

Proximal Sensing of Coral Features: Spectral Characterization of *Siderastrea siderea*

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Abstract: Remote sensing has been suggested as a potential tool for monitoring coral-reef ecosystems. However, before remote sensing can be viewed as a practical monitoring and diagnostic tool for entire coral communities, there is a need to understand the spectral responses from individual coral species. Toward that end, it seems important to not only establish the range of natural variability in spectral reflectance but also to develop procedures to enhance understanding of the spectra. This paper describes our data collection approach as well as a procedure for examining the spectral features associated with one species of coral (*Siderastrea siderea*). The

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paper also examines the spectral variability in reflectance within samples of the same species and suggests a procedure for highlighting the spectral positions of absorbers/pigments, thus yielding useful information about pigment composition in one coral species.

INTRODUCTION

Despite the fact that coral reefs have important biological, aesthetic, and economic value, they are being destroyed at an alarming rate (Wolanski et al., 2003). There is a need to not only develop baseline maps depicting the spatial patterns of coral reefs on a global scale but also to document the changing conditions associated with the world's reefs over time (Hochberg et al., 2003). Remote sensing techniques have been employed by many researchers for monitoring the health of, and changes in, coral-reef ecosystems (e.g., Green et al., 2000) as well as to map general benthic habitat types (e.g., sand, seagrass, corals, hard substrate) in reef environments (e.g., Khan et al., 1992; Ahmad and Neil, 1994; Matsunaga and Kayanne, 1997; Dobson and Dustan, 2000; Maeder et al., 2002; Mishra et al., 2005, 2006b). While multispectral, aircraft- and satellite-based observations have been used to study coral reef environments for some time (e.g., Lyzenga, 1978, 1981; Biña et al., 1979; Jupp et al., 1985; Jupp, 1986; Kuchler et al., 1988; Bierwirth et al., 1993; Mumby et al., 1998), few reef-scale, long-duration studies been performed (Dunston and Halas, 1987). Hyperspectral data, in particular, offer high potential for characterizing and mapping coral reefs because of their capability to identify individual reef components based on their detailed spectral response (Clark et al., 1997; Holasek et al., 1998; Holden and LeDrew, 1999; Hochberg and Atkinson, 2000; Hochberg et al., 2003). Several researchers have attempted to exploit hyperspectral data (from airborne or satellite platforms) to study coral groups (e.g., Mumby et al., 1998; Hochberg and Atkinson, 2000; Mishra et al., 2004, 2007), but only a relatively small number of researchers have attempted to characterize coral groups using field radiometers at close range. This situation exists despite the fact that the fundamental concepts for *remote sensing* of corals should be developed by means of *proximal sensing* (the latter term as used by Fussell et al., 1986).

Proximal Sensing of Coral Features

As an example of the authors who have undertaken proximal sensing of corals, we may include Clark et al. (1997, 2000), Holden and LeDrew (1998, 2000, 2001), Myers et al. (1999), Hochberg and Atkinson (2000), Schalles et al. (2000), Lubin et al. (2001), Hochberg et al. (2003), Joyce and Phinn (2003), Kutser et al. (2003), and Mishra et al. (2006a). Hochberg et al. (2003) provided a comprehensive literature review on *in situ* remote sensing research pertaining to coral reef environments. For example, Maritorena et al. (1994) took spectral reflectance measurements of sand, *Sargassum* sp., *Turbinaria* sp., *Boodlea* sp., *Porolithon onkodes*, and *Corallinacea* sp., but did not study the spectral differences among these bottom-types. Miyazaki and Harashima (1993) and Miyazaki et al. (1995) acquired both laboratory and *in situ*

reflectance measurements for several coral species, rocks, and sand, and concluded that there were minimal differences between those three benthic community types.

Holden and LeDrew (1998) performed a statistical investigation on a total of 22 *in situ* reflectance measurements, representing bleached and non-bleached *Acropora*, dead coral rubble, and algae-covered dead corals. They applied cluster, principal components, and derivative analyses to show that statistically significant spectral differences could be detected between healthy *Acropora* and bleached/dead *Acropora*. Holden and LeDrew (1999) have also shown that a high-resolution *in situ* spectral library can be developed to differentiate among various coral types as well as bleached coral substrate. Myers et al. (1999) described how hyperspectral optical spectra can be used to differentiate between pigmented and bleached coral and coral versus macroalgae. They reported on five *in situ* reflectance spectra for bleached and pigmented coral (*Montastrea cavernosa*), a red crustose alga, a brown algae, and a red alga (*Rhipocephalus phoenix*) at Lee Stocking Island, Bahamas. Their objective was to demonstrate an empirical relationship between pigmentation and reflectance. In Kaneohe Bay, Oahu, Hawaii, Hochberg and Atkinson (2000) measured a total of 247 *in situ* reflectances of three coral species (*Montipora capitata*, *Porites compressa*, *Porites lobata*), five algal species (*Dictyosphaeria cavernosa*, *Gracilaria salicornia*, *Halimeda* sp., *Porolithon* sp., *Sargassum echinocarpum*), and three sand communities (fine-grained carbonate sand, sand mixed with coral rubble, coral rubble). They used derivative analysis and multivariate techniques of stepwise wavelength selection and linear discriminant analysis to show that the spectral separation of basic bottom-types (coral, algae, and sand) is possible with as few as four non-contiguous narrow wavebands. Joyce and Phinn (2002) analyzed reflectance from corals with three distinct morphologies (open branching, closed branching, and table) and determined that the three are distinguishable by the differing amount of shadow each morphology generates. Minghelli-Roman et al. (2002) measured reflectance for 152 coral colonies in the Red Sea and were able to discriminate between 14 genera of hard and soft corals using ratios of only six wavebands. Finally, Mishra et al. (2006a) used *in situ* coral reflectance spectra from Ocean Optics hyperspectral radiometers on a adjustable buoyancy device to predict percent live cover of corals.

A review of the above literature dealing with proximal sensing of coral features has highlighted the fact that a wide array of procedures is being used for collecting basic spectral reflectance data from coral features. For example, Hedley and Mumby (2002) concluded that a great deal of uncertainty and inconsistency exists in the spectra of features that can be used to discriminate reef benthos. This is attributable to the fact that the total number of measurements has been few, methods have been dissimilar (producing data of varying quality), and objectives have focused on very localized measurements for a few species. These differences in procedures used might lead to differences in: (1) measured spectral reflectance; (2) conclusions about the natural variability of measured spectral reflectance for a particular species of coral; (3) inferences about the spectral features (e.g., wavelength of pigment absorption) associated with corals (specifically the magnitude of reflectance); and (4) conclusions regarding pigment composition in the corals under investigation. Finally, there are apparent difficulties associated with disaggregating the composite spectral signal upwelling from a large coral community. The many diverse coral shapes, sizes, and colors/pigment suites (not to mention the impact of the water column) present the remote sensing

specialist with a myriad of complex problems indeed. Spectral reflectance depends on many confounding variables associated with subsurface data collection and the bidirectional issues associated with coral. As a result, reflectance, in and of itself, may not provide the necessary information about not only the complex of pigments but also the status or condition of corals (i.e., biophysical information). Therefore, a procedure that is resistant to these confounding factors should be devised for spectral characterization of corals.

Objectives

The objectives of our work were to: (1) document the spectral features of *Siderastrea siderea* as distributed within one study site in the Western Caribbean; and (2) develop a technique to improve standard approaches for characterizing spectral features of coral.

STUDY AREA

The study area for the work summarized in this paper was Roatan, one of the “Bay Islands” of Honduras. Located in the Western Caribbean (16°20' N/86°30' W), Roatan is about 64 km north of the Honduran mainland. The focus of our activity was the Sandy Bay Marine Reserve and the westernmost portion of the island (Fig. 1). The diving industry is well developed in Roatan, and the health of the reef is critical to the economy of the island’s populace.

The reefs of the Bay Islands contain at least 52 species of stony corals, at depths ranging from 2 to 8 m. Coral species include Star corals (*Montastrea annularis*, *M. franksi*, *M. faveolata*, *M. cavernosa*), Brain corals (*Colpophylia natans*, *Diploria spp.*), Sheet and Lettuce corals (*Agaricia agaricites*, *A. larcki*, *A. undata*, *A. fragilis*, and *Leptosiris cuculatta*), Flower coral (*Eusmillia fastigiata*), Pillar coral (*Dendrogyra cylindrus*), Boulder Brain coral (*Colpophylia natans*), Symmetrical Brain (*Diploria strigosa*), and Massive Starlet (*Siderastrea siderea*). For this research, we focus only on *Siderastrea siderea*.

METHODS AND MATERIALS

Dual Field Radiometers

An innovative approach using dual Ocean Optics USB-2000 spectroradiometers was employed for collecting spectra for samples of *Siderastrea siderea* in Roatan (see Lawson et al., 2006). The *siderea* coral species was chosen for the study because of their state of decline on many, if not most, of the Caribbean’s reefs (Jackson et al., 1992; Bythell and Sheppard, 1993; Aronson and Precht, 2001; Bruckner, 2002), with the decline attributed to a combination of white-band disease, temperature stress, predation, and hurricanes. Ocean Optics systems were used to record the spectral response for targets in 2048 individual channels ranging from 350 to 1000 nm with a spectral resolution of about 1.5 nm. Radiometer #1, equipped with a 25° field-of-view optical fiber, was pointed downward to measure the upwelling radiance of *siderea* (L_{λ}^{coral}). This fiber optic was positioned over each coral at approximately 10 cm from

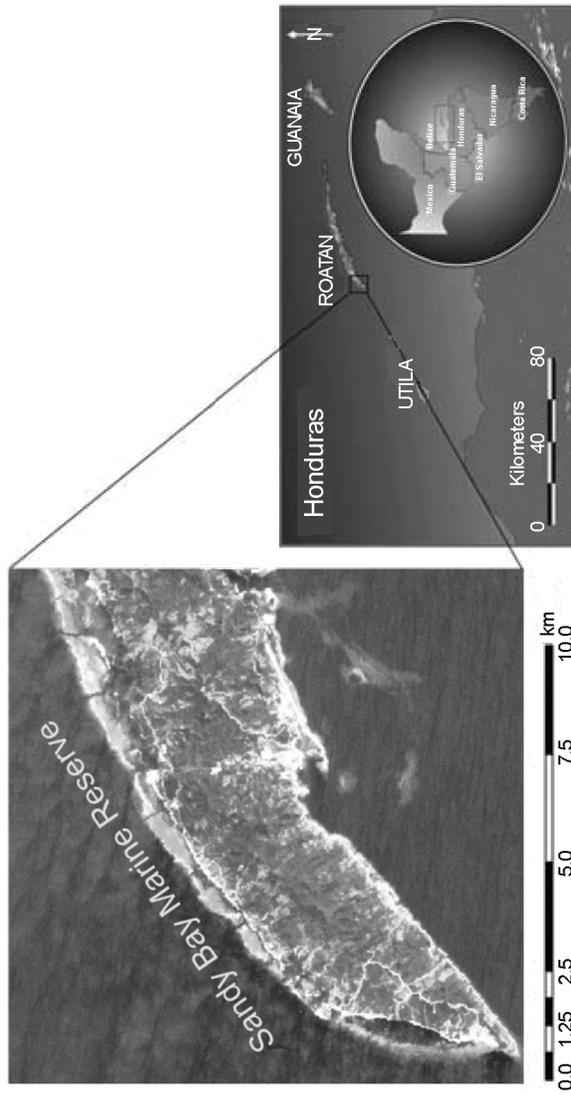


Fig. 1. Location of Roatan Island, Honduras in Central America.

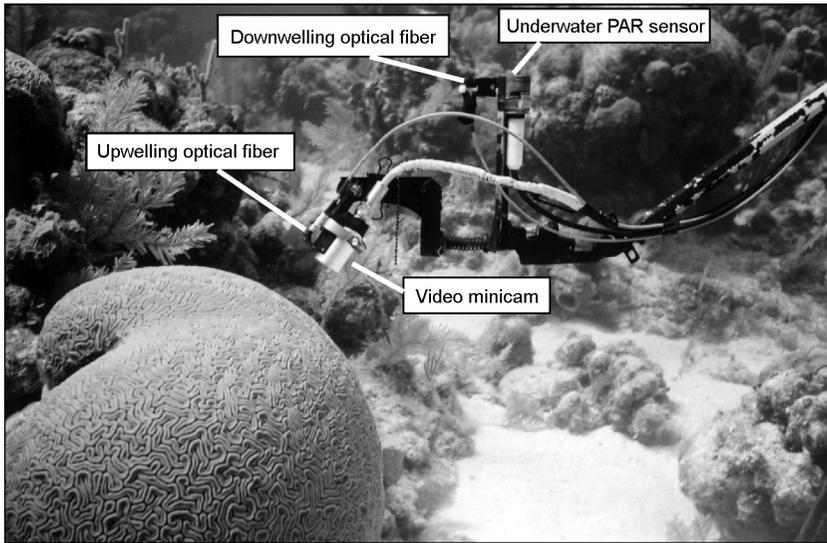


Fig. 2. Deployment of dual-radiometer fiber optics attached to black PVC wand, which also carries a mini-cam and light communication system.

its surface, and we attempted to maintain this consistent distance during each measurement. Radiometer #2, equipped with an optical fiber and cosine diffuser (yielding a hemispherical field of view), was pointed upward to simultaneously measure incident irradiance (E_{λ}^{inc}). Both optical fibers were attached to a single black PVC “wand” and deployed underwater by divers. The fibers are attached to the short piece of PVC such that the one with the cosine diffuser is pointed upward, and the other is pointed downward (Fig. 2). A noteworthy aspect of the procedure is that we measure spectral reflectance *in situ*; i.e., *under the water and at the precise depth of the coral of interest*.

The inter-calibration of the radiometers was accomplished, in order to match their transfer functions, by measuring the upwelling radiance (L_{λ}^{cal}) of a white Spectralon reflectance standard simultaneously with incident irradiance (E_{λ}^{cal}). Typically, we scanned a calibration panel above the water surface prior to and immediately upon completion of the sampling. To mitigate the impact of solar elevation on radiometer inter-calibration, the anisotropic reflectance from the calibration target was corrected in accord with Jackson et al. (1992). Percent reflectance (ρ_{λ}) was computed as:

$$\rho_{\lambda} = (L_{\lambda}^{coral}/E_{\lambda}^{inc}) (E_{\lambda}^{cal}/L_{\lambda}^{cal}) * 100 * \rho_{\lambda}^{cal}.$$

Here ρ_{λ}^{cal} is the reflectance of the Spectralon panel linearly interpolated to match the band centers of each radiometer. Radiometer #2 was linearly interpolated to match the band centers of Radiometer #1. The Spectralon panel reflectance was linearly interpolated to match the band centers of Radiometer #1.

One critical issue with regard to the dual-fiber approach is that the transfer functions of both radiometers must be identical and unchanging during the time of measurement. We have tested our Ocean Optics instruments under laboratory and field conditions, and found that over a four-hour period, the standard deviations of the ratio of the two transfer functions did not exceed 0.004.² With our dual-radiometer approach, there is no need to continuously use a standard white reference panel, and data can be collected during marginal illumination conditions (Lawson et al., 2006).

In addition to the fibers, the wand is equipped with both a “mini-cam”—a CCD device with a 3.6 mm lens, which provides a real-time video stream of the coral surface being scanned by the fiber-optic system, thus permitting the computer operator to “capture” a representative still image of the target.

Sampling Scheme

A total of seven representative samples of *Siderastrea siderea* were selected randomly for scanning by an experienced marine biologist/diver (J. Keck). Spectra were collected on March 6, 7, and 8, 2002 under generally clear skies. The data collection occurred between 9:40 a.m. and 12:30 p.m. Central Standard Time. The sampled corals were growing between 3 and 10 m in depth. Six reflectance spectra were taken over each sample, and each spectrum was the result of averaging of four individual scans compiled over approximately 5 to 10 seconds total. However, we did not perform any destructive sampling of coral to acquire the coral pigment content.

RESULTS

Identification of the important spectral features associated with *Siderastrea siderea*, as sampled at various locations within the Sandy Bay Marine Reserve, was the first objective of our work, and several of those features are common to all seven samples from Roatan Island. As is shown in Figure 3, low reflectance (<6%) is characteristic of the blue range of the spectrum with reflectance minima around 425, 460–470, and 500 nm. In the green range, some evidence of absorption (reflectance minima) can be seen near 530 and 580 nm. Reflectance increases toward longer wavelengths, reaching a maximum at about 608 nm. The shape of the peak around 608 nm varies among the samples. It was quite narrow with a steep decrease toward longer wavelengths in sites F, H, and I (Fig. 3A), whereas in sites P and Q (Fig. 3B), and also A3 and A4 (Fig. 3C), the long-wave “wing” of the peak was almost flat. The magnitude of the peak ranges from about 10% (Fig. 3A) to about 28% (Fig. 3C). Although a well-developed reflectance minimum in the red range was common to all samples, the width of the trough and its shape varies considerably (as was the case for the peak around 608 nm). A quite narrow and pronounced trough occurs between 662 and 668 nm in sites P and Q (Fig. 3B); in the other sites, the trough was much wider with widths of 20 to 30 nm in the range 630–660 nm. Around 675 nm, reflectance increases sharply, reaching 30% (Figs. 3B and 3C).

The spectral features of *Siderastrea siderea* in the blue and green regions are barely distinguishable in the reflectance spectra. To facilitate interpretation, we used

²For additional details, see Dall’Olmo and Gitelson (2005).

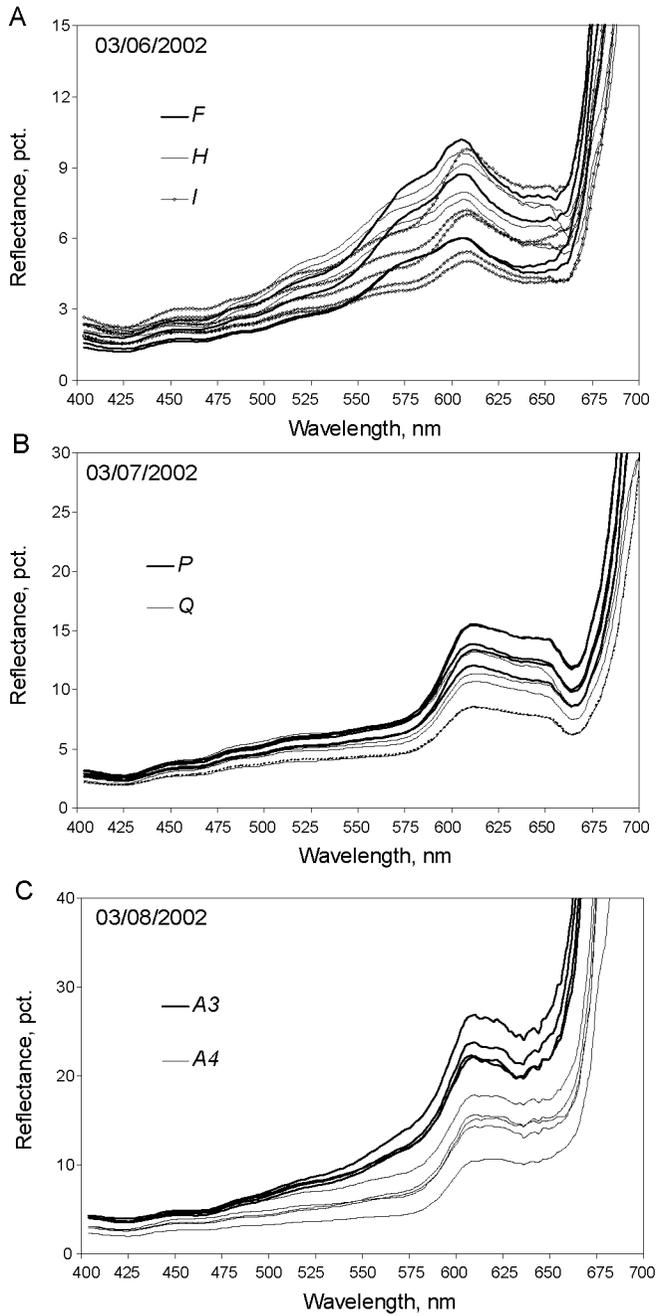


Fig. 3. Reflectance spectra taken over samples of *Siderastrea siderea* in different locations in the Sandy Bay Marine Reserve on March 6 (A), 7 (B), and 8 (C), 2002. The magnitudes of reflectance varied considerably even in spectra taken over the same sample.

reciprocal reflectance, $(\rho_\lambda)^{-1}$ as has been done for terrestrial vegetation at leaf and canopy levels (Gitelson et al., 2003a, 2003b). After transforming the data to $(\rho_\lambda)^{-1}$, which is a proxy of the ratio of the absorption coefficient of the target and the back-scattering coefficient, coral spectral features in the blue and green regions were much more readily apparent and the information content provided by the transformation increased considerably (Fig. 4).

To find the positions of peaks (thus, absorption bands of the pigments) within the reciprocal reflectance spectra, we approximated the spectra, in the range 400–700 nm, using Gaussian functions (Fig. 5). The optimal position, height, and width of these functions were determined in order to minimize both the differences between spectra and sum of Gaussian functions over the valid spectral range. A close approximation by Gaussians centered at 424 nm, 462 nm, 494 nm, 530 nm, 578 nm, 630 nm, and 662 nm was achieved. The peak position, height, and area of the Gaussian functions were then collected for each of the peaks in each spectrum (Fig. 4 and Table 1).

It should be noted, however, that the shape of the reciprocal reflectance spectra in the red range of the spectrum (beyond 600 nm) permitted, in some instances, approximation by more than one set of Gaussian functions. Unlike the five predominant peaks in the range 400–600 nm, reciprocal reflectance beyond 600 nm may be approximated by two peaks around 630 and 660 nm, and sometimes by three peaks (the third smaller peak appeared at 644 nm).

The magnitude of $(\rho_\lambda)^{-1}$, as well as magnitude of reflectance ρ_λ , varied considerably, even within one sample site (Figs. 3 and 4). We tried to keep constant the position of the downward sensor with respect to each coral; however, even small changes in sensor position led to substantial changes in magnitude of $(\rho_\lambda)^{-1}$ due to the bidirectional reflectance factor of coral and the inevitable slight change in distance between sensor and coral target, among other factors. The coefficients of variation (CV) of $(\rho_\lambda)^{-1}$ for one coral sample were between 5 and 29% and tended to increase toward longer wavelengths (Table 2).

When investigating specific spectral features associated with corals (e.g., pigment content, position of absorbers/pigments, pigment composition, the relative magnitude of absorption in each spectral band, etc.), one must minimize the variability in reflectance for the same sample. Taking into account that variation in factors affecting reflectance measurement is inevitable (and that it is difficult to imagine a technique that will eliminate this variation), we suggest normalizing reciprocal reflectance to the integral under the curve $(\rho_\lambda)^{-1}$ in the Photosynthetically Active Radiation (PAR) range (400 to 700 nm), $\Sigma(\rho_\lambda)^{-1} = (\rho_{\text{par}})^{-1}$. The variability of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for each site (Table 3 and Fig. 6) was much smaller than that of $(\rho_\lambda)^{-1}$; the CV of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for each site decreased at least fourfold (compare Tables 2 and 3).

Small variability of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for each sample made it possible to not only infer details concerning the specific spectral features of measured coral but also to compare spectral characteristics of all corals in the seven sample locations. We found it remarkable that the variability of the magnitudes of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ between samples was quite small, leading us to conclude that the suggested normalization is a good mechanism for characterizing the spectral features of corals. In Table 4, the median magnitude of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$, standard deviation, and coefficient of variation are presented characterizing seven *siderea* samples (each

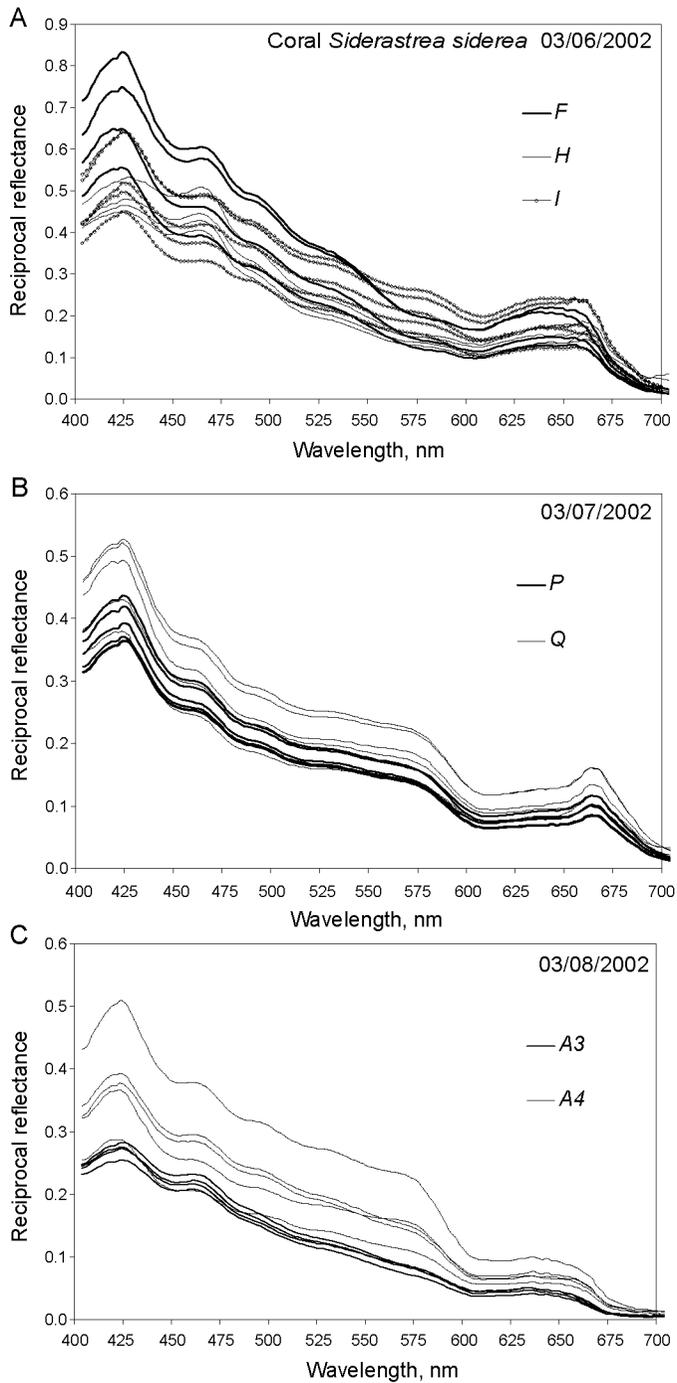


Fig. 4. Reciprocal reflectance spectra of *Siderastrea siderea* taken on March 6 (A), 7 (B), and 8 (C), 2002 in different locations in the Sandy Bay Marine Reserve.

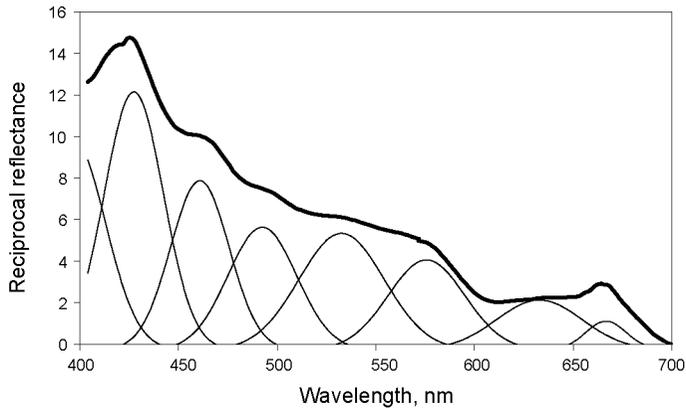


Fig. 5. Approximation of a reciprocal reflectance spectrum by Gaussian functions. The peak position and its width remained quite stable for all 42 spectra analyzed (Table 1).

Table 1. Peak Position and Width at Half Maximum of Gaussian Functions Approximated Reciprocal Reflectance Spectra of *Siderastrea siderea* Taken in Seven Sites^a

Peak position, nm:	424	462	494	530	578	630	662
STD, nm	3.2	2.0	2.1	1.7	1.5	1.5	3
Peak width, nm	47	34	35	51	46	41	36
STD, nm	7	3	3.5	3	4.5	7.5	6.6

^aSTD is standard deviation of peak position and width at half maximum for 42 spectra approximated.

coral is represented by six spectra) located at depths from 3 to approximately 10 m. In the range 400–600 nm, the CV of the function $(\rho_{\lambda})^{-1}/(\rho_{par})^{-1}$ reached a maximum of 16.4% at 578 nm. In the range beyond 600 nm it increased significantly, approaching 30% at 630 nm and above 50% at 650 nm.

DISCUSSION

The reflected signal at wavelengths longer than 650 nm is greatly affected by solar-induced fluorescence of chlorophyll in the zooxanthellae. Variation in coral reflectance, fluorescence yield, depth to corals, and solar zenith angle combine to affect the reflectance in the red region. The contribution of fluorescence to total reflectance varies greatly as a function of illumination conditions (e.g., Mazel, 1997). Fluorescence enhancement of the reflectance is greatest when the coral: (1) absorbs light at wavelengths that are transmitted well by seawater; and (2) emits light efficiently at wavelengths that are moderately or strongly attenuated by seawater. Such is

Table 2. Coefficient of Variation (CV) of Reciprocal Reflectance (in percent) of *Siderastrea siderea* Taken in Seven Sites^a

Peak position, nm:	424	462	494	530	578	630
F	16	18	18	18	19	21
H	7	10	11	10	9	13
I	17	17	17	18	21	28
P	8	8	8	8	9	12
Q	13	16	17	18	18	19
A3	4	5	5	6	8	8
A4	21	22	23	26	29	22

^aCV was calculated as the ratio of the standard deviation of six spectra taken at each site to the median value of reciprocal reflectance at each site.

Table 3. Coefficient of Variation (CV) of the Function $(\rho_{\lambda})^{-1}/(\rho_{\text{par}})^{-1}$ (in percent) of *Siderastrea siderea* Taken in Seven Sites^a

Peak position, nm:	424	462	494	530	578	630
F	4.0	0.7	1.4	2.3	4.3	4.8
H	2.5	1.4	1.6	1.7	2.9	3.7
I	4.1	2.9	2.9	2.3	2.9	8.7
P	2.1	1.5	1.4	1.0	0.7	7.6
Q	4.0	1.1	2.5	2.5	2.6	3.9
A3	1.0	1.6	2.0	0.8	3.9	4.6
A4	1.6	3.2	2.5	2.0	7.1	4.9

^aCV was calculated as the ratio of the standard deviation of six spectra to the median value of the function at each site.

the case for chlorophyll fluorescence at 685 nm, where water absorbs strongly and incident irradiance at depth in the red (685 nm) is much less than incident irradiance in the blue and in green (where the zooxanthellae absorb light). The change is dramatic; for the same fluorescence efficiency at a depth of 3 m, the enhancement of reflectance at 685 nm will be fourfold, while at 5 m it will be 9.5-fold and at 10 m 90-fold. As a result of this enhancement, the shape of a coral reflectance spectrum in the red range changes according to the depth where coral resides. As depth increases, the reflectance minimum due to chlorophyll absorption (as one would observe above the water surface around 676 nm) shifts toward shorter wavelengths.

It is quite interesting and instructive to compare the reflectance spectra taken in sites P (Fig. 3B) and A3 (Fig. 3C), where the effect of incident irradiance on reflectance enhancement in an underwater environment is demonstrated. Because the

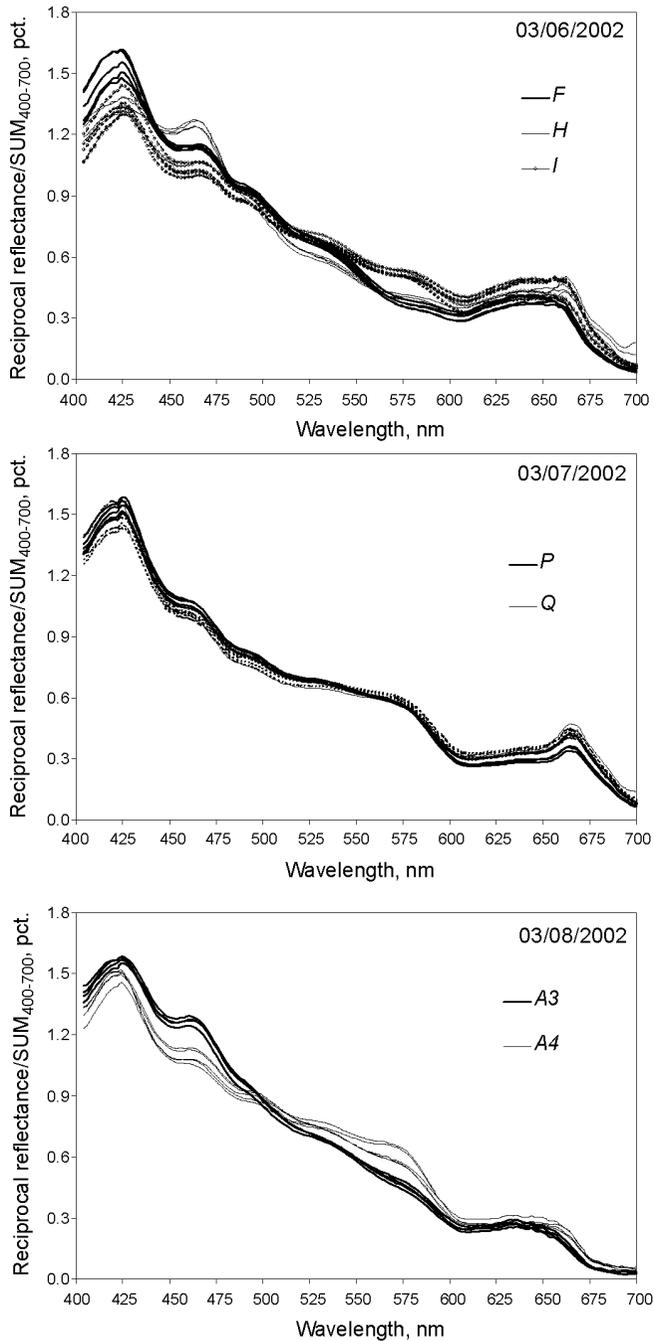


Fig. 6. Reciprocal reflectance spectra of *Siderastrea siderea*, $(\rho_\lambda)^{-1}$, normalized to reciprocal reflectance in the Photosynthetically Active Radiation (PAR) range from 400 to 700 nm, $(\rho_{\text{par}})^{-1}$. The coefficient of variation of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for each sample (and between samples) dropped significantly compared to that of the function $(\rho_\lambda)^{-1}$ (compare with variability of $(\rho_\lambda)^{-1}$ in Fig. 4).

Table 4. Median Value of the Magnitude, Its Standard Deviation (STD), and the Coefficient of Variation (CV) for Five Gaussian Peaks Approximating the Function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ in the range 400–630 nm

Peak position, nm:	424	462	494	530	578	630
Median	1.50	1.08	0.91	0.68	0.51	0.11
STD	0.09	0.10	0.06	0.04	0.08	0.37
CV, %	6.4	9.6	7.1	6.6	16.4	29.5

depths at sites P and A3 were quite different (3 m versus 10 m, respectively), downwelling irradiance at 550 nm in site P was 1.5 times higher than in site A3, while at 685 nm it was 25 times higher than in site A3. Decreased incident red light in site A3 led to a drastic enhancement of the fluorescence component of reflectance at 685 nm. An increased contribution of fluorescence to the total reflectance resulted in a shift of the reflectance trough (at 676 nm with no attenuation by water) toward shorter wavelengths; at site P it appeared around 666 nm, while at site A3 around 634 nm. Thus, chlorophyll fluorescence, which plays a minor role in the reflectance spectra of terrestrial vegetation, is very important in coral reflectance in the specifically limited underwater environment. At wavelengths longer than 630 nm, water absorption is much higher than in the blue and green and the “spectral behavior” of coral reflectance depends considerably on depth. In addition to normal attenuation by water, this phenomenon severely constrains the use of the red spectral band for monitoring the status of corals remotely.

To study spectral features of coral in the blue and the green ranges, we suggest using reciprocal reflectance, which is closely related to the Kubelka-Munk remission function, $f_\infty = (1 - \rho)^2/2\rho \cong a/b$, where a and b are absorption and scattering coefficients of the medium, respectively (Kortüm, 1969; Gitelson et al., 2003a). The remission function is the infinite reflectance of an ideal layer, in which a further increase in thickness results in no noticeable change in reflectance. The Kubelka-Munk model appears to be appropriate for corals where algal pigments, distributed above and/or within the aragonite mineral layer, absorb not only downwelling light but also light reflected by the mineral layer. Reciprocal reflectance was found to be closely related to the pigment content in both leaves (Gitelson et al., 2003a) and plant canopies (Gitelson et al., 2003b); thus, in studying spectral features of coral reciprocal reflectance, we hoped to discern the subtle aspects of coral spectral behavior. The use of (R^{-1}) permits analysis of spectral features with higher sensitivity than when using reflectance alone. The procedure also brings some understanding of the magnitude of absorption (because $R^{-1} \propto a/b$, and the absorption coefficient in corals within the visible range plays the main role in spectral properties of coral).

We have found that reciprocal reflectance reveals much more detail regarding spectral features than reflectance alone, especially in the blue and green ranges. It shows at least five distinctive spectral features in the range 400 to 600 nm. However, the magnitude of reciprocal reflectance, as well as reflectance, varied even for one sample (Fig. 4, Table 2). These variations in reflectance are presumed to be due to

inevitable change during measurement in the position of the upward- and downward-looking sensors with respect to both the coral target and the sun. It is physically impossible for a diver to hold the sensor in the exact same position (e.g., perfectly level) while measuring even a few spectra for one coral; moreover, the change in diver position with regard to the sun is inevitable during a move from one coral to the next. The change in “observer-object-sun” geometry leads to variation in reflectance due to: (a) the bidirectional reflectance factor of the microscale coral surface configuration; (b) the spatial variability of pigment content and composition of a coral sample; and (c) a change in downwelling irradiance measured by the upward-looking sensor when its position relative to the sun changes. We believe that the above-mentioned reasons caused most of the variability in the reflectances measured in the same sample site for the same coral species. We should emphasize that even for very consistent measurement techniques, different samples would likely be seen differently due to the bidirectional reflectance factor. Additional variation in reflectance of the same type of coral might be due to not only different pigment contents and compositions but also due to different slopes of the substrate where the particular coral “resides.”

Variability in the reflectance spectra of a target, and its great dependence on sensor-sun-target geometry, occurs in terrestrial vegetation as well as in other objects with anisotropic reflectance (e.g., Asrar, 1989). Therefore, the *magnitude* of reflectance (as well as reciprocal reflectance) per se is not particularly useful for spectral characterization in the case of vegetation status, and various vegetation indices have been developed to minimize the effect of bidirectional reflectance when attempting to either infer the general spectral characteristics of vegetation or retrieve specific biophysical properties. Thus, for corals, it was necessary to find a derivative of reflectance that is minimally sensitive to the bidirectional reflectance factor, as is, for example, the Normalized Difference Vegetation Index for vegetation (Rouse et al., 1974). For the corals studied, we suggested normalizing $(\rho_\lambda)^{-1}$ to $(\rho_{\text{par}})^{-1}$, which made it possible to significantly decrease the variability of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for each sample measured and, thus, to make a comparison between samples (Fig. 6, Table 3).

Spectra of $(\rho_\lambda)^{-1}$ and of $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ in the range 400–600 nm can be approximated by seven Gaussian functions. Peak positions and widths of the Gaussians were quite stable for the 42 approximated spectra. The spectral peaks, shown in Table 1, were detected reasonably well within all coral spectra in the range 400–600 nm, and are considered representative for *siderea*. Such an approximation provided reliable identification of the individual pigments present in freshwater algae (e.g., Gitelson et al., 2000), in which, as is the case with corals, the absorption maxima overlap. For the *Siderastrea siderea* samples studied, peaks in the reciprocal reflectance spectra suggested the presence and contribution of accessory pigments to the upwelling signal. All peaks revealed in the $(\rho_\lambda)^{-1}$ spectra might be associated with specific algal pigments (peridinin, chlorophylls c_2 and c_3 , diadinoxanthin; e.g., Owens et al., 1987; Rowan, 1989; Bidigare et al., 1990; Johnsen et al., 1994; Myers et al., 1999; Salih et al., 2000) and host-based coral green fluorescent protein pigments, which have many fluorescence excitation peaks, including one around 425 nm (Hedley et al., 2004). However, the magnitudes of the Gaussian functions do not necessarily represent pigment absorption in corals, as was the case for freshwater algae (Gitelson et al., 2000).

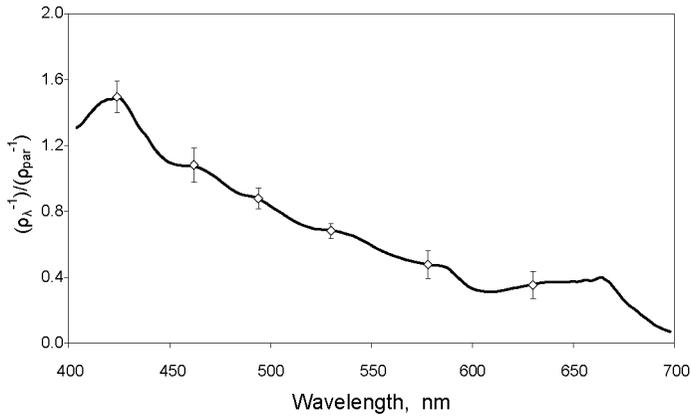


Fig. 7. Median magnitude of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ and its standard deviation (bars) for *Siderastrea siderea* taken in seven different locations in the Sandy Bay Marine Reserve.

Fluorescence of corals occurs at 486 nm, 515 nm, 538 nm, 575 nm, and 583 nm (e.g., Mazel, 1997; Mazel and Fuchs, 2003), and the fluorescent signals might affect both the occurrence and magnitude of individual absorption peaks. This is especially true for peaks of reciprocal reflectance at 530 and 575 nm, where the contribution of fluorescence signals at 530, 575, and 583 nm might be enhanced with increase in depth to the sampled coral. Nevertheless, the quite stable peak positions and their widths suggest that the approximation revealed fundamental spectral features of *Siderastrea siderea*.

Our study addressed a fundamental question: is there a “representative” spectral reflectance signature for *Siderastrea siderea* that accurately characterizes this coral species and that can be used in a “library” for coral-type recognition (i.e., is there a “baseline signature”)? Another related question was: what is the particular spectral characteristic that best facilitates identification of the species? Our research suggests that reflectance alone is not sufficient for coral recognition and “typing.” The high variability of reflectance is the result of many factors (noted above), all of which diminish the utility of reflectance as a means of discriminating coral type. Our suggested function or transformation of reflectance, $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$, as shown in Figure 7, allowed us to refine the characterization of *Siderastrea siderea*. Our preliminary results indicate that the approach should work well for characterizing any coral species; nevertheless, we advocate testing the procedure on many various coral types.

The magnitude of reciprocal reflectance is a proxy for the absorption coefficient (Gitelson et al., 2003a; Enriquez et al., 2005), and the use of $(\rho_\lambda)^{-1}$ opens the way to estimate non-destructively pigment content and composition in each sample, as was successfully demonstrated in leaves (Gitelson et al., 2006), fruits (Merzlyak et al., 2003), and phytoplankton (Dall’Olmo and Gitelson, 2005). However, the variability of reflectance for each sample will create uncertainties in pigment estimation.

The use of the function $(\rho_\lambda)^{-1}/(\rho_{\text{par}})^{-1}$ for studying spectral characteristics of corals substantially decreases the effect of variability in reflectance due to variability of affecting factors. Thus, this technique offers a mechanism for comparing spectral

features of different samples and probably between the species, such as peak positions, their width, and relative magnitude of each peak (ratio of peak magnitudes). It is important to note that the use of ρ^{-1} normalization to ρ_{par}^{-1} is a way to subtract from spectra the effect of variability in coral “brightness” (variation in pigment content) *underlying pigment composition itself*. Minimal variability in the function $(\rho_{\lambda})^{-1}/(\rho_{\text{par}})^{-1}$ shows that despite different pigment content, a particular species has its own specific pigment composition that is virtually invariable in healthy corals. Thus this technique perhaps could be used to distinguish between different coral species as well as between samples of the same species with different pigment composition. So, using this technique, one has to remember that it “masks” the real magnitude of ρ^{-1} , and thus coral brightness, and does not allow comparison in pigment content between the samples and the species.

CONCLUSIONS

1. Spectral features of *Siderastrea siderea* in the red range of the spectrum, as derived from reflectance, relate to chlorophyll absorption, but are also strongly affected by both high water absorption and the depth to the sampled coral. This, of course, severely limits the use of the red spectral region not only for characterizing individual corals at close range but also for monitoring and evaluating coral status remotely.

2. We suggest that the best approach to studying the spectral characteristics of corals is to use the reciprocal of reflectance, which reveals much more information than reflectance, especially in the blue and the green ranges. Gaussian functions approximated reciprocal reflectance and have quite stable positions and widths for all samples measured, suggesting that they have utility for spectral characterization of corals. However, reflectance and reciprocal reflectance spectra of the same sample varied and are greatly dependent on observer-sun-coral geometry, which is similar to what takes place when measuring vegetation and other objects possessing anisotropic reflectance. Therefore, the magnitude of reflectance and reciprocal reflectance does not alone suffice for characterizing the spectral properties of coral; an additional step is required.

3. We suggest using the function $(\rho_{\lambda})^{-1}/(\rho_{\text{par}})^{-1}$ for characterizing pigment composition in corals, and we found this function to be almost invariant with respect to survey conditions for each sample measured. Therefore, we conclude that this function can be used as a representative spectral signature for *Siderastrea siderea*.

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