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REMOTE SENSING OF CORAL REEFS: AN OVERVIEW.

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Cover

Shuttle photograph captures massive phytoplankton bloom in the Great Barrier Reef

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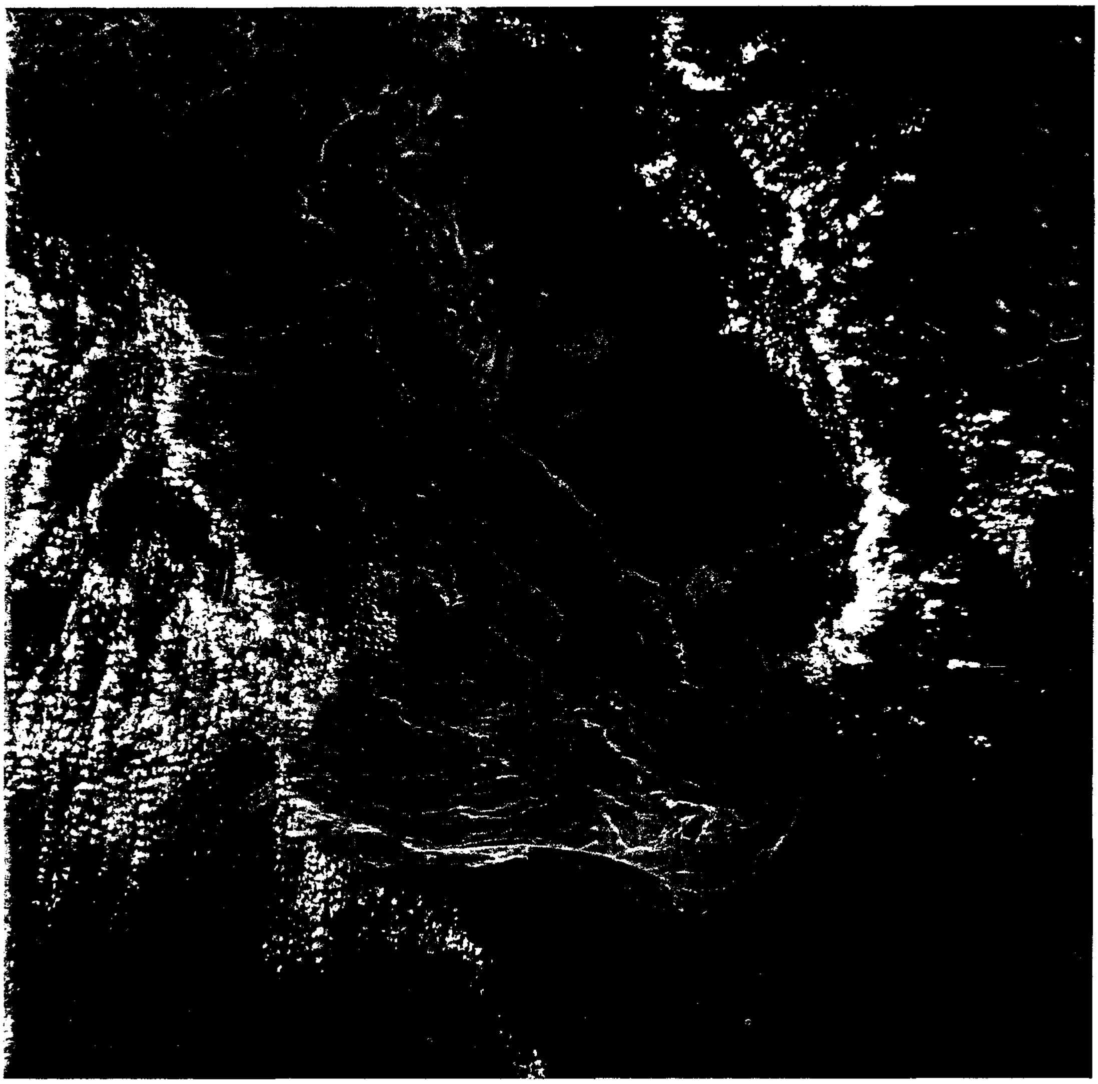
The Space Shuttle Earth Observation Project (SSEOP) observes the Earth from hand-held photographs taken by trained astronauts using a NASA-modified Hasselblad 500 EL/M 70 mm camera and a Linhof Aero Technika 45 127 mm camera. Coverage began in April 1981 and consists of near-vertical natural colour photography taken from a perspective 300 km above the Earth. Such photography varies in scale from 1 : 700 000 to 1 : 1 000 000.

The cover displays a hand-held 70 mm Hasselblad photograph taken aboard Space Shuttle Flight STS-9, during orbit 20 on 29 November 1983. It is of a massive phytoplankton bloom in the Capricorn Channel of the southern Great Barrier Reef, Australia. The bloom starts at 22°50′S, 152°50′E and stretches for well over 150 km, the full extent of which is not captured by the photo. The photo covers an area located between Rockhampton on the Queensland mainland and the Swain Reefs on the Great Barrier Reef.

Efforts to locate personnel who observed this particular bloom have been successful. Zoologists from the Australian Museum were in the region at the time and they provided the following ground observations. The bloom was phytoplankton, brown in colour and thick in patches. It was first sighted on the day of the Shuttle photo, (29 November 1983). This was a relatively calm day after a week of strong south-easterly winds. At dive sites, the plankton were restricted to the surface layer of the water with visibility unaffected. On 30 November 1983 the sea was very smooth and the bloom noticeably thicker. It broke up into solid blocks as their yacht moved through it. The group anchored at Great Keppel Island and did not see the bloom again.

Marine algologists who have observed similar phenomena from the ground and aircraft are confident that it is the blue-green alga *Oscillatoria erythraea*, formerly recorded as *Trichodesmium erythraeum* (Drouet 1968). The bloom is caused by mass accumulations of the alga which fixes nitrogen from the air and so gas vacuoles cause them to float at the surface (Ulbricht 1983). Individual filaments of the alga are in the vicinity of 0·01 mm in diameter. Usually about fifty are loosley welded together to form a small raft just visible to the naked eye, as a sawdust-like fleck (Cribb and Cribb 1985). These small filament rafts are concentrated by the wind into massive rusty surface streaks at scales compatible with the synoptic satellite view. The bloom depicted is being moved as a front by a tidal stream and in a south-easterly direction. East–west movements within the bloom suggest that currents are also asserting their influence. The integrity of the filaments over large distances supports the observation of little or no wind at the time.



A massive phytoplankton bloom in the Capricorn Channel of the southern Great Barrier Reef, Australia, as captured on a 70 mm Hasselblad photograph taken aboard the Space Shuttle.

It is important to monitor *Oscillatoria erythraea* blooms because large accumulations may lead to the death of nearly all small marine animals in the vicinity. Death is probably due to the depletion of dissolved oxygen by the rotting mass and to the release of a toxin from within the algae. Among coast dwellers in Brazil, a recurring illness of respiratory trouble, fever, muscular pain and rash has been linked with appearance of *O. erythraea*. Inhalation of minute droplets of the toxin in the atmosphere are thought to be the cause. Along the Great Barrier Reef, some believe that coral scratches are more likely to turn septic when *O. erythraea* is in the water (Cribb and Cribb 1985).

The occurrence of these surface blooms at synoptic scales are also of interest to oceanographers, since the small planktonic organism creates a vast painting of hydrodynamic processes which are not visible at ship or aircraft scales.

Space shuttle photography is a valuable source of ancillary information on Earth resources. For example, this particular bloom was not recorded by LANDSAT and was only partially recorded by the NOAA AVHRR. As equally important though, such photography and its routine examination draw our attention to spectacular and unusual events.

Acknowledgments

Dr. R. Bryan Erb, NASA Earth Sciences and Applications Division, is acknowledged for supplying the photograph and bringing it to our attention. Ms Anne Hoggett, Australian Museum, Division of Invertebrate Zoology, Sydney, is thanked for responding to an advertisement and acknowledged for the ground information.

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Remote Sensing in the ASEAN Region: An Australian Perspective.

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ABSTRACT

Remote sensing has been proven as a powerful tool for the monitoring and management of natural resources. this tool is now finding application in the countries of the South east Asian region. While some countries, such as Thailand, are already advanced in the use of remote sensing, others are only now transferring this technology into the role of resource management. Recent developments in micro-computer based systems have brought digital image processing within the reach of scientists and resource managers.

This paper describes a programme of technology and application exchange between Australia and the ASEAN countries to establish a remote sensing capability for each member country. Through an ASEAN-AIMS-AIDAB programme the microBRIAN system, developed by CSIRO in Australia, was installed in five ASEAN countries. These systems were then linked to existing facilities and applications developed.

A number of applications are now underway within the AIDAB funded Coastal Living Resources Project (CLRP) project including the mapping of coral reefs ecosystems, the monitoring of land use patterns, mangrove mapping and the analysis of coastal sediment patterns. Case studies are presented using both Australian and ASEAN data and the implications for remote sensing, in particular to remote sensing in the tropical zone, are discussed. The projects have highlighted a number of problem areas unique to the tropics, these include the high incidence of cloud, the quality (generally poor) and high price of data and finally the inadequacy of technical back-up and support.

The future trends as they effect the ASEAN-AIMS-AIDAB project are assessed including the new generation of satellites, solutions to the problems unique to remote sensing in the tropics, the problems of continuity of data and the impact of technological change.

INTRODUCTION

While satellite data has been available for over ten years and aerial photographs for far longer, little of this data has been made available to agencies involved directly with the management and monitoring of coastal resources. One of the prime reasons for this has been the expense of the hardware needed to process and analyse digital remotely sensed data. With the advent of low cost yet powerful Personal Computers the cost of the hardware has fallen to the point where a number of systems are available at prices affordable to Government agencies.

The availability of remotely sensed data to researchers and managers comes at a time when many of the countries of the South East Asian region are experiencing greater pressure to monitor and manage the resources of the coastal zone. Coastal zone ecosystems tend to be the most utilised, this is particularly true for many of the South East Asian countries where much of the available land is in the coastal zone. As populations increase most of the burden is placed on the coastal zone resulting in the conversion of natural ecosystems to modified ones. This process, if not modified and controlled, can have disastrous effects in the ability of the coastal zone to continue to provide resources.

This combination of limited resources and increased pressure for their utilisation has necessitated the development of agencies to monitor and manage the coastal resources. Remotely sensed data provides a unique and essential tool in this task for a number of reasons. It provides an historical data base, for example the Landsat MSS data is available back to the mid 1970's, also a spatial data set and a continuous data set with images taken every 18 to 22 days.

To help bring the technology of digital remote sensing to those agencies involved directly with research and management of the coastal zone in the South East Asian region the Australian Government through the Australian International Development Assistance Bureau (AIDAB), the Association of South East Asian Nations (ASEAN) and the Australian Institute of Marine Science (AIMS) has implemented a programme of technology and application exchange. The project has involved the positioning of a microBRIAN image processing work station in five of the ASEAN countries and the development of a number of applications designed to aid ongoing research and to provide new information for resource management.

This paper presents some of the initial applications under way through the ASEAN-AIMS-AIDAB Coastal Living Resources Project (CLRP). The paper also highlights some of the problems encountered and future developments, both in technology and applications, and the effect it will have on the project and the countries of the South East Asian region.

MATERIALS AND METHODS

The microBRIAN system

The microBRIAN system was developed by CSIRO in Australia initially for the mapping of shallow water systems for the Great Barrier Reef Marine Park Authority in their role as managers of the Great Barrier Reef (BRIAN stands for Barrier Reef Image ANalysis). The system has since been commercialised through an arrangement with CSIRO and an external company (MPA Pty Ltd - see acknowledgements for address) and the system extended to a multi-purpose image processing system.

The system is based around an IBM type AT Personal Computer with a RBG high resolution colour monitor and a colour ink jet printer. The system has an option of a 1600 BPI tape drive with software for directly reading image data on Computer Compatible Tapes (CCT's), though this was not supplied initially with the systems used in the project due to monetary restrictions though the Philippines have since bought a tape unit with one on order for Thailand. A full discussion of the BRIAN system (the mainframe version of microBRIAN) can be found in Jupp *et al* (1985) and details of the microBRIAN system from the commercial distributors.

Data Sources

Most of the data available for the last ten years has come from the Landsat series of satellites launched by the American Government initially under NASA and now under EOSAT. The data from Landsat satellites one through to five comes from a sensor called the Multi-Spectral Sensor (MSS) which has a resolution or pixel size of approximately 60 by 80 meters and a scene coverage of 185 by 185 kilometres. The MSS instrument has sensors in the green, red and two in the infra-red part of the spectrum.

On the latest two Landsat satellites another instrument called the Thematic Mapper (TM) has been carried giving 30 metre pixel resolution for the same scene size. The TM also has more spectral bands with bands in the blue and thermal infra-red as well as bands in the green, red and near infra-red part of the spectrum. Importantly the TM data is collected at the same time as the MSS data so that the two co-register, this allows the two data sources to be overlaid directly.

The French SPOT satellite, operated commercially through SPOT Image, gives very high resolution images (pixel resolution of 20 by 20 metres) with a scene size of approximately 60 by 60 kilometres. The data has only three spectral bands centred around the green, red and near infra-red part of the spectrum. Full details of all the satellite sensors can be found in Richards (1986).

This year should also see the availability of data from the Japanese MOS-1 satellite, this has instruments similar to the Landsat MSS but with a pixel resolution of about 50 by 50 metres. Future developments include another SPOT satellite, Landsat 6 and maybe 7 satellites as well as the development of the Polar Platform with a variety of instruments.

In addition to the satellite born sensors there are a number of aircraft mounted sensors that either replicate the satellite sensors or provide increased spectral resolution along with the increased spatial resolution. These scanners tend to be expensive to operate due to the high cost of the aircraft facilities but this is balanced out, to a degree, by the quality of the data. For the South East Asian region the only likelihood of this sort of data becoming available is as a joint project with an external government body such as the United States survey departments.

In choosing the data source to use for a particular project three main criteria are important, these are; spectral resolution, spatial resolution and the cost and availability of the data. In the past most of the work involved the Landsat MSS data, in the future as a number of data sources become available it may become possible to choose data for particular analysis.

ASEAN-AIMS-AIDAB CLRP Project

The remote sensing part of the project has been co-ordinated through AIMS, the distributors of the microBRIAN system and an external consultant: Dr Debbie Kuchler of Mapping and Monitoring Technology Pty Ltd. The microBRIAN systems were first installed in the latter part of 1986 with one system in each of Thailand, the Philippines, Malaysia, Indonesia and Singapore. The systems were placed in agencies involved with research and management of the coastal zone including shallow water habitats and coastal ecosystems.

In early 1987 both Dr Kuchler and representatives from the CSIRO division responsible for the development of the microBRIAN system visited each country to hold workshops. Some problems were found with the hardware necessitating the transport of some of the hardware back to Australia to be fixed. Problems with hardware and obtaining images delayed the project some time so that by mid 1988 each country had images pertaining to areas of interest and a number of applications are now being developed.

RESULTS

This paper presents a number of case studies rather than data as such. the results section will deal with a number of applications within the Living Resources in Coastal Areas project.

1. Mapping of coastal land forms - Bedok coast Singapore.

The study site for the Singapore images is the Bedok coast between Singapore city and Changi airport. The area is being transformed from the original coastal land form through land reclamation and urbane development. The imagery is used to assess the effect of these developments. particularly the transport developments between Singapore city and Changi airport on the surrounding marine and terrestrial systems.

Because Singapore is small and falls on the junction of four Landsat scenes SPOT HRV XS data has been used. This provides the resolution required and gives good discrimination of urbane features though it has little historical value with data only available for the last few years. The microBRIAN system is located at the Singapore National University within the Zoology Department. While some problems obtaining data has occurred it is hoped that more SPOT data can be bought.

If more data can be obtained there are a number of projects currently under way that could use the remote sensing as a tool of investigation. One such project is the mapping of the remaining mangrove resources. Small areas of mangroves are present along the Strait of Johor but these are under threat from aquaculture activities. It is hoped to map the remaining mangroves using SPOT data to ascertain the area. distribution and condition of the remaining mangrove ecosystems.

2. Broad resource survey - Gulf of Thailand.

The work in Thailand involves resource surveys of part of the Gulf of Thailand. The gulf is important for fisheries and has a number of heavy industrial plants located around it. The survey project hopes to identify and map a number of coastal vegetation types and to examine the interaction of these ecosystems to the marine environment. Of particular interest is thermal pollution from industrial plants into the Gulf and the resulting effect on nearshore fisheries.

Thailand has its own Landsat receiving station and supplies data to most of the countries of the South East Asian region. This has given them a large image library. particularly of MSS data. and it makes sense to use this resource in initial broad survey applications. The Landsat MSS data provides large scale data with low cost and low processing overheads. For these reasons. for the initial studies. the MSS data has been selected over some of the newer. high resolution data.

3. Broad resource surveys - Peninsular Malaysia.

The study area is the Tangong Dawa coastal area on Peninsular Malaysia. Again the emphasis is on broad scale surveys of resources. this data has been lacking until recently. The remote sensing project is forming an important part of obtaining a data base on the extent and condition of various coastal ecosystems.

The microBRIAN system is located at the University Pertania Malaysia which is an agricultural University located in Kuala Lumper. This location provides access to scientists working in agricultural projects as well as fisheries and coral reef resource personnel.

Again problems have been experienced with the hardware and images have been difficult to obtain. Image acquisition has been difficult for a number of reasons. The high cost of the SPOT data combined with the long delay has made it unfeasible for these sort of broad scale resource surveys. The Landsat TM data is only just becoming available. The Landsat MSS data while relatively cheap is often of poor quality. this seems particularly true of data from the Thailand Landsat station. and again has a long access time. All of these data sources suffer the common problem of cloud cover. finding cloud free images of the areas of interest is often difficult.

4. Coral reef mapping. resource surveys - the Philippines.

More than any country in the South East Asian region. the Philippines has recognised the importance of managing the coastal zone in the face of increasing population pressures. Through large increases in the use of aquaculture ponds and the growing of coastal rice. large areas of coastal habitat. mainly mangroves. have been utilised. Similarly the coral reefs suffer extensively from destructive fishing techniques and from the removal of coral rock for building. Further away from the coast much of the timber forests have been removed. this. through increased siltation. can lead to the destruction of much of the coastal marine resources. Finally the expansion of urbane areas threatens much of the remaining intact coastal ecosystems.

The Philippines are advanced in the use of satellite remote sensing for resource surveys through experience with the use of a G.E. Image 100 image processor. This system was located at the Natural Resources Management Center (NRMC) in Manila but due to its age was becoming increasingly unreliable. The microBRIAN system provided a replacement and allowed the continuation of the work.

A number of projects are continuing through a new management agency called NAMRIA. Projects underway include geomorphological mapping of reefs with Apo reef as a test site. In areas such as Batangas and Palawan changes in urbane spread and the corresponding decrease in mangrove habitat is being mapped using a combination of digital satellite data and aerial photography.

5. Coral reef mapping, island surveys - Indonesia:

The study site for Indonesia is the Seribu archipelago of islands near Jarkata. The islands have both forest and sandy areas and are surrounded by reef development. The project involves the mapping of the island ecosystems as well as the reefs around them. Landsat MSS data is used for reasons of cost and availability though the small area of the islands would make a higher resolution data source more applicable. The project has just begun and it is hoped to back up remote sensing work with some field studies.

Indonesia now has a Landsat receiving station giving it access to a large volume of data. Now that this data is available within the country the application side needs to be expanded so that full use of this facility, for management and research, can proceed.

There are a number of studies that are being developed to make use of the Landsat data. One involves the tracking of sediment and pollution rich water from the area around Jakarta across to Sumatera. Another involves mapping mangrove resources in a study site on the eastern of Java near Surabaya. Here remote sensing data will be integrated into existing data bases to provide an overview to the site state and dynamics.

6. Coral reef mapping, mangrove surveys - Australia:

While not part of the ASEAN-AIMS-AIDAB project the Australian Institute of Marine Science has undertaken a number of studies in similar ecosystems to those of the ASEAN countries using remote sensing.

One project is investigating the detection in the change in reef substrate caused by the Crown-of-Thorns (*Acanthaster planci*) starfish. This starfish consumes coral and often occurs in large numbers. the result is that the coral cover quickly drops and is replaced by algae. This coral to algae shift is what the investigators are hoping to detect. Before this can be achieved a number of ground truthing methods have to be formulated and tested and the validity of extracting biological information from satellite data demonstrated. The work currently is involved with answering the latter two points with the aims of detecting the impact of the Crown-of-Thorns starfish on the reef ecosystem.

Another project involves the comparison of Landsat TM data and aerial photography for mangrove surveys. The aerial photographs were taken in 1964 with the TM images taken in 1986. Comparison of the two data sets shows that many of the mangrove features have been stable throughout this time span. this may challenge many of the ideas scientists have about the stability of mangrove systems especially in a cyclone prone district.

The results presented here represent the first stages of some of the applications. many of these applications are biased towards large scale resource surveys as this data has not been available until this project. Once this need has been satisfied more detailed research projects will be initiated.

DISCUSSION

This project has highlighted a number of areas where remote sensing can play a part in the research and management of the coastal zone. It has also highlighted a number of problem areas that need to be corrected before remote sensing can find a wider application in the South East Asian region.

Much of their initial effort was put into the setting up of the systems and establishing a system of technical and hardware support. This has been made difficult by the distances and cost involved in moving personnel as well as a lack of anticipation that this would be a problem area. One of the key points that the project needs to address is the provision of hardware technical support through maintenance contracts in each country. The provision of this would drastically reduce the down time of the systems and must be seen as a major priority for future projects.

Once the systems were installed and running the second priority was the training of personnel. The microBRIAN software is by no means trivial and requires a long period for both familiarising with the software and then extending this to expertise in particular applications. One problem that was encountered was that the personnel that were trained were often transferred to other projects or were only concerned part time with this project. This meant that much of the expertise was lost. the assignment of one or two people full time to the microBRIAN system was seen as a vital step in ensuring that the expertise was transferred to each country. The provision of a microBRIAN operator in each country also allowed for the introduction of maintenance plans for the hardware. in particular for the ink-jet printers that require constant maintenance.

The training was done through workshops and concentrated "hands on" work by the appointed people. it was found that it was essential to follow up training with regular visits to ensure that the training was successful and that the work was progressing.

One final point that will become more important if the project continues is the upgrading of the systems as technology changes. For example the cost of mass storage devices (such as hard disks) has fallen dramatically opening the possibility of upgrading the memory capacity of the installed machines. It has been found that the tape drive option is essential as it allows the image tapes to be read directly rather than needing another system to subset and re-format the images. The problem of data acquisition will only be solved if each unit can process the data from the satellite ground stations independently instead of the current situation where this is done by an outside agency. At the moment only the Philippines has a tape unit with one on order for Thailand. if the project continues it is hoped to rectify this.

Most of the work in the initial phase has concentrated on applications based on broad scale resource surveys. The data source best suited to this. based on the criteria set out previously. is the older Landsat MSS data.

This data source has a wide coverage. good historical data is available and it is relatively cheap and easy to acquire and process. For countries such as Singapore for which the MSS data is not suitable the higher resolution SPOT data may be better. I think it is important. at time when people are switching to the higher resolution data. to remember that the MSS data has a continued role for large scale surveys.

The cost of the SPOT data is high and some of the early data are of questionable quality, this combined with a long delay in obtaining new images makes it less attractive for many of the countries of the South east Asian region. The Landsat TM data because it coincides with the MSS data it may be valuable in supplementing the MSS data in areas where higher resolution, both spatial and spectral, is required. This combination of MSS and TM data may prove to be the most efficient data source.

All the data suffers from the problem of cloud cover. In a study of the use of Landsat MSS images to estimate rice crops in Bangladesh and Thailand. Currey *et al* (1987) found that cloud cover so effected the area that the imagery was not an efficient method of crop estimation. The answer to this may come from two directions. The first may come from active sensors that are able to penetrate the cloud cover. As none of the countries in the South East Asian region have the capability of launching their own sensors they have to rely on other countries to identify the problem and to design sensors that can overcome it.

The second answer may be to use digitised aerial photographs. these are often available through archives and for small regions achieve a much higher resolution than that of satellite images. The draw back is the high price of obtaining new images, the cost of digitising them and the difficulty in obtaining images of a particular place at a particular time.

The problem of cloud highlights the fact that most of the countries of the South East Asian region and indeed Australia, rely on sensors designed and deployed by other countries. This has the effect of locking these countries into the development path of the more advanced countries. The trend to data with higher resolution but also an associated higher cost may exclude some of the countries from using remotely sensed data in a routine fashion. For many of these countries the Landsat MSS is the most effective data source, the MOS-1 satellite of the Japanese may provide continuity of data if the Landsat MSS data ceases to become available. The problem of data cost and acquisition rights is one that has to be addressed if remote sensing is to expand in this region.

CONCLUSION

The project has highlighted a number of problems associated with the development of applications based around complex tools. The remote sensing equipment and methodology requires a commitment in terms of personnel for the true worth of the method to be realised.

One of the lessons to come from this project is that any technical equipment requires within country service contracts and any company tendering for overseas contracts must realise this and budget accordingly.

A second point involves the commitment of personnel. For any transfer of technology to work there must be a constant group of people that have the time and resources to ensure that the transfer process is a cumulative process. For this project this has been confounded by the problems with the hardware and in obtaining images. It is hard to justify the dedication of a person to a project that has no relevant data (images) or where the hardware essential for the project is inoperable.

The above points refer to any programme of technology transfer. there are a number of points that have come out that relate to the remote sensing aspect.

The first is that for many countries and for many applications the Landsat MSS data is the most efficient data source currently available. The MSS data has good historical global coverage. it is still relatively cheap and can be received within the South East Asian region. If this data is overlaid with the newer TM data where higher resolution is required then this may provide a compromise between cost and image resolution.

The second is that for remote sensing to become a major part of the research and management activities in this region there has to be a commitment to the continuity of the data and to maintain a reasonable cost structure.

The problem of cloud is one that probably will not be addressed in the near future. the solutions such as active sensors or air-born sensors may prove to be too expensive for routine work. The dependence of these countries to the development plans of other countries. in terms of technology change and development. may result in inappropriate data and so see remote sensing decrease in value as a tool for management and research.

Finally the application side of remote sensing should drive the technology. not the other way around. this applies to all levels from the data sources to the processing systems. It must be remembered that the current applications are biased towards answering very basic questions about the coastal zone and so requires a technology suited to this. Once this has been done then more complex research orientated applications can be developed.

The role that remote sensing plays in the development and management of the coastal zones in the countries of the South East Asian region depends on the ability of government agencies to integrate remote sensing into routine management programmes. The success or otherwise of this depends on how the technology is presented. this why projects such as this one are of importance to both remote sensing as a science and to remote sensing as a tool of investigation and management.

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For people interested in the microBRIAN system the commercial retailers. as of 1988 are:

MicroProcessor Applications Pty Ltd
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Blackburn. Vic 3130 Australia.
Phone: 03 - 894 1500

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STATUS OF HIGH-TECHNOLOGY REMOTE SENSING FOR MAPPING AND MONITORING CORAL REEF ENVIRONMENTS

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ABSTRACT

This review paper assesses from a market perspective the status of high-technology remote sensing for mapping coral reef environments. The goal is to eventually obtain an operational digital mapping and monitoring system for coral reef environments using technology which is appropriate from the users point of view. Current technologies are unable to fulfill this goal because of their lack of refinement for coral reef environments. The development of a spatially and spectrally versatile sensor customized for users needs is proposed.

INTRODUCTION

Remote sensing technology exploits the fact that variations in the physical properties of sunlight being reflected from water bodies, shallow seas and submerged features is providing a wealth of information on coral reef ecosystems. For high-technology operational sensors such as airborne scanners and those deployed on satellites, their adoption requires the recording, interpreting and use of this information to be more cost/effective than the traditional practices of aerial photography and ground survey.

The application of high-technology remote mapping techniques to coral reef management and research began with the launch of ERTS-1 in 1972. The technology encompasses three main elements:

- Imagery and other data forms acquired by a wide assortment of sensors aboard ships, aircraft or orbiting satellites
- Information interpretation techniques ranging from conventional visual image interpretation to sophisticated interactive computer systems
- Means of presenting the information as a useful product, such as base-map overlays, colour-coded thematic maps, computer-generated maps and statistical data.

Research and Development (R&D) is often claimed to be the process which results in a usable end product. However, for high-technology coral reef remote sensing this process has been ineffective in harnessing a potential mass of users who have been interested but hesitant to use the products. This can be interpreted as saying "please put them in a usable form". This request from the marketplace highlights the fact that high-technology remote sensing for coral reefs will only be adopted as a common mapping and monitoring method if it is researched, developed, market tested, customized and finally marketable as a user-tailored tool. Consequently, this review paper assesses the status of high-technology remote sensing (from hereon referred to as remote sensing), from a marketplace perspective and for the mapping of coral reef environments.

Considerable world-wide R&D efforts have been expended on testing and developing the earth resources mapping value of remotely sensed data. These efforts are reviewed against the goal of obtaining an operational digital mapping and monitoring system for coral reef environments using technology which is most appropriate from the users point of view.

SENSOR SYSTEMS FOR CORAL REEFS

Aboard Satellite Platforms

Applied research on the capability of satellite based sensor data for mapping coral reef environments has been conducted since 1975 (Smith et al. 1975). The research has concentrated on the informational value for both mapping and surveying (Jupp et al. 1982) of data which have been collected from wavelengths selected for their suitability to a range of earth resources targets. The satellite-based sensors are listed in Table 1. Landsat MSS (Bina et al. 1978, Jupp, 1985) and Nimbus-7 CZCS sensor data (Claasen et al. 1984, Hallock 1988) have been the most researched and applied. The conclusions of the work highlight that for mapping purposes, sensor design and capability has the major control over the informational value of the scanned physical variations in the reflected light. From a monitoring viewpoint, the major control over data value is the pre-programmed orbital satellite platform and the deployment of largely non-programmable sensors which do not allow the supply of routine standardized coral reef data. This problem is often highlighted by researchers (Kuchler 1985). Since the supply of data is opportunistic, there has been very little effort put into designing a coral reef monitoring program based on remote sensing. This is because the information is difficult to obtain. Jupp (1986) believes the solution to the problem lies in adopting the multiplatform (satellite, aircraft, ship and buoy) sampling strategy proposed for the NASA supported MArine Resources EXperiment (MAREX) program (OCS Working Group, 1982).

For synoptic-scale mapping, a satellite-based sensor is required because the nature of the platform allows the uniform measurement of the

Table 1. Some mapping and monitoring applications amenable to high technology remote sensing of coral reef environments.

Mapping and Monitoring Applications	ENVIRONMENTAL PARAMETERS DETECTABLE VIA REMOTE SENSING												
	Benthic vegetation	Currents eddies	Water colour	Sea surface temperature	Suspended sediments	Wave height	Wind velocity	Topography	Topographic aspect	Bottom type	Upwelling areas	Chlorophyll a	Bathymetry
Identification of reef covers	X							X	X	X			X
Identification of fishing grounds		X	X	X				X			X	X	X
Identification of fish nursery areas	X	X	X	X	X			X	X	X	X		
Primary productivity estimates											X	X	
Mapping of mangroves and marshlands			X		X			X	X				X
Mapping of seagrass beds	X							X					X
Mapping of shallow water depths								X					X
Mapping of potential sites for aquaculture													
Environmental monitroing of chlorophyll a			X								X	X	
Fishing operations	X	X	X	X	X	X	X			X	X		X
Coral harvesting								X		X			X
Phytoplankton blooms		X	X								X		
Effects of coral blasting	X		X		X			X	X	X			
Dynamite fishing activities	X		X		X			X	X	X			
Mapping of reef zones	X									X			
Mapping of reef perimeters								X		X			X
Geocoding of reefs								X					X
Mapping water quality parameters		X	X			X	X						
Mapping coral spawn		X		X			X						
Monitoring reef health	X	X	X	X	X	X		X		X	X	X	X
Assessing sea surface roughness						X	X				X		
Assessing bottom topography						X	X	X					
Platforms and/or sensors	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS AVHRR NIMBUS- CZCS*	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS AVHRR NIMBUS- CZCS*	AMS MOS-1 NOAA AVHRR NIMBUS CZCS* L'sat TM	Dig. APs AMS VTIR L'sat MSS L'sat TM SPOT MOS-1	SEASAT* GEOS1-3* SLAR	NIMBUS7* SEASAT* SLAR	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS	Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS	L'sat MSS L'sat TM SPOT MOS-1 NOAA AVHRR NIMBUS CZCS* AMS	LIDAR NIMBUS CZCS* AMS	LIDAR Dig. APs L'sat MSS L'sat TM SPOT MOS-1 AMS

Legend

LIDAR = Laser Depth Sounder and Laser Fluorosensor
* = Archive data only
APs = Aerial photo's
AMS = Airborne Multispectral Scanner
Dig. = Digitized
L'sat = Landsat

abundance and distribution of phenomena in time and space. Experimental research has shown that for synoptic mapping the most tailored system (platform:orbit characteristics:optical sensor combination) for coral reefs was the Nimbus-7 Coastal Zone Color Scanner (Wolanski et al. 1984). The market testing of this system has been undertaken by the Great Barrier Reef Marine Park Authority and the Australian Institute of Marine Science in their Great Barrier Reef Crown of Thorns Starfish Program. For coral reefs generally and even given the large 348,700 square kilometre extent of the Great Barrier Reef, this satellite-sensor combination could be refined to give a smaller spatial footprint of around 400 metres. Furthermore, this requirement needs to be expressed to the developers of the new generation of Ocean Color Imagers. The compatibility of the NOAA-AVHRR combination for Sea-Surface Temperature mapping of coral reef environments will be assessed in the near future by the Australian Institute of Marine Science in consultation with the Great Barrier Reef Marine Park Authority.

The first progress towards interpreting and presenting satellite data in a usable form was made in the area of bathymetry and survey (Bina 1979, Doak et al. 1980, Pirazzoli 1984). The Great Barrier Reef Marine Park Authority invested heavily in the development of standard bathymetric map products (Jupp et al. 1984). From its origins within a research institute (CSIRO), the technology was successfully transferred to an operational mapping bureau (Australian Survey Office). The Marine Park Authority motivated and participated in the development and market testing of the technology because high priority information is required for recommending Park boundaries and developing zoning and management plans. Increasingly, as more types of satellite images become available, this technology imagery is being consulted in attempts to understand the nature and cause of significant events and problems within coral reef ecosystems (Oliver et al. 1987, Bour et al. 1985, D.M.S. 1985).

The common and significant element in all this work, is that the information supplied does not completely meet the user's need and as Kelleher (1983) points out, even at a significant cost saving over conventional data collection methods. This is because the data which is supplied by the satellite sensor has been collected from wavelengths selected for a range of earth resources targets other than coral reefs. Consequently, Lyzenga (1987) suggests co-ordinating the imagery with other traditional data. Thus, it is opportunistic that the data can even 'largely meet the informat- ion need' (Kelleher 1983) of the user (see Table 1). The current testing of data from recently deployed SPOT HRV (Ricard et al. 1988) and MOS-1 satellite sensors from coral reefs in the Indian Ocean, South-East Asia, South Pacific and Australian regions will generally come to the same conclusion. This is because there is no current satellite based sensor which has been spectrally and spatially customized for specific coral reef mapping tasks. The problem of the equatorial cloud cover associated with coral reefs has also not been addressed.

Aboard Airborne Platforms

Considerable amounts of airborne sensor data has been collected over coral reefs in New Caledonia and the Great Barrier Reef. Unfortunately, due to the lack of resources the Great Barrier Reef data awaits a rigorous investigation. Analysis of the New Caledonian data has resulted in usable end products in the form of habitat and water depth maps (Bour et al. 1985, Kuchler et al. 1988). These products however, still await market testing.

Problems which hamper the operational adoption of airborne sensor data are currently similar to those for the satellite based sensors. Data supply is opportunistic in the sense that it either has to be especially commissioned or it results from an invitation to participate in a multi-client mission. For cost reduction purposes these missions are usually limited to a specified region. Similarly, the sensors which are the most readily and frequently available are both generalized for oceanographic applications and hardware controlled. Consequently, they lack the versatility required to spectrally and spatially map the complex array of coral reef features. This is partly evidenced by the increasing practice of digitizing existing or commissioned aerial photography (Maniere & Jaubert 1985, Courboules 1988, Catt & Hopley 1987, Kuchler, Bour & Joannot - work in progress, Tetembia reef, New Caledonia).

DIGITAL IMAGE PROCESSING FOR CORAL REEFS

The evidence in the literature plus the increasing use of image processing systems in institutions concerned with coral reefs highlights the recognition of the storage, information processing and value-added roles that digital image processing technology is playing in the mapping and monitoring of coral reef environments. Their versatility and utilization ranges from education about reef environments, digital analysis of historical and current aerial photographic records, airborne scanners and satellite data and the merging, comparison and enhancement of multi-source data.

Digital image processing is a broad scientific field out of which has developed many digital image processing systems. The considerable variety and availability of these systems now requires an interested party to do extensive market research before making a commitment. Any system that is chosen for users working within coral reef environments must be compatible with their conditions and customized for their mapping needs. A small micro-based image processing system called microBRIAN (Jupp et al. 1985) has contributed significantly towards fulfilling these requirements.

MicroBRIAN is a comparatively inexpensive, compact system in which the BRIAN (Barrier Reef Image ANalysis) algorithms have been tailored to the mapping of shallow water environments. The system at present, is the end-product resulting from an extensive research and development phase. The ASEAN countries participating in the ASEAN-AIMS-AIDAB Living Resources of Coastal Areas program have contributed over the last two years to the market testing of the system. Their input is invaluable in attempts to optimize its customization. Scientists at the University of La Reunion and managers from the Great Barrier Reef Marine Park Authority have also participated.

The goal of these efforts is to produce an accessible and useful digital mapping and monitoring tool which has been customized for shallow water and coral reef environments. Such a tool must be superior to the current, commonly used and traditional methods of mapping and monitoring. When the goal is achieved, digital mapping techniques will eventually become adopted on a mass scale. This is because the information required for management will be more accessible, more reliable and more organized. This in turn will lead to more effective management and hopefully wiser use of coral reef resources.

TECHNOLOGY TRANSFER

Progress in transferring high-technology remote sensing tools into the mapping and monitoring activities of coral reefs has been comparatively slow. The reasons why can be categorized into three areas; namely, the general geographical isolation of users and thus the unavailability of experts and advice support people; the need for further refinement in the various technologies; and, consequently, the lack of a total digital mapping package. Since these three obstacles are preventing the mass adoption of technological advancements, they need to be overcome.

Plans are underway with researchers at James Cook University to develop an advice support service to aid in technology transfer. The objective is to devise a computerized software consultancy package that asks for a users mapping or monitoring requirement, recommends a cost-effective remote sensing tool and justifies its appropriateness. The goal is to make specialist remote sensing advice accessible to managers and mapping personnel located within coral reef environments. It is planned to offer the software as a utility package on the microBRIAN system.

CONCLUSION

The goal is an operational digital mapping and monitoring system for coral reef environments using the technology which is most appropriate from the users point of view. The principle obstacle to the attainment of this goal has been the lack of precise refinement of the technologies.

Currently, the most widely used remote sensing technology is aerial photography because it utilizes the versatility of an airborne platform and its information is easily accessible. Aircraft are the most appropriate platforms for routine regional remote data collection within equatorial coral reef regions. Since aerial photographs render significantly higher quality information when interpreted using digital image analysis, the customization of an airborne digital mapping sensor system would appear attractive from the users perspective. The cost/effectiveness of such a system would be a function of the spectral and spatial versatility of the instrument and its operational commitments within the global marketplace. The compatibility of the sensor's data with a microBRIAN image analysis system located with the ground-based user would supply the pieces required to develop an operational digital mapping and monitoring tool in a regional context. In order to satisfy the synoptic mapping requirements, a similar sensor needs to be designed for deployment on a satellite platform.

If this argument is accepted by the coral reef R&D community, the next step in the progress towards providing an operational digital mapping and monitoring tool for coral reef environments is the identification of the processes required to network the three customized pieces (satellite sensor, aircraft sensor and data analysis system) together.

ACKNOWLEDGEMENT

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Coral reef survey method for verification of Landsat MSS image data

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ABSTRACT

The use of remote sensing techniques demands some method for checking the accuracy of the data obtained. "Survey controlled reef assessment" (SCRA) is a survey method developed for the verification of Landsat MSS reef cover classification maps. It utilizes satellite-based ground control, remotely sensed images and visual observation. Data collection and assignment to a quadrat with known geographic coordinates allows its integration with ancillary data. A recent excercise on Hardy Reef, Great Barrier Reef, Australia is used as an example.

Surface covers on coral reefs can be mapped at any level of spatial detail, dependent on the mapping tool and purpose. The Landsat multispectral scanner (MSS) maps at a spatial resolution of approximately 59 x 79 m. When using Landsat images for coral reef mapping, the problem is to determine the scale of spatial detail at which coral reef covers are resolvable. This is achieved by image classification, with the resulting product being a classified reef cover map. The use of remote sensing techniques, however, demands that the accuracy of such maps be checked. Furthermore, the spatial compatibility between surface reef covers and a Landsat MSS image is highly variable, a function of varying reef sizes and depths of submergence. Consequently, the gross variability of reef covers on the classified image has to be compared with similar scale reef cover patterns on the ground.

A method for verifying Landsat images is needed. This article outlines the problem and proposes an appropriate survey method.

EXISTING VERIFICATION METHODS

Verification of Landsat coral reef image maps poses the problems of achieving ground control, devising a suitable sampling strategy, and developing a data recording technique. The two reported verification methods approach these problems in different ways. A method adopted by Mayo *et al* [7] and Kuchler [3] uses a post (Landsat) image classification sampling strategy which results in numerous pixel-sized point sampling units. For example, a study on Heron Island Reef resulted in 341 sample sites [3]. The point sampling unit, the sampling strategy and the detailed mapping scale were devised for a particular and in-depth research purpose. They are demanding and, consequently, operationally unfeasible. Ground control was achieved by the use of a rectified photomap from which photo information for selected points was located on the ground.

The laboratory-based method adopted by Jupp *et al* [5] is an interpreter-based verification system which overcomes the difficulty and expense of remote coral reef field visits. It relies on scientists who have extensive knowledge of specific reefs to interpret the Landsat classified reef cover classes. The interpretations are then used to map remaining unknown reefs within the respective full Landsat scene. Ground control is usually achieved through aerial photograph overlays. Since the method is relatively quick and inexpensive, it is operationally very attractive, but the maps for the unknown reefs still need to be verified.

The technique presented here is an attempt to compromise between these two verification methods.

METHOD

Survey controlled reef assessment (SCRA) is a method for obtaining proportional area estimates of reef covers at a specified satellite image scale and within quadrats with known geographic coordinates. These survey-controlled quadrats form the map base and survey control is currently the most accurate geographic positioning system available.

The survey method should be compatible with the task. Since the task was to estimate the surface area of reef covers at image scales, a general assessment survey technique as outlined by Kenchington [2] was employed. A combination of ground control points, remotely sensed images and visual observation was used. A recent exercise on Hardy Reef, Great Barrier Reef, Australia (Figure 1) provides our example.

PRE-SURVEY REQUIREMENTS

Before the actual ground survey and for survey planning purposes, several requirements have to be fulfilled regarding images, data recording, ground control, equipment and personnel.

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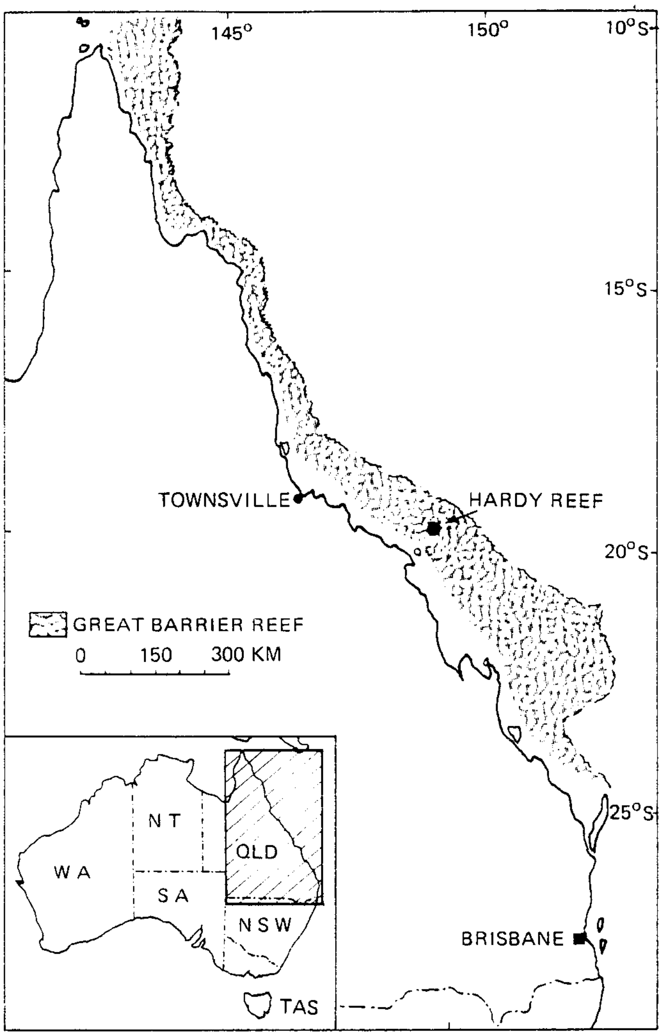


FIGURE 1 Location map

IMAGES

Optimally, all available images for the particular reef to be surveyd should be collected together for use in survey planning. Such images may have been acquired aboard aircraft or satellites and may have been generated using cameras or scanners.

The following seven images, if requested in advance, are available for most reefs on the Great Barrier Reef and constitute a "reef survey planning set".

(1) a raw Landsat MSS image map (Figure 2), which provides a comparative base for the other images in the set.

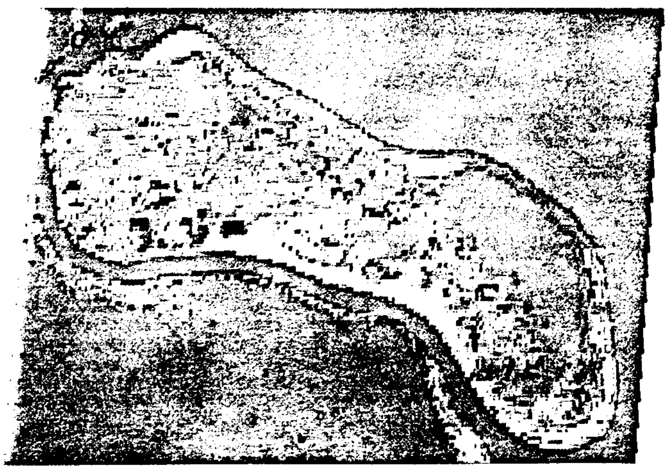
(2) a classified Landsat MSS image (17 classes, Figure 3). For Hardy Reef, 17 was the maximum number of classes required for a general inventory of surface reef covers.

(3) a classified Landsat MSS image (seven classes, Figure 4). The maximum number of classes into which the image is classifed is usually based on the variation within the image data and/or the mapping purpose. For the number of classes chosen, a classified image with approximately half that number of classes should also be produced. This latter image is invaluable when it becomes evident in the field that the original number of classifications was too high.

FIGURE 2 Landsat MSS raw data image of Hardy Reef (scale 1:30000)

(4) a Landsat MSS exposure image map (Figure 5), which enhances topographic and aspect information [5].

(5) a Landsat MSS depth of penetration image map (Figure 6), which gives an indication of approximate water depths and turbidity levels [5].



DESCRIPTION

COLOUR	DEPTH (M)	SUBSTRATA	
	>15	UNKNOWN	
	11.7 - 15	UNKNOWN	BAND 4 ZONE
	8.3 - 11.7	UNKNOWN	
	5 - 8.3	UNKNOWN	
	3.5 - 5	CORAL	
	3.5 - 5	CORAL; SAND	
	3.5 - 5	SAND	
	2 - 3.5	CORAL	
	2 - 3.5	CORAL; SAND	BAND 5 ZONE
	2 - 3.5	SAND	
	0.5 - 2	CORAL	
	0.5 - 2	CORAL; SAND	
	0.5 - 2	SAND	
	0.2 - 5	CORAL	
	0.2 - 5	SAND	BAND 6 ZONE
	0 - 0.2	CORAL	
	0 - 0.2	SAND	

FIGURE 3 Landsat MSS 17 class classified image of Hardy Reef (scale 1:30000)

COLOUR	DEPTH (M)	SUBSTRATA	
	>15	UNKNOWN	BAND 4 ZONE
	10 - 15	UNKNOWN	
	5 - 10	UNKNOWN	
	2.0 - 5	CORAL	BAND 5 ZONE
	2.0 - 5	SAND	
	0 - 2.0	CORAL	
	0 - 2.0	SAND	

FIGURE 4 Landsat MSS seven-class classified image of Hardy Reef (scale 1:30000)

(6) colour or black-and-white aerial photographs.

(7) a 1:5000 rectified photo map or orthophoto map [6].

If some of these images are unavailable, the following three fulfil the minimum requirements for planning:

(1) a classified Landsat MSS image (17 classes, Figure 3);

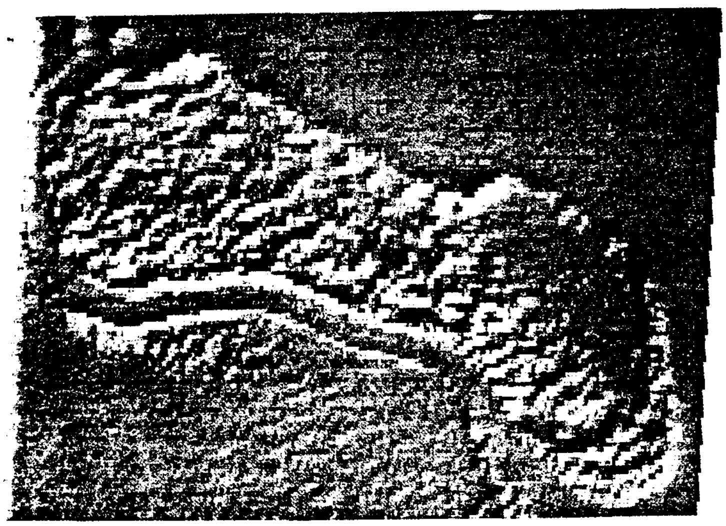


FIGURE 5 Landsat MSS exposure image of Hardy Reef (scale 1:30000)

FIGURE 6 Landsat MSS depth of penetration image of Hardy Reef (scale 1:30000)

(2) a classifed Landsat MSS image (seven classes, Figure 4);

(3) colour or black-and-white aerial photographs.

DATA RECORDING

Recording reef survey site details and reef cover information requires the following items:

(1) data sheets (preferably on waterproof paper) as illustrated in Figure 7.

(2) laminated xerox copy of aerial photo for using in the field. The aerial photo information is invaluable for marking the area covered by sites, recording buoy positions and details, devising an "order to visit" strategy, and planning transect patterns.

(3) laminated (ortho) photo map, if available, which may provide better information than the conventional aerial photo.

GROUND CONTROL

Ground control is a particular problem for coral reefs because of the general lack of topography and surveyed points. Ground control can be achieved by at least three methods which are listed below in descending order of accuracy.

(1) Absolute survey control involves the cooperation of hydrographic surveyors with a sounding vessel. Survey control is established by satellite doppler observations on at least two, but preferably four reference points in the area. The control point is usually marked by scaffolding towers erected on the reef. Distance-measuring equipment on the survey boat provides simultaneous ranges to each reference point allowing instantaneous computation of precise ($\pm$ 3 m) ground coordinates. Quadrat corners can be set and marked by buoys over predetermined image locations or can be positioned and later measured.

A REEF NAME: OBSERVER NAME:
TIME: SITE NO:
DATE: TOW NO:

B PRIMARY STRUCTURE - THE FLOOR

Slope: ——— °
Depth: ——— meters
——— % SAND on floor
——— % live organisms (hard or soft corals and sponges but not macro algae)
——— % dead standing coral
——— % macro algae
——— % RUBBLE on floor (includes dead non-standing coral)
——— % BENTHIC VEGETATION on floor (not including macro algae)

C SECONDARY STRUCTURES on or rising FROM FLOOR
——— % SMALL BLOCKS (< 1 m diameter) on floor
——— % live organisms
——— % dead standing coral
——— % macro algae
——— % LARGE BLOCKS (> 1 m diameter) on floor
——— % live organisms
——— % dead standing coral
——— % macro algae
——— % PLATFORM rising from floor
——— % live organisms
——— % dead standing coral
——— % macro algae
——— % sand

FIGURE 7 Survey data sheet

(2) Cartographic survey control uses either an orthophoto map of a rectified photo map to obtain geographic coordinates for a selected ground point. Errors in the coordinates are caused by the photogrammetric process by which the maps are produced [6] and the precision with which a coordinate can be read from a map.

(3) Photographic survey control uses high-resolution aerial photographs to locate photo points for use as ground control. Since it is not possible to acquire truly vertical photographs, however, the photograph contains a degree of displacement and is not an absolute representation of reality. Non-rectification of the photograph allows significant scale errors to occur because of radial lens distortion.

Methods one and two can be used in the SCRA technique, although—because of its superior level of accuracy—the first is recommended and used here.

EQUIPMENT

Five items of equipment are essential to the survey task:

(1) weighted buoys which are numbered. Since it is not uncommon for buoys to be removed, it is suggested that they also be marked "research".

(2) one flat-bottom dinghy (*eg*, an inflatable "Zodiac" with two 15 hp outboard motors for safety).

(3) manta tow board, tow rope and snorkelling gear [1].

(4) hand-bearing compass.

(5) equipment for measuring water depth.

PERSONNEL

Using the SCRA technique and absolute survey control requires two teams of people:

(1) the ground control team (which comprises two hydrographic surveyors) and,

(2) the reef cover assessment team consisting of a minimum of three people whose responsibilities are alternated: one person for boat manoeuvering and navigation; one person for manta-towing and survey observation; and one person for safety surveillance of manta-tow, debriefing and data recording.

If only two people are used, the process is less safe, more tiring and considerably slower and, as a consequence, probably less accurate.

SURVEY PLANNING

The first step in survey planning is to define the sampling unit. The SCRA technique uses a quadrat, with the location and size being a function of the class variation within the Landsat image. The selection of survey sites relies on an understanding of

- the basic principles involved in remote sensing of submerged features
- the geomorphic environment of a coral reef
- a classified Landsat MSS image map, and
- the verification purpose.

In the selection process, four basic factors should be considered:

(1) Surface feature type: the type of surface feature to be surveyed is determined largely by class variation patterns in the classified image. These patterns relate to topography, water depth and water quality which significantly affect the reflected energy recorded by either an aerial photograph or Landsat MSS image.

(2) Sample size and shape: no work has been done on the optimum sample size or shape for Landsat verification at coral reef scales or for reef sampling in general [8], but the size and shape must be easily resolvable on the particular classified Landsat MSS image to which the survey task is oriented. From experience, it has been found that quadrats larger than 1.8 hectares (four pixels) are suitable for general verification work. The question of optimum quadrat size is probably reef- dependent, however, and still needs to be answered after the accumulation of further practical experience. A rectangular shaped quadrat is the easiest to locate on a Landsat image because of its rectangular pixel.

(3) Number, distribution and location of sites: since the purpose is to verify a Landsat MSS classification map in terms of reef cover, the number and

distribution of sample sites is governed by the variability within the particular classified map. The minimum number of sample sites is one per classified class. Since different reef cover types may be spectrally similar, however, at least two sites per class and in different geographic environments should be assessed. Such sites should be as diverse as possible in terms of topography, water depth and water quality.

Vertical aerial photographs (either black-and-white or colour) at least provide a reference base for determining the distribution, location and finally delimitation of survey quadrats. Areas are chosen after simultaneous inspection of the variation in reef cover patterns on the aerial photographs, (ortho) photo map and classified Landsat image. The areas may be homogeneous or heterogeneous. Selected areas are delimited on all three types of image and finally transferred onto the xeroxed aerial photo for use in the field.

The quadrats and the gross geomorphic structures shown on the (ortho) photo map are traced for each site (*eg*, Figure 8A) for line transect planning and later use in the field.

(4) Homogeneity or heterogeneity of cover: the cover within a sample quadrat may be either homogeneous or heterogeneous. The concept and conditions of homogeneity and heterogeneity are outlined extensively in Joyce [4]. Here it will suffice to say that homogeneity obtains when the sample site environment is generally uniform in respect of topography, water depth and quality, and distribution and arrangement of reef covers. Heterogeneity is therefore any situation which does not fulfil these conditions.

The final step in survey planning is the documentation of survey procedures. This involves designing strategies for the ground control team, the reef cover assessment team and inter-team coordination. The control team locates the quadrats marked on the (ortho) photo map or aerial photographs and delimits them using the marked buoys. A sketch map traced for the site from the (ortho) photo map or aerial photos (*eg*, Figure 8) is annotated with the following information for each quadrat: (1) distance between buoys; (2) compass bearing between buoys; and (3) ground coordinates of one corner for use with absolute survey control method.

The cover assessment team uses the traced sample site information to devise a line transect path which covers all reef cover types within the quadrat (a recommended pattern is shown in Figure 9).

IMPLEMENTATION OF SURVEY PROCEDURES

SURVEY CONTROLLED GROUND POINTS

After the ground control team has located and derived the coordinates for the sites on the reef and marked the quadrat corners with buoys, their sketch diagram showing distances and compass bearings between buoys is given to the reef cover assessment team.

VISUAL OBSERVATIONS

Visual observations supply qualitative data on reef cover distribution and patterns and quantitative data on cover type. Depending on site conditions, systematic visual recordings—following the line transect pattern—can be obtained by a manta tow across the area, walking or snorkeling, or observations from the boat.

Before starting the visual survey, the observer is briefed on the conceptual basis of the data sheet, *ie*, to conceive of the quadrat environment as composed of a primary structure (the floor) with all other structures being both secondary and attached. The surface covers on these primary and secondary structures are then assessed. (Data collection and assignment to a quadrat with known geographic coordinates allows integration with ancillary data.)

DATA RECORDING

The data sheet illustrated in Figure 7 consists of three sections for recording the reef cover information. Section A is for recording the site details, section B for information on the primary floor structure, and section C for secondary structures which are either on or rising from the floor. In sections B and C, there are two levels of information entry.

In section B, the first level relates to the type of cover on the primary floor structure, *eg*, how much of the floor was covered by sand, rubble, benthic vegetation? The second level relates components on the

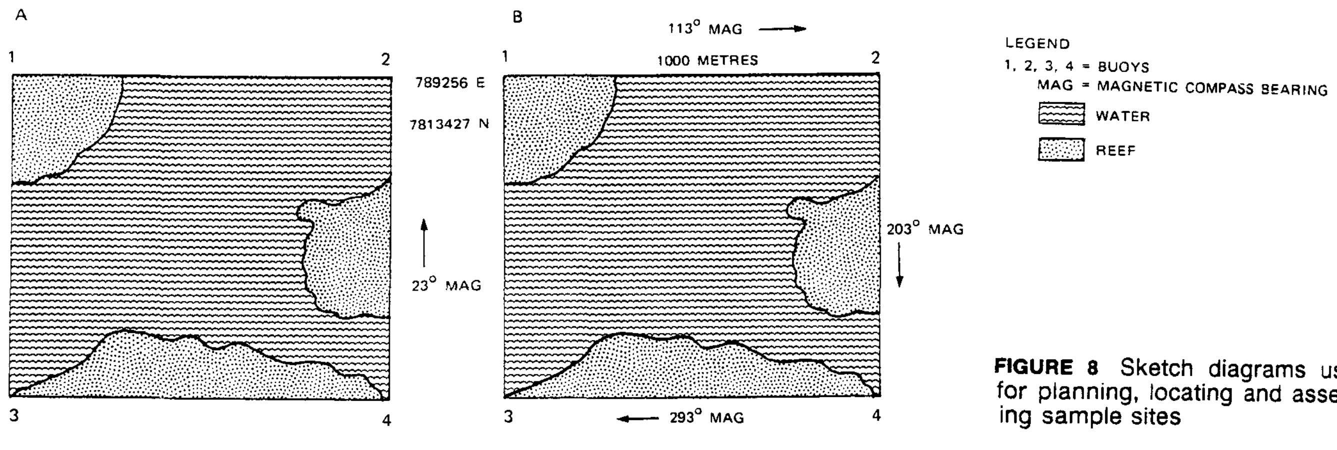


FIGURE 8 Sketch diagrams used for planning, locating and assessing sample sites

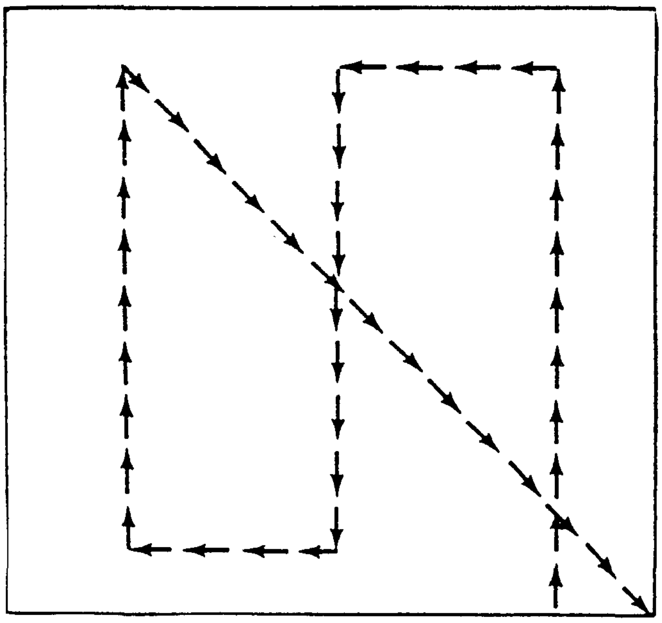


FIGURE 9 Suggested linear transect coverage pattern to assess reef cover composition within a quadrat

floor which are not secondary structures, *eg*, the percentage of live organisms attached to the sand covered floor. In section C, the first level of information relates to the secondary structures on or rising from the primary floor structure, for example, were there any small blocks, large blocks or platforms on or rising from the floor? The second level of information relates to the surface cover on each secondary structure, *eg*, the percentage of live organisms on the small blocks.

DISCUSSION AND CONCLUSION

Given the remote marine environments of coral reefs, mapping their resources is logistically difficult, expensive and time-consuming. The notion of mapping them from remotely sensed satellite data was proposed as an alternative cost- effective strategy. It has since gained acceptance and the results are classified reef cover image maps. Because the spectral and spatial resolution of coral reef features on Landsat images is still being researched, however, the initial maps need to be verified against ground conditions. To fully utilize the remote sensing solution, the problem of obtaining coral reef ground information has to be temporarily solved since it is part of the problem of verifying Landsat image maps.

As noted above, the two methods attempted previously have been used on different scales and for different purposes. Neither is suitable as an operational verification programme, however.

In contrast, the SCRA technique described here uses absolute survey control as its map base, a quadrat as the sampling unit, a combination of aerial photo and Landsat classified image information to determine quadrat locations, and environment-dependent transect methods and planning for visual observation.

The survey controlled map base is the most precise system currently available [6]. The qualitative method for locating verification sites is based on image variation and employs both aerial photos and classified images. Thus it recognizes the possibility of spectral similarity for some reef covers. Even though the selection of sample sites is not statistically defined, the variation within the Landsat data is statistically sampled in the classification process [5]. To maximize the quality of the selection process, however, it is critical that the interpreter clearly understands the basic principles involved in remote sensing of submerged features, the geomorphic coral reef environment, classified classes on a Landsat image map, and the verification purpose.

In evaluating the method for reef cover assessments, due weight must be given to the psychological basis of the perception of variability of cover and proportional area coverage. (The nature of such general assessment survey techniques is fully discussed in Kenchington [2].)

The survey controlled reef assessment technique has been employed on Hook and Hardy reefs on the Great Barrier Reef, where it has proved successful for verifying reef covers mapped at Landsat MSS scales.

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RESUME

L'utilisation des techniques de télédétection demande de la méthode pour vérifier la précision des données obtnues. Une évaluation d'un levé contrôlé de récifs (SCRA) est une méthode de levé développée pour la vérification des cartes de classification des couvertures de récifs Landsat MSS. Elle utilise des contrôles sur satellite, des images de télédétection et des observations visuelles. L'acquisition de données et l'attribution à un quadrat avec des coordonnées géographiques connues permet leur intégration avec des données subordonnées. Un exercice récent, sur le récif Hardy, du récif de la Grande Barrière en Australie est pris à titre d'exemple.

RESUMEN

El uso de la tecnicas de Sensores Remotos requiere de algun metodo para la comprobacion de la exactitud de los datos obtenidos. "Survey controlled reef assessment" (SCRA) es un metodo de estudio desarro llado para la verificacion de mapas de clasificacion de covertura de arrecifes usando Landsat MSS. Se utiliza control terrestre por medio de satelites, imagenes remotamente sensadas y observaciones visuales. La coleccion de datos y la asignacion a un cuadrante con coordenadas geograficas conocidas permite su integracion con datos auxiliares. Se utiliza como ejemplo un estudio reciente en Hardy Reef, Great Barrier Reef en Australia.