Optics of the Sea Floor

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Introduction

The Bahamas. You drop off the side of a small boat in clear tropical waters and swim over a lightly current-rippled bright sand bottom, spotted with brown patches of microalgae. You pass over a dark patch of seagrass, the blades bending slightly in the gentle current. Next a bare patch, and then the bottom rises up a meter and you are over multicolored corals and algae, with intricate branchings and textures. Idyllic and complex.

New England. You slip over algae- and mussel-coated boulders in the shallows to enter the green, cold water, then swim out over a flat bottom of medium brown sediment. Sand dollars leave a light-colored trail as they overturn sand grains and graze on the microalgae. Small mounds of brighter sand reveal the homes of burrowing animals that pass sand grains through their gut, stripping the algae away completely. Patches of dark seaweed, some green, some brown, some reddish, grow on and surround the rocks that rise straight out of the bottom. The rock wall is half covered by encrusting tunicates and plumose anemones.

The optical properties of the water play a strong role in determining what biology you will find on the bottom...

Two very different optical water types, two very different benthic environments. Yet, these images of small-scale variability in bottom type, biological involvement in seafloor appearance, and rapid changes in depth are typical scenes you might encounter at the sea floor. The optical properties of the water play a strong role in determining what biology you will find on the bottom, and the biology of the sea floor plays a dominant role in determining how light interacts with the ocean floor.

Research in ocean optics concentrated on the deep-water environment for many years, achieving a high level of understanding of the factors that contribute to both inherent and apparent optical properties (IOPs and AOPs). The efforts in measurement and experimentation were supplemented by strong theoretical work, resulting in robust analytical models. The increasing sophistication of the field has led to the successful treatment of ever weaker effects, including inelastic processes (Raman and fluorescence). The funding of deep water optical research also led to the development of a wide array of specialized instruments for deployment from ships or installation on moorings.

A shift of focus to shallow water presents a new set of challenges. The impact of the sea floor on upwelling radiance can arise from elastic (reflection, scattering, and absorption) and inelastic (Raman and fluorescence) processes. The horizontal scales of interest in shallow water can be very small, and the edges between bottom types with radically different optical properties can be sharp. In many environments the three-dimensional variability is significant and complex, with step changes in depth, varying slope, and highly textured structure. The diversity of organisms that must be considered is also greater for shallow water than for deep. Shallow waters are generally associated with coasts, currents, and terrigenous inputs, and the optical properties of the water column and the sea floor can vary rapidly in time as well as in space.

It is important to understand how light interacts with the sea floor. Benthic habitats are exceedingly valuable for their role in marine ecological systems, as sources of commercial resources, and as tourist destinations. In many coastal environments the standing biomass and productivity on the sea floor exceed the integrated biomass in the overlying water column. Powerful tools for high resolution imaging–in both the spatial and spectral dimensions–are becoming more readily available and there is great interest in applying these systems to map and monitor coastal environments. With recent advances in detectors, imaging systems, data storage and signal processing, we can record optical signatures at an overwhelmingly rapid rate. Much needs to be learned about the optics of the sea floor to put those gigabytes of spectral-image data to practical use. How do seafloor physical, chemical, and biological processes determine the spectral signatures of the bottom? Conversely, what can measurement of spectral signatures tell us about those processes? How stable are these signatures in time, or how well can we understand the temporal variations?

Much of what we do know about the spectral characteristics of seafloor features dates to the last decade. Prior to that, research involving optical measurements of the bottom was largely concerned with determination of water depth from remotely sensed data, and depended on information from a limited number of spectral bands (Lyzenga, 1978; Paredes and Spero, 1983; Philpot, 1989). In developing his model for seafloor reflectance Lyzenga (1978) used data from beach sand, dark soil, and wheat leaves, noting the 'absence of reliable reflectance measurements for actual bottom materials'. In a later paper he (Lyzenga, 1979) included reflectance data from several bottom types measured with a spectroradiometer fitted with a submersible fiber optic probe. Spitzer and Dirks (1987) measured the spectra of a limited number of samples of sand, mud and vegetation in the laboratory. Carder et al. (1993) and Lee et al. (1994) based their efforts in interpreting remote sensing reflectance data on a limited number of bottom albedo spectra representing very general bottom types (sand, mud, and vegetation). In all of these investigations a single 'typical' spectrum for each bottom type was applied across the entire study area. Lee et al. (1994) pointed out that 'direct bottom albedo measurements are lacking at individual stations and are needed for a wide variety of bottom types.'

Determining water depth and mapping bottom features are obvious and important applications of seafloor optics. Intelligent management of coastal resources will be greatly aided if we learn to rapidly map new regions and monitor known regions for change. Using optics to identify what is on the bottom is one challenge, with a real question as to the level of specificity that can be achieved. Knowing what is on the bottom as a function of time will provide insight into the processes taking place. Beyond identification, though, it would be valuable to be able to use optics to directly assess the condition of seafloor organisms, and to infer process from current state. How well these ambitious goals can be met is yet to be determined. Coral bleaching, which involves a radical change in the reflectance of the coral surface, may be the most obvious spectral change of interest, but there are many other stress factors that produce much less obvious changes.

Looking down from above is not the only perspective on the seafloor optical question. Some researchers don't care about mapping at all, but are very concerned with the flux of light at the sea floor as it relates to biological processes. Corals and their algal symbionts adjust to life over a range of light levels through a number of adaptations (Dustan, 1979, 1982; Falkowski and Dubinsky, 1981). Light also affects other features of corals, including color, growth form, activity, and ecological distribution (Kawaguti 1937; Weinberg, 1976; Lasker, 1979; Rogers, 1979). Macroalgal distribution, too, can be influenced by light (Markager and Sand-Jensen, 1992). Light also plays a major role in the productivity of seafloor biological communities (Wethey and Porter, 1976; Porter et al., 1984; Ackleson and Klemas, 1986). Light penetration in sediments is critical in determining the distribution of microalgae and bacteria in the upper layers (Jorgensen and Des Marais, 1988). This list could go on and on. There are also researchers interested in the role of color in the ecology of seafloor organisms, who seek a better quantitative understanding of the optical characteristics of their subjects (Wicksten, 1989).

Sea floor Optical Properties

We can speak of inherent and apparent optical properties for the seafloor just as we do for the water column. The inherent optical properties are those associated with the properties of the surfaces themselves—their reflectance, absorbance, and transmittance. For sediments, for example, the reflectance of the surface arises from a combination of factors including particle composition and origin; refractive index, grain size, orientation and packing; microbial films; and microalgae. For individual seagrass blades, factors include chlorophyll concentration and presence of epiphytic growth. A coral's reflectance arises from a combination of pigments in the symbiotic algae and in the host tissues, and from the structure of the underlying carbonate matrix.

The spectral and spatial distribution of light leaving the sea floor at any given time are apparent properties, dependent on the incident radiance distribution. The light illuminating the bottom varies with all the usual factors, including time of day, latitude, and the IOPs of the overlying water column. For the sea floor we have to add in shading by three-dimensional neighbors, wave focusing, and factors like motion of flexible features (seagrasses, macroalgae, soft corals) under the influence of waves and currents.

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The fluorescence of surfaces is also an apparent property. The fluorescence excitation and emission spectra and the fluorescence efficiency are inherent properties, but the fluorescence emitted at any given time will depend on the intensity and spectral distribution of the illumination. The significant fluorescence effects in open water are associated almost exclusively with the red fluorescence of chlorophyll and the orange fluorescence of phycoerythrin, a photosynthetic accessory pigment in cyanobacteria. On the seafloor we find those pigments in abundance, but we also encounter uniquely fluorescing substances in corals (Figure 1), anemones, sponges, and numerous other organisms. Carbonate sediment also fluoresces, apparently from the incorporation of organic matter in the calcium carbonate matrix.

Seafloor optical properties can vary strongly in both space in time. Many benthic features are discrete, with well defined edges and often an associated change in height. To an observer, the bottom can go from light to dark in the space of millimeters. There can also be quite significant temporal variations. Some portion of the benthic microalgal community moves vertically in response to light and tidal changes (Paterson, 1998). The changing density of algae within the top few millimeters of sediment can alter the reflectance properties (Paterson et al., 1998). Grazing and burrowing animals feed on the benthic microalgae, producing local changes in the seafloor reflectance. Physical factors can also play a role in sediment optical properties, separating the sediment constituents by size in the peaks and troughs of sand ripples. As one moves away from the bottom, the presence or absence of sand ripples results in larger-scale variations in both the magnitude and directional properties of seafloor reflectance.

Photosynthesizing organisms exhibit changes in pigmentation at both short (seconds to minutes) and long (weeks to months) time scales in response to changes in illumination and other forcing factors. Corals contain symbiotic algae, called zooxanthellae, that are the source of the brown color of most colonies, and that undergo these short- and long-term variations. Under conditions of stress the corals sometimes expel a significant fraction of their algal symbionts, resulting in a overall lightening that is termed bleaching.

In the absence of current seagrasses protrude vertically from the sea floor. An observer looking straight down would see some mixture of seagrass blades and sediment, varying with the density of blades. In a tidal current the blades bend, increasing the horizontal projected area, resulting in a net darkening of the bottom. On a time scale of months a seagrass meadow can expand or contract, depending on a variety of growth conditions. On a time scale of days individual seagrass blades are colonized by a variety of epiphytes, including microorganisms, macroalgae, and metazoans. This growth can cover portions of the blade, preventing light from penetrating to the leaf and changing its reflectance (Figure 2). Preliminary studies indicate that when this overgrowth is well developed it accounts for removal of approximately 60% of the light in peak chlorophyll absorption bands that would otherwise reach the blade. In addition to affecting seagrass optical properties this also has a marked effect on plant productivity.

The CoBOP Project

The Coastal Benthic Optical Properties (CoBOP) program is a multidisciplinary research initiative sponsored by the Environmental Optics Program of the U.S. Office of Naval Research. CoBOP's mandate is to investigate light in shallow water, with a particular emphasis on the interaction of light with the benthic environment—the sea floor and any organisms that may be present. There are two main components to the CoBOP program: a basic science component investigating the interaction of light with seafloor surfaces, both organic and inorganic; and a remote sensing effort utilizing emerging technologies for seafloor imaging and classification.

CoBOP's science component addresses the interaction of light with the bottom through a combination of measurement, experiment, and mathematical modeling. The objectives are to develop new instruments to measure the optical properties associated with coastal benthic environments; verify state-of-the art radiative transfer models for optically-shallow water; and inves-

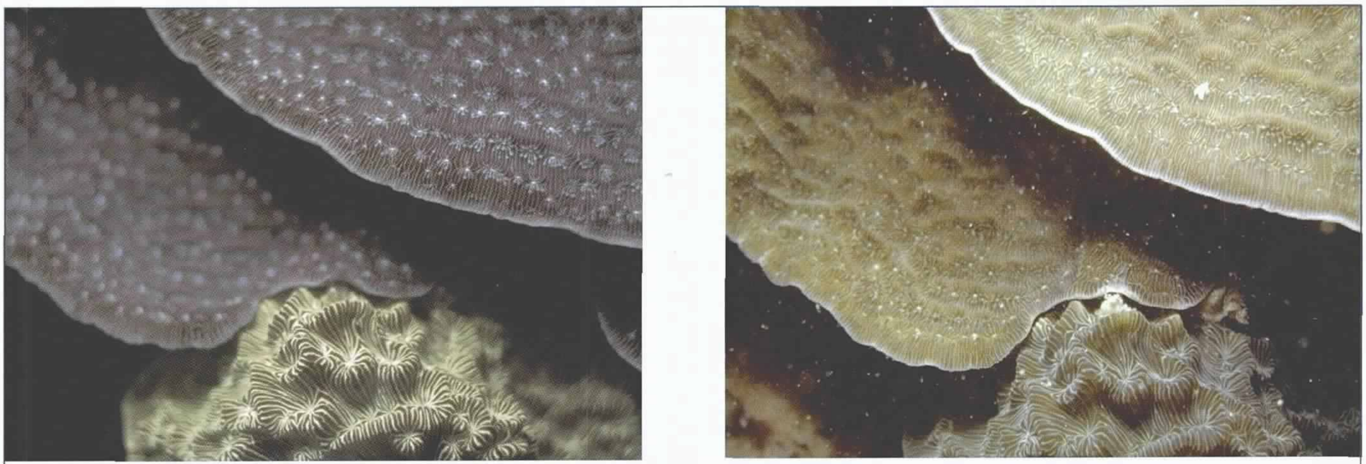

Figure 1. *Fluorescence of two corals. The photograph on the left was taken with a conventional underwater electronic flash and records the corals as they would appear under daylight illumination. The image on the right was made with the flash modified to emit only ultraviolet light, stimulating fluorescence in pigments contained in the coral tissues. The fluorescence image reveals two of the many colors and patterns of fluorescence observed in corals. (Photo by the author.)*

tigate the biological, chemical and physical processes associated with measured benthic optical properties. The remote sensing component utilizes state-of-the-art in-water and airborne systems to image large areas of the seafloor.

The main CoBOP field site is Lee Stocking Island (LSI), in the Exumas chain of the Bahamas. LSI is home to the Caribbean Marine Research Center, a National Undersea Research Center operated by the Perry Institute for Marine Science for the U.S. National Oceanic and Atmospheric Administration. This site was chosen because of the ready access it afforded to a variety of bottom types at a range of depths, combined with shore-based accommodation and laboratory facilities capable of handling over sixty scientific staff and up to five research vessels with additional scientific personnel—plus an airstrip to handle the project aircraft carrying a hyperspectral imaging system. Since the emphasis of CoBOP is on the seafloor the relatively clear water was a desirable feature, avoiding the added complexity associated with highly variable temperate waters with high loads of phytoplankton and suspended matter. Additional CoBOP fieldwork is being conducted in Monterey Bay, California, a site with very different seafloor and water column properties.

Measuring the Optical Properties

Measuring the inherent and apparent optical properties of the seafloor poses challenges that are very different from those faced in deep water oceanography. It is no longer adequate to lower an instrument over the side, with the assumption of a reasonable scale of horizontal stratification and confidence that the measurement you make is about the same as the one you would have made 10 meters away. We add the complexities of a highly three-dimensional surface, varying in color and texture over small spatial scales. Sensors must be positioned precisely relative to the features being measured.

The lessons learned in measuring optical properties in open water provide a foundation for approaches to measuring the optics of the seafloor, but it has been necessary to adapt existing instruments or develop entirely new ones. An example of the former case is a WET Labs ac-9 modified by a team at Oregon State University to be mounted on a SCUBA tank (Zaneveld et al., in press; Figure 3). This instrument measures the absorption and attenuation of water samples at nine wavelengths, and was used on the CoBOP project to explore optical properties of the near-bottom water column as a function of seafloor type. The diver holds a flexible tube so that water can be sampled at precise heights above any substrate, and the unit was also fitted with a probe to draw pore water from different depths in the sediment.

With this system the team documented significant differences in the nature, amount and size distribution of suspended particulates over coral reefs as compared to immediately adjacent sediments. Particulates over the reef tend to have less phytoplankton, relatively more small particles and less total suspended matter, all of which are consistent with the reef community filtering out the relatively large phytoplankton. By adding a 0.2 micrometer filter to the sensor intake to exclude the larger particulates, the team found that the level of dissolved organic matter, the product of reef community digestion, increased over the reef relative to the sand. These precisely positioned optical measurements demonstrate the intimate interaction between the bottom community and the optics of the water column.

An example of the latter category is the instrument that Ken Voss and associates at the University of Miami

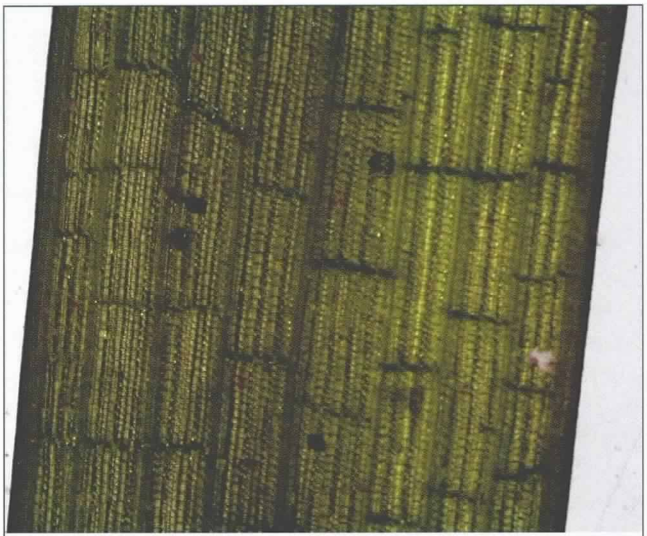

Figure 2. *Microscope images of growth of epiphytes on seagrass leaves. The blade on the top is approximately 2 weeks old, while the one on the bottom is 4–6 weeks old. (Photo by Lisa Drake, Old Dominion University.)*

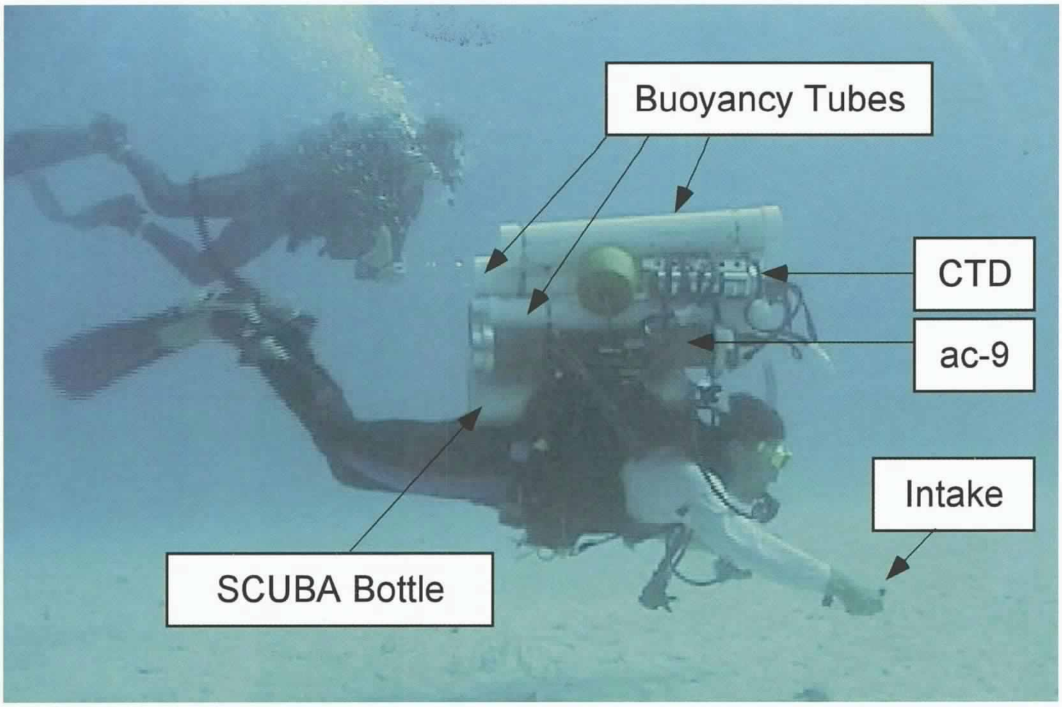

Figure 3. *SCUBA diver with a tank-mounted package for measuring optical and oceanographic properties. The instruments include a 9 wavelength absorption and attenuation meter (WET Labs ac-9) and a conductivity-temperature-depth sensor (CTD, SeaBird SBE 37-SI). Alternatively, a spectral fluorometer (WET Labs SAFIRE) can be used in place of the ac-9. The entire unit can be doffed and donned by the diver in the water and is trimmed for neutral buoyancy. Samples are collected through the probe in the diver's hand, and an adapter enables sampling of pore water from within the sediments. (Photo by Kevin Wyman.)*

developed to measure the bidirectional reflectance distribution function (BRDF) of sediments (Voss et al., 2000). A full BRDF measurement completely describes the relationship between light striking and leaving a surface as a function of incident and reflected angles. A surface can range from purely specular, like a mirror, to purely diffuse (Lambertian).

A SCUBA diver places the BRDF-meter over the surface to be measured and initiates the measurement sequence with an underwater keypad. The measurement portion of the instrument (Figure 4) resembles an inverted salad strainer. The instrument sequentially illuminates the sample surface at three wavelengths (light emitting diodes centered at 479, 568, and 654 nm), at each of 8 zenith angles from 0° to 65°. The light reflected from the 3 cm^2 sample area is measured at the same range of zenith angles as the illumination and at 28 azimuthal angles from 0° to 360°. For each measurement the light is collected by optical fibers and brought into a common "block array" that is imaged on a cooled CCD camera. A separate image of the reflected light field is made for each LED color and position. The combined results provide a fairly complete picture of the BRDF of the surface. With this unit Voss and his colleagues have determined that the BRDF of typical sediments is nearly Lambertian for near normal incident angles (less than 25°). At larger incident angles a 'hot spot', an area of enhanced reflectance, occurs in the backward direction. This hot spot can have reflectance factors greater than a factor of two above other directions. Typical natural samples show very little, if any, specular (forward scattering) reflectance.

For point measurements of the reflectance of features on the bottom some have taken the approach of using field spectrometers fitted with long fiber optic cables (Hochberg and Atkinson, 2000), so that the operator stays on the surface while a diver positions the measurement probe over targets of interest. The DiveSpec, a fully portable diver-operated spectrometer for measuring the spectral characteristics of discrete features underwater, was developed in the author's laboratory (Figure 5; Mazel, 1997). The measurement probe head is connected to the instrument housing by an electrical cable and a liquid light guide. The probe head holds an array of blue, white, and red LEDs that together provide illumination from approximately 400 to 800 nm. The light passes through a 20° diffuser and illuminates the sample from above (0°). The sample probe is placed over the surface to be measured, excluding ambient light. The light guide penetrates the probe circumference and is directed at the center of the illuminated area at a 45° angle, and conducts the light back to the spectrometer in the instrument housing. Reflectance measurements are made by first recording the light reflected from a reference standard, then from the sample of interest, and computing the ratio. The

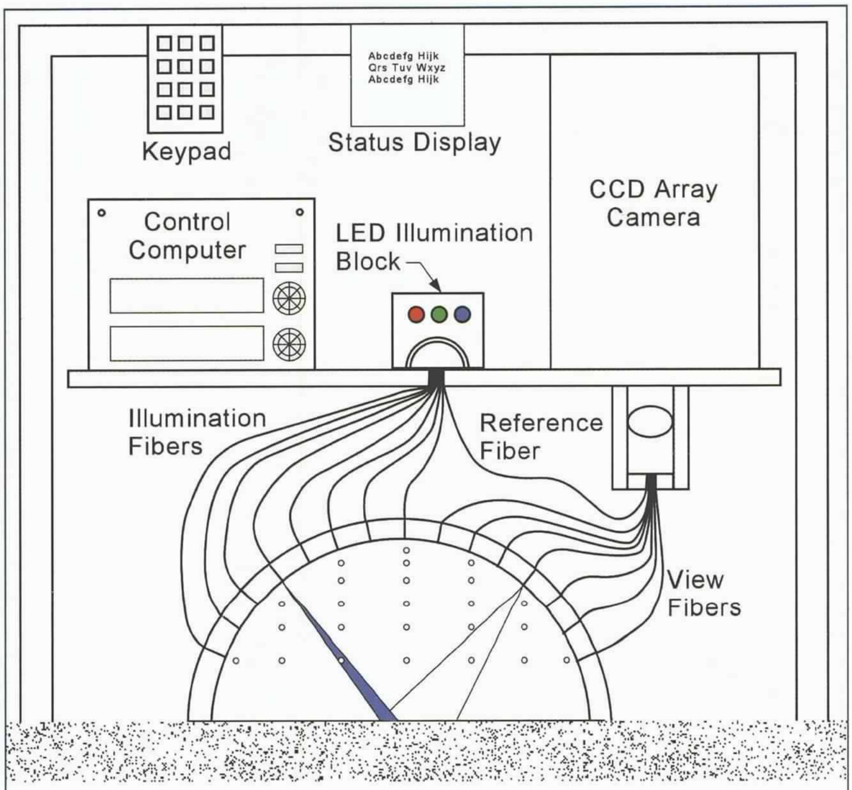

Figure 4. *Illustration of the BRDF-meter developed by Ken Voss and associates at the University of Miami.*

DiveSpec displays the data on an LCD display for real-time quality control. Measurements take less than a minute, enabling the operator to make numerous readings during a dive. The DiveSpec output comprises a database of spectral signatures of representative seafloor organisms and substrates.

Another new instrument is the HydroRad, developed by Robert Maffione and associates at HOBI Labs (Figure 6). HydroRad consists of up to four miniature spectrometers mounted in a watertight pressure housing, coupled to light collectors by fiber optic cables. The working ends of the fibers can be fitted with light collectors with a cosine weighting factor for measuring plane irradiance, isotropic light collectors to measure scalar irradiance, or restricted field-of-view collectors to measure radiance. The spectrometers measure the light spectrum from approximately 400 to 900 nm, with 0.3 nm spectral resolution. Data collection can be completely automated for moored operations, or operated manually as a self-contained instrument. In a typical configuration used during the CoBOP research program two of the HydroRad's spectrometers were connected to plane-irradiance collectors mounted approximately 10 cm from the bottom, one facing up and one facing down. The collectors were on the end of a narrow 2 meter boom that kept them away from the shadow of the instrument and its supports. The ratio of these upwelling and downwelling irradiances gives the bottom spectral albedo, or irradiance reflectance. The other two spectrometers were connected to light collectors mounted on a surface spar buoy attached to the instrument frame. One of these collectors measured downwelling irradiance just above the surface, while the other collector measured upwelling radiance just below the surface. From these two measurements the remote-sensing reflectance can be derived. These moorings were left in place for days at a time, logging data internally.

One objective of these measurements is to characterize the spectral albedo of various bottom types under conditions varying as a result of changes in ambient illumination (e.g. sun angle) and physical forcing (currents or wave action). Another objective is to measure the spectral light field at the top and bottom of the water column

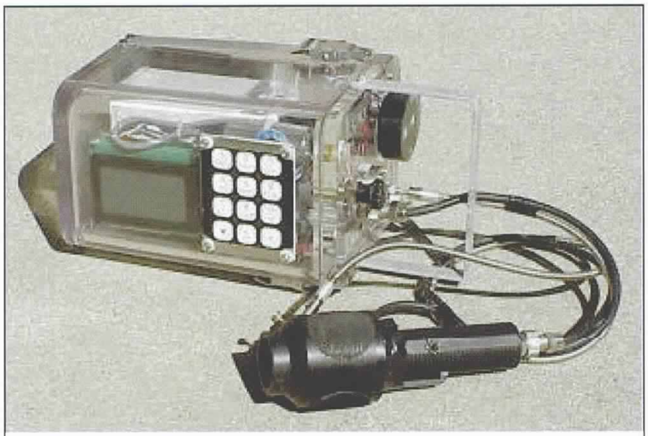

Figure 5. *Prototype DiveSpec benthic spectrometer developed by the author and associates at Physical Sciences Inc., to record spectra from discrete seafloor features. The DiveSpec measurement probe excludes ambient light and illuminates the subject with either multicolor LEDs to produce full-spectral light for reflectance measurements, or narrow-band blue LEDs for fluorescence measurements. Results are displayed in real time on the LCD display. The operator interacts with the system via the alphanumeric keypad on the housing.*

Figure 6. *(Left) divers next to HydroRad instrument deployed at Lee Stocking Island, Bahamas. The narrow pole holding the light collectors protrudes to the right from the instrument housing; (Right) detail of a cosine collector at the end of the probe. A second collector faces down to gather upwelling light. Fiber optic cables carry the light to spectrometers in the underwater housing, where the data are recorded. Irradiance reflectance of the seafloor is computed in post-processing. The HydroRad instrument can also be outfitted with fiber cables leading to a surface spar buoy that measures downwelling irradiance and upwelling radiance, from which remote sensing reflectance can be computed. (Photo by Robert Maffione.)*

simultaneously for the purpose of developing and testing shallow-water radiative transfer models.

While most investigators are looking at the light that is reflected from sediments, others are more interested in the light that penetrates *into* the seafloor. From the strictly physical point of view, sediments can vary widely in composition, grain size, grain packing, and other factors. Biologically, sand grains can be coated with microbial biofilms and colonized by benthic microalgae, some of which are mobile. All of these factors influence how light will be scattered and absorbed as it interacts with the grains. As the light changes in intensity and spectral distribution with depth in the sediment, the kind of biological community it can support also changes. Researchers have developed fiber optic probes (Kuhl and Jørgensen, 1992) that permit precise investigation of this light penetration at very fine scales.

The measurement and imaging of seafloor fluorescence is less common, but is of great interest because of the kind of information this additional spectral dimension can provide. Ultraviolet-excited underwater fluorescence photographs reveal the variety of colors and patterns that can be seen in the fluorescence of some corals (Figure 2), as one example. Depending on the environment, fluorescence is more or less common on the seafloor. Carbonate sediments fluoresce, while siliclastic sediments do not. The red fluorescence of chlorophyll in benthic micro- and macroalgae is widespread, with additional orange fluorescence from the photosynthetic accessory pigment phycoerythrin in the red algae and cyanobacteria. Some sponges fluoresce, as do some other benthic invertebrates. We still have a lot to learn about the extent of this phenomenon.

The larger-scale images of seafloor fluorescence made by the Fluorescence Imaging Laser Line Scanner (FILLS) (Jaffe et al., this issue) exhibit a remarkable differentiation among bottom features. FILLS was used during the CoBOP project to collect data over reef, sediment, and seagrass bottoms. It appears that many types of organisms can be distinguished by their fluorescence emissions in the FILLS imagery, suggesting that a combination of spectral and spatial analysis of the fluorescence images could prove valuable in rapid and automated mapping of reef and other environments (Figure 7).

In situ and laboratory measurements were made during CoBOP to help in understanding how the fluorescence characteristics of seafloor features are manifested in the FILLS imagery. The DiveSpec instrument described earlier also contains high intensity blue LEDs with peak emission at approximately 470 nm. These can be energized separately from the LEDs used for reflectance, stimulating fluorescence that is collected by the liquid light guide and recorded by the spectrometer. The results reveal that the many colors of fluorescence observed in corals apparently come from a limited number of fluorescing pigments in the host tissues (Mazel, 1995).

Another approach to measuring fluorescence has been pioneered by Paul Falkowski and associates at Rutgers University. They originally developed Fast

Repetition Rate Fluorometry (FRRF) to probe the photosynthetic potential of phytoplankton, and as part of the CoBOP project have developed a new diver-operated version to measure the variable fluorescence of seafloor organisms, including corals, seagrasses, and benthic microalgae (Gorbunov et al., 2000). The FRRF pumps the chlorophyll with blue light and measures the change in fluorescence as photosynthetic reaction centers are filled. The magnitude and temporal characteristics of the variable fluorescence provide insight into the photosynthetic mechanism of the subject. The FRRF and a related technique, Pulse Amplitude Modulated fluorometry, are now being routinely applied to coral health studies (Beer et al., 1998; Lesser and Gorbunov, 2001).

Radiative Transfer Theory and the Sea Floor

The seafloor also poses challenges for radiative transfer models (Mobley, 1994), which typically assume horizontal homogeneity of optical properties, with variation only in depth. If the bottom was considered at all it was treated as a uniform Lambertian (diffuse) surface. Sharp transitions from one bottom type to another, step changes in depth, and sloping bottoms all pose challenges to such models. As part of the CoBOP program Curt Mobley, the developer of Hydrolight (Mobley, 1994), developed a full three dimensional Monte Carlo radiative transfer code to deal precisely with these effects. This new code was used in conjunction with the 1-D Hydrolight model to determine when the full three-dimensional treatment was needed, and when appropriate simplifying assumptions permitted use of the more efficient model. He also investigated the significance for models and measurement and imaging systems of the degree to which true bottom reflectances are Lambertian or non-Lambertian, incorporating the BRDF data collected by Ken Voss.

Applications and Needs

By understanding how biological and physical processes result in the optical properties we measure we hope to be able to solve the inverse problem and use the optics to tell us about those processes. If optical measurements can be reliable indicators of identity, state, or process the door is opened for rapid, wide-area, non-destructive mapping of seafloor resources from in-water, shipborne, airborne, or spaceborne detector platforms. The technical ability to generate gigabytes of high resolution—both spatial and spectral—images of the coastal environment outstrips our ability to interpret that data efficiently. Many people are interested in this problem, however, and the potential payoff is enormous.

There have been many papers describing applications of remote sensing to seafloor mapping (e.g. Loubersac et al., 1991; Luczkovich et al., 1993). Many of these are largely phenomenological, where the researchers ground-truth selected portions of an image to learn how to interpret that image as a whole. This approach is valuable but tends to be limited to specific images and sites. By looking at the optics of the seafloor and the overlying water column researchers are now attempting to take a first-principles approach. The payoff should be a more general solution, and the tools needed to apply a variety of sensors at a variety of sites

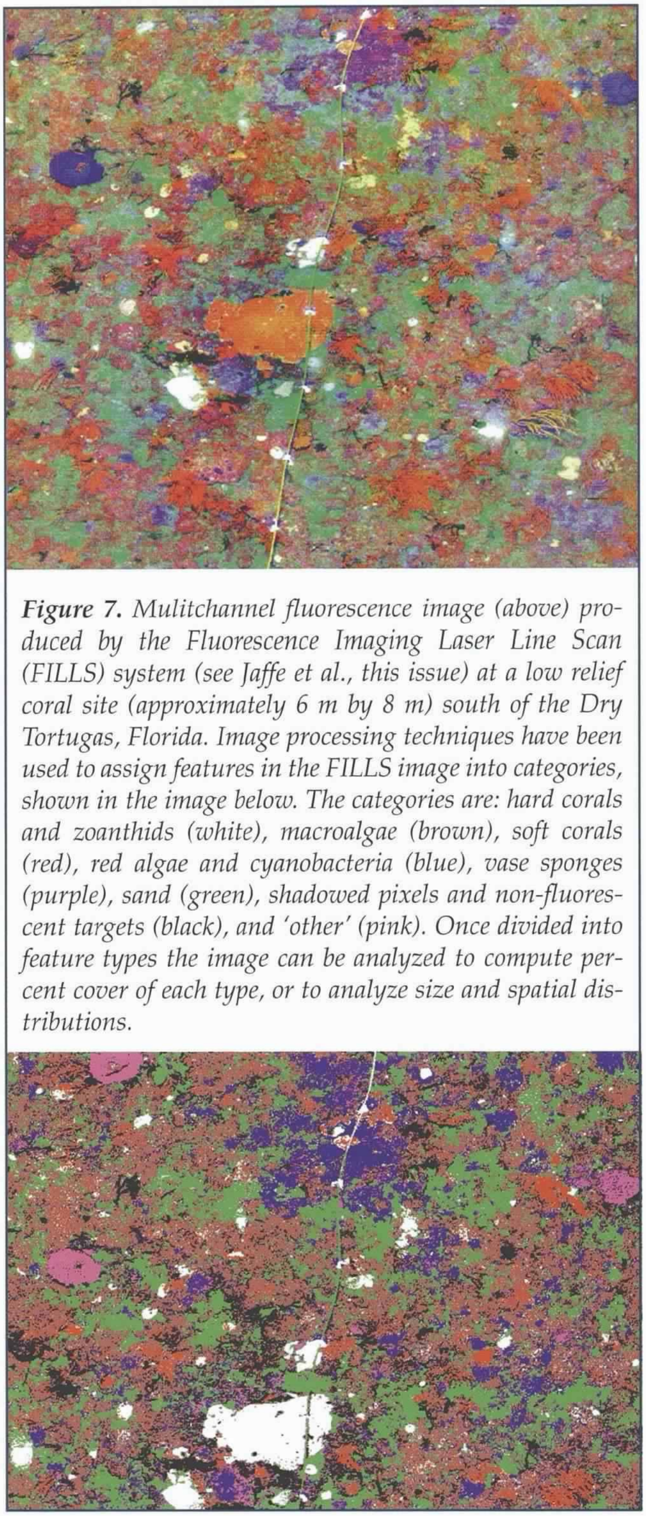

Figure 7. *Mulitchannel fluorescence image (above) produced by the Fluorescence Imaging Laser Line Scan (FILLS) system (see Jaffe et al., this issue) at a low relief coral site (approximately 6 m by 8 m) south of the Dry Tortugas, Florida. Image processing techniques have been used to assign features in the FILLS image into categories, shown in the image below. The categories are: hard corals and zoanthids (white), macroalgae (brown), soft corals (red), red algae and cyanobacteria (blue), vase sponges (purple), sand (green), shadowed pixels and non-fluorescent targets (black), and 'other' (pink). Once divided into feature types the image can be analyzed to compute percent cover of each type, or to analyze size and spatial distributions.*

to address a variety of questions.

Much still needs to be done to learn just how much information can be derived from spectral measurements of the sea floor, and with what constraints. To what level of specificity can we aspire? We will probably be able to distinguish red from green from brown macroalgae, but will distinctions within those groups be possible? Similarly, we may be able to distinguish corals from algae or sponges, but how many individual coral species will we discriminate? And will we be able to optically detect stress in corals before it reaches the extreme condition of bleaching?

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Many efforts are addressing these questions by collecting and analyzing in situ and remotely sensed data to see just how far we can go, dealing with both spatial and spectral scales (Knight et al., 1997; Mumby et al., 1997; Holden and Ledrew 1998, 1999, in press [a]; Hochberg and Atkinson, 2000; Clark et al., 2000). A lot of initial effort is going into cataloging signatures and looking for the best wavebands for distinguishing features of interest. Much will still be gained simply by distinguishing among major functional groups, such as corals, algae, sponges, sand, rubble, etc. Many labor-intensive *in situ* monitoring programs only record bottom cover data to the level of functional group, and do a good job of tracking short- and long-term ecological changes with that information.

We must also anticipate the spectral constraints imposed by the water column. The deeper the water, the narrower the spectrum that will be available to an instrument that must look through the entire water column. Algorithms that use spectral information in the water transmission window will fare better than those that require the full spectrum (Lubin et al., 2001; Holden and LeDrew, in press [b]). The greatest loss is in the red part of the spectrum, above about 600 nm. In-water instruments with their own active light sources may fare better than passive airborne instruments, but at the cost of much reduced coverage. The severity of the *in situ* coverage challenge may be alleviated by increased availability of cost-effective autonomous underwater vehicles capable of long duration missions.

Another topic that needs more work is the issue of scale. Many of the new measurements described here are being made at scales of square centimeters or less. The 'footprints' of most imaging detectors are much larger, on the order of one to several square meters for airborne hyperspectral sensors, to tens of square meters to square kilometers for spaceborne imagers. The size scale of many seafloor features is much smaller than the sensor footprints, so we enter the realm of spectral mixture analysis to determine the fractional contributions of various endmembers (prototypical spectra for features of interest) to the measured spectrum. The endmembers are what we are after with the precise *in situ* measurement of seafloor spectral characteristics.

Another scale issue arises from the three-dimensionality of many seafloor features. For example, at very small scales, a sediment bottom can be considered flat, but as we incorporate a larger area the presence of wave- or current-induced ripples becomes significant. A rippled surface will certainly have a different BRDF than a flat surface, all else being equal. Corals can range in form from flat to hemispherical to branched, so there will be effects on bulk reflectance that have not yet been investigated. There is still much to be done in this regard.

The intense interest in valuable shallow coastal environments and rapidly advancing technologies for imaging and measurement combine to provide an opportunity to make great strides in understanding and utilizing the optics of the seafloor. Programs like CoBOP and the efforts of researchers around the world are leading to a marked increase in publications on seafloor spectral characteristics, algorithms for discrimination of bottom features, and applications to real problems of environmental assessment and management.

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