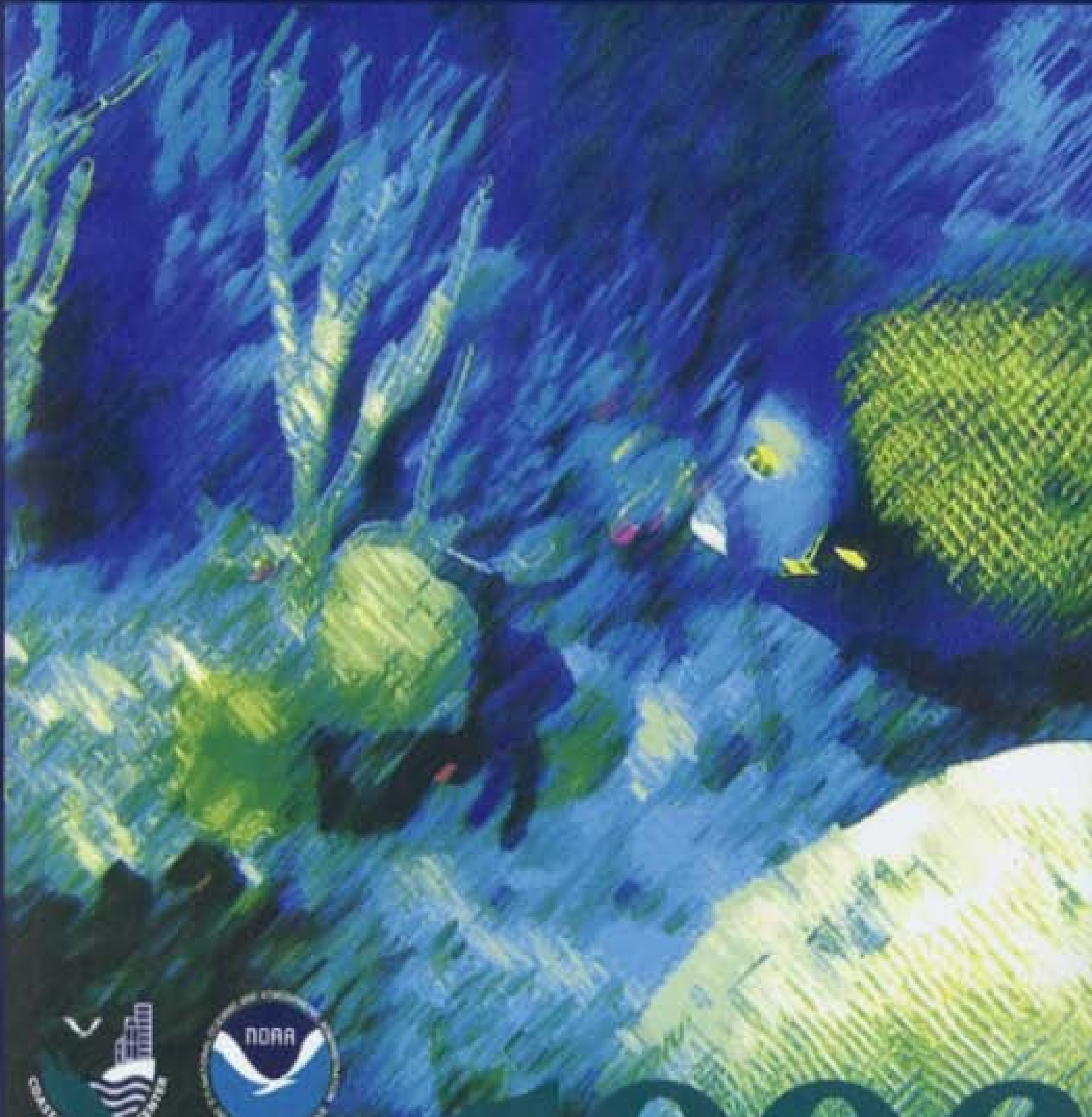
CORAL REMOTE SENSING WORKSHOP



September 17-18 1996

PROCEEDINGS AND RECOMMENDATIONS

Sheraton, Brickell Ave. Miami, FL

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EXECUTIVE SUMMARY

Coral reefs exist in warm, clear, and relatively shallow marine waters worldwide. These complex assemblages of marine organisms are unique, in that they support highly diverse, luxuriant, and essentially self-sustaining ecosystems in otherwise nutrient-poor and unproductive waters. Coral reefs are highly valued for their great beauty and for their contribution to marine productivity. Coral reefs are favorite destinations for recreational diving and snorkeling, as well as commercial and recreational fishing activities. The Florida Keys reef tract draws an estimated 2 million tourists each year, contributing nearly $800 million to the economy. However, these reef systems represent a very delicate ecological balance, and can be easily damaged and degraded by direct or indirect human contact. Indirect impacts from human activity occurs in a number of different forms, including runoff of sediments, nutrients, and other pollutants associated with forest harvesting, agricultural practices, urbanization, coastal construction, and industrial activities. Direct impacts occur through overfishing and other destructive fishing practices, mining of corals, and overuse of many reef areas, including damage from souvenir collection, boat anchoring, and diver contact.

In order to protect and manage coral reefs within U.S. territorial waters, the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce has been directed to establish and maintain a system of national marine sanctuaries and reserves, and to monitor the condition of corals and other marine organisms within these areas. To help carry out this mandate the NOAA Coastal Services Center convened a workshop in September, 1996, to identify current and emerging sensor technologies, including satellite, airborne, and underwater systems with potential application for detecting and monitoring corals.

For reef systems occurring within depths of 10 meters or less (Figure 1), mapping location and monitoring the condition of corals can be accomplished through use of aerial photography combined with diver surveys. However, corals can exist in depths greater than 90 meters (Figure 2), well below the limits of traditional optical imaging systems such as aerial or surface photography or videography. Although specialized scuba systems can allow diving to these depths, the thousands of square kilometers included within these management areas make diver surveys for deeper coral monitoring impractical. For these reasons, NOAA is investigating satellite and airborne sensor systems, as well as technologies

Figure 1. Shallow water coral reefs provide adequate light penetration and reflection for limited airborne and spaceborne imaging and analysis.

which can facilitate the location, mapping, and monitoring of corals in deeper waters.

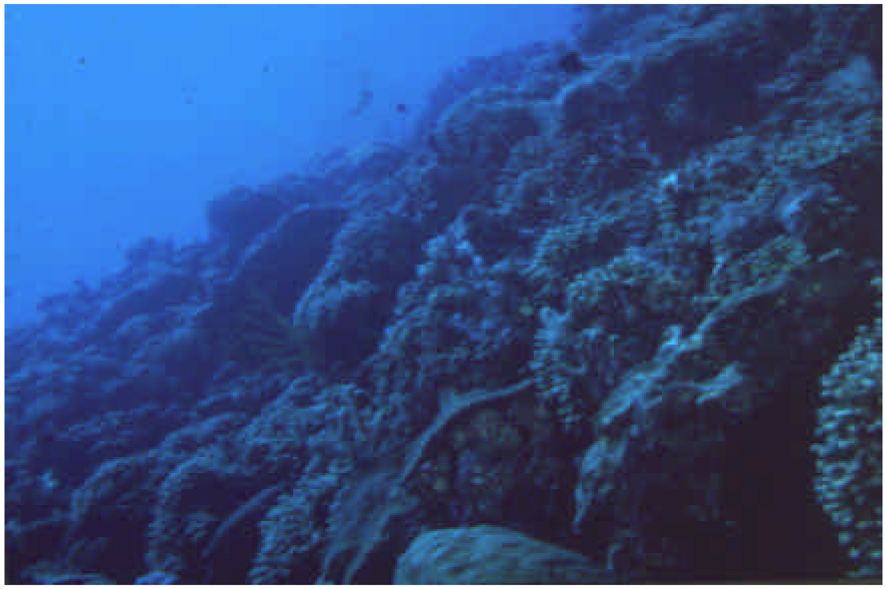

Figure 2. Deep and steeply-sloped reefs have limited solar radiation and reflection and may not be detectable to airborne or spaceborne optical sensors, requiring alternative technologies for adequate detection and characterization.

The following systems were discussed as having potential application for detecting, mapping, and assessing the condition of corals. However, no single system is capable of accomplishing all three of these objectives under all depths and conditions within which corals exist. Systems were evaluated for their capabilities,. including advantages and disadvantages, relative to their ability to detect and discriminate corals under a variety of conditions.

1. <u>Satellite Imaging Systems</u>

Several sensors are currently in use that have various spatial and spectral resolutions. The two most promising existing sensors for coral reef mapping are the System Pour l'Observatio de la Terre (SPOT) High-Resolution Visible (HRV) sensor (in panchromatic mode) and the Landsat Thematic Mapper (TM). These have spatial resolutions of 10 and 30 m^2 respectively. Both systems involve directing reflected light from the earth's surface onto an array of detectors that are sensitive to specific wavelengths. The HRV sensor is a broad band sensor that responds to all visible light. The TM sensor is sensitive to the blue through the middle-infrared portions of the spectrum. Of the two, the SPOT sensor is more desirable due to its greater spatial resolution.

Advantages

Both systems are currently in use for this type of mapping. They produce data in a raster format that is easily imported into a Geographic Information System (GIS). The data is georeferenced. This type of imagery can detect up to 75% of existing coral resources present. Because of the large areal coverage provided by satellite imagery and the established infrastructure for product dissemination the cost per unit area is relatively low.

Disadvantages

The spatial resolution of high-altitude/space platforms is currently insufficient to detect important features <10m in size. There is difficulty associated with mapping/measuring coral on steep reef slopes. Coral detection is limited to shallow (<20m) water depth. Image acquisition is limited by orbital configurations and atmospheric conditions.

2. <u>Aerial Photography</u>

Modern aerial photography is acquired with precision optics and camera systems that produce very high spatial resolution images. Aerial photographs are usually taken at fixed intervals that ensure sufficient overlap and sidelap for later stereoscopic viewing. Due to distortions inherent in aerial photography, objects are usually not represented in their actual position or configuration. Photogrammetry is often used to remove these distortions and produce georeferenced map information. The results are three-dimensional models of the earth surface, or vector line data for features of interest that are registered to a real-world coordinate system. The spectral sensitivity of aerial films ranges from slightly into the ultraviolet through the visible and into the near infrared (350-900nm); however, the spectral resolution of aerial film usually does not exceed the constraints of the film dye layers (~100nm) unless selectively filtered.

Advantages

Low-altitude photography provides sufficiently high spatial resolution to detect less than one meter-square features. Aerial photography is currently in use for this type of mapping. Very large-scale imagery is able to identify actual coral. It also has the potential for imaging up to 75% of existing coral resources. Aerial photography can be easily analyzed/interpreted.

Disadvantages

As with satellite imagery, it is difficult to map or measure coral on steep reef slopes. It is illegal to acquire in some countries. It can become very expensive over large areas. Color films have limited spectral resolution. It requires georeferencing and photogrammetric manipulation to import into GIS. It is effective only in shallow (<20m) water depths.

3. <u>Airborne Hyper-Spectral Imaging</u>

Several multi- or hyper-spectral sensors have been deployed from aircraft. These use similar imaging techniques to those used on satellites, but record reflected light in very discrete slices (many specific bands). The slight differences in spectral response through one or more of these bands has great potential for identifying species composition and stress response of individual species. These systems have increased spatial resolution that lower altitude sensing provides; however, they are also vulnerable to some of the motion effects of any airborne platform. Two of the currently operational systems are the A the Compact Airborne Spectrographic Imager (CASI). This system has a spectral sensitivity from 400-880nm (blue to near infrared).

Advantages

Multi- and hyper-spectral systems are sensitive to subtle variations in spectral response that could be used to identify and characterize coral. It may provide some information on water chemistry.

Disadvantages

Hyper-spectral imagers produce very large quantities of data that require analysis. The algorithms for analysis are not well developed. There is generally less of a spectral response from coral than other submerged features such as vegetation due to water absorption/attenuation and optical properties of coral polyps; therefore there is less usable data returning to the sensor. Effective use requires good understanding of water chemistry at time of acquisition. Ancillary data, particularly water depth, is critical to success for coral mapping. Appropriate band selection dependent on particular study area and conditions is also critical for processing. The imagery is ineffective below 20m in depth even under optimal conditions.

4. Airborne Laser Fluorosensing

A number of airborne laser fluorosensors have been flown in recent years, primarily to measure chlorophyll concentrations in surface waters. These systems typically stimulate in the bluegreen (usually around 480nm) and can detect multiple spectral responses. The spatial resolution is dependent on altitude but is typically in the centimeter to meter range.

Advantages

Low-altitude laser fluorosensing provides sufficiently high spatial resolution to detect variations in fluoresence response over relative small patches of exposed or shallow corals. The variability in the response can potentially be attributed to coral speciation and condition.

Disadvantages

It is difficult to interpret the information. It is effective only in exposed or very shallow water (<10m) reef areas. It produces very large quantities of data that require analysis. The algorithms for analysis are not well developed. Ancillary data, particularly water depth, is critical to success for coral mapping.

5. Airborne LIDAR

LIDAR (LIght Detection And Ranging) sensing involves emitting laser pulses from an airborne sensor to the water surface and receiving reflected laser energy from the water surface as well as energy reflected from features beneath the surface. The arrival time difference between these two returns provides a depth measurement. In the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system, operated by the U.S. Army Corps. Of Engineers, the pulsing laser is scanned across the aircraft track. Differential GPS is used to determine the sensor position and attitude during the pulsing/scanning process. The laser in this system is a 200Hz, Nd:YAG operating in the infrared and green frequencies. In addition to the airborne components, SHOALS also consists of a data processing system located on land in the staging area. This hardware/software system imports the stored airborne data, performs Quality Assurance/Quality Control (QA/QC) functions, calculates depth and position information and produces final results. The data processing system is located in a mobile lab approximately the size of a semi-trailer.

Advantages

This is an efficient method for determining shallow (≤ 50m) bathymetry. It is useful for surveying shallow water where ship-borne sensors cannot travel. It provides complete coverage of the study area. Acquisition and processing of data is relative fast. It can work to 40m depth. It has potentially high spatial resolution. It also has the potential for some fluorescence analysis.

Disadvantages
It has been limited to relatively small areas (1-20 sq. mi.) due to staging and acquisition costs. The spatial resolution is affected by depth and optical spreading of the laser beam. The system does not identify coral. More calibration will likely be required before it will be useful for coral identification. Below 15m this technology cannot differentiate features as small as three square meters. As with any system using light energy, it is vulnerable to turbid water conditions. Due to the types of platforms used and the necessity for the processing facility, significant mobilization issues must be considered.

6. Side-Scan Sonar
Side-scan sonar is an acoustic imaging technique that scans a swath of bottom at an oblique angle. These systems are typically towed from a boat with data being logged digitally. Of the several systems currently operational, the high-frequency instruments are most appropriate to coral mapping. These have high spatial resolutions (objects as small as 1-4 m^2 in size can be imaged). They can also be towed from smaller vessels and operate in both deep water and water as shallow as 3 m. Side-scan sonar has most often been used for mapping sea floor geology. Mosaics developed from several parallel swaths provide large areal coverage of a study area. These mosaics have a similar appearance to airborne remotely sensed images. Some ground reference data is needed for system calibration in the initial steps of a survey. Ground reference data is needed for system calibration in the initial steps of a survey. Due to the geometry of side-scan sonar imagery, airborne radar analysis techniques show promise for some further data extraction.

Advantages
This technique measures bottom features on a large (100's of sq. m to 10s of sq. km) scale (i.e. large areal coverage). It is not weather, or time-of-day dependent. It can sometimes image features as small as trawl marks that are indicative of human activity. It can be deployed from boats as small as 10m in length. On a small platform it is relatively inexpensive. It is not limited by depth. It is a proven and available technology.

Disadvantages
It provides only general information on bottom features. Only relatively large features are detected. Sea conditions affect completeness of coverage due to vessel motion. The ability to consistently image features is affected not only by range, but orientation to ship track. It takes a relatively long time to image an area due to slow vessel speed. Thermoclines and sea noise affect the signal. The oblique image geometry requires special analysis techniques to produce georeferenced information.

7. Multi-Beam Sonar
This technology consists of an acoustic out-beam that is directed at the sea floor, and a series of return beams that are cross-polarized to the first. Three parameters of data are recorded: the time of arrival; direction of arrival; and intensity of backscatter. The image swath is 7.5X depth. This technique is similar to side-scan sonar but has higher resolution and provides bathymetric

information in addition to backscatter. Both of these data types can be merged to produce georeferenced, detailed feature maps of the bottom.

Advantages
It can be deployed from small boats. A training course for operation is available. Feature space analysis is possible on the signal. The data are in a format that can be integrated into GIS. It is appropriate to micro- or meso-scale mapping. This technique is currently being applied in Asia. Bathymetric information is provided as well as backscatter information. These systems can have relatively high spatial resolution.

Disadvantages
Swath widths are dependent on depth. Sea conditions affect completeness of coverage due to vessel motion. These systems are somewhat expensive ($\$4K/km^2$). The minimum depth for operation is 10m. the resolution cell at 45m depth is relatively large (up to 10 m^2). Data gathering is slow. Prototype systems have relatively high maintenance and power requirements.

8. <u>Acoustic Signal Processing</u>
These systems work with other acoustic sounding and imaging devices to increase the usable information content of the signal. Systems such as the Marine Micro Systems, LTD RoxAnn, and the Army Corps of Engineers SAVEWS systems can detect very subtle differences in substrate which can, with proper ground truthing, be used to identify specific types of benthic habitat, potentially including live versus dead coral.

Advantages
Relative low cost and ease of use. Processes signal from existing depth sounders or bathymetry systems. Very sophisticated signal discrimination/identification capability. Proven commercial systems in wide use. Can cover large areas at relatively low cost.

Disadvantages
Not an imaging system. Requires additional depth sounding device if not present. Data interpretation can be difficult. Requires extensive calibration and ground truth.

9. <u>High-Resolution Acoustic Imaging</u>
Several high-resolution systems are currently operational. These include small hand-held devices such as the Underwater Ultrasonic Imager (UUI), as well as larger towed systems such as the Synthetic Aperture Sonar (SAS). The UUI uses an acoustic lens system with a high-frequency transducer array. This produces a bandwidth of 1/4 . Several diver-held sonar systems also employ this technology with multiple acoustic beams that can be set for various ranges. These systems can record depth, altitude above bottom, bearing, and X,Y location. The SAS system is deployed in a self-powered submersible vehicle and is used to detect and identify targets in water ranging in depth from 0.3 - 24.0m.

Advantages

These systems are not time-of-day dependent. Images can be obtained in relatively poor water conditions. There is the potential to image very small features (<1m resolution). Roughness features such as different bottom types and submerged vegetation can be imaged. polygon-type data can be produced. Hand-held units can provide extremely high ($\leq$ 1cm) resolution.

Disadvantages
There is some effect on image quality due to sediment in water column. It is difficult to obtain images in shallow water areas due to multipath reflection.. Initial calibration is required. The hand-held units require diver operation

10. Submerged Multi-Spectral Optical Sensing
This type of sensing is typically done using divers or towed vehicles. A number of sensors fall into this category including reflectance spectroradiometers, and bottom cameras and fluorometers. These sensors require a light source that is calibrated to produce specific wavelengths to be most effective. The spectral sensitivity of these systems range from broad bands (i.e. 350-900nm) to over 15 discrete channels.

Advantages
These systems have the ability to detect living vs. dead coral (i.e. XYBION camera). Several of the sensors are currently commercially available. They can use ambient light or artificial light sources.

Disadvantages
The results are very interpretation sensitive. They require clear water for characterizing coral. They must be operated by Remotely Operated Vehicles (ROV) or divers; therefore, areal coverage is limited and the logistical support requirements are high.

11. Underwater Fluorescence Spectroscopy
Many systems are in use to measure ambient and stimulated fluorescence. These are typically diver operated and very site specific systems. However, these systems can provide good quantitative information relative to organism condition. They can also be used to calibrate other more remote sensor systems.

Advantages
Well understood technology. Many operational and experimental units. Relatively inexpensive and easy to use.

Disadvantages
Requires a power source. Very limited coverage. Limited information provided.

12. Multi-Spectral Laser Line Scanner

This approach incorporates a synchronized scanning and detection system, focused on the bottom or other target at a fixed distance from the sensor platform. The imaging system consists of a narrow laser beam that is swept across the scene, perpendicular to the motion of the sensor platform, using a rotating mirror. A narrow field-of-view detector is offset from the illumination beam and is synchronized to intersect the laser beam at a fixed distance from the sensor platform. Due to the laser/sensor offset the confounding effects of path radiance (photons scattered by the intervening water column) are eliminated from detection, greatly increasing the imaging distance. While traditional underwater camera or video systems can detect objects out to 2 light attenuation lengths, laser line scan systems are capable of producing high-contrast, high spatial resolution images of targets greater than 5 attenuation lengths from the sensor platform. Laser line scan systems are now commercially available from several venders, generally producing images of backscatter or reflectance at 532 nm. One experimental laser line scan system, developed by Raytheon, is equipped with a 488 nm laser and four detectors. By placing band-pass filters centered at 488 nm, 520 nm, 570 nm, and 685 nm in front of the detectors, it is possible to image benthic fluorescence as well as primary reflectance. Presently, this experimental system is deployed from a small submersible and is thus limited to operations in areas deeper than about 15 m in order to avoid platform motion due to surface waves. In addition, the system operates best at night when the ambient light levels are at a minimum.

Advantages

Due to its relative closeness to the target the system has a very high spatial resolution. It can image coral features as small as 3/16^{ths} of inch in size. Data on coral condition and speciation may be obtained. It can image through more than 5 attenuation lengths of water. A swath width of up to 30m can be obtained.

Disadvantages

Only one experimental multispectral system is currently available. The system requires concurrent bathymetric and water chemistry measurements. Currently the system is deployed as a submersible vehicle with high associated logistical costs. Because of its size the platform is cumbersome and difficult to use. The resulting data are not georeferenced. The minimum depth of deployment is 10m. The system must be operated at night.

Table 1. General Comparison Of Available Technologies For Coral Mapping/Monitoring

Technology	Platform	Advantages	Disadvantages	Cost
Satellite Imaging	Satellite	Large areal coverage,	Low spatial resolution, Atmospheric interference, Affected by water conditions	$2.4K/scene
Aerial Photography	Aircraft	High spatial resolution, Easily collected	Analog data format, Affected by water conditions	$2-12K/day
Hyper-Spectral Imaging	Aircraft	High spectral spatial resolution	Large amounts of data, Spectral information degraded by water filtration	$2-12K/day
Airborne Laser Fluorescence imaging	Aircraft	Rapid data collection. Potential for detecting living coral and condition	Large data stream. Requires extensive ground truth. Limited to shallow water (to 20m). High power requirements.	$5-15K/day
Airborne LIDAR	Aircraft	Bathymetry over large areas, Works in shallow water, Rapid data collection, Good spatial resolution	Limited ability to distinguish coral, Slightly affected by water conditions	$1-6K/ sq.mi. averaging $17-20K/day
Side-Scan SONAR	Towed Vehicle	Deep water capability, High spatial resolution	Slow data collection, Limited shallow water capability	$30-150K/Unit $4-8K/day
Multi-Beam SONAR	Towed Vehicle	Bathymetry, High spatial resolution	Vessel motion may produce gaps, Slow data collection.	$6K/hr
Acoustic Signal Processing	Boat/Ship	Proven Technology. Very high signal resolving capability. Relatively low cost. Works with existing depth sounders.	Not and imaging system. Requires extensive ground truthing.	$22K Purchase $100-1000/day
High-Resolution Acoustic Imaging	Diver/ROV	Very high spatial resolution	Experimental, Limited areal coverage	$250K
Submerged Optical Sensing	Diver/ROV	Detailed analysis, Identifies living coral.	Limited areal coverage, Extensive calibration needed	$1.5-2.5K/day
Underwater Fluorescence Spectroscopy	Diver/ROV	Detailed analysis, aids in identification of species and condition	Very site specific - limited coverage - requires calibration and detailed interpretation	$300-2000/day
Laser Fluorescence Spectral Scanning	ROV/Sub	High spatial resolution, Coral speciation - potentially condition	Experimental, Limited areal coverage, Only one unit.	$14K/day

Cost data shown in this table are general and for rough comparison purposes only. Actual costs for each system will vary depending on study area extents, time, location, etc. These data generally refer to operational expense to gather raw data. Costs for system configuration/purchase, post-processing, or analysis is not reflected in these figures.

DINNER KEYNOTE ADDRESS

Assessing The Coral Reefs Of The World: A Multifaceted Strategy

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There is a widespread consensus that many coral reefs around the world are in states of degradation. However, the degree and rate of degradation and their impacts on reef resources are difficult to estimate. Ecosystems for which reef-building corals are a significant feature range form shallow or surface-breaking geomorphological reefs and non-structural coral communities, to a variety of structures or assemblages scattered across the shelves of the tropics and subtropics. Of these, only the near-surface reefs have been reasonably well charted, particularly those which pose hazards to navigation. For purposes of fisheries analysis and the conservation of biodiversity, it is important that all types of reef-building coral assemblages be accounted for. Shelf assemblages, while generally thought to be in pristine condition, may be subjected to substantial damage associated with widespread trawling. Priority tasks for the immediate future would include determining the extent and distribution of coral reefs and determining their degrees of degradation and the causes thereof. Both tasks should involve a wide variety of sampling methods, including satellite, aerial and ship-borne sensors, as well as underwater surveys by scientists, managers and volunteers. The processes of assessment and improving assessment strategies can both be greatly facilitated by central consolidation and wide dissemination of the information generated. ReefBase: a Global Database of Coral Reefs and their Resources was designed to fill this role. ReefBase is the official database of the Global Coral Reef Monitoring Network of the International Oceanographic Commission, IUCN and UNEP. Both ReefBase and the GCRMN directly address priority actions identified in the Framework for Action of the International Coral Reef Initiative (ICRI), which has been endorsed by representatives of more than 70 governments. ReefBase, now in its third year of operation, is being modified to accommodate large volumes of field data, as well as to serve as a means for disseminating digital imagery and similar data to facilitate the management of the world's coral reefs.

LUNCHEON KEYNOTE ADDRESS

Coral Reefs: The Problem Child of Environmental Monitoring and Remote Sensing

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Abstract

At a time when coral reefs are under increasing pressure, no agreement on standard monitoring methodologies has been reached outside labour intensive ground surveys requiring sophisticated sampling techniques and statistical analysis. Aerial photographs and satellite imagery have provided baseline data at a reefal scale but most remote sensing methodologies have been unable to provide the resolution required to monitor changing biotic covers and reef health.

Some basic problems, such as variable water depth and quality over coral reefs, have long been recognised and at least partially resolved. Even the geometry of reefs makes them difficult to map, with the major biotic component of interest, corals, concentrated on the planimetrically narrow reef slope. This of course presumes that corals are the main target species of interest and it could well be that other species, such as sea grasses or macro algae, may be just as important as indicators of health and change.

The basic problem is that we are trying to map a very complex ecosystem and in the past have not always differentiated between ecological zones and biotic cover. Changes to the total reef system and even ecological zones are slow and observable only after major environmental change has taken place and therefore of little value to management. At the level of biotic cover the problem is the complexity and scale of the system. Individual corals are rarely more than a few millimeters across, making up colonies no more that a metre or two in diameter. Any section of the reef is made up of numerous size clusters as well as numerous species. There is a complexity of shape from smooth and rounded to the most intricate branching morphology which obviously affects the spectral properties of the surface. These spectral properties are also affected by variable water depth, by mucous coatings when exposed at low tide, and by the fact that the pigmentation of corals is related most closely to the symbiotic *zooxanthellae*, minute organisms which can migrate within colonies or even evacuate them according environmental conditions. Add to this the high natural variability of coral reef structures (which for sea grasses and macro algae can include major seasonal shifts) then the end result is a major conundrum for remote sensing methodology.

Our solution has been to take a simplistic approach which recognises the multispectral capacity of satellite data but which have ground resolutions no better than ten meters. However, such data have difficulty mapping ecological zones and cannot approach the mapping of biotic covers. Taking advantage of the low tide exposure of reefs on the Great Barrier Reef, we have undertaken vertical photography at altitudes between 500' and 7000' using both true colour and

near infra-red film. The images have been scanned and digitsed with pixel sizes down to 7cm ground resolution. Manipulation of the resulting spectral data and application of band ratio and supervised classification techniques, has produced an ability to map biotic covers such as coral, seagrasses and macro algae, with accuracies of greater than 95%, from altitudes of 3000' and differentiation of head, branching and soft corals with similar accuracies from altitudes of below 1000'. The methodology has provided data for reef management in Thailand, confirming it as a simple, cost effective technology capable of being used in developing countries.

However, we see this as an interim technology which is building up a bank of information on the spectral properties of reefs and the resolution required to provide data useful for management. Within the foreseeable future satellite data are unlikely to provide a resolution of less than 5m, although some of the new airborne multispectral scanners are the most likely source of data with the spectral properties and resolution needed.

Introduction

Attempts have been made to apply remote sensing techniques to coral reef research throughout the 20th century. This is not surprising given the environmental complexity and intricate patterns of coral reefs, combined with the paucity of relevant information on hydrographic charts and logistic difficulties of systematic ground survey (Hopley, 1978). In Australia vertical aerial photographs of the Great Barrier Reef were taken as early as 1925, and a 1928 vertical photograph by the Royal Australian Air Force of Low Isles was used as a baseline survey by the first Royal Society expedition to the Great Barrier Reef, led by Sir Maurice Yonge in 1928.

Subsequently, aerial photographs were used extensively in conjunction with the field surveys carried out on reefs by many disciplines with quite extravagant claims being made about their usefulness (e.g. Steers, 1945). In fact, the use of photography was mainly to locate field sites, illustrate scientific results, or at best, delineate morphology or biological zonation.

Similarly, when the first colour photographs from a hand held camera became available from the 1965 Gemini flights and the launch of earth observing satellites shortly afterwards, many claims were made about the potential value of the imagery to reef studies (e.g. Smith *et al*, 1975; Jupp *et al*, 1985a). There is little doubt, at the regional or reefal scale, Landsat imagery, in particular, has been extremely useful. For example, the first comprehensive coverage of the Great Barrier Reef at a scale of 1:250000 was completed during the 1970s using a combination of Landsat and aerial photographic imagery, with further accuracy added to the series in the early 1980's (Jupp *et al*, 1985a).

Nonetheless, it became clear very early that the coarse pixel size of Landsat imagery was a major hindrance, limiting interpretation to ecological reef zonation at its coarser scale (see Kuchler, 1984). As satellite platforms with better resolutions have come into operation, attempts have been made, particularly by the French using SPOT data to map at the community level. For example, using the coral index method (a supervised classification technique) of Bour *et al*, (1996), Bour and Pichon (in press) have mapped coral dominated reef flat communities on Yonge Reef, Great Barrier Reef, using a SPOT image in which the pixel size was 20m x 20m. Although the resulting map is impressive, it is doubtful whether or not a repetition of the exercise could pick up changes of anything but the grossest kind (e.g. major cyclone devastation).

In many ways there has developed an enigma in which remote sensing is seen as being, or having, major potential for reef science and management and yet results have not been forthcoming. This has been highlighted at a number of reef oriented remote sensing conferences. As early as 1982 the Great Barrier Reef Marine Park Authority hosted an international symposium at James Cook University. In spite of many subsequent workshops, more problems than answers have resulted. Only five years ago at this same location, Miami, a workshop on coral bleaching, coral reef ecosystems and global change, identified reefs as 'ideal candidates for remote sensing.' Resolution was seen at that time as being the major constraint of existing systems with aircraft borne sensors being identified as the most likely to produce data at the scale required. This paper will review the reason why reefs are such difficult targets for remote sensing and monitoring and will describe how a small team at James Cook University working closely with the Great Barrier Reef Marine Park Authority has come up with a simple, yet effective method of overcoming at least some of the problems.

Why Are Reefs So Difficult?

No terrestrial ecosystem has the complexity of a coral reef. Heterogeneity is both spatial and temporal, factors which demand high resolution for any meaningful observations. The complexities commence with the gross environment and extend to the target biotic and non-biotic surfaces of the reef.

<u>Environmental Complexities</u>

Water cover and water quality:

Coral reefs have a water cover of variable depth. Whilst the optical properties of water are clearly well known and limit the penetration of at least the optical part of the spectrum to, at best, tens of metres, variable organic and inorganic particulate matter within the water column is a new dimension which was recognized in the early studies of satellite imagery (see for example, Jupp *et al*, 1985). However, at least some of the difficulties have been overcome (e.g. Kendall and Jupp, 1981) and applied with varying degrees of success to determining the bathymetry of reef surfaces, (e.g. Pirazzoli, 1984; ORSTOM, 1992). Further understanding of the properties of the water column have also allowed interpretation of submerged reef surfaces in some instances (e.g. King *et al*, 1996). Complexity is also added by the fact that in areas of large tidal range at low tide part of the reef may be exposed, parts still covered by water. In extreme tidal area such as on the Great Barrier Reef with tidal ranges greater than 3m on extreme Spring low tides the whole reef flat and part of the upper reef slope may be exposed. This may simplify interpretation of at least the exposed areas.

Reef Geometry:

Few parts of a coral reef are flat surfaces, even the so-called reef flat. Whilst this alone may not cause major problems, if coral cover is the major target of coral reef remote sensing then it is unfortunate that the gross concentration is on the marginal reef slope on the majority of the world's reefs. Where the reef margins are relatively steep the planimetric expression is extremely limited. Indeed, there are many instances of vertical or even over-hanging reef margins. There are obvious restrictions for vertically positioned remote sensing platform, such as satellites or aircraft.

Complexity of reef shape and zonation:

Complexities of the reef's shapes have always meant that even the most detailed scaled maps are approximations only of the reef morphology. Complex patch reefs may have a surface expression which extends over only a meter or two. Superimposed over reef surfaces, however, are clearly identifiable ecological and morphological zones, particularly where energy levels on the reef margin are high (e.g. Hopley, 1982, chapter 10). These zones are determined largely by energy conditions and exposure and for this reason are generally parallel to the front edge of the reef. The result is zones which are linear, sometimes less than 10m in width and thus at the margins of determination from satellite imagery with even the best resolution. This was very well demonstrated by Kuchler, (1984).

Complexities of the Target Surfaces

Species diversity:

Even within single ecological zones it is rare for a single species to completely dominate the surface. This is particularly true of areas covered by living corals, with Indo-Pacific reefs having greater complexity than those of the Atlantic. Greater homogeneity in other areas covered by turf algae, crustose coralline algae, or macro algae or seagrass beds may similarly be made up of single species.

Discontinuities of cover:

Coral reefs are made up of a discontinuous biotic cover over a non-biotic substrate consisting of sediments and older reef rock. Whilst in some parts of the reef the biotic cover maybe 100%, over most of the reef's surface the cover is discontinuous and in a variety of patterns. For example, a discontinuous coral cover may consist of coral colonies of various shapes separated by areas of sand. Given a fine enough resolution, the majority of pixels will land on either the coral surface or the sand with relatively few 'mixels'. In contrast seagrass may be distributed over a reef flat in a very different way, varying from dense to relatively light cover. Even within the dense beds part of the sand substrate may still show through the cover. At any resolution finer than the size of individual blades of seagrass, pixels will display a combination of both blades and sand substrate. Even in ground surveys the methodology used for monitoring these surfaces is very different (see for example, English *et al*, 1994**).**

Natural variability through time:

Not only is there great species diversity on reefs, through time the actual species makeup may change even on the most pristine of reefs. We know that reefs are attuned to natural disturbances which occur frequently through such impacts as tropical cyclones, outbreaks of crown-of-thorn starfish, a number of diseases, and variations in salinity and temperature (Done, 1992a, 1992b). With recovery for complex reefs taking ten to fifty years (Colgan, 1987; Wells, 1988), most reefs are likely to be in some stage of recovery rather than be in a stable state equivalent to the climax vegetation of a terrestrial ecosystem. Scleractinian corals, although hard, are also continuously growing at rates of 1cm or more radial extension for massive corals and rates of up to 20cm extension for branching corals per year. This is sufficiently rapid to be able to be detected on an annual basis in reef survey methodologies. Possibly even more important is the fact that some of the algal covers have very distinctive seasonal variability, a characteristic which also extends to seagrasses. From our own work described below, we believe that temporal variability can be so great that it is dangerous for ground truthing not to be undertaken at the same time that remotely sensed data is collected.

Complex geometry of coral colonies:

Coral colonies have a great variety of shapes, ranging through a full spectrum of massive with flattish surfaces to intricately branching. Even the same species may have several colonial forms. We have noted that the spectral characteristics of reef surfaces varies very greatly with colonial morphology, with greater proportions of shadowing associated with the more intricate forms. Indeed, it is basically this characteristic which has allowed us to differentiate coral life forms (see below).

Variations in pigmentation:

The pigmentation or colour characteristics of the majority of corals, including soft corals, results not so much from the coral itself, but largely from the *zooxanthellae* which inhabit the endodermal tissues of the coral. These are minute unicellular plants containing chlorophyll with all the spectral characteristics of terrestrial vegetation. They are also found in other reef organisms including giant clams and foraminifera. Density of 'colour' in the corals is very closely associated with the density of *zooxnthellae* within the tissues. This may vary with time, e.g. associated with tentacular retraction, although the *zooxanthellae* which have a very strong influence on the calcification process of the corals, require light for photosynthesis and therefore during the day time are concentrated on the higher more irradiated portions of the coral colonies. Particularly high concentrations are associated with corals which have tentacles extended during the day, e.g. Fungiids and *Goniopora* sp. Under stress, coral have tended to expel *zooxanthellae* therefore affecting their spectral characteristics (see below). Further complications to the reflectance characteristics of coral colonies is the fact that during exposure they may exude mucus coatings which have the ability to change a rough surface into one which is apparently smooth with very high reflectance values, to the extent that sun-glinting may occur from the surface.

<u>The Resolution Required of Monitoring and Remote Sensing Techniques</u>

The purpose of this workshop is to examine techniques which can be used to measure change on coral reefs and the health of coral reefs. The most realistic fundamental level for this is the individual organism, e.g. the individual coral polyop or the individual seagrass plant. However, the natural variability at such a level may be such as to produce so much noise that indicators of change possibly attributed to anthropogenic causes would not be assessable. At the other end of the scale are the ecological zones recognised for so long on reefs. However, these are so coarse that the rate of change from either anthropogenic or natural causes is too slow and becomes detectable only weeks after the causative event. Even this larger scale is at the resolution limits of currently available satellite imaging.

The acceptable level of resolution for detecting change and health of coral reefs would appear to be that of the life form or individual coral colony, sizes of which may range from centimeters to several metres. Remote sensing has not been able to provide this degree of resolution in the past and at the present time almost exclusively it is ground surveys which provide the necessary monitoring methodologies. Line transect and permanent quadrat techniques (see English *et al* , 1994) are generally regarded as the most reliable for monitoring coral reefs. Transects are typically 20m long, quadrats $1m^2$ Obviously, such labour intensive techniques can only be applied to a very small portion of a total reef and therefore sophisticated sampling and statistical analysis are required in order to detect change within acceptable probability limits. An example from such a monitoring program comes from Magnetic Island near Townsville, where a resort and marina development proposed in 1985 resulted in the setting up of a monitoring program which required fourteen survey stations in five bays, each station having two sites on the reef flat and two sites on reef slopes. Each of these sites required four 20m transects, giving a total number of 224 transects. In addition 900 individual corals were marked and photographed at eight stations. Although the tourist development eventually fell through, even the most sophisticated analysis of the results did not lead to a general agreement on trends in reef health at the surveyed sites. Only remote sensing can possibly produce the comprehensiveness of survey from which results may be unambiguous. However, the methodologies require a resolution far less than 1m.

An Interim Solution- Digitised Aerial Photography

The Requirements Of A Remotely Sensed Coral Monitoring Program

The above discussion suggests that the most important problems to overcome in a monitoring program are related to the resolution. At best, imagery is required at a scale of a few centimeters and at the margins of usefulness a resolution approaching that of the size of coral colonies on the targeted reef is mandatory. This can rarely be more than 1m and our experience suggests that 20cm is possibly at this outer limit.

The importance of the *zooxanthellae* in determining the properties of corals, both hard and soft, also needs to be taken into account, especially as some other reef covers, such as seagrasses and macro algae are chlorophyll-containing plants. The near infra-red part of the spectrum is considered to be highly important in determining discrimination patterns.

Our solution has been the application of digitised aerial photography to the reef monitoring problem. High resolution is achieved both through the low altitude of the photography and the high resolution of the digitising process. The spectral range is stretched by using both true colour and false colour near infra-red films. The other complication of water cover was overcome by taking advantage of the large tidal range on the Great Barrier Reef. At low Spring tides, entire reef flats and parts of the upper reef slope are exposed. Thus photography was timed to coincide with such tides occurring during the middle of the day. More recent work is attempting to resolve the water cover problem. This program developed at James Cook University in close cooperation with the Great Barrier Reef Marine Park Authority has also been funded in part by the Royal Forestry Department of Thailand, responsible for the marine parks of Thailand. Their requirements also put a further restraint on the development of the technology, which needed to be simple, relatively inexpensive and applicable to reefs in developing countries where much of the need for monitoring in concentrated.

History of the Project

The project has had a development history of more than 20 years incorporating the author and several postgraduate students. In 1973 a Masters student was involved in mapping fringing reef flat sediment zones. It was suggested to her that as the reef she was examining had a cover of both seagrasses and macro algae, that the use of near infra-red film may help to discriminate zones. The resulting photography using 35mm film indicated a very clear zonational pattern and in particular high reflectance from the reef margin corals. In 1976 therefore, an Honours student, Ms Annette van Stevenick, was given a thesis topic which involved the comparison of various photographic emulsions for discriminating reef zones. It was during this project that high infra-red reflectives coming from corals was proven to be related to *zooxanthellae* (van Stevenick, 1976; and Hopley and van Steveninck, 1977). Limitations of the 35mm format led to the next stage (1979-1984) during which a Ph.D. project extended the work to the increasingly available Landsat satellite imagery, which was compared with the results from aerial photography for, again, mapping reef zonations (Kuchler, 1984). This work was also closely allied to the work of Jupp and colleagues at CSIRO, who were similarly developing Landsat imagery for reef management purposes (see for example, Jupp *et al*, 1985a).

Results clearly indicated that available satellite imagery had insufficient resolution for application to larger scale management problems. The present program was commenced in 1986 to examine whether colour and false colour aerial photography could determine impact patterns produced by crown-of-thorns starfish on the Great Barrier Reef reefs. The program conducted by the author and Ms Pauline Catt, Director of the Remote Sensing Centre at James Cook University, indicated that the near infra-red photographs clearly indicated coral colonies which were largely dead as a result of the infestations. However, patterns were not always clear and from this work the scanning, digitising and application of microBRIAN (Jupp *et al*, 1985b) programs to the results was developed (Catt and Hopley, 1988, 1991). The work was later extended to monitoring reefs for global sea level rise (Hopley and Catt, 1988). By this stage vertical aerial photography using a Hasselblad aerial camera and 70mm commercial aerial film was an integral part of the program.

Significant development of the project took place with the Ph.D. thesis work of a Thai student, Thon Thamrong-nawasawat, working closely with an Honours candidate, Mr. Chris Linfoot, whose major contribution has been the manipulation and development of the computer programs. The ground truthing methods and results of mapping reported are largely from Thamrong-nawasawat (1996). Ongoing work includes attempts to map submerged reef features using similar approaches (MSc candidate, Mr. Nicholas Buzza) and the application of the technique to a real world problem related to the impact of sewage outfall on a reef adjacent to a major aboriginal settlement in the Palm Islands (Ms Shonagh Withey, UK student attached to the Sir George Fisher Centre, 1996).

The Technique

Aerial photography was undertaken using a Hasselblad 80mm focal length aerial camera and 70mm commercial aerial film, from varying heights between 500’ and 7000’. The film was developed and printed at standard aerial photographic sizes and scanned and digitised as described in Thamrong-nawasawat (1996).

Spectral Data, Resolution and Rectification

The scanning camera recorded numeric data for each wave band, the photography scanned three times with blue, green and red filters respectively. The end result is that there are three data files for each of the true colour and false colour photographs, each file containing numeric data of one wave band.

During the developmental stages the PC being used restricted the process to digitising photographs at 1000 x 1000 pixels by lines, thus producing 3 megabytes of data. This produced pixels of approximately 11cm size using 500' photography and 66cm for 3000' photography. Experimentation determined that the lower limits of resolution for mapping coral cover was approximately 66cm (3000' photography) and for coral life forms, 22cm (1000' photography). However, our current project is extending the work using main frame computer facilities and it is possible that digitising at 2000 x 2000 pixels by lines, using approximately 24 megabytes of data will be manageable. Note that at least 240 megabytes of hard disc is required for each of the mapping operations. Details of area coverage and pixel size at various scanning resolutions is shown in Table 1.

TABLE 1.
AERIAL COVERAGE AND RESOLUTION

FLYING HEIGHT	AERIAL COVER m^2	PIXEL SIZE cm 1000 x 1000	PIXEL SIZE cm 2000 x 2000
500'	110 x 110	11	5.5
1000'	220 x 220	22	11
3000'	660 x 660	66	33

In development stages, the area covered by a single aerial photograph only was analysed to overcome the problems of joining. However, the present project is attempting to use up to eight overlapping photographs and methodologies of averaging and normalising the data to overcome possible small differences in processing are being developed. Some geometric rectification was also necessary and control points established on the reef flat were used in this process (see below).

Ground Truthing

Standard ecological survey techniques were used for collecting surface data for ground truthing processes. Data was collected in areas of uniform coral cover from 10m x 2m transects and in areas of more diverse coral cover from 20m x 2m transects. Records of life form cover within these transects was recorded using a 35mm camera on a frame 1.6m above the ground (over 1000 ground truthing photographs were taken in this manner). For macro algal and seagrass areas 0.5m x 0.5m quadrats were used randomly scattered over the target area. All transects and quadrat areas were marked at each corner using a 0.5m x 0.5m plastic sheet for coral cover and brightly coloured buoys for the vegetation studies. Sufficient ground data was collected so that it could be divided into training and testing sets.

Data Analysis

The majority of image processing and analysis used microBRIAN, the processing system developed from the research by the CSIRO into remote sensing techniques applicable to the Great Barrier Reef largely using satellite data (see Jupp *et al*, 1985b).

Several image processing techniques were tested but did not produce sufficient accuracy, these included image enhancement, principle component analysis and band transformation and band ratio techniques. Both unsupervised and supervised classification techniques were also attempted. Greater success was clearly associated with supervised classification. There are three supervised classifications within the microBRIAN program:

- nearest neighbour with migration of means
- parallelepiped
- Bayesian maximum likelihood

Although maximum likelihood had the potential to provide more accurate data, nearest neighbour was chosen as the technique for further development as it is simpler, consuming much less consultation time with presentation of results with acceptable accuracy. Table 2 clearly shows the advantages of the supervised classification with accuracies ranging from 74% to 100%. The mapping of the major biotic covers is highly accurate for all except soft corals. Here the problem may be that at low tide the soft coral colonies take on highly variable shapes. The greatest problem with soft corals was differentiation from massive hard corals. Both had very similar mean reflective values in the blue wave band whilst in the infra-red band higher reflectance from the smooth surfaces of the soft corals was recorded. Band ratio techniques were therefore the best for differentiating between the two. In all forms of classification the infra-red band proved to be the most valuable.

The First Management Application - In Thailand

The development of digitised aerial photography on the Great Barrier Reef, involving a Thai Ph.D. student, always had in mind the application of the technique to developing countries where high technology and highly trained personnel were scarce. Thus, towards the end of the project the Royal Thai Forestry Department, with responsibilities for the Marine National Parks of Thailand, funded a unique program directed at the Surin Marine National Park.

The Surin Islands are in the Andaman Sea, some 50km offshore from mainland Thailand. The majority of visitors are Thais, not overseas tourists, and snorkeling over the reef flat and reef edge is the main activity which is creating concern for park management. Thus the DAP technique was ideally suited to these targeted areas. However, the smaller tidal range of the Andaman Sea means that even at low tide these reefs are largely covered with water and although photography was undertaken at low tide there was still a water cover of between 0.5m and 1m over most of the

TABLE 2.
MAPPING ACCURACIES (%)

TARGET	IMAGE ENHANCEMENT	ANALYSIS BAND RATIO	SUPERVISED
Hard corals	73	96	97
Sand	98	98	99
Dead corals	72	84	94
Massive corals	62	68	91
Branching corals	81	84	99
Large branching corals	82	83	95
Soft corals	70	78	83
Sand	99	97	100
Dead corals	73	76	81
Soft corals branching	61	68	74
Soft corals platey	68	73	78
Seagrass	78	100	100
Seagrass - sparse	78	100	81
Seagrass - medium	78	100	85
Seagrass - dense	78	100	94
Macro algae	87	94	100
Macro algae - small	81	94	100
Macro algae - large	94	97	100

target reefs. This was critical for the near infra-red photography in particular, although the water was not sufficient to block out all reflectance.

Limited ground truthing allowed an assessment of the accuracy of the techniques and considering the circumstances this was surprisingly high. 3000' combined colour and infra-red photography produced 100% accuracy for mapping non-living covers and 89% for living cover. The combined images taken from 1000' resulted in 90.8% accuracy for massive corals, 86.7% for branching and 100% for sand and other non-biotic covers. For one reef (Chong Kard) a 1000' infra-red image was used alone, producing accuracies of mapping of 94% for massive orals, 84.5% for branching and foliose forms, and 100% for seagrass. We believe that this study clearly demonstrated the affordability and efficiency of digitised aerial photography for large scale, small area reef management applications.

A Great Barrier Reef Application - Great Palm Island Reef Flat

A project is currently underway for the Great Barrier Reef Marine Park Authority, which is the most ambitious yet for applied digitised aerial photography. The approximately 5.5km^2 reef flat in front of the Aboriginal settlement on Great Palm Island just north of Townsville, requires monitoring to assess the effects of diversion of sewage which has previously been emptied, largely untreated, on to the reef flat. The total reef is approximately 7.4km long and approximately 1.8km at its widest point. The inner part of the reef flat is blanketed by a sand cover with some mangrove development. The outer reef flat and the outer part of a natural channel which dissects the reef have good coral cover. The central part of the reef flat has large extents of seagrass beds. Closer to the reef edge the reef flat consists of dead and living reef flat corals with a heavy cover of macro algae.

Although the present exercise is largely to provide the baseline survey for determining future change, commercial colour photography is available for this reef flat from 1978, 1987 and 1991. In addition, in 1991 some low level infra-red was taken from 1000' as part of a project for Dr. Terry Done of the Australian Institute of Marine Science. These photographs are allowing some assessment of past changes and further illustrate one of the advantages of digitised aerial photography: that for many areas earlier photography may be available which allows for at least some kind of comparison with the present.

Colour and infra-red photography was obtained from 1000', 3000', and 7000'. 7000' photography is largely used for location, whilst the major mapping of biotic covers (corals, algae, and seagrass) is being extracted from the 3000' photography. Approximately 4km^2 of the reef flat is being mapped requiring 8 scenes taken at 3000' from both colour and infra-red sets. This is the largest area yet to be targeted for this methodology. In addition, the 1000' photography which samples strategic locations of the reef flat, rather than being comprehensive, is being used to provide giant quadrats 220m x 220m in size which will map life forms and hopefully, where overlap with the 1991 low level infra-red is available, provide some comparison of change over a five year period.

The scale of the project is such that some further development is being undertaken. For example, use of more than single photographs is requiring development of averaging and normalising procedures to the matching of the spectral properties from adjacent photographs. Also, new statistical techniques are being developed which take into consideration the comprehensive coverage of the targeted area of the reef flat (rather than the complicated sampling procedures normally used for ecological surveys of reefs), and which take into account the accuracy levels (generally 90-100%). In addition, comparison of the mega quadrats is also necessitating some modification of the comparative statistical procedures. Both the size of the data bank being created and the necessity for more rapid processing has resulted in at least parts of the process being undertaken on a mainframe computer, rather than a PC which had been used previously.

Comparison With Some Developing Systems

We would be the first to admit that our digitising aerial photographic system as it currently exists is cumbersome and time consuming and there seems little doubt that in the not too distant future, its advantages will be built into some of the newly emerging remote sensing technologies. Interestingly, many of these are using aircraft rather than satellites as the observing platform in order to obtain the required resolution and flexibility of timing which is not available from the majority of satellites.

Within the light detection and ranging LIDAR sensors are those capable of mapping intricate bathymetry, such as is associated with coral reefs, for example, the Australian Laser Airborne Depth System (LADS), which has been used on large areas of the Great Barrier Reef (Leech and Abbot, 1995). LIDAR systems can also incorporate the sensing of potential fluorescence of chlorophyll and some induced fluorescence from, for example, *zooxanthellae* included in the corals, thus having the potential to detect reef health. LIDAR has already been used in a field experiment in Hawaii to obtain spectral imaging data from coral reefs (Rhoads *et al*, 1996).

In Australia and elsewhere aircraft mounted multispectral scanners are also being developed for a number of purposes which could be applied to coral reefs. The spectral range of these instruments ranges from the visible into the thermal infra-red, including the near infra-red range considered so important in this paper. Whilst the majority of systems collect data for relatively broad bands of the spectrum, similar to the Landsat thematic imagery, development of hyperspectral imaging (HIS) is providing data in a wide range of extremely narrow channels. For example, the compact airborne scanner instrument (CASI) developed in Canada, has the ability to scan in 288 spectral bands between 430 and 879nm. Although many of these are useful for reef mapping (Jupp,1994) the system is limited by a 2.5m ground resolution. A further hindrance to development of such instruments is the lack of ground truthing to allow for accurate interpretation. This can only come with time.

In Australia a Daedalus 1268 airborne scanner has been used to map coastal seagrass habitats in wetland areas (Allen, 1993). This airborne thematic scanner scans data in 11 wave length bands ranging from blue to far thermal infra-red (420-1300nm). However, it is limited by a 2m ground resolution and with only two such instruments available in Australia there has been little opportunity to apply the system to coral reef mapping.

Australia is also in the process of developing its own airborne scanner called AAVIS (Australian Airborne Visible and Infra-red Scanner). This scanner will have similar potential to CASI but the potential for applying to reef remote sensing is being incorporated into its development.

Clearly, these instruments indicate the way ahead. However, I believe it will be quite some considerable time before they are generally available for use and being applied to coral reef management problems. With the majority at the present time, the resolution at 2m or greater is far too coarse and particularly with the HIS system considerable development work is required to interpret the mass of data which is produced.

It should also be remembered that the majority of the world's reefs are in developing rather than developed nations and the cost and technology required for these systems may be beyond their means without targeted aid. In most cases the cost of acquisition of the instruments is hundreds of thousands of dollars; they require a dedicated twin engine aircraft as the platform; and considerable technological skill is required in both collecting and interpreting the data.

Conclusion

Digitised aerial photography is seen as an interim technology awaiting the complete development of some of the sensing systems discussed above. However, it is providing information which will be useful with respect to the resolution required to monitor reef health and on some of the spectral properties of the target biotic surfaces. It is a system which is relatively cheap and does not require technology which means that it is available for use in developing nations. Further, commercial digitising electronic cameras with inbuilt memories to store up to 90 scenes are becoming available on the general market and the potential for these systems is currently being explored. They provide the possibility of bypassing the scanning process. They also have the potential for recording data in the near infra-red range although further discussion with the manufacturers is required on this matter.

Like all aircraft and satellite based systems, the major area of reef which is exposed to monitoring is the reef flat. Further work is required on the biotic cover of reef flats to determine whether they accompany, precede or follow changes to the major coral cover on reef fronts. It has been suggested that development of algae on reefs may be the antithesis of coral health, i.e. an increase in area or density of algae indicates a decline in reef health. However, recent work has suggested that macro algae distributions on reefs may be independent of factors which affect coral health (CRC, 1996).

Twenty-five years ago information gained from satellite platforms was seen as being the holistic antidote to monitoring requirements in a wide range of environments including coral reefs. The resolution of the data has shown to be the major drawback of this source of data and at least in the near future this is unlikely to change. For example, a recent survey of French remote sensors indicated that for SPOT imagery a 5m resolution was maximum required for most uses, though obviously not for coral reefs. Inflexibility of the timing overpasses is also a major problem of satellite sourced data. Thus in the foreseeable future it is aircraft platforms and their sensors which appear to provide the suitable systems for coral reef remote sensing.

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TECHNICAL PRESENTATIONS AND DISCUSSION SUMMARIES

The U. S. Army Corps of Engineers SHOALS Airborne LIDAR

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The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system was developed through a joint Memorandum of Understanding under the U.S./Canadian Defense Development Sharing Program. The SHOALS system provides the capability to acquire high spatial density bathymetric data utilizing state-of-the-art lidar technology consisting of a scanning laser transmitter and receiver that produces 200 soundings per second, operates from an airborne platform, and includes a mobile ground-based data processing system. This design permits SHOALS to be a highly mobile system capable of rapidly covering large areas producing greater bathymetric resolution for modeling applications.

SHOALS began its transition from a prototype toward a fully operational hydrographic survey system in April of 1994, when the system was employed by NOAA to test its ability to resolve the complex shallow water bathymetry for critical areas in Florida Bay. These areas were identified by NOAA as high priority areas for water circulation modeling. The information gained provided the opportunity to further evaluate minimum depth detection capabilities.

LIDAR TECHNOLOGY

The SHOALS system utilizes state-of-the-art lidar technology. The term lidar is an acronym for **LI**ght **D**etection **A**nd **R**anging. The system operates by emitting laser pulses that travel from an airborne platform to the water surface where some of the laser energy for each pulse is reflected back to the airborne receiver. The remaining energy penetrates the water surface, propagates through the water column, reflects off the sea bottom, and returns to the airborne sensor. The time difference between the surface return and the bottom return corresponds to water depth. As the light travels through the water column and reflects off the sea bottom it undergoes scattering, absorption, and refraction, which attenuates the return energy and limits the maximum depth of lidar penetration or depth of bottom detection. The maximum depth the system is able to detect is related to an interaction of bottom radiance, incident sun angle and intensity, and water turbidity. Maximum depth detection is limited predominately by water turbidity and is relatively insensitive to shifting bottom types. As a rule of thumb, the SHOALS system is capable of sensing bottom depths equal to two or three times the Secchi depth. Thus, if a Secchi depth was measured to be 5 m then the maximum depth of SHOALS system bottom detection would be approximately 10-15 m.

Minimum depth detection is also a limitation when performing lidar surveys. As depths become shallow, a condition is reached where the surface and bottom return signals overlap so that water depth cannot be determined. However the use of a sophisticated depth extraction algorithm was designed to permit a minimum depth determination of 1.7 m. Surveys conducted in Florida Bay allowed for further testing of minimum depth capabilities and subsequently demonstrated the ability to measure depths of about a meter.

THE SHOALS SYSTEM

SHOALS is composed of two separate systems: the airborne system and ground-based data processing system. The airborne system operates from a NOAA Bell 212 helicopter and performs the task of data acquisition. The ground-based data processing system provides the data post-processing to calculate position and depth for each laser pulse. This design permits SHOALS to be a highly mobile system capable of producing a 4 meter sounding grid under normal operating conditions, however, the scan pattern and survey speed can be modified to obtain even higher or lower sounding densities. The SHOALS system performance specifications are presented in Table 1.

Table 1. SHOALS system performance specifications

Maximum depth	40 meters
Minimum depth	0.9 meters
Vertical accuracy	±15 cm
Horizontal accuracy	±3 meters
Sounding density	3-15 meters
Operating altitude	200-800 meters
Scan swath width	½ aircraft altitude
Operating speed	20-100 knots
Operating temperature	5-40 degrees C
Data processing	2 hrs processing for 1 hour of data
Aircraft	Bell 212
System mobilization/demobilization	8 hrs to install; 6 hrs to demobilize

Airborne System

The airborne system is divided into three subsystems; Transceiver (TRS), Airborne Positioning and Auxiliary Sensors (APASS), and Acquisition, Control and Display (ACDS). These combined with the ground-based Data Processing System (DPS) comprise the SHOALS system.

The Transceiver Subsystem consists of the laser, scanner, and receiver. The function of the TRS is to transmit laser pulses in a defined scan pattern and receive backscattered energy from these pulses to produce laser depth soundings and aircraft altitude information. The system consists of a 200 Hz Nd:YAG (Neodynium:Yittrium-Aluminum-Garnet) laser operating in the infrared and green frequencies. Returned laser energy is detected using several optic sensors providing the ability to discriminate between surface, bottom, and land returns.

The Aircraft Positioning and Auxiliary Sensors functions are to collect information from the Global Positioning System (GPS), inertial reference system (IRS), and video imagery system. Differential GPS is used for horizontal positioning and the IRS provides information about aircraft attitude, including roll, pitch, heading, and vertical acceleration. Included as an auxiliary sensor is a video camera to record a video image of the areas being surveyed.

Central to the SHOALS system is the ACDS, which provides an operator interface and monitors and controls the airborne system. The ACDS provides five functions: data collection, operator interface, pilot guidance, airborne depth processing, and system integrity. The data collection function acquires and manages all data as it flows through the system and records it on high density magnetic tape at a rate of over 300 Kbytes per second. The operator interface allows human interaction between the operator and the system with access to all elements of the airborne system. The pilot guidance function provides aid to the pilot in navigating to the survey site and along each survey line. The airborne depth processing function calculates and displays preliminary water depth in real time, providing a means for data quality checking during the survey mission.

The last and perhaps most important function is system integrity. This function precisely coordinates all elements of the airborne system by continually monitoring and interrogating communications between the various system components. Without precise (billionths of seconds) component timing the system could not function as a unit.

Data Processing System

The Airborne System acquires a tremendous volume of raw data during a single mission. The DPS consists of the hardware and software required to post-process the lidar data. Its main functions are to: 1) import airborne data stored on high density data tape; 2) perform quality control checks on initial depths and horizontal positions; 3) provide display and edit capabilities; 4) calculate depth and position (XYZ) values for each sounding; and 5) output final positions and depths for each sounding.

The interface between the airborne system and DPS is via the high density tape containing the raw data acquired during the survey mission. All of the data types (GPS, IRS, lidar returns, etc.) are collected at varying rates and recorded in an asynchronous format. The primary task of DPS is to transfer the raw data from the survey and store it in a database which requires some degree of pre-processing so that the information can be synchronized into a complete data set. DPS possesses a fully automated capability to post-process the data and update the database with corrected depth and horizontal positions within the accuracies presented in Table 1. The software accomplishes this by identifying the surface and bottom returns from the airborne data. Depths are determined by computing the differences between the arrival times of the surface and bottom returns and applying corrections for depth biases associated with light propagation, water level fluctuations, and various inherent system characteristics. Sophisticated modeling algorithms are used to predict and apply corrections associated with these biases.

Because depths are determined using the water's surface, errors are introduced by surface waves and aircraft fluctuations. During data acquisition a sophisticated algorithm models the waves and swells to determine a mean surface so that depths can be referenced to a common mean water level. Error introduced by wave heights up to 2 meters are removed using this method. An inertial reference system is utilized to compensate for the roll, pitch, and vertical fluctuations in the aircraft's movements. This information is supplied to the laser scanner for correction of these motions during surveying. Determining a mean water surface and isolating the aircraft's fluctuations allows for an accurate estimation of the mean water level. Applying tidal corrections then produces a depth reference to a known water level datum such as mean low water.

A manual processing capability allows hydrographers to evaluate anomalous data by providing display and edit functions of sounding data and system parameters. Video imagery of the survey area permits visual scrutiny of the area to aid the hydrographer in deciding whether to exclude suspect data from further processing. Output from the DPS is an accurate digital data set of XYZ (positions/depths) for each laser sounding that is compatible with most GIS and other contouring and mapping systems.

Hyperspectral Airborne And In Situ Optical Sensing

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In many coastal oceans of the world, the flora and fauna are under stress. In some areas sea grasses, coral reefs, fish stocks, and marine mammals are disappearing at a rate great enough to capture the attention of, and in some cases, provoke actin by local, national, and international governing bodies. The governmental concern and consequent action is most generally rooted in the economic consequences of a collapse of coastal ecosystems. The ability to make effective management decisions is hampered, however, by a lack of historical or even contemporary data quantifying the standing stock of the natural resource of concern. Without resource assessment, neither policy decisions intended to responded to ecological crises nor those intended to provide long-term management of coastal resources can be prudently made.

Due to the dynamic nature of properties in coastal waters, interpretation of remotely sensed imagery and the prediction of viability using imagery from spacecraft and aircraft are difficult. The complexity is due in part to the interaction of light with a convolved suite of dissolved and particulate materials and, in shallow areas, with the sea bottom. Improved in-situ optical measurements of the water column and bottom are needed to develop and test environmental optical models for coastal waters. To that end, we have developed and tested an initial suite of instruments for use on unmanned underwater vehicles (UUVs) for acquiring in-situ optical measurements and for imaging the bottom. These vehicles include both remotely operated and autonomous underwater vehicles (ROVs and AUVs).

This contribution presents a methodology designed to assess the standing stock of immobile coastal resources (e.g. sea grasses and corals) at high spectral and spatial resolutions utilizing a suite of instrumentation operating from unmanned underwater vehicles to augment hyperspectral remote observations from space and aircraft. These observations exploit the spectral albedo and fluorescence signatures of the bottom flora and fauna. In situ field results include measured, hyperspectral (512 channel) upwelling radiance and downwelling irradiance, up welling and down welling diffuse attenuation coefficients, imagery of the passive and active bottom albedo, and imagery of naturally and artificially stimulated bottom fluorescence. Also presented are bottom imagery, water properties, remotely acquired imagery of the Florida Keys, and inverse model calculations of pigments, gelbstoff, and bottom albedos.

Above Water:

Let:
dA= grass area
$400m^2$-dA= soil area

Pixel Radiance = $\frac{E_d}{p} * [P_g * dA + P_s * (400 - dA)]$

Extraction of P_g and P_s is not difficult with hyperspectral data since equation is linear: Boardman 1995.

Below Water- Equations are non-linear:

<u>Components of R_{rs}</u>: $R_{rs} \equiv L_w / E_d(o+)$

$$R_{rs}(l) = R_{rs}^{w}(l) + R_{rs}^{b}(l) + R_{rs}^{f}(l) + R_{rs}^{R}(l)$$

(Lee et al. 1994)

w: Elastic scatter from molecules and particles.
b: Bottom reflectance.
f: CDOM fluorescence.
R: Water Raman scattering.

<u>Optically Shallow Water:</u>

$$R_{rs} = R_{rs}^{w} * R_{rs}^{Shallow} + R_{rs}^{Bottom}$$

$$R_{rs}^{Shallow} = 1 - \exp\left\{\frac{K_d}{-3.2(a_{tot} + b_b)} D\right\}$$

$$R_{rs}^{Bottom} = 0.173\, r(l) \exp\{-2.7(a_{tot} + b_b)D\}$$

(Carder et al. 1993c)

Hyperspectral Approach:
Main Contribution is from R_{rs}^{w}:

$$R_{rs}^{\ w}(l) = 0.176^{*}\left\{\frac{\mathrm{b_{bm}}(l)}{Q_m} + \frac{\mathrm{b_{bp}}(l)}{Q_p}\right\}\left\{\frac{1}{\mathrm{a_w}(l)+\mathrm{a_p}(l)+\mathrm{a_g}(l)+}\right\}$$

$$or \doteq .54 * \frac{\mathrm{g}}{\mathrm{Q}}\frac{b_b}{a} = .54 * .0936\frac{\mathrm{b_b}}{\mathrm{a}}$$

*0.176 derived from (.54 * .33) (Lee et al. 1994)

$b_{bm}(l)$: Backscattering by water molecules.

Known, (Smith and Baker 1981)

Q: Ratio of irradiance to radiance.

Separates into Q_m & Q_{p}.

Q_m : Average value taken at 3.3.

Q_p : Solved with b_{bp}.

$b_{bp}(l)$: Backscattering by particles.

Determined according to Lee et al. 1992

$$\mathrm{b_{bp}}(l)/Q_p = \mathrm{X}*(640/l)^{\mathrm{Y}} \quad \mathrm{b_b} \doteq b_{bp}$$

where X is an indication of the magnitude of b_{bp}, and Y is an indication of cell size distribution.

$a_w(l)$: Absorption due to water molecules.

Known, (Smith and Baker 1981).

$a_p(l)$: Absorption due to particulates.

Determined according to Kishino et al. 1985.

$a_g(l)$: Absorption due to gelbstoff.

Determined according to Bricaud et al. 1981.

In situ Optical Instruments Suite and quantity measure/provided.

Hyperspectral (512 channel downwelling) Irradiance Meter	$E_d(\lambda)$ 350-900nm
Hyperspectral (512 channel upwelling) Radiance Meter	$L_u(\lambda)$ 350-900nm
Xybion IMC-301 GEN-III-B 6-channel Intensified Bottom Camera	Reflectance and/or fluorescence imagery: 415,445, 490, 520, 550, 670 nm
Dual-laser altimeter/chlorophyll probe	Altitude, benthic chlorophyll absorption (650, 675 nm)
Rare-earth-doped, Metal-Halide Arc Lamps (DeepSea Power and Light)	Iron, Gallium, Indium, Thallium Iodide, Sodium Scandium, Indium UV, “Daylight” irradiance spectra
WETLabs Spectal absorption and fluorescence Instrument (SAFIRE)	6-channel absorption/excitation: 228, 265, 310, 340, 375, 435 nm 16-channel fluorescence: 228, 265, 310, 340, 375, 400, 430, 470, 510, 540, 590, 630, 685, 810, 900 nm
WETLabs ac-9	9-channel absorption and attenuation: 412, 440, 488, 510, 560, 630, 650, 676, 715 nm
Sea Tech analog Transmissometer	beam attenuation, c (660 nm)
Sea Tech Digital Transmissometer	beam attenuation, c (448 nm)
Sea Tech Light Scattering Sensor	optical backscatter (830 nm)
Sea Tech and WETLabs Fluorometers	Blue excitation, red chlorophyll fluorescence
Sony XC-999 color camera	RGB imagery

Submerged Laser Multispectral Fluorescence Line Scanner

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The most recent advancement in underwater imaging technology is the Laser Line Scanner (LSS). This approach incorporates a synchronized scanning and detection system, focused on the bottom or target at a fixed distance from the sensor platform (Fig. 1.). The imaging system consists of a narrow laser beam that is swept across the scene, perpendicular to the motion of the sensor platform, using a rotating cam equipped with mirrors. The narrow field-of-view detector is offset from the illumination beam and is synchronized, using a different set of mirrors on the same rotating cam, to intersect the laser beam at a fixed distance from the sensor platform. Only photons backscattered or reflected from the intersection of the laser beam and the detector field-of-view are detected, thus eliminating the effects of path radiance that reduces the range capability of traditional camera systems. When the system is configures so that the illumination-detection intersection coincides with the ocean floor, the result is high resolution images of the benthic environment. Since the confounding effects of path radiance (photons scattered by the intervening water column) are eliminated from detection, the imaging range is greatly increased. While traditional underwater camera or video systems can detect objects out to 2 attenuation lengths, LLS systems are capable of producing high-contrast, high spatial resolution images of targets greater than 5 attenuation lengths from the sensor platform. LLS systems are now commercially available from several venders and all of these systems are monochromatic, generally producing images of backscatter or reflectance at 532 nm.

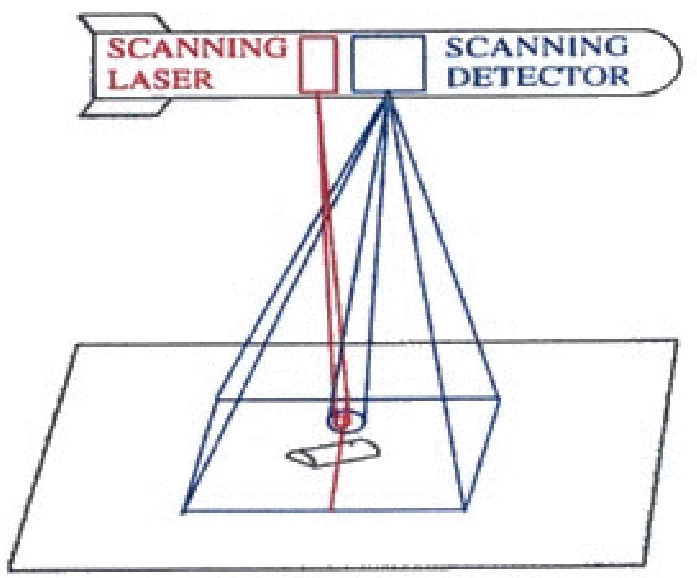

Figure 1: Laser line scan technology eliminates the efforts of path radiance (photons scattered into the detector by the intervening water column) and greatly increases the imaging range (>5 attenuation lengths).

One experimental LLS system, developed by Raytheon, is equipped with a 488 nm laser and four sensors. By placing band-pass filters in front of each detector, it has been shown possible to image benthic fluorescence. An example of the sort of imagery possible in coral reef areas is shown in Fig. 2, where the four detectors were fitted with filters centered at 488 nm, 520 nm, 570 nm, and 685 nm filters. The 488 nm image (the left panel in Fig. 2) is the reflectance of the ocean floor at 488 nm and reveals little in the way of coral coverage, although some conclusions may be drawn from the shape of various benthic features. A composite fluorescence image (the right panel in Fig. 2), on the other hand, reveals an astonishing amount of information pertaining to coral coverage and species distribution. In this image, blue is

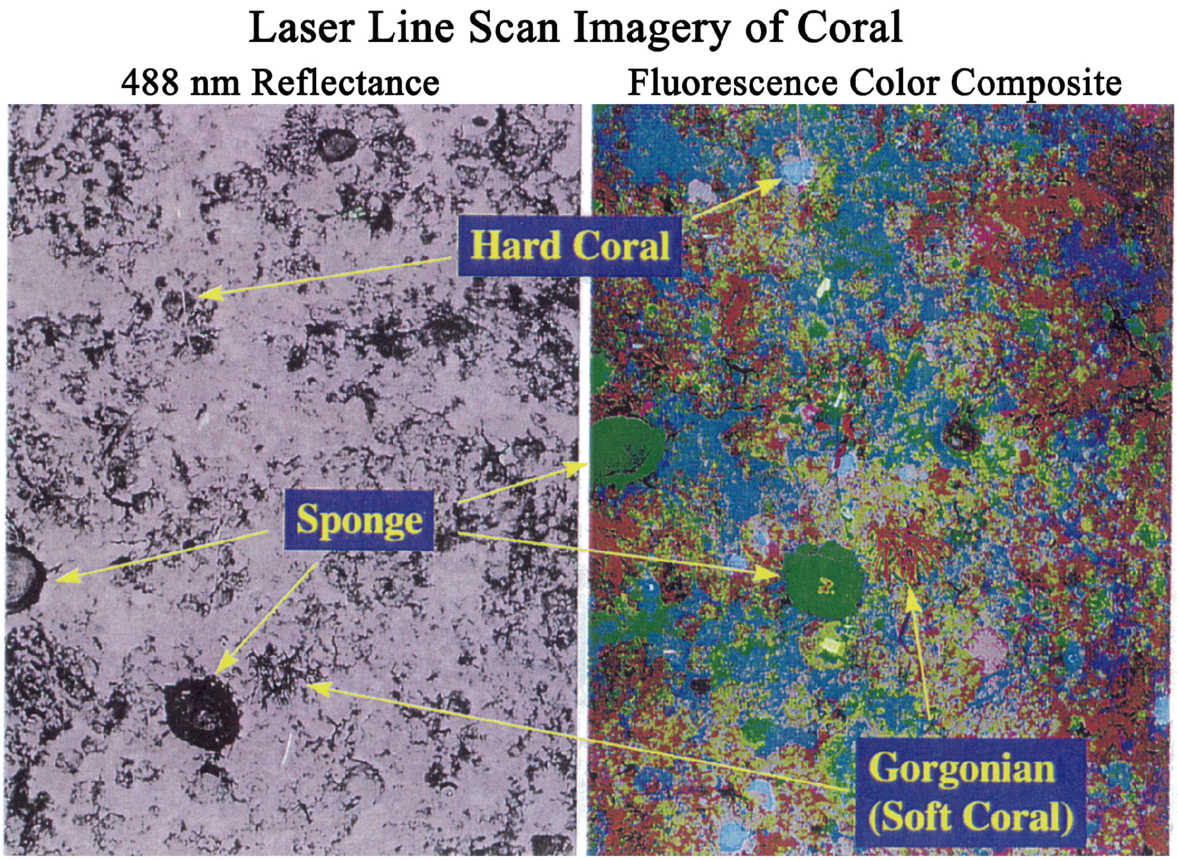

Figure 2: Benthic reflectance (48 nm) and fluorescence maps of a coral environment, located in the Dry Tortugas, collected by the spectral LLS, developed by Raytheon. The site was located in 20 m of water and is currently a permanent NOAA coral monitoring site. The site is marked with a line on the ocean floor, seen as a vertical linear feature within each image. The fluorescence color composite is constructed from co-registered emission images at 520 nm (blue), 570 nm (green), and 685 nm (red).

assigned to 520 nm emission, green is assigned to 570 nm emission, and red is assigned to 485 nm emission. Features appearing red (benthic algae and gorgonians) are dominated by chlorophyll fluorescence. Sponges appear green, due primarily to 570 nm fluorescence. Several species of hard coral fluoresce brightly in all three fluorescence bands and appear white in the image. Presently, this experimental system is deployed from a small submersible and is thus limited to operations in areas deeper than about 15 m in order to avoid platform motion due to surface waves. In addition, the system operates best at night when the ambient light levels are at a minimum.

The fluorescence LLS system is currently involved in an ONR-funded program called Coastal Benthic Optical Processes (CoBOP). The goal of CoBOP is to better understand the interaction of light with the ocean floor so that algorithms to interpret LLS images and other remote sensing data can be developed based on first principles rather than empirical relationships. The work is being managed by Dr. Steven G. Ackleson, ONR (703-696-4732; ackless@onr.navy.mil), and detailed information regarding CoBOP can be found on a web site developed by Dr. Charles Mazel, MIT at (http://nightsea.mit.edu/research/cobop/cobop.html).

Acoustic Side Scan Imaging

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Sidescan sonar is an acoustic mapping tool towed from a ship at speeds of 4-6 knots that insonifies a swath of sea floor and provides acoustic images that are similar to oblique aerial photographs on land. A variety of sidescan sonars are available that range from high frequency systems (500 kHz) that insonify a 25-50 m wide swath of sea floor to low frequency systems (6.5 kHz) that insonify swaths 45 km wide. These systems have been used extensively by marine geologists in the US during the past twenty years. Initially the systems were entirely analog and were used to locate and identify targets and to do reconnaissance geologic mapping based on widely spaced tracklines. More recently, sidescan sonar data are being logged digitally, processing techniques have improved, navigation has improved, and computers are faster so that now digital sidescan sonar mosaics of large areas can be acquired and digitally processed rapidly, and are a standard product of USGS field mapping programs.

For coral reef mapping, probably the higher frequency systems (50-500 kHz) are the most appropriate because they can be used in shallow water and because of the detail that they can resolve. 50-100 kHz systems can be towed in water as shallow as 3 m, provide a swath of 100-1500 m (depending on the water depth), and can resolve features as small as 1-4 m depending on the swath width and data sampling rate used. 500 kHz systems provide higher definition, but the swath width normally is reduced to 50 m or less. The USGS has been using sidescan sonar to systematically map inner shelf areas, and as an example a continuous coverage sonar image of a 12 by 15 km area (180 km^2) of the inner shelf off Sarasota, FL (depths 3-12 m) was mapped in 5 days. The sonar mosaic, when integrated with bathymetry, subbottom seismic profiles, and surface sediment samples, also collected during the cruise, reveal a complex and spatially variable surficial geology. These digital sidescan sonar mosaics would provide valuable base maps for a coral reef monitoring program as they would help map the distribution of coral reefs, and show their relation to the surficial and shallow subsurface geology.

High Definition Acoustic Imaging

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Shallow Water Acoustic Challenges

Very Shallow Water Environmental Issues
- -Numerous Microinhomogeneities in the Water Column.
- -Targets may bury due to wave induced effects.
- -Acoustically Harsh regime
  - -high ambient noise levels
  - -acoustic penetration into sediment
  - -at shallow grazing angles

General Sonar Performance Trends

At high operating frequencies, resolution is increased but aperture width and identification range are decreased. If the Horizontal / Vertical bandwidth is decreased, range, resolution, and complexity / cost increase while area coverage decreases. If the tilt angle is either increased or decreases, the range decreases. An increase in water depth results in increased range. The Distance above water can either increase or decrease the range depending on water depth.

EOD Technology Program - Underwater Ultrasonic Imager

Operates on densely populated 2d high frequency transducer array (1.5 - 3.0 MHz) in the focal plane of an acoustic lens system. The advantages of this system include low power, high resolution (quarter degree), and a small and lightweight system. Range is the major limiting factor with this system. The best imagery is produced at ranges of 10-50 feet. Range limited technology is presently under development. The system can be operated by a diver or remotely operated vehicle (ROV). Acquisition costs should be in the range of 50,000-100,000 US dollars.

APL / University Of Washington - Diver-Held Sonar Mod 2

This system operates on a frequency of 750 kHz. It is composed of 64 acoustic beams formed by a set of three thin lenses (including one doublet), 32 beams at 0.5^{o} (Azimuth) by 7^{o} (Elevation) and 32 beams at 0.75^{o} (Azimuth) by 7^{o} (Elevation). The sonar image has a 40^{o} Field Of View (FOV). The center 16^{o} FOV contains the 32 0.5^{o} beams and the left and right sectors of 12^{o} FOV each contain 16 0.75^{o} beams.

The sonar display has five maximum range options: 66, 33, 16, 8, or 4 yds The display is updated approximately 6 times/s at 66 yds and 9 times/s at shorter ranges. The real-time information available to a diver includes a high resolution sonar display, sonar depth, sonar altitude, sonar bearing, time into mission, (X,Y) location of sonar, (X,Y) location of way-point, and graphical indication of sonar bearing re next way-point.

Diver Sonar Model S300

Operates on a frequency of 500 kHz. It has 64 beams with widths of 3º Horizontal by 15º Vertical. The scan angle is 60º. The maximum range is 50 meters and dimensions are 12.2 inches by 3.2 inches (diameter).

Diver Sonar Model S303

Operates on a frequency of 500 kHz with beam widths of 1 º Horizontal by 15º Vertical. The maximum range is 50 meters and dimensions are 12.2 inches by 3.2 inches (diameter).

Synthetic Aperture Processing (SAS) - Shallow and Very Shallow Water Sensors.

This system detects, classifies, and identifies targets in 10 to 80-foot water depths. It has a 1-inch by 1-inch resolution at 180 kHz, a 45-yard range, a 90-yard pathwidth at 8 knots and a 0.36 square nautical miles / hour coverage rate. It utilizes motion phase error correction. The quadratic focusing error is removed by multiplying each received signal by a phase. Beamforming is accomplished by summing complex values over the synthetic aperture length.

COBRA ATD Minefield Detection

Airborne multispectral mine detection through the use of standard RS-170 video signal utilizing spinning filter wheel with six filters (400-900NM) and intensified with gating capability for automatic exposure. A stabilized platform is not required. Location information, DGPS/GPS, aircraft altitude and attitude, is encoded. Utilizes an algorithm for automated for minefield detection and displays minefield locations.

COBRA Technology Transfer For Coral Monitoring

Currently, a low cost ($250K) Coastal Battlefield Reconnaissance and Analysis (COBRA) airborne multispectral video system with GPS location incoded in video with multispectral processing algorithms is available. To be used for coral monitoring, a reconfiguration of hardware and modification of software would be required. The resulting predicted capabilities include locating and sizing of coral reefs, long term change detection, reef health determination (?), a predicted 3-5 attenuation length penetration distance in a 1.5 cubic foot package weighing less than 50 lbs requiring approximately 150 watts of power (currently flown on a Cessna 172).

MultiBeam Sonar: Potential Applications for Coral Monitoring

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Abstract:

Over the past few decades, revolutionary changes have taken place in our ability to map and visualize the ocean floor. These changes, brought about by the concurrent, rapid advancement of sonar technology, positioning and orientation technology, computer hardware, data bases, signal processing and visualization techniques, are beginning to result in detailed depictions of large pieces of the seafloor that are, in many ways, analogous to airborne or satellite derived images of the earth's surface. At the core of these new technologies is the development of multibeam sonar systems that use beam-forming techniques to insonify large swaths of the seafloor while producing high resolution (both lateral and vertical) bathymetry and seafloor imagery (backscatter). Among others, the Ocean Mapping Group of the University of New Brunswick has been pursuing research and developing tools related to multibeam sonar mapping for a number of years. This work has been directed, for the most part, at hydrographic and geologic problems, but many of the tools and approaches developed are equally useful for monitoring changes in the shape of coral reefs, and monitoring fish populations above them.

The extremely high data rates associated with multibeam sonars (as much as gigabytes per hour) present a range of data processing challenges. The Ocean Mapping Group has developed a full suite of software tools for the real-time and near-real time display, editing and visualization of multibeam sonar data that can produce near-finished maps and 3-D images on board the research vessel. These tools have been used on a number of surveys (e.g. off Eureka, CA, off New Jersey, and the Stellwagen National Marine Sanctuary). In each case the combination of detailed bathymetry and sonar imagery provide quantitative depth information and a qualitative description of the spatial distribution of seafloor materials and textures (e.g. rocky areas, sands, gravels, etc.).

While the qualitative picture of the distribution of seafloor types is a very useful tool for a number of applications (including coral monitoring), efforts are currently under way to attempt to extract more quantitative seafloor property information from the sonar record. These efforts include the analysis of the characteristics of the vertically incident acoustic waveforms and evaluation of the angular dependence of backscatter. To facilitate this research, several interactive software tools have been developed that allow for the simultaneous exploration of sonar data in both geographic and statistical parameter spaces. The ultimate objective of this work is to provide a robust approach to remote seabed classification.

We have also developed a suite of interactive 3-D data exploration tools to facilitate interpretation of these complex data sets. A 6-degree of freedom mouse (bat) allows for interaction with massive (10's to 100's of megabytes) datasets with simple hand movements and exploration in a natural and intuitive fashion. Data points can be selected in 3-D for position, depth or other

attributes and measurements can be made in the 3-D space (3-D GIS); the 3-D scene can be viewed in true stereo with special glasses. We have recently used these tools for real-time visualization of mid-water targets including schools of fish.

Properly processes multibeam sonar data con contribute a range of coral monitoring applications including:

1. real-time use in planning monitoring programs;
2. use of archival or newly collected data for comparison with retrospective analyses of coral monitoring data in order to identify shape changes and;
3. the assessment of the level, nature, and impact of human activity on coral reefs.

Field Validation of Laser-Induced Fluorescence Spectroscopy

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Abstract

Coral reefs represent an important global ecosystem. Reefs support fisheries and tourism, provide a significant sink for atmospheric carbon dioxide and are important centers of marine biodiversity. Despite their biologic and economic importance coral reefs are increasingly threatened by human activities (Dustan, 1987). Recently, "bleaching" of corals, i.e. loss of photosynthetic pigmentation, has occurred at numerous globally-distributed sites and is known to be induced by elevated temperatures. Many investigators have suggested that this represents an early warning signal of greenhouse warming. Regardless of the cause, the health of many reefs is in decline. Current techniques (site-specific in situ surveys) are inadequate to determine the spatial extent of reef decline (D'Elia et al. 1991). Optical sensing methodologies from remote platforms (boats, aircraft, satellites) are urgently needed (Hardy et al. 1992). Using a newly-developed self-contained underwater benthic spectrofluorometer we have assembled a library of spectra of Caribbean reef organisms. Spectral signatures allow differentiation between major reef types (seagrass, coral, bleached coral, and dead algal-encrusted coral). Algorithms based on these spectra will be applied to remotely-sensed data to map and monitor major reef ecosystem types and identify areas of reef decline.

Project Goals And Methodology

Our overall goal is to develop methods for monitoring the health of coral reefs from remote platforms (boats, aircraft and satellites). We collect in situ data on the optical properties of healthy and stressed reef populations. The resulting catalog of species and habitat-specific spectra will allow formulation of passive and active optical algorithms. These algorithms, used with remote instrumentation, should allow us to determine, in a rapid and cost-effective manner, the spatial extent of different reef types, including bleached coral, over large areas.

Data Collection And Analysis

We have measured in situ fluorescence spectra of corals and other reef organisms using our newly-developed hand-held battery-operated underwater benthic spectrofluorometer (BIF). The instrument, carried by a diver, collects both passive and active spectra between wavelengths of 395 to >800 nm. In the active (fluorescence) mode, ultraviolet, blue or green light is selected as the excitation energy and passes through a light guide pointed at the surface of the organism. Chlorophyll and other pigments present in the organism are excited and emit longer wavelength radiation (fluorescence). The fluorescence is collected through a fiber optic cable and the spectra stored on a hard disk for later downloading to a PC. In the passive mode the instrument is used to record ambient down-welling and reflected energy.

We have also collected passive and active spectra over large scale (several hundred meter) reef transects. Passive spectra are collected using a small boat and a towed instrument in the downward -looking mode. Active fluorescence spectra are collected over reef transects using the NASA airborne oceanographic laser (AOL) (Hoge et al 1986a&b).

Coincident with spectral data, we collect samples of coral and other reef organisms for determination of pigment densities. Samples are frozen returned to our laboratory, and analyzed by spectrophotometry and high performance liquid chromatography (HPLC).

We compare in situ spectra and pigment densities between colonies of the same species, between different species and between healthy and stressed (bleaching) colonies.

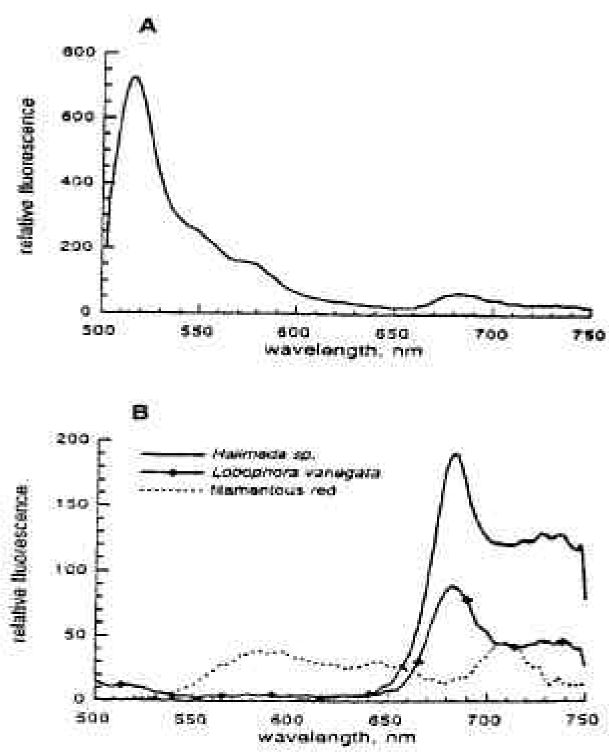
We have collected hundreds of spectra and pigment samples. Primary field study sites have been Lee Stocking Island, Bahamas and the Key Largo National Marine Sanctuary, Florida. Secondarily, we have collected data from Hawaii and Belize.

To determine Coral sensitivity to temperature-induced bleaching, three species of Caribbean coral were held in an outdoor flowing sea water system at ambient (29 C), warm (31 C), and hot (34 C) temperatures for up to 200 hours.

Results And Accomplishments

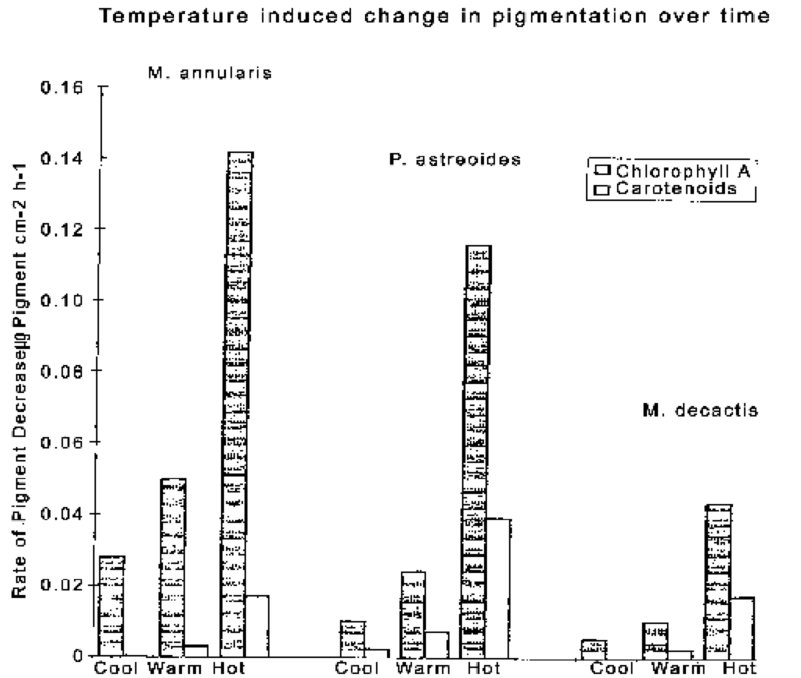
Our data indicate that fluorescence and/or passive spectra can be used to differentiate between major types of reef organisms (corals, seagrass, macro algae, bleached coral, an dead algal-turf covered coral). Furthermore, our results suggest that these spectra can be measured from remote platforms. Optical instruments aboard remote platforms (boats, aircraft, and possibly satellites) offer great potential for monitoring the health of coral reefs.

Figure 1

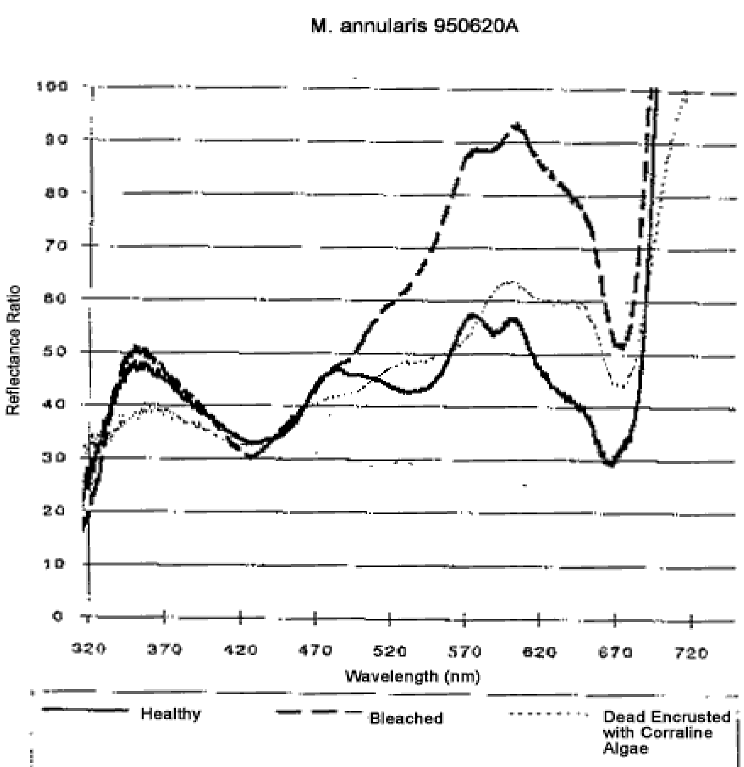


Macroalgal fluorescence spectra are similar, while coral spectra differ both between colonies of the same species and between species. Most healthy corals, unlike macroalgae, exhibit fluorescence spectra with dominant peaks in the 500 to 550 nm range (Figure 1). Coral tissue, rather than zooxanthellae, may be responsible for coral fluorescence peaks in this region (Mazel, 1995). This lower wavelength fluorescence appears promising as a method to distinguish reef coral from macroalgae, while chl-a fluorescence emitted from the coral zooxanthellae at 685 and 740 nm may be important for pigment quantification.

Chlorophyll a (chl-a) and peridinin pigment densities over the surface of corals are similar between colonies of the same species, but differ significantly between species. The quantity of pigment per zooxanthela sometimes differs among colonies of the same species as well as between species. Peridinin surface density increases with increasing chl-a density.



The rate of temperature-induced bleaching of corals increases with increasing temperature and is also a function of species sensitivity. For the three species we examined *Montastrea annularies* is most sensitive, *Porites aseroides* moderately sensitive and *M. decactis* least sensitive (Figure 2). Bleaching of Montastrea species is primarily the result of zooxanthellae loss.



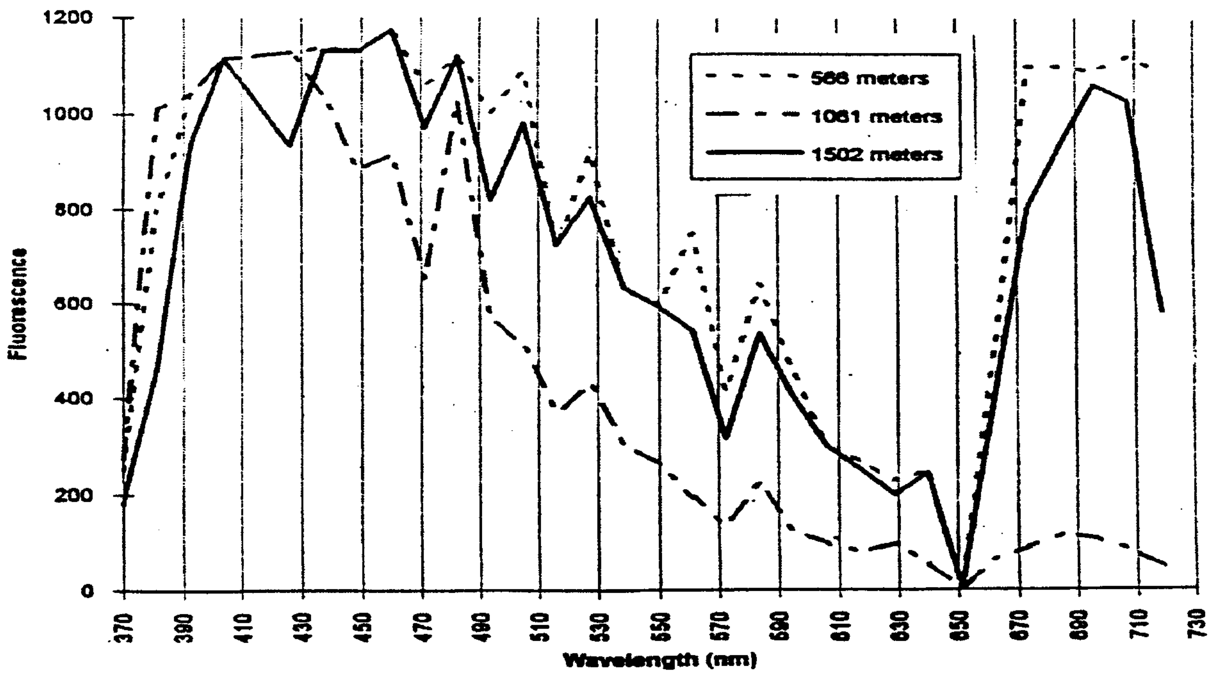
In the Florida Keys in situ measurements indicate major differences in spectra between healthy, bleached, and dead algal-encrusted coral (Figure 3).

On a larger scale, transects across hundreds of meters of reef areas with downward-looking boat-mounted passive instruments and aircraft-mounted active instruments, we are able to differentiate major differences in optical properties associated with major reef types (Figure 4).

Remote sensing could become a standard tool of resource managers, government agencies, and international research groups for monitoring the health of, and detecting changes in, coral reefs.

An accurate baseline of reef conditions over large areas (including optical properties and sea-surface temperatures) would become available as a gauge against which to compare long-term changes in reefs due to climate change or other anthropogenic influences.

Figure 4



Three fluorescence spectra from reef at Puako, Hawaii, generated using the NASA AOL system. Each spectrum corresponds to a different distance point along the aircraft transects (Transect 32222). Excitation wavelength = 355 nm (UV). Peaks around 685 nm represent chlorophyll fluorescence. Peaks below 600 nm may result from substances in coral tissues.

CONCLUSIONS

No single system has the capability to locate, delineate and determine the condition of corals at a scale that would permit effective resource management. A two-tiered analysis emerged as the most efficient approach. The initial stage would consist of identifying and mapping the potential location of significant outcrops of corals. This stage would use relatively synoptic and low resolution sensors to rapidly and efficiently search wide areas. The second stage would consist of methods to first confirm the presence of living corals, and then to determine the status or "health" of the coral reef. This last stage is the most critical, providing the capability for systematically monitoring condition of corals within the vast coastal trust areas for which NOS is responsible.

The following systems were discussed as having potential application for detecting and assessing the condition of corals

Mapping Location:
- Satellite Imaging
- Aerial Photography
- Airborne LIDAR
- Airborne Hyper-Spectral Imaging
- Side-Scan Sonar
- Multi-Beam Sonar

Monitoring Condition:
- Airborne Laser Fluorosensing
- Underwater Multispectral Imaging
- Acoustic Signal Processing
- High-Resolution Acoustic Imaging
- Underwater Laser Line Scanning
- Underwater Fluorescence Spectroscopy

A. Mapping Stage

The goals of the initial mapping stage would be to detect and delineate reefs or significant patches of corals. Technologies applicable to this stage should allow detection of features 5 meters square or greater in size at depths to 50 meters. As a first level mapping effort, satellite imagery, especially the SPOT 10 meter panchromatic data, appears to be the most promising commercially available source. Aerial photography and hyperspectral imaging should be applicable for more detailed and localized settings, or within subsets of larger areas. Airborne LIDAR is a highly promising technology for more detailed delineation in clear waters because of its ability to rapidly sample both shallow areas and areas as deep as 40 meters on a fairly broad scale (10's of kilometers). Methods that show promise for corals in water conditions that preclude optical sensing from satellite or airborne sensors include multi-beam bathymetry for feature detection and acoustic signal processing for feature differentiation. These techniques can produce detailed (5 to 10 meter resolution) map data over relatively broad areas (100's of kilometers) and depths (surface to 100+ meters).

B. Monitoring Stage

The assessment of the biotic condition of corals requires more information than can generally be acquired using satellite, airborne, or surface sensor technologies. This stage must provide sufficient information to differentiate living from dead or damaged corals and provide additional information which can be used to evaluate overall reef condition and trends. It is not expected that this level of detail can be obtained uniformly over large, management-sized areas. The technologies considered included high resolution close range acoustic imaging, underwater multispectral video, and both active and passive fluorescence measurements.

An experimental underwater multispectral laser fluorosensor, under development by the Office of Naval Research, appears to show great promise. This system measures individual variations in stimulated fluorescence spectra produced by different reef organisms, including corals. These variations appear to be species specific, are not limited to photosynthetic pigments, and appear to show additional variability which may be related to health of the organism.

The goals of the monitoring stage are to differentiate living from dead reef habitat and to provide additional information which can be used to evaluate reef condition and trends. It is not expected that this type of data can be obtained uniformly over large, management-size areas. Therefore a sampling scheme that selects specific representative sites to be examined in detail is required. More general characterizations may be necessary to design a statistically sound sampling approach prior to or concurrently with the actual monitoring. Of the technologies represented, the emerging technology of underwater laser line scanning appears to provide the most useful information. This technology is applicable in any water depth and takes advantage of the variation in fluorescence produced by different reef organisms, including coral species. Disadvantages include the complexity of the system, the limited area of coverage, and the data processing and algorithm development requirements. Other approaches, such as underwater multispectral video and passive fluorescence sensing, have similar advantages and limitations.

In general, individual study area conditions will largely determine the technologies that will be applied. The workshop attendees agreed that the objectives were attainable in a staged approach and should meet the mandated requirements of NOS for monitoring coral reefs. There is a need for more information on high-resolution acoustic imaging technologies. Much of this information is available to NOAA, but could not be presented during the workshop due to the sensitive nature of the technology.

The next step in developing an operational coral monitoring effort within NOAA should be to solicit input from the management community. This would provide information in the following areas: a) the expected scales for a monitoring effort; b) local environmental parameters relevant to effective monitoring; c) expected financial resources available for the monitoring effort; and d) possibilities for local collaboration. Demonstration pilot studies should then be designed and conducted to test the application of these systems for mapping and monitoring corals.

APPENDIX A

AGENDA

September 17, 1996

9:00 am	Opening and Introductions: John Mark Dean University of South Carolina
9:15 am Welcome	Margaret Davidson Director, NOAA Coastal Services Center
10:00 am	Airborne LIDAR Jeff Lillicrop U.S. Army Corps of Engineers
10:45 am	Break
11:00 am	Airborne Hyperspectral and Passive Submerged Optical Sensing Ken Carder University of South Florida
11:45 am	Submerged Laser Line Scanner Steve Ackleson Office of Naval Research
12:30 pm	Lunch
2:00 pm	Acoustic Side Scan Imaging Dave Twichell U.S. Geological Survey
2:45 pm	High Definition Acoustic Imaging Jody Wood Naval Surface Warfare Center
3:30 pm	Break
3:45 pm	Multi-beam Bathymetry David Wells University of New Brunswick
4:30 pm	Summary and Discussion
7:00 pm	Dinner Keynote Address John W. McManus

International Center for Living Aquatic Resources Management (ICLARM)

September 18, 1996

9:00 am	Airborne Active/Passive Fluorescence Jack Hardy Western Washington University
9:45 am	Group Discussion: Existing Technologies
10:30 am	Break
10:45 am	Group Discussion: Existing/Emerging Technologies
12:00 pm	Luncheon Keynote Address David Hopley James Cook University
1:30 pm	Group Discussion: Anticipated Technologies and Research Recommendations
3:30 pm	Break
3:45 pm	Review and Summary
5:00 pm	Adjourn

APPENDIX B

LIST OF PARTICIPANTS

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APPENDIX C

LIST OF ACRONYMS

AAVIS	Australian Airborne Visible and Infra-red Scanner
ACDS	SHOALS Acquisition, Control and Display Subsystem
AOL	NASA Airborne Oceanographic Laser
APASS	SHOALS Airborne Positioning and Auxiliary Sensors
AUV	Autonomous Underwater Vehicle
BIF	Battery-operated In situ Fluorescence underwater benthic spectrofluorometer
C-CAP	NOAA Coastal Change Analysis Program
CASI	Compact Airborne Scanning Instrument
CDOM	Chromophoric Dissolved Organic Matter
COBRA	Coastal Battlefield Reconnaissance and Analysis multi-spectral sensor
CSC	NOAA Coastal Services Center
CSIRO	Australian Commonwealth Scientific and Industrial Research Organisation
DGPS	Differential Global Positioning System
DOC	U. S. Department of Commerce
DPS	SHOALS Data Processing System
FMRI	Florida Marine Research Institute
GCRMN	Global Coral Reef Monitoring Network
GIS	Geographic Information System
GPS	Global Positioning System
HIS	Hyperspectral Imaging System
HPLC	High Performance Liquid Chromatography
HRV	SPOT High-Resolution Visible sensor
Hz	Hertz - cycles per second
ICLARM	International Center for Living Aquatic Resources Management
ICRI	International Coral Reef Initiative
INS	Inertial Navigation System
IRS	Inertial Reference System
IUCN	International Oceanographic Commission
LADS	Australian Laser Airborne Depth System
LIDAR	Light Detection And Ranging
MIT	Massachusetts Institute of Technology
MSS	Landsat Multispectral Scanner
Nd:YAG	Neodynium : Yittrium-Aluminum-Garnet solid state laser
NASA	National Aeronautics and Space Administration
NCSC	NOAA Coastal Services Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRL	Naval Research Laboratory
OCRM	NOAA Ocean and Coastal Resource Management
ONR	Office of Naval Research
PACON	Pacific Congress on Marine Science and Technology
PC	IBM-Compatible Personal Computer
QA/QC	Quality Assurance/Quality Control

RADAR	Radio Detection and Ranging
ROV	Remotely Operated Vehicle
SAS	Synthetic Aperture Sonar
SHOALS	Scanning Hydrographic Operational Airborne Lidar Survey system
SONAR	Sound Navigation and Ranging
SPOT	System Pour l'Observation de la Terre
TM	Landsat Thematic Mapper
TRS	SHOALS Transceiver Subsystem
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAE	U. S. Army Corps of Engineers
USC	University of South Carolina
USGS	U.S. Geological Survey
UUI	Underwater Ultrasonic Imager
UUV	Unmanned Underwater Vehicles
WES	U. S. Army Corps of Engineers Waterways Experiment Station
YAG	Yittrium-Aluminum-Garnet solid state laser medium