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DEVELOPMENT OF A CANOPY REFLECTANCE MODEL FOR CORAL REEF AREAS: INFERENCES FROM FIELD SPECTRAL MEASUREMENTS AND MODELING EFFORTS

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ABSTRACT: In recent times, the observation of coral reef areas by remote sensing methods has received wide attention due to emerging worldwide environmental concerns such as coral degradation and its counteractive conservation measures. However, a vast majority of these efforts proceeded without the benefit of applying suitable geometric optics and physical radiative transfer models in resolving the reflectance behaviour of coral reef. This study focuses on the development of a directional reflectance model appropriate for analyzing coral reef areas, emphasizing the importance of shape, form and shadowing of coral canopies as main factors in influencing their appearance in images or real scenes. Here, coral canopies are treated as an assemblage of three-dimensional objects that varies with certain coral component characteristics. A combination of geometric-optical and turbid models similar to that applied commonly in plant canopies, were then modified and used to obtain a more comprehensive estimate of coral reef reflectance. These reflectance calculations are further subjected to models of radiative transfer through intervening media (object-water-atmosphere) to derive a feasible at-sensor spectral response. Results of model simulation indicate sensitivity of reflectance on viewing and illumination angles. Field spectral measurements of coral reflectance confirm this finding. The BRDF data collected and the model developed from this study can be further utilized for remote sensing data image analysis.

1. INTRODUCTION

Portrayal of coral reef areas in terms of morphological characteristics are important since they account for some of the effects of flow, sediment distribution and nutrient diffusion over coral regions. Quantitative parameters based on morphological features are helpful in the aspects of coral conservation (Edinger and Risk 2000, Mumby et. al 2000) or reef parameterisation for proper hydrodynamic modeling of coral-covered areas (Massel and Gourlay 2000). If remote sensing techniques are to be used for coral reef inventory, morphological rather than taxonomic discrimination may be more realistic and achievable because the contrasting features of the former may be more explicitly captured by imagery and that separation of the latter according to spectral properties may elicit complications due to similarity in biophysical contents making up coral materials. Moreover, recent advances in radiative transfer theory allowed for a more thorough description of the shallow water column in terms of light penetration. This welcome development not only enables analysis of sea bottom reflectance but also provides means to relate effects of light attenuation on coral abundance, diversity and distribution (Fortes, 2001). The treatment of recent efforts in modelling reef reflectance has been confined to the assumption that coral canopies are flat objects lying beneath the sea floor, neglecting the likely significant effects of shadowing, topography and morphological properties of objects underneath (Lubin *et al*., 2001). With the advent of off-nadir-perspective, high-resolution satellite-based sensors and mainstream use of low-altitude optical imaging systems, it is only proper that remote sensing methods applied to coral reef monitoring require detailed investigation on the sensitivity of sensor to shadowing and other effects of coral structure and bottom relief variations, at both micro and macro scales. Bidirectional reflectance distribution function (BRDF) modelling techniques offer an advantage in this respect due to its ability to describe surface reflectance for all combinations of incident and reflected angles.

2. OBJECTIVE

The overall goal of this research is to develop a canopy reflectance model for coral reefs taking into account the variations in coral morphology and sea bottom composition and provide useful inputs in the development of an efficient spectral inversion method to estimate some biophysical properties of coral reefs. The BRDF approach will be utilized for shallow water regions (Case 1 waters) where the sensor's depth of penetration would still be effective.

A primary step in achieving these goals is to determine which among morphological features measurable in coral types are sensitive to spectral responses. One purpose of this exercise is to collect spectral and angular BRDF data for coral canopies and to document changes in BRDF patterns as they relate to *in situ* biophysical measurements.

3. THEORETICAL BACKGROUND

The following three sections below describe the approach to coral reef reflectance modelling. First, the proper geometric model as physical representation of coral canopy and its subsequent directional reflectance behaviour is presented. Then, the necessary mechanism for radiative transfer of coral reflectance through water column is determined and finally, an atmospheric correction procedure is introduced to obtain a valid top-of-atmosphere reflectance.

3.1 Geometric-optical model for coral canopy

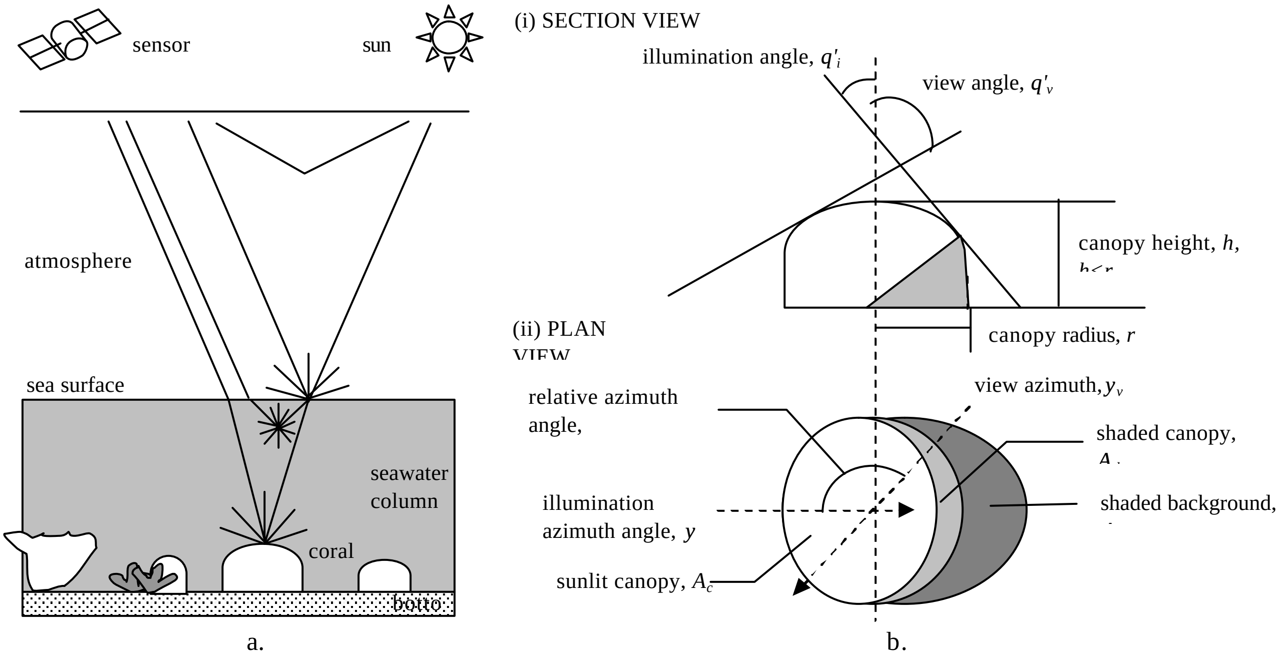


Figure 1. a.) A conceptual diagram of the radiative transfer model for a underwater target passing through a coupled ocean-atmosphere medium; b.) Geometry of an illuminated hemisphere and cone and its shadow, simulating a dome-shaped coral morphotype. View and illumination angles from the zenith are denoted by q'_v and q'_i respectively.

Reef corals are known to exist diversely both at inter- and intra-specific levels. As such, grouping them according to form by spatial clustering techniques may not be a suitable approach for coral classification, nor will it have any practical application in describing coral habitats. An alternative approach to defining physical representation of coral reefs, for purposes of BRDF modelling, would be to adopt terminologies used in describing coral growth forms or morphotypes (Veron, 2000) as a basis for devising proper geometric entities. Hence, the following four morphotypes are proposed which may be feasible to use: 1.) explanates or circular sheets or plates, with measurable diameter and thickness. 2.) hemispherical mounds or dome-shaped mass; 3.) arborescents or tree-like branches, which can be approximated as half-ellipsoids or cones and 4.) encrusting, arbitrarily shaped surface that can be thought of simply as flat and extensive. Analysis of these shapes will be complimented by any of the following structural components comprising the morphotypes: 1.) cylindrical, randomly-directed branches or twigs; 2.) laminar, almost flat, forming a tier; 3.) foliaceous, multilobate, forming a whorl.; 4.) solid with spongy-like or smooth texture and 5.) columnar, with components taking on pillar-like shapes.

From the above classification system, one can draw at most 20 combinations of morphotypes fitted with one type of structural component, some pairs of which are less likely to occur than the others. As an illustrative example, we consider the geometry of a hemispherical canopy as illustrated in Figure 1b and derive the necessary expressions for its radiance-irradiance relationships based on the Li and Strahler geometric model (1985). Just at the top of a single canopy, the mean reflectance may be regarded as a linear combination of areas with respect to illumination geometry expressed as follows:

$$R_s = \left(A_g R_g + A_c R_c + A_d R_d + A_t R_t\right)\Big/A \text{ and } \left(A_g + A_c + A_d + A_t\right)\Big/A = 1 \qquad (1), (2)$$

where A_i = variables describing the proportions for scene components. A refers to the total coverage area (e.g. of the pixel); R_s is the top of the coral canopy reflectance while the g, c, d, and t subscripts indicate illuminated bottom, illuminated canopy, shadowed bottom and shadowed crown, respectively. R_g, R_c, R_d, and R_t refer to the reflectance values of areas as described by their subscripts. A_g is the illuminated bottom area, with its proportion dependent on the size of the hemisphere, or in general terms, the area occupied by coral individuals or colonies present within the sensor signal range. Some possible sea bottom substrate materials can be sand, stones, gravel or rocks, seagrasses and mud. These patch areas unoccupied by coral colonies or individuals may be expressed in terms of gap probability functions (Strahler and Jupp, 1990). The reflectance quantities in the above equation implicitly depend on wavelength and are thus omitted here.

After computing the equivalent proportions of areas occupied according to their interaction with incident radiance, the reflectance values through the illuminated as well as shaded surfaces are computed. Radiance responses from interaction of incident rays to solid coral stands are confined only within the surface, and as such, any point from a massive coral surface, thought to simply emulate a Lambertian reflectance

$$R_c = \tfrac{1}{3} v \sec q_i' \sec q_v' \cos^2\left(J/2\right) \qquad (3)$$

will suffice. For hollow, or porous canopies like branching or columnar corals, however, we utilize the volume scattering BRDF by Roujean *et al*. (1992) to describe the light scattering through randomly oriented corallite layers of the form

$$R_c = \frac{2}{3p^2}\frac{\left[(p - J)\cos J + \sin J\right] v + \left(\sin J - J\cos J\right) t_c}{\cos q_i' + \cos q_v'}\left[1 - \exp(-bF)\right] + \frac{v_b}{p}\exp(-bF) \qquad (4)$$

Here, b=0.5/(cosq'_i+cosq'_v) and where J is the scattering angle between incidence and reflection equal to cos^{-1}(cosq'_icosq'_v+sinq'_i sinq'_v). For an isotropic distribution, v and v_b are the single scattering albedo of the corallites and bottom materials respectively, which serve as the coral inherent optical properties, while t_c is the transmittance value for the water-corallite interface. The randomly oriented corallite layers with coral density r, canopy height h, and area A, depending on the growth form type will have a volume integral:

$$F = \int_{A_c} r\, h dA \qquad (5)$$

3.2 Shallow water radiance reflectance model

Having computed the underwater at-object reflectance for a single canopy, that is, the overall reflectance at the bottom, R_s, we now proceed to compute for its relationship with the at-sensor reflectance R_{rs}. An application of a two-flow approximation to the radiative transfer in single water layer of uniform optical properties, valid at depth, z (in meters) just above the coral canopy with reflectance R_s, yields (Durand *et al*., 2000):

$$R_{0-} = R_\infty + \frac{\left[R_s - R_\infty\right]\left[1 - R_\infty^2\right]}{R_\infty\left[R_s - R_\infty\right] + \left[1 - R_\infty R_s\right]\exp\left(2z\sqrt{a^2 + 2ab_b}\Big/\cos q_v'\right)} \qquad (5)$$

where R_{0-} is the subsurface irradiance reflectance; a and b_b are the total absorption and backscattering coefficients respectively both of which incorporates bio-optical effects of chlorophyll-*a* presence. R_∞ is the subsurface irradiance reflectance for an infinitely deep water body with the same optical properties as shallow water body given by:

$$R_\infty = b_b\Big/\left(a + b_b + \left(a^2 + 2ab_b\right)^{0.5}\right) \qquad (6)$$

Due to refraction at the medium interface, there is a need to restore the view and incidence angles, q_v and q_I respectively which should now be corrected by setting $q_v = \sin^{-1}\left(n_w \sin q_v'\right)$ where $\mathrm{n_w} \approx 1.34$ is the index of refraction of the seawater and q_v is the sensor's zenith angle. The same analogy can be drawn for the sun zenith angle q_v. Furthermore, it is to be noted that as light propagates through the atmosphere in downward direction and crosses the air-water interface, it is refracted into a cone of less than 2p steradians. While light from this cone can be scattered to and from the region outside it, light scattered outside the cone cannot reach the atmosphere. Fresnel's formula gives the top-of the seawater surface irradiance reflectance value, R_w.

3.3 Atmospheric radiative transfer

The actual interest of remote sensing image analysis is to quantify the radiance from sea surface reaching the sensor at the top of the atmosphere. This requires incorporation of effects of atmospheric effects such as ozone column abundance and atmospheric path radiance. The midlatitude summer model of MODTRAN3 was used to create atmospheric transmittance profile for a given solar spectral radiance, F^0 to which the computed reflectance above-water surface are multiplied yielding the at-sensor spectral reflectance, R_{rs} on top of the atmosphere, or plainly:

$$R_{rs} = 100p\,\mathrm{MODTRAN3}\left(R_w\right)/F^0 \tag{7}$$

4. STUDY SITE, FIELD METHODS AND DATA

During a field campaign last July 2001, reflectance measurements were obtained for three healthy coral species found in Shiraho Reef, Ishigaki Island (24° 21' N, 124°15' E), Okinawa Prefecture, Japan. Prior to the actual reflectance measurements, physical dimensions including heights and diameters, branch sizes and spacing were obtained for each of the selected corals. Using an S2000 spectroradiometer with circular FOV of 22°, top of the canopy reflectance curves were also measured over and just beneath the water surface. Underwater reflectance measurements were done at five angular and three azimuth angles marked at 30° intervals and 45° (fixed at 30° view angle) respectively about 20 cm away from the target coral for morning and afternoon observations to observe diurnal changes. Precise solar altitude and azimuth was determined using the equation of time which required geographic coordinates obtained from a GPS while the direction of the line forming the angular measurement was read from a diver's compass. Spectral measurements were mostly conducted in early mornings and late afternoons to avoid effects of sun glitter on sea surface reflectance.

As an input for the radiative transfer model through water, the computational parameters were programmed as follows: salinity was set at 35% while chlorophyll-a value was pegged at 0.5 mg m^{-3} based on field data used in a previous study (Yamano and Tamura, 2000). Neglecting the effects of ocean roughness, a flat air-water interface (0 wind speed) is assumed with the absence of foams or whitecaps. For the atmospheric model, sensor altitude was fixed at 40 km. with no cloud or rain, under stable and low aerosol content simulating tropical maritime weather conditions. The radiance calculations are carried out for 35 (atmospheric) computational streams for 4*p* steradians.

5. RESULTS AND DISCUSSION

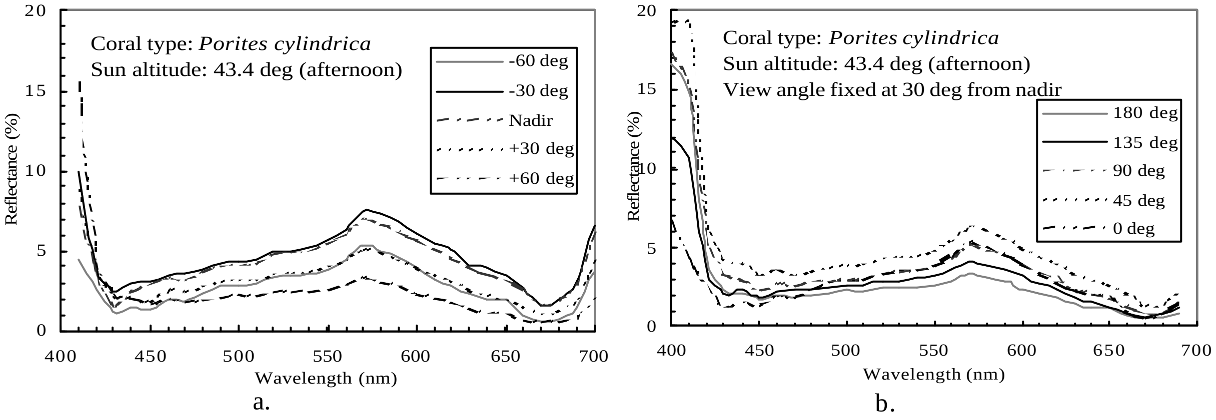
Table 1 summarizes results of structural measurements conducted on three coral canopies, whose values also serve as input parameters for the BRDF simulation. Figure 2 presents typical BRDF spectral signature plots generated from the multiview and multidirectional underwater spectroradiometer measurements of corals submerged to depth of about 1.5 m. Initial assessment of the multiview plots (Figure 2a) suggests differences in spectral responses with maximum variability especially evident in the 450-650 nm wavelength ranges, although at very subtle magnitudes (2-4% reflectance). Based on the figure, high spectral responses may be obtained from view angles nearest sun zenith, which in this case is the –30° curve, and gradually reduces as view angle veers away from illumination angle. Although the same remark can be drawn for the multidirectional (Figure 2b) spectral measurements, where viewing directions closest to the sun azimuth would yield the highest responses (45°), the differences in the curves are not as pronounced as the multiview reflectance graphs. Aside from sensitivity to directional reflectance, there may be other reasons for the observed spectral differences, such as for example, the spatial distribution of the algae *Zooxanthellae* responsible for coral color and the presence of other non-coral materials. Visually, it is safe to assume that the algae uniformly distributed over the coral components throughout the canopy and that non-coral objects on the canopy surface would have negligible effects.

Moreover, the already faint differences in spectral response magnitudes are further downgraded as irradiance reaching seawater surface is diffuse-attenuated integrally through depth. Comparison of spectral measurements between top and below water surface over the coral canopies demonstrates this fact. Effects of specular reflectance caused by sun glitter are, for obvious reasons, absent in the underwater reflectance curves.

Table 1. Structural measurements for coral canopies.

Coral type	Growth form	Structural	Dimensions	Volume

		component	Form	Component	Density
Porites cylindrica	hemispherical* mounds	Cylindrical fingers	80 cm height 140 cm diameter*	1.5 cm diameter fingers	0.47m^3/m^3
Heliophoracea	hemispherical* mounds	Columnar plates	82 cm height 110 cm diameter	6 cm x 1 cm columns	0.34 m^3/m^3
Montipora sp.	branching, flatbed	Cylindrical	1 m^2 area	2 cm diameter fingers	0.32 m^3/m^3



a. b.

* the shapes described are strictly defined as truncated semiellipsoids.

Figure 2. Spectral measurements of *Porites* coral canopy acquired at a.) varying zenith angles taken at constant azimuth; b.) varying azimuth maintaining constant zenith. Note that there is about 6° difference in relative azimuth between the lines outlined by view angle measurements and sun direction at the time of observation.

BRDF modeling computational results as represented in Figure 3a confirms the dependence of coral canopy reflectance on sun angle, which as expected, reaches maximum as viewing and illumination angle approach zenith values. The sharp peak when both sensor and the sun are at zenith position (e.g nadir illumination and view angle) accounts for the strong specular reflectance exhibited by the sea surface. On the other hand, isoreflectance curves in Figure 3b indicate greater reflectance distribution at portions where viewing directions are parallel to and opposite the sun azimuth. This is also due to the effect of direct illumination and sun glitter respectively. On top of the water surface, radiance values increased due to the contribution of surface reflectance but further modulated by atmospheric Rayleigh scattering. In addition, if coral density values are modified, the overall reflectance results in an apparent fluctuation to almost 35%. It can also be established that from moderate to large angles, the geometric reflectance function strongly depend on the balance between the bottom material and the coral canopy, than if it were viewed at near nadir. This observation however, is not evident if water depths are increased as the thickening water column attenuates the canopy reflection component.

6. CONCLUSIONS

In-situ directional reflectance measurements indicate that there are indeed differences in spectral response behaviour of target corals relative to its view and solar illumination conditions. These differences in reflectance values are further evident as it varies according to the type of coral canopy measured, which may well be related to the morphological make-up of the canopy, such as size, shape and the type of structure of the components. A coral canopy BRDF model has been developed to physically describe the directional reflectance phenomena, which at preliminary evaluation, explains well enough the multiview and multidirectional reflecting mechanism from submerged target to water and atmospheric mediums. However, the weak magnitudes and small relative differences in the directional spectra within one canopy may pose certain complications in efforts to estimate biophysical characteristics of coral reefs.

Results from this modelling exercise and field measurements, nonetheless improve our understanding of BRDF properties of submerged objects and possess valuable information which can serve as a basis for actual application of the model to compare with and analyze satellite- or air-borne imagery and eventually lead to more accurate diagnostic measurements of coral reef conditions and. An extension of this work would involve extending the geometric model to other combinations of growth forms and structural composition. The inevitable goal is to solve for the inverse relationships among various morphotype-structural component combinations as it relates to reflectance, an exercise of practical value when doing remote sensing studies considering that its potential application would be to apply the method inversely in the analysis of remotely-sensed data. Parameterisation techniques must also be evaluated in order to come up with an efficient inversion algorithm.

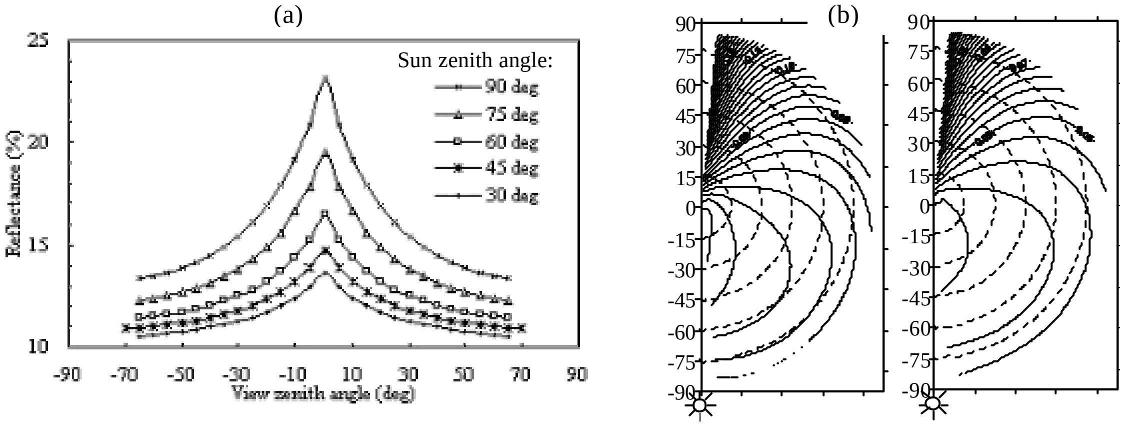


Figure 3. At-sensor spectral responses (l=570 nm) simulated for a hemispherically-shaped *Porites* canopy (a) shows four different sun zenith angles azimuthally perpendicular (y =90) against view angle found to be rotationally symmetric, (b) depicted in a BRDF polar plot scheme, where the relative azimuth is from $y_i = 0$ as indicated by the ☼ symbol in counter-clockwise direction, left: $q_i = 60°$, right:$q_i = 30°$. The dashed lines radial from the center represents the view zenith angles and while the contours represent the isoreflectance curves.

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