomorphological subzones detectable by remote sensing, especially when using airborne data (Borstad et al. 1997; Clark et al. 1997; Pratt et al. 1997; Holasek et al. 1998; Mumby et al. 1998*a,b*).

Hyperspectral sensors with contiguous spectra will allow more sophisticated multiband algorithms. They will also allow the use of methods similar to those used in spectroscopy (e.g., derivative analysis, spectral modeling, matrix inversion) in the interpretation of remotely sensed data. Improved space borne and airborne sensors promise much for the future. However, further remote sensing studies on coral reefs are feasible only if the myriads of different bottom covers are spectrally resolvable. This has to be achieved in the presence of complicating effects caused by atmospheric gasses, the air–water interface, the water column, and the spatial resolution provided by the sensor.

Traditionally, interpretation of remote sensing data has been image based. In this approach, cluster analyses are used to group pixels in a remotely sensed image into as many

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different classes as are statistically significant. Each class is then ground truthed to determine an appropriate class name (i.e., sand, rubble, living corals, etc.). It is also possible to infer classifications based solely on the image information without having any ground truth data or using some preliminary knowledge about the study site or general reef geomorphology. Remote sensing algorithms used for making thematic maps can be single band algorithms or multiband algorithms (channel ratios, their combinations, etc.). Statistical relationships are sought between measured spectral values and coral reef substrate types to develop the algorithms.

The main disadvantage of image-based methods is that the algorithms are sensor specific, site specific and often time specific as well (i.e., these relationships cannot be applied to different sensors, in different places, or at different times with any confidence). In the present study, we have chosen to use a physics-based method for the interpretation of our remotely sensed data. Our spectral library of various coral reef substrates together with the inherent optical properties of the water measured above the reefs enables us to simulate spectra of coral reef substrates as measured by an airborne or space born sensor. Radiative transfer models allow us to model radiation as it travels through the atmosphere. When combined with detailed knowledge of the various sensors the information from the spectral library, the water, and the atmospheric transmission models allow us to accurately simulate the response of airborne or space born sensors for the various coral reef substrates. This then allows us to assess the suitability of various sensors for detecting various coral reef substrates.

The physics-based method has a number of advantages in comparison to the image-based methods (adapted from Dekker et al. 1999):

1. The physics-based method allows the application of one algorithm to a time series of image data from the same sensor for the same region. This allows time series of maps (e.g., coral cover) to be easily derived.
2. The physics-based method allows various sensors to be tested for detection of coral reefs without actually purchasing the images (i.e., simulations can effectively replace testing instruments if the instrument characteristics are well known and understood).
3. All processing can be carried out on a PC; thus enabling transfer of the methodology at low costs.
4. The physics-based method allows reduction in the amount and frequency of in situ and laboratory-based measurements. Only initial measurements are needed to establish the optical properties of the relevant waters and coral reef substrates in an area. Once the optical properties are established, repeat measurements are only required in the case of calibration/validation activities or in the case of significant changes in the specific inherent optical properties of the reef.
5. They allow for retrospective studies on historic satellite and airborne remote sensing data (e.g., Landsat MSS images from 1973). Since modeling does not necessarily require in situ measurements at the time of image acquisition, it is possible to use all historical data given that we can make the assumption that the spectral signatures of the various coral reef substrates are consistent over time.

Assessing the biological health of a coral reef requires at

least a capability to distinguish living coral (with symbiotic algae, *zooxanthellae*) from dead coral covered by turf algae. Algal pigments, such as the main photosynthetic pigment chlorophyll *a*, determine optical properties of almost all coral reef benthic substrates. For example, the color of living hard and soft corals can be mostly attributed to their symbiotic algae (see Fang et al. 1995 for an explanation and further references). Dead corals, rubble, and even sand particles are covered with thin layers of algae (Stephens et al. 2000; Kutser et al. 2000*a,b*, pers. comm.), and mud can also contain various types of algae (Paterson et al. 1998). Separating each of these substrates from one another or from seagrasses is only possible if we are able to detect accessory pigments typical to each algal class. For example, the *zooxanthellae* belong to the Dinoflagellates and the typical pigment feature for these algae is the presence of chlorophyll *c₂*, whereas cyanobacteria (covering dead corals) contain phycobiliproteins, etc. (Jeffrey et al. 1997). The spectral information required to resolve the various substrates has to be obtained with very fine spectral resolution (the pigment absorption bands are often narrow) and through a water column with variable depth and optical characteristics.

Published reflectance spectra of various coral reef substrates and other shallow water benthic types are presented in Maritorena et al. 1994; Holden and LeDrew 1997, 1998, 1999; Holden et al. 2000; Myers et al. 1999, Clark et al. 2000; Hochberg and Atkinson 2000; Louchard et al. 2000; Schalles et al. 2000; Stephens et al. 2000; Wittlinger and Zimmerman 2000; Zimmerman and Wittlinger 2000; Lubin et al. 2001. However, the number of different substrates studied in most cases was limited. Many of these papers concentrate on solving problems of limited scope rather than studying the variability in optical properties of the various coral reef substrates or separability of different substrates from each other using their reflectance spectra.

The benthic communities of the Great Barrier Reef (GBR) are characterized by a high biodiversity (e.g., there are over 400 different hard coral species alone, Veron 1993). Thus, a large and comprehensive spectral library of substrate types is needed in order to resolve the spectral variability found in the GBR. We have made the first step to collect a spectral library (Kutser et al. 2000*a,b*, pers. comm.) and to characterize inherent optical water properties in the GBR. The aim of the present paper is to study the scope and limits of optical remote sensing instruments for spectral discrimination of benthic communities on the Great Barrier Reef, simulating their spectral performance. We have chosen three instruments for this purpose: Hyperion as an example of hyperspectral space born sensors, Advanced Land Imager (ALI, on the same EO-1 platform as Hyperion), as a space born multispectral sensor, and Hymap as an hyperspectral airborne sensor. In the process, we hope to be able to make more general comments on the ability of optical remote sensing to distinguish between the various building blocks of a coral reef ecosystem.

Methods

Study site—Field measurements were carried out in the central Great Barrier Reef (GBR), near Townsville (Fig. 1).

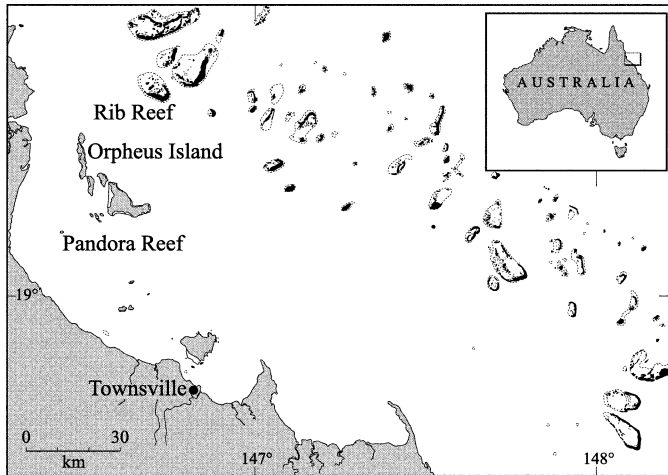


Fig. 1. Location of study sites.

The campaign was conducted on board the Australian Institute of Marine Science's (AIMS) research vessel *RV Lady Basten* in October 1999. Study sites were selected to cover a large variety of bottom types and optically different water masses. Rib Reef (a midshelf reef) was selected as a clear water site and Pandora Reef as a relatively turbid inshore reef. Fringing reefs between Orpheus and Phantom Islands were chosen as intermediate between these two. The actual substrate types studied in each site were selected by AIMS coral biologists and ecologists in order to obtain a set of results that would represent the most dominant features of the GBR (e.g., main coral and algae species).

Most of the *in situ* measurements were carried out in perfect weather conditions: cloudless skies, no wind, no waves or swell above the reef tops. However, during the last day of the trip we experienced increased winds, which caused resuspension of sediments near Orpheus and Phantom Islands, which made the water more turbid than all of the other sites, including the near-shore Pandora Reef.

Field measurements—Water samples were collected from each site, usually at two depths (surface and near bottom) in order to characterize optical properties of the water column above the reefs. Particulate absorption spectra were measured on GF/F filters before and after pigment extraction, using a GBC 916 UV/VIS spectrophotometer with an integrating sphere attachment. Colored dissolved organic matter (CDOM) absorption spectra were measured using a 10-cm pathlength quartz cuvette after filtration through a 0.2- μm polycarbonate filter. Total and CDOM absorption spectra of water samples before and after filtering (0.2- μm filter) were also measured using a point source integrating cavity absorption meter PSICAM (Kirk 1995, 1997). These measurements were carried out immediately after water sampling on board the research vessel. The water samples were also filtered and stored in liquid nitrogen for later pigment analysis. A Hydroscat-6 (HobiLabs) was used to measure vertical profiles of the backscattering coefficient at six wavelengths (442, 488, 555, 589, 676, 852 nm). The total absorption and backscattering coefficients measured in three study sites are presented in Fig. 2. Chlorophyll concentration varied from

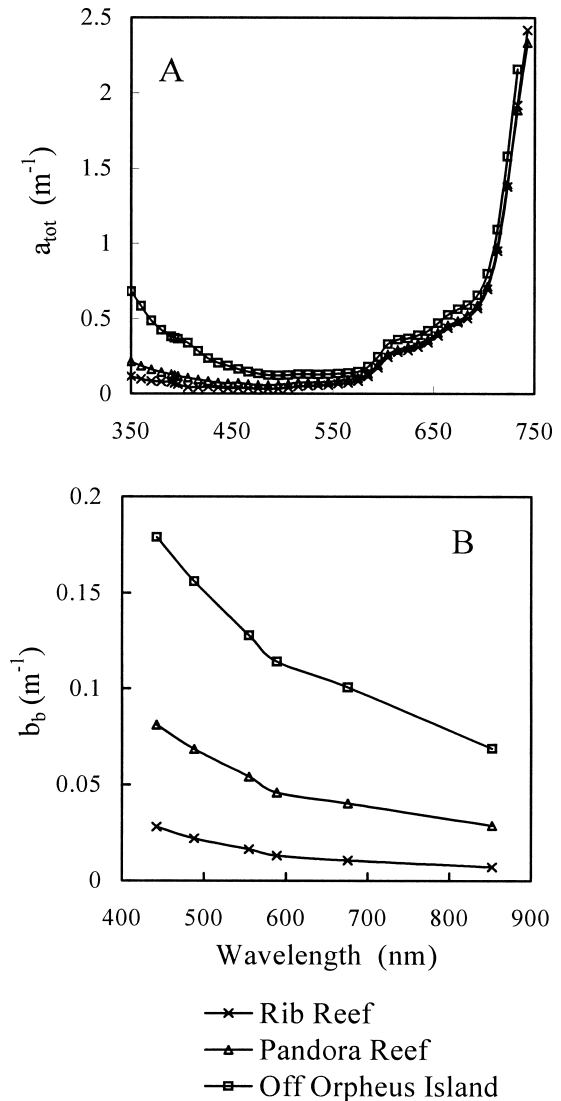


Fig. 2. Optical water properties in study sites. (A) The total absorption coefficient measured using a point source integrating cavity absorption meter PSICAM; (B) The total backscattering coefficient measured by Hydroscat-6.

0.05 $\mu\text{g L}^{-1}$ at Rib Reef to 0.35 $\mu\text{g L}^{-1}$ near Orpheus Island. This data set enables us to partly characterize the water column in different parts of the GBR, which allows us to model the influence of the water on the remotely measured signal.

Reflectance measurements—There were no off-the-shelf instruments available at the time for *in-water* measurements. Consequently, an underwater hyperspectral radiometer based on two Zeiss MMS-VIS spectrometers was designed and built at CSIRO Marine Research. Each spectrometer had a nominal wavelength range of 300 to 1,100 nm and an effective range of about 350 to 900 nm. The spectral resolution (full width half maximum [FWHM]) of the Zeiss instruments was 10 nm, using a 3.3-nm pixel interval. The signal to noise ratio (SNR) of these Zeiss instruments was better than 1,000:1. The spectrometers together with electronics hardware were housed in a waterproof case. Upward-looking

(diffuse Teflon) and downward-looking (clear acrylic) optical heads were mounted at the ends of 1-m long aluminum tubes, which were rigidly attached to the pressure case and connected by quartz optic fibers to the Zeiss spectrometers. A 60-m underwater cable and connectors allowed RS232 communication between the spectrometers and a notebook computer at the surface. The 1-m fiber-optic extensions, when combined with the 60-cm long housing and the length of the arms of the diver, allowed the small optic head arrangement (with a total housing diameter of 2 cm) to be kept well away from the diver, which ensured that all reflectance measurements were free of most diver and instrument shadow, even when operated close to the substrate. All in situ data were collected from inflatable boats with aluminum bottoms, with the boat (housing the computer operator) anchored well away from the direction of the sun. In practice, the divers controlled the positioning of the boats with respect to the measurement site, thereby minimizing any effects from boat shadow.

The two Zeiss radiometers used in our instrument were not fully calibrated. Thorough radiometric calibration of the full system (the Zeiss spectrometers with electronics, fibers, and optical heads) is needed before calculating reflectance as a ratio of upwelling radiance and downwelling irradiance measured by two Zeiss spectrometers. Owing to a lack of appropriate calibration facilities at the time of this work, a number of relatively simple techniques were used for the measurement of reflectance. All substrate measurements were accompanied by measurements of downwelling irradiance reflected from a standard Teflon sheet, 30 cm by 30 cm (calibrated in a laboratory against a Spectralon standard). The substrate reflectance was then calculated as a ratio of radiance from the substrate against the downwelling irradiance reflected from the Teflon panel. Calculating reflectance in this way we get normalized reflectance (substrate radiance is normalized to panel radiance). We also assume that the substrates are near Lambertian surfaces. This assumption is true if we are measuring close to the coral. This assumption may become an issue in the case of colony scale measurements, especially measuring colonies of branching corals (Joyce and Phinn 2002).

Spot measurements of individual substrate types were made from about 15 cm above the substrate, resulting in a field-of-view of about 3 cm. Each measurement took about half a minute, capturing over 100 spectra (depending on the integration time) above each substrate. Each spot measurement was accompanied with a photo record (often three-dimensional stereographic). Substrates were identified by AIMS biologists, generally at a species level. Samples of the substrate were taken in conjunction with most spot measurements and were taken back to the ship for laboratory analysis.

We also tested other methods to measure reflectance of different coral reef benthic substrates: in a wading pool and in a laboratory spectrometer. More detailed descriptions of the methodology and instruments used during this experiment are presented in Kutser et al. 2000*a,b*, pers. comm.

Remote sensing sensors—No airborne or space borne remote sensing data were obtained during the field experiment,

since our aim at the time was to study the spectral resolvability of various substrates both in situ and above the water. This can be modeled with the combination of three sets of data: a spectral library of substrate reflectances, a set of inherent optical properties of waters typical to the GBR, and the radiometric and spectral characteristics of the remote sensing sensors.

Hyperion is the first civilian hyperspectral space borne sensor. It was launched in November 2000. Hyperspectral space borne sensors are possibly the only cost-effective method for monitoring coral reef health on a reef as complex and large as the GBR without having to subsample. As mentioned earlier, multispectral space borne instruments are limited in their ability to resolve benthic types. The very high spectral resolution of airborne hyperspectral sensors is capable of overcoming many of the shortfalls of the multispectral sensors; however, these airborne platforms are expensive to run for large regions. In these cases, space borne sensors are considerably more cost effective if the spatial resolution is adequate.

One of the aims of this work is to investigate the advantages of hyperspectral instruments in comparison to broadband multispectral sensors. The spectral resolution of Hyperion is 10 nm (FWHM) in the wavelength range 440–2400 nm (see Fig. 3A and Table 1) with a spatial resolution of 30 × 30 m. The instrument signal to noise ratio (SNR) is on average around 150:1 throughout most of the visible spectrum as stated by the manufacturer. In wavelengths below 500 nm, the SNR drops almost linearly toward the shorter wavelengths but is still 50:1 at 450 nm. We have access to Hyperion data as members of the science validation team. One of the images obtained in Australia (19 March 2001) contains Cairns Reef, located about 300 km north of our field study site. We estimated the environmental signal to noise ratio (SNR_E) as

$$\text{SNR}_E = \frac{\bar{L}}{\sigma(L)} \quad (1)$$

where \bar{L} is the mean radiance in each band over a large uniform patch of optically deep water within the image and $\sigma(L)$ is the standard deviation. The size of the uniform area can be determined by increasing the number of pixels step by step (1 × 1, 3 × 3, 5 × 5, etc.) until $\sigma(L)$ reaches asymptotic level (Dekker and Peters 1993). With this image, the SNR_E of the Hyperion was around 100:1 near 550–560 nm and around 40:1 at each end of the visible spectrum. It must be noted that this signal to noise ratio is relevant for the conditions represented by this particular image and includes surface, atmospheric, and sensor effects.

Broadband multispectral satellite sensors have been used to map coral reefs since the seventies and used operationally since the early eighties (Jupp et al. 1985). The Advanced Land Imager (ALI) is on the EO-1 platform along with Hyperion. ALI is an improved Landsat 7 (SNR 250:1; 2.5 times that of Landsat) and a possible precursor of Landsat 8. The ALI data allowed us to investigate whether a low noise broadband sensor is theoretically capable of detecting substrate types rather than just mapping corals reefs and their geomorphological zones. Four ALI bands (the normalized

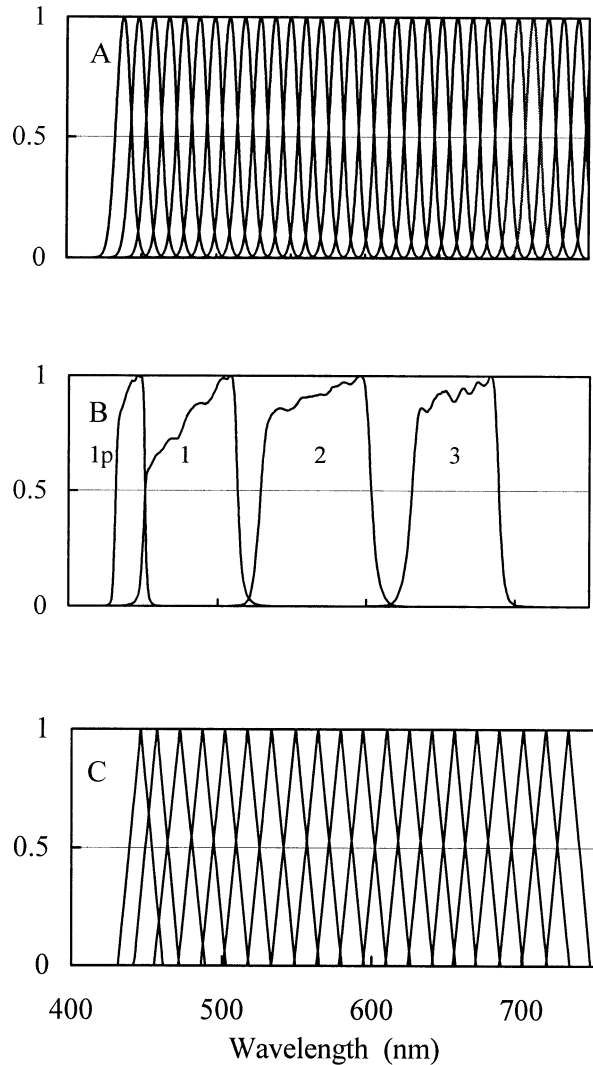


Fig. 3. Normalized spectral responses of the sensors used in this study. (A) Hyperion, a space borne hyperspectral sensor on the EO-1 platform; (B) Advanced Land Imager (ALI), a space borne multispectral sensor also on the EO-1 platform; (C) Hymap, a hyperspectral airborne sensor.

spectral response functions of ALI are shown on Fig. 3B) are within the wavelength range where we can expect to receive useful signals from the benthic substrates (400–750 nm). There is practically no signal coming from the water or the substrate in wavelengths greater than 750 nm due to significant absorption by pure water, which starts at around 600 nm.

Each pixel in an image is a mixture of many different

coral benthic types, termed a “mixel.” These mixels complicate the interpretation of remote sensing data. Until recently, airborne sensors were the only way to acquire hyperspectral images of coral reefs. The high spectral and spatial resolution (being equal to or better than the spatial variability of a coral reef, i.e., less than 1 m) of these instruments makes them very suitable for applications on the highly complex coral reefs. Space borne sensors with similarly high spatial resolution (e.g., IKONOS, 1 m) do not yet have comparable spectral resolution and hence struggle to resolve coral reef substrate reflectance spectra. Most current space borne sensors cannot resolve the highly complex spatial structure of a coral reef due to poor spatial resolution. Hyperspectral sensors increase the spectral resolution of mixels and, with spectral libraries, improve our ability to unmix the signal and resolve the make-up of each mixel scene.

Modeling—Three sets of calculations were carried out in order to simulate the radiances of various benthic substrates as would be detected by various remote sensing sensors. The hyperspectral library was used to characterize various substrates. Reflectance just above the water surface was calculated using the Hydrolight 4.1 (Sequoia Scientific) radiative transfer model. Hydrolight is a radiative transfer numerical model that computes radiance distributions and derived quantities for natural waterbodies. The model solves the time-independent radiative transfer equation to obtain the radiance distribution within and leaving any plane-parallel water body. Input to the model consists of the absorbing and scattering properties of the water body, the nature of the wind-blown sea surface and of the bottom of water column, and the sun and sky radiance on the sea surface.

Remote sensing reflectance was calculated as

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda)} \quad (2)$$

where L_w is the water leaving radiance (total radiance minus sky radiance) just above the water surface and E_d is the downwelling irradiance. Radiance at the sensor level was calculated using an atmospheric model as described below.

Our aim was to estimate the maximum depths at which the various substrates are spectrally resolvable. For this we chose to use the optical properties of our clearest study site at Rib Reef. The water at Rib Reef was clear with virtually no sediment and very little phytoplankton. The absorption and scattering were therefore dominated by the water and not by suspension or solution loads. Because of this, we employed a simple Case I model in Hydrolight (Morel and Maritorena 2001) with Petzold (1972) phase function of av-

Table 1. Technical characteristics of remote sensing sensors used in model simulations.

Sensor	Spectral Resolution (FWHM)	Spatial resolution	SNR	Spectral range	Number of spectral bands
Hyperion	10 nm	30 m	160:1	350–2,400 nm	240
Hymap	15 nm	3 m (variable)	1000:1	440–2,480	126
ALI	60 nm	30 m	250:1	430–2,440	10

erage particles. The chlorophyll concentration was set at $0.05 \mu\text{g L}^{-1}$, similar to the Rib Reef measurements, and was set to be constant throughout the water column (as it was during the measurements). A semiempirical sky model (RADTRAN) was used within the Hydrolight calculations to account for atmospheric attenuation of solar radiation. The basic settings were for a solar zenith angle of 10° , relative humidity 80%, and visibility 15 km. Wind speed was chosen to be 2 m s^{-1} , similar to the conditions during the in situ measurements. Calculations were performed with 1-nm step intervals from 350 to 750 nm. Water depths were set between 1 and 15 m with a 1-m step, and at 20 m and 25 m. The reflectance of the optically deep water case was calculated using the same Hydrolight model parameters as for the finite depth water column calculations.

An in-house atmospheric model similar to MODTRAN 3 was used to calculate the radiance spectra at the sensor level. The above-water reflectances calculated using Hydrolight were multiplied by π to obtain irradiance reflectance for input into the atmospheric model. Atmospheric parameters were selected to mimic the conditions typical for a clear spring day in Townsville (latitude 19°S), which are similar to the actual conditions during the field measurements. The radiance spectra were calculated for two altitudes, at the satellite sensor (700 km) and at the airborne sensor with an altitude of 1.5 km.

The radiance detectable by the sensors (Hyperion, ALI, Hymap) was calculated by integrating over each band. These were calculated by multiplying the radiance at the sensor level by the normalized band passes of each sensor and then integrating over each band. We assume that two substrates are separable from each other in a given water depth by a sensor if the difference between the spectral radiances measured above the two substrates is greater than the $1\text{-}\sigma$ noise level of the particular instrument at the appropriate bands. Differences in spectral radiances were calculated between all substrates in all water depths by subtracting the radiance of one substrate from the radiance of another substrate at the same depth. The differences between the substrate radiance at each water depth (1 to 15 m, 20, and 25 m) and of optically deep water were also calculated.

During this modeling, it was assumed that each measurement by a sensor was of a "pure" substrate type, (i.e., no mixels). This enables an intercomparison of spectral characteristics for each of the sensors that is independent of spatial resolution.

Discussion

Hyperspectral library—The total number of substrates for which reflectance spectra were collected during this experiment was in excess of 140. These were divided into eight groups in order to reduce the number of substrates used during the model simulations. The groups were living hard coral, dead hard coral, soft coral, sand, green algae, red algae, brown algae, and cyanobacteria covered surfaces. These groups are based on a combination of optical and biological properties. Optical properties are just as important as biology in determining the substrate groupings. For example the dead

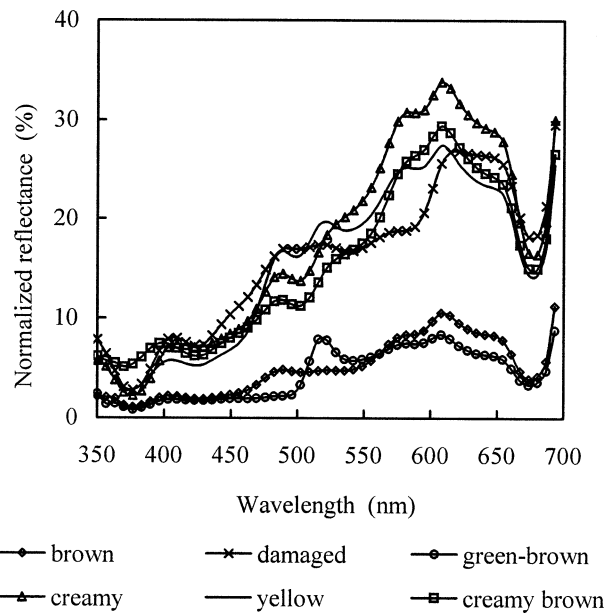


Fig. 4. Within species variability between in situ measured reflectance spectra of differently colored colonies of living plate coral *Acropora hyacinthus*. One yellow colony was mechanically damaged.

coral group includes both dead intact colonies and rubble. Sand is mostly finely ground coral rubble that can exhibit similar optical properties to rubble.

Coral colonies of the same species may have slightly different coloration (Veron 1993; Takabayashi and Hoegh-Guldberg 1995). We examined this phenomenon using three coral species: *Acropora hyacinthus*, *Pocillopora verrucosa*, and *Porites massive*. Each of these species exhibit variability in reflectance spectra both in magnitude and shape (Kutser et al. pers. comm.). The spectral reflectances of six differently colored colonies of plate coral (*A. hyacinthus*) were measured during our field experiment (Fig. 4). Since the intraspecies variability in reflectance spectra is almost as high as interspecies variability, an averaged living coral spectrum was used for further analysis. Similarly spectra of soft coral, dead coral, and sand were each averaged. The sandy bottoms studied during our field experiments were relatively dark compared to the bright white coral sand measured by Maritorea et al. (1994). Crustose coralline algae that covered some of the dead coral colonies and a recently dead coral colony covered with filamentous algae had relatively high reflectance values; this made the average dead coral reflectance spectrum relatively similar to an average living coral spectrum. In the present study the dead corals were divided into recently (less than 1 month) dead and long time (considerably greater than 1 month) dead corals. Long time dead corals are mainly covered with turf algae and are usually significantly darker than living coral and therefore more easily separable.

Only a small number of reflectance spectra were collected for algae. It was therefore not valid to calculate averages for each algae class. Instead a single reflectance spectrum was used for each of four algae groups: green algae were rep-

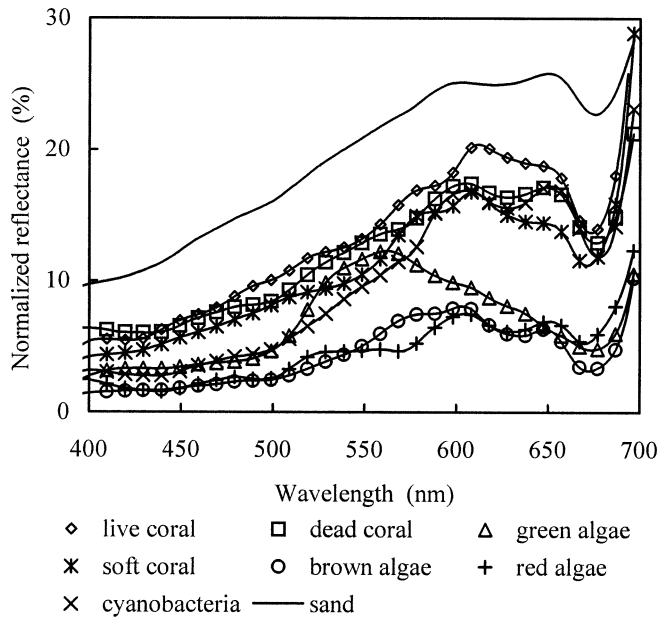


Fig. 5. In situ measured radiance reflectance spectra used in the modelling. The live coral, dead coral, sand, and soft coral spectra are averages of each group. Green algae are represented by a reflectance spectrum of *Chlorodesmis*, brown algae by a *Sargassum*, and red algae by a *Rhodophyta* spectrum, cyanobacteria with an unknown species.

resented by a reflectance spectrum of *Chlorodesmis*, brown algae by *Sargassum*, and red algae by *Rhodophyta* and we had a reflectance spectrum of substrate covered with a film of cyanobacteria (Fig. 5). The relatively few published algae reflectance spectra (Maritorea et al. 1994; Wittlinger and Zimmerman 2000) are similar to our results in spectral shape and reflectance values (see also Kutser et al. pers. comm.).

Most of the visible range spectral features typical to each substrate class are located in the wavelength region between 550 and 700 nm (Kutser et al. 2000a,b, pers. comm.), as shown in Fig. 5. Water absorbs light strongly in the red and near-infrared part of the spectrum. For example, pure water absorption coefficients, $a_w(\lambda)$, at wavelengths 400, 550, 600, and 700 nm are 0.00663, 0.0565, 0.2224, and 0.624 m^{-1} respectively (Pope and Fry 1997). Most of the substrates have high reflectance in the near-infrared part of the spectrum, but absorption of light by water is higher in this part of the spectrum ($a_w(750) = 2.47 \text{ m}^{-1}$ according to Smith and Baker 1981). Just 1 to 2 m of the clearest water on top of any coral reef substrate absorbs practically all the infrared radiation and makes this part of the spectrum unsuitable for remote sensing purposes.

Other authors (Holden and LeDrew 1998, 1999; Hochberg and Atkinson 2000; Louchard et al. 2000; Schalles et al. 2000; Lubin et al. 2001) have measured reflectance spectra of corals in other regions of the world's oceans. In general, they found similar spectrum features to those exhibited in the GBR corals, algae, and sand. The exception was the reflectance spectra measured by Schalles et al. (2000) in the Red Sea. The Red Sea corals often have a reflectance peak close to 570 nm and reflectance shoulders near 510 and 630

nm. In contrast, their results from the Caribbean are similar to the results presented here. Thus this Great Barrier Reef benthic substrate spectral library can perhaps be used more widely.

Simulated Hyperion performance for detecting coral reef benthic substrates—Our simulation of radiance spectra show that the spectral differences between any two substrates at wavelengths greater than 650 nm rarely exceed Hyperion noise levels for water column depths greater than 4–5 m. Fortunately hyperspectral sensors have many bands, and it is possible to use bands where spectral radiance (or reflectance) differences between substrates are less significant but where attenuation of light by water or its constituents is smaller, thus enabling discrimination of substrates.

Some examples of spectral differences between two substrates are shown in Figs. 6–7. Figure 6A shows that there are four spectral regions that can be used to differentiate live corals from dead corals. Differences are largest near 700 nm, but these differences are above the instrument noise level only in waters shallower than 3 m. This depth increases to 2 m if we also consider the environmental noise present in actual images. The next peaks in spectral difference spectra are near 620 and 570 nm, and these differences are measurable in waters shallower than 5 m and 13 m, respectively. The differences between live and dead corals are seen in waters up to 20 m deep near 500 nm, but this spectral region alone cannot be used to separate the two substrates since many substrates at different depths may provide similar signals in such a narrow part of the spectrum.

Figure 6B suggests that with Hyperion it will be theoretically possible to separate spectra of average living hard and soft corals from each other in waters up to 15 m deep. It must be noted that this situation may be more complicated if we have hard coral and soft coral species that are similar spectrally (more alike than the average of 66 hard corals and average of 15 soft corals used in these calculations). On the other hand some hard corals have very distinctive features in their reflectance spectra; therefore, separating these particular corals from any other substrate type is likely to be straightforward.

Figure 6C simulates the difference between radiances of red algae and green algae detected by Hyperion. Green algae have reflectance spectra that differ from most other coral reef substrates (see Fig. 5). Their reflectance is relatively high in the wavelength range 510–580 nm and is low in almost all other wavelengths in the visible part of spectrum. Red algae have higher reflectance in wavelengths greater than 650 nm, but those differences cannot be seen in waters deeper than 1 m. Relatively high reflectance of green algae in wavelengths near 550 nm makes it easy to separate green algae from red algae. Two substrate types that have low reflectance values in the visible part of the spectrum are brown algae and red algae. Nevertheless there are two wavelength bands (near 520 and 570) that can be used to separate these two substrates from each other in waters less than 10 m deep, as can be seen in Fig. 6D.

The mapping of the occurrence and extent of coral bleaching is a desirable capability for monitoring of coral reef health. It is necessary to know the optical properties of

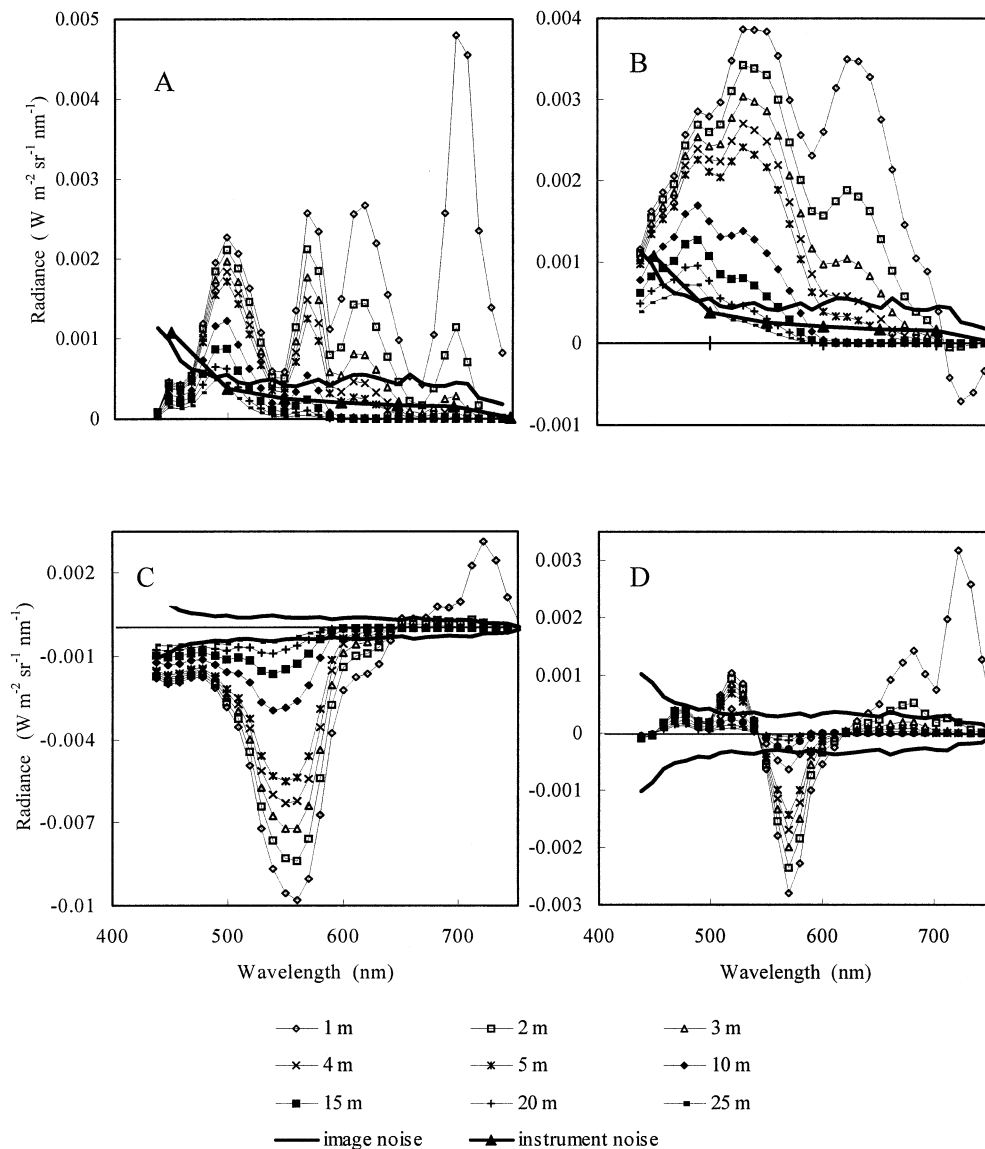


Fig. 6. Differences between simulated upwelling radiance spectra (A) Average hard coral and average dead coral. (B) Average hard coral and average soft coral. (C) Red algae (*Rhodophyta*) and a green algae (*Chlorodesmis*). (D) Red algae (*Rhodophyta*) and a brown algae (*Sargassum*). Calculations were performed for various water depths. Selected depths plotted on the figure. The radiances were simulated at satellite altitude for Hyperion spectral bands. The instrument noise level is calculated using the SNR of the instrument (Table 1). The image noise level is calculated using SNR_E estimated using Eq. 1 and a Hyperion image from Cairns Reef obtained on 19 January 2001. Each marker represents a Hyperion band.

bleached corals, recently dead corals, and long time dead corals to be able to estimate whether these substrates are spectrally resolvable by an airborne or space borne sensor. There were no recently bleached corals in the study area. Optical properties of bleached corals are most probably similar to bright white coral sand, and it will be relatively easy to separate other substrates from the bleached corals. There may be difficulties in separating bleached corals from sand, but availability of multitemporal images of a study area would solve this problem.

This study was able to investigate the difference between

live, recently dead, and long time dead coral spectra. The study area had been visited by one of the AIMS teams less than a month prior to this fieldwork. Using this field knowledge, we were able to find a dead *Acropora hyacinthus* colony, which was accurately estimated to have been dead for a maximum of one month. The colony had been killed by crown-of-thorn starfish (*Acanthaster*). This colony was already covered with a thin film of fine green filamentous algae, and the reflectance spectra were similar to those of dead corals (having a double peak in its reflectance spectra at 607 and 650 nm, indicating phytoplankton absorption at approximately 630 nm).

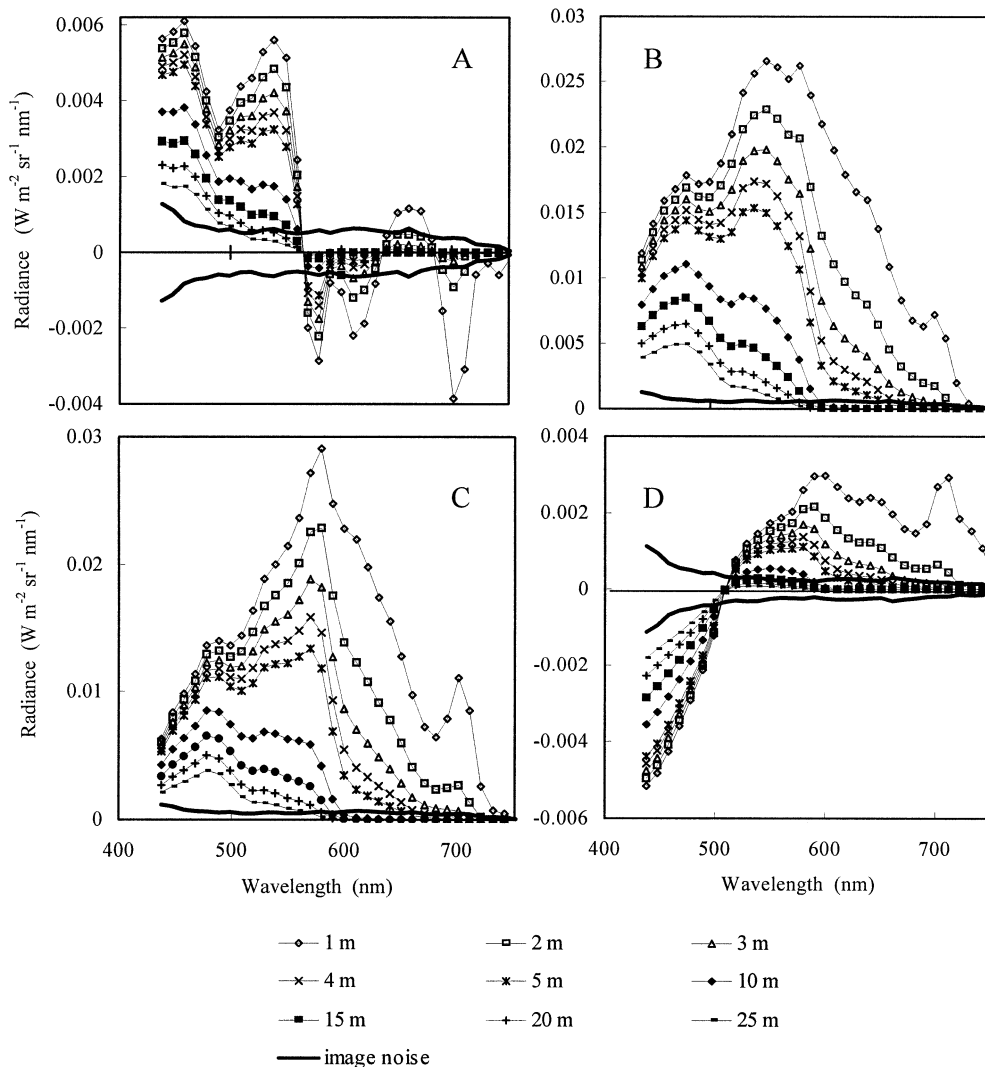


Fig. 7. Differences between simulated upwelling radiance spectra. (A) Recently (less than a month) dead colony of plate coral *A. hyacinthus* and a living (creamy) *A. hyacinthus* colony. (B) Recently (less than a month) dead colony of plate coral *A. hyacinthus* and a long time dead colony of *A. hyacinthus* covered with black turf. (C) Living *A. hyacinthus* colony (creamy) and a long time dead colony of *A. hyacinthus* covered with black turf. (D) Long time dead *A. hyacinthus* colony covered with black turf and optically deep water. Calculations were performed for different water depths. Selected depths plotted on the figure. The radiances were simulated at satellite altitude for Hyperion spectral bands. The image noise level is calculated using SNR_E estimated using Eq. 1 and a Hyperion image from Cairns Reef obtained on 19 January 2001. Each marker represents a Hyperion band.

Colonies that have been dead for more than a year were covered with dark filamentous algae (“black turf”). The species composition of these dark algae differs from the composition of those that invade the corals immediately after the corals have died. The reflectance of recently dead coral is almost as high as most living *A. hyacinthus* colonies and is higher in the UV and blue part of the spectrum (Kutser et al. pers. comm.). A minimum in the UV part of the radiance spectrum, typical to many *Acropora* corals, is also missing in the spectra of dead corals. Absorption in the UV part of the spectrum of living corals is probably caused by pigments in coral tissue to protect symbiotic algae from damage

caused by extensive sunlight (Salih et al. 2000). The absence of this absorption feature is probably an indicator of missing coral tissue. Unfortunately most sensors do not have bands capable of collecting UV information. Interestingly, Hyperion has spectral bands in the 350–440 nm region, but these data are currently unreliable due to calibration problems.

A series of model runs using Hydrolight and the previously mentioned atmospheric model were used to study the spectral separability of living corals from recently dead and long time dead corals. A creamy colony of plate coral *Acropora hyacinthus* was selected as a typical example of living corals on the reef top. The other two colonies were *A.*

hyacinthus eaten by the *Acanthaster* less than a month ago (as described earlier) and a long time dead colony covered with black turf. Results of the modeling are shown in Fig. 7. The recently dead colony and living colony had similarly high reflectance values but with different spectral shapes. The recently dead coral reflectance was higher in wavelengths below 560 nm and between 640 and 680 nm (see Fig. 7A). This probably indicates that the thin algal layer (of the dead coral) covering the bright coral skeleton is absorbing less light than the living coral tissue (of the live coral) with symbiotic algae covering effectively the same type of coral skeleton. The largest differences between live and recently dead corals occur at wavelengths around 460 and 540 nm. The spectral difference in the shorter wavelength region is attenuated less (in clear oceanic waters) by increasing water column depths, which makes this part of the spectrum suitable for separating recently dead corals from live corals.

Spectral differences between 1 month dead coral and long time dead corals as well as living corals and long time dead corals are relatively high (note the scale difference between Fig. 7A and Fig. 7B–C). Reflectance values of the black turf are very low (below 5%). Therefore a question may arise as to whether we can separate long time dead corals from optically deep water. Modeling results show (see Fig. 7D) that the wavelength region below 500 nm can be used to separate long time dead corals from optically deep water in waters of depths up to 25 m.

Clark et al. (2000) have also found that recently dead, long time dead, and living corals can be separated from each other. Although their findings were restricted to the reflectance spectra of *Porites* corals in French Polynesia, our study has found it to be more widely applicable. The main difference between their results and our results from the GBR is that the long time dead corals studied by Clark et al. (2000) have higher reflectances than living and recently dead corals. This can be explained because the coral (*Porites*) studied by Clark et al. has a relatively low reflectance. Both our reflectance measurements and those of Clark et al. show that reflectance values of *Porites* corals are below 17% in the visible part of the spectrum (compare with max 35% of *A. hyacinthus* in Fig. 4). The long time dead colonies studied by Clark et al. (2000) were covered with encrusting algae that have reflectance values higher than the living *Porites* corals. We found that most living corals have reflectance values higher than *Porites* corals and most long time dead corals are covered with relatively dark algal turf. Therefore the tendency we found in reflectance values is from brighter to darker comparing living to recently dead to long time dead corals.

Simulated ALI performance for detecting coral reef benthic substrates—The Landsat series of instruments has been used for mapping coral reefs since the mideighties. ALI is an improved version of the Landsat 7 sensors (SNR 250:1; 2.5 times that of Landsat) and a possible precursor of Landsat 8. Four ALI bands (1p, 1, 2, and 3; see Fig. 3B) have a useful wavelength range for sensing benthic substrates (i.e., between 350 and 750 nm).

Differences in the radiance levels between live and dead corals are detectable by ALI in waters up to 25 m deep. It seems reasonable to assume that a broadband sensor package

like ALI is capable of separating the live and dead corals in waters up to 25-m deep (Fig. 8A). Figure 8A illustrates a typical case for broadband sensors: Band 1p radiances detectable above different substrates are similar and band 3 radiances are becoming similar in waters deeper than a few meters. Figure 8B illustrates a case where most of the four ALI bands can be used in separating two substrates from each other. Sand is more reflective in the shorter wavelength range than the average living coral; therefore, most differences in radiance between sand and coral occur in bands 1p, 1, and 2.

The same plate coral *Acropora hyacinthus* colonies (creamy live colony, 1 month dead colony covered with green filamentous algae, and long time dead colony covered with black turf), used earlier for Hyperion simulations, are also used in the ALI simulations. ALI should also be capable of detecting differences between recently dead coral and living corals as seen in Fig. 8C (the same results for Hyperion are in Fig. 7A). Bands 1p and 1 show a clear difference between long dead and live corals. ALI should also discriminate bright recently dead corals from dark long time dead corals as shown on Fig. 8D (see Fig. 7B for a Hyperion comparison).

Note that the ALI Band 1p (440 nm) is often unusable (similarly to Fig. 8A). This is because the reflected radiance detectable by ALI does not change significantly for most substrates. Band 3 (660 nm) is strongly influenced by water depth. This leaves us only two ALI bands (in cases of waters deeper than a few meters) to develop band ratio type remote sensing algorithms for detecting different substrates. It is not possible to develop reliable algorithms for detecting many different substrate types in waters with variable depth with only two useful spectral bands. However, ALI may still be a useful tool if the number of different substrates in a particular reef is small and the variability in water depth is known.

Simulated Hymap performance for detecting coral reef benthic substrates—A Hymap image of Cairns Reef obtained on 12 September 2000 was used to estimate environmental SNR_E with the method described earlier. In some bands the SNR_E was as low as 20:1 due to sun glint. Three different noise levels are plotted in Fig. 9. This figure shows how depth affects the ability to separate live and dead corals in relation to changing SNR. The specified sensor SNR of Hymap is 1,000:1. Clearly the instrument noise is not limiting our ability to separate coral reef substrates in any wavelength (Fig. 9). However, environmental noise in this particular image limits the depths to which the two substrates can be separated. Figure 9 has a plot of a third noise level as an example of what can be achieved if one can improve the SNR_E (by removing sun glint) from 20:1 to 100:1. In this case that depth of separability for these two substrates would increase from 8 to 25 m when using the 500 nm band and from 3 to 11 m when using the 570 nm band.

The simulations presented here show no significant difference between the performances of airborne (Hymap) and space borne (Hyperion) hyperspectral sensors if we ignore spatial resolution differences (i.e., if we assume that both instruments are measuring pure substrates). Improved (4-m

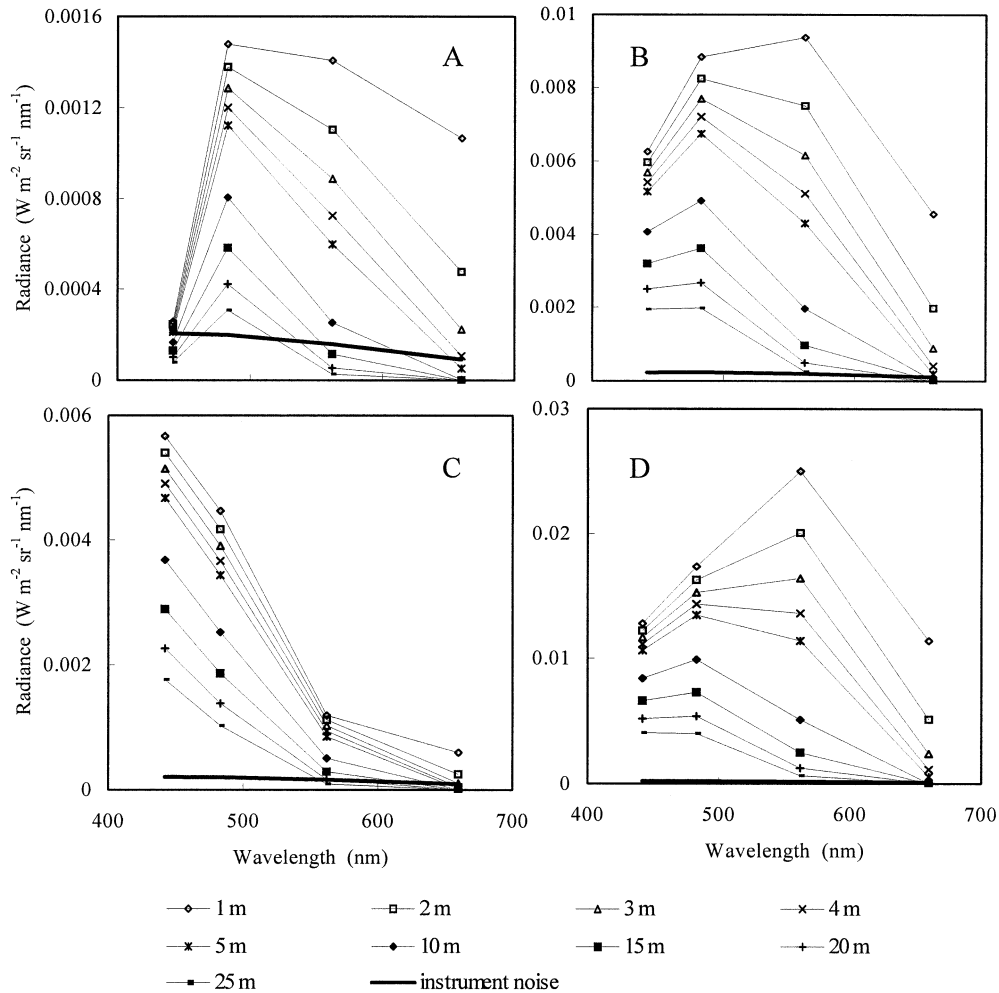


Fig. 8. Differences between simulated upwelling radiance spectra. (A) Average hard coral and average dead coral. (B) Average sand and average live coral. (C) Recently (one month) dead *A. hyacinthus* colony covered with filamentous algae and a creamy living *A. hyacinthus* colony. (D) Recently (one month) dead *A. hyacinthus* colony covered with filamentous algae and a long time dead *A. hyacinthus* colony covered with black turf. Calculations were performed for different water depths. The radiances were simulated at satellite altitude for ALI spectral bands. The noise level is calculated using the instrument SNR from Table 1. Each marker represents the central wavelength of an ALI band.

spatial resolution) hyperspectral space borne sensors have been built already (OrbView-4/WarFighter), but failed during launch. Hyperspectral space borne sensors with a spatial resolution closer to dimensions of coral colonies could be a valuable tool in monitoring coral health, especially in regions inaccessible by airborne instruments.

The results of this study show (Figs. 4 and 5) that intra-species variability in reflectance spectra of living corals is as high as interspecies variability between the corals. Therefore it is unlikely that remote sensing algorithms can be developed for mapping various living corals at the species level. There may be a few exceptions involving corals with very distinct spectral features.

Most of the variability in reflectance spectra of coral reef bottom types is concentrated in the wavelength region between 500 and 700 nm where the water absorbs light strongly, causing the radiance spectra to be similar when measured

by an above-water sensor. Hyperspectral sensors are capable of using spectral bands above 600 nm for separating substrates in clear oceanic waters up to 5–6 m deep. Substrate separation is possible in deeper waters if they possess spectral features that occur in shorter (440–600 nm) wavelength ranges. Depths where some substrates may be separable from each other may be limited to just a few meters in cases where all spectral differences in their reflectance spectra occur only near 700 nm or in the near-infrared part of the spectrum.

The modeling results of this study show that all substrates have measurably different reflectance spectra when detected by a broadband sensor like ALI. However, only two ALI bands are above the instrument noise level with which to separate live and dead corals in waters deeper than 4–5 m. The development of useful algorithms generally requires more information than that provided by just two bands. Nev-

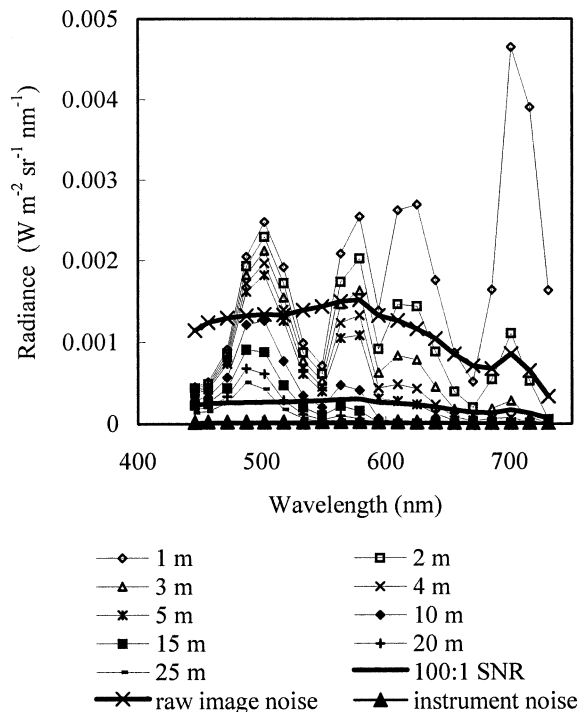


Fig. 9. Differences between simulated upwelling radiance spectra of the average hard coral and average dead coral. Calculations were performed for different water depths. The radiances were simulated at an altitude of 1.5 km for HyMap spectral bands. The instrument noise level is calculated using the SNR of the instrument (Table 1). The image noise level is calculated using SNR_E estimated using Eq. 1 and a raw HyMap image from Cairns Reef obtained on 12 September 2000. The noise level calculated using SNR 100:1 is plotted in the graph as an example of environmental noise after removing sun glint from the image. Each marker represents a HyMap band.

ertheless, ALI may still be a useful tool if the number of substrates in a particular reef is small and the variability in water depth is known.

Our simulations show that the signal to noise of the sensors considered in this work will probably be acceptable for mapping coral reef substrates. The spectral difference between the coral reef benthic substrates and attenuation of light by water column above the substrates are the main factors limiting the ability of remote sensing techniques for monitoring coral reef health. Other optically active substances such as suspended matter, phytoplankton, and colored dissolved organic matter will decrease the depth to which optical sensing is able to separate living corals from dead corals, required for monitoring reef health.

We carried out model simulations with water properties similar to those of Orpheus Island shown on Fig. 2 using a case II water properties model. The modeling results (not presented in this paper) show that the increased amount of CDOM in the water dramatically reduces the depths to which different coral reef benthic substrates can be separated. This is mainly due to a decrease in light penetration in the wavelength range of 400–500 nm. At longer wavelengths the difference decreases due to the decreasing absorption by CDOM. The depths where substrates are separable in turbid

water are similar to those in clear oceanic water when the wavelength range of 500–700 is used.

Hyperspectral sensors have three main advantages over broadband sensors. They are capable of detecting narrow spectral features, which increases the number of substrates that can be separated. Their large number of spectral bands increases our capability to unmix substrate spectral signatures. The hyperspectral sensors can also distinguish between substrates in deeper waters.

This study shows that it is possible to separate long time dead corals from recently (less than 1 month) dead corals. This is important for detecting bleaching effects since algae invade dead corals within weeks and remote sensing data may not be available during the short period when the bleached corals are bright white and more easily detectable by remote sensing instruments. With respect to polar orbiting satellite data, this delay could be caused by a combination of low return frequencies and high cloud cover as in the tropics during the summer, when the corals are at most risk of bleaching.

Most of the coral reef benthic substrates can be separated from each other using hyperspectral sensors in waters less than 5–6-m deep. Fortunately the majority of reef tops are closer to the water surface. Currently there is little information being collected on reef tops due to a high risk to divers and boats in the shallow waters. Optical remote sensing is useful not only as an excellent tool for monitoring large or remote areas, but it also makes it possible to study shallow reef areas not easily accessible by divers.

This study has shown that the coral reef benthic substrates differ from each other optically and that various remote sensing sensors should be able to detect these differences. However, spatial scale is a key issue, since it is not reasonable to assume that each pixel is a pure substrate. Almost all current sensor spatial resolutions are such that their image pixels are mixtures of a number of substrate types. These spatial effects will be the topic of future research by the authors.

This study has demonstrated the ability of optical remote sensing to distinguish between the various building blocks of a coral reef ecosystem. It has demonstrated the potential for the new hyperspectral satellite sensors such as Hyperion, especially once their spatial resolution is improved. It has also highlighted the limitations with respect to the depth of water overlying the reefs. Nevertheless, even when considering the limitations of this technique, passive visible spectrum remote sensing as a tool for monitoring coral reef health has significant potential.

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