THE APPLICATION AND POTENTIAL OF REMOTE SENSING IN THE GREAT BARRIER REEF REGION

Great Barrier Reef Marine Park Authority
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David L. B. Jupp

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Great Barrier Reef
Marine Park
Authority

P.O. Box 1379
Townsville, Qld, 4810
Telephone: (077) 818811

The application and potential of Remote Sensing in the Great Barrier Reef Region.

David L.B. Jupp
CSIRO
Division of Water and Land Resources

SUMMARY

Water movements in the form of currents, internal waves, eddies and moving boundaries between water masses (oceanic fronts) are primary elements driving the Great Barrier Reef (GBR) system. The physical and chemical characteristics of the water column, as major factors in the short and long term development of the GBR biological system, subdivide the physical system into its component water masses. The material carried by the physical system consists of biota and suspended solids of natural (eg phytoplankton) and man induced (eg pollution) composition.

Existing remote sensing devices provide an opportunity to gather valuable data on these dynamic physical and biological systems, and the complex of inter-reef communications they provide. Remote sensing by Landsat is already established as a tool for the establishment of a basic fixed-reef data base for the GBR. This (static) data base is effective for current inventory and many planning needs. However, future management within the GBR system must use an information base which does not neglect the essentially dynamic interdependency between the reef environments and the communities which exist within and between them.

In the dynamic GBR physical system, events at whole GBR level may be as significant as events at within reef level. The problem of encompassing the wide range of time and space scales involved is one which only aircraft and satellite remote sensing in combination with ship and reef based studies can solve. This report addresses the way in which remote sensing opportunities exist to provide such integration and identifies a program of research and development which may achieve it.

Keywords: Great Barrier Reef Region, Remote Sensing Applications, resource planning and management, data bases.

Postal address: The Chairman, Great Barrier Reef Marine Park Authority,
P.O. Box 1379, Townsville, Q. 4810

TABLE OF CONTENTS

List of Tables

List of Figures

1. INTRODUCTION

1.1 Report background

The Great Barrier Reef (GBR) stretches about 1900 kilometres along the coast of Queensland from Torres Strait in the north to its southern most point, some 90 kilometres offshore from Gladstone.

Because of this extent, the GBR poses many problems for a management body like the Great Barrier Reef Marine Park Authority (GBRMPA) when data for inventory, monitoring or impact modelling need to be available or collected. The most obvious problem is one of scale. The GBR region covers an area of about 348,700 square kilometres. The map base problem is almost as great, since a satisfactory cartographic base for the GBR does not yet exist.

The CSIRO Division of Water and Land Resources has co-operated in a developmental study of remote sensing of the GBR with the GBRMPA and the Australian Survey Office (ASO). Methods developed during a CSIRO research project funded by the Australian Marine Sciences and Technologies Advisory Council (AMSTAC) were used. This project investigated the use of remotely sensed data from the Landsat satellite series as an aid to management of the GBR.

The scope of the study (see section 2.2) included an evaluation of Landsat imagery for the inventory, survey design and monitoring needs of the Authority in its planning and management roles. It also included an evaluation of the accuracy of Landsat data as a cartographic base for the GBR and as a means for shallow water depth assessment.

On the basis of these studies, a set of specifications for the products of Landsat analysis has been drawn up which balance the planning needs of the GBRMPA with the consistent ability of Landsat data to meet those needs. The ASO has taken over the computer software and methods developed in these studies and is currently extending the mapping program to the rest of the GBR.

The Landsat based information system is summarized briefly in section 2.2 and fully described in a series of reports listed at the end of this report. This report proceeds from that basis to investigate areas where the information base is currently poor, but where a wide variety of remote sensing data opportunities exist to be utilized to overcome the problems of scale and information base faced by researchers, planners and managers in the GBR region.

1.2 Remotely sensed data

Remote sensing has played and will continue to play an essential role in providing information for management of the GBR Marine Park.

As reviewed in this report, remote sensing is taken to mean earth observation by recording data from the electromagnetic spectrum - which includes light, radiated heat, radar and radio waves. The recording is done by a sensor, which may be a camera for light and the sensor is carried on a platform, which may be an aircraft or satellite. The narrowness of the band of wavelengths included in a sensor's measurement defines the spectral resolution and the range of wavelengths of the spectrum covered defines the spectral extent of the sensor.

Since no combination of platform and sensor(s) can cover all of the space, time and spectral scales needed for a complete information package, remote sensing of the GBR must encompass a wide range of methods, from satellite coverage through aircraft and ships to floating and moored buoys.

An information base which may be developed from remotely sensed data includes,

(i) A fixed reference spatial data base - or inventory,

(ii) opportunistic, but nevertheless useful, historical records of dynamic events - such as sediment plumes or plankton blooms, and

(iii) designed detection, monitoring and assessment schemes for natural and man induced dynamic flows within the GBR system.

Established remote sensing methods have already been used for inventory and both established and archived data exist for opportunistic monitoring as described later in this report.

The information potential of (iii) is the most difficult to obtain and to accomodate within existing data base structures. It is, however, the most important type of remote sensing input to models of the dynamic components in the GBR system. These include current speed and direction, circulation dynamics and their interactions with coastal sediment transport, pollution dispersal, phytoplankton dynamics and the highly significant and mobile boundaries between water masses - the oceanic fronts (cf Middleton, 1983).

1.3 Sampling strategy

Given the wide range of space and time scales involved in such processes the sampling strategy proposed for the MAREX (MArine Resources EXperiment) program (OCS Working Group, 1982) and supported by the Ocean Sciences Board (1982) is applicable to the GBR data base. This strategy proposes a multiplatform (satellite, aircraft, ship and buoy) approach to the measurement of ocean primary productivity (Smith et al., 1981, 1982). The mathematical methods and remote sensing techniques which have proven effective in measuring chlorophyll in the open ocean and provide the basis for the MAREX Report are yet to be assessed and developed in the shelf and coastal environment of the GBR. The basic design, however, is still sound as a basis for this assessment and development.

The appropriate combination of methods to be employed is a function of the space and time resolution and extent of the relevent phenomena as well as the spectral resolution and extent of the instruments deployed on the platforms.

'Resolution' will be taken to mean the minimal dimension which contains the variation of a feature, or event, and 'extent' to mean the distance or time over which it persists. These dimensions may be illustrated graphically on a space and time plot like Figure 1. This Figure has been adapted from Esaias (1981) and derives biological resolutions and extents from Walsh et al (1977).

Biologically, resolution is related to the basic social scale (including competition for example) and extent to the general environmental scale of the phenomena (cf Platt, 1972). The limits shown in Figure 1 are consequently only illustrative since the general interaction between biological and physical processes (as well as the scales at which one or the other dominates, cf Denman et al., 1977) is as yet poorly known and is a topic which the remote sensing techniques described in this report may well address.

Specifically, this report describes a number of the remote sensing opportunities which have been and could be used to provide information for the kind of phenomena plotted in Figure 1. It provides the background and detail for the paper presented at the Great Barrier Reef Conference in Townsville in September 1983 (Jupp, 1983), develops in the context of the GBR some of the issues discussed by Carpenter (1982), and complements the discussion papers on physical oceanography of the GBR lagoon contained in Middleton (1983).

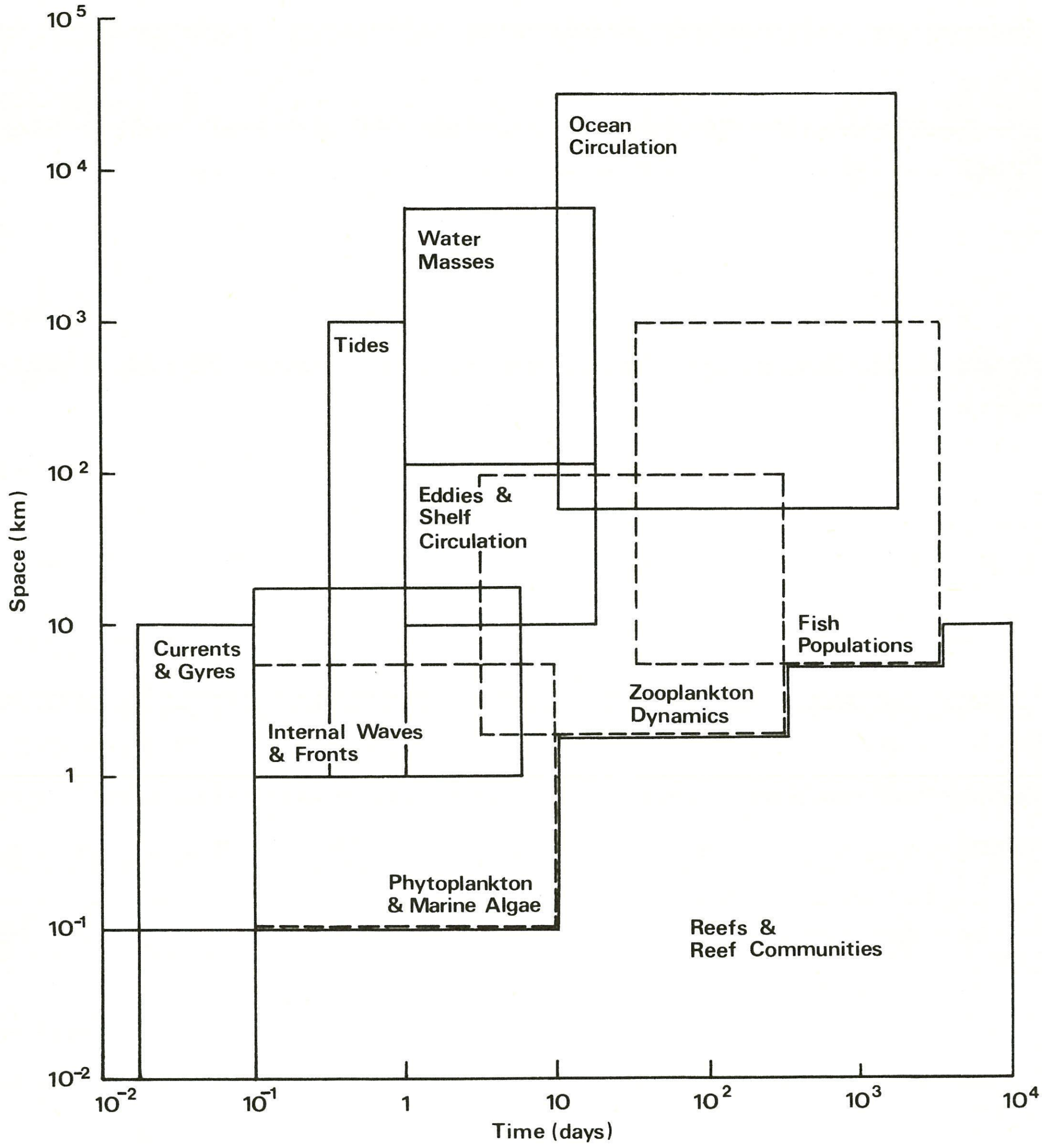

Figure 1. Resolution and extent of GBR phenomena in time and space dimensions.

2. ESTABLISHED REMOTE SENSING OF THE GBR

Up to this time, remote sensing of the GBR has been restricted to traditional aerial photography and photointerpretation, and to Landsat satellite data which became routinely available in Australia in late 1979.

2.1 Aerial photography

Aerial photography, both historical and recent, provides the most detailed image data available for the GBR system. However, much of the historical photography is taken at high altitude, is panchromatic, taken at non-optimum time of day and tide and is uncontrolled.

The Australian Survey Office (ASO) and the Queensland Department of Mapping and Surveying are gradually replacing this photography with low level colour photography and are extending cartographic control over much of the GBR (Lamond, 1982). However, the process is time consuming and expensive, and up until recently much work has had to proceed in Marine Park planning with unsatisfactory photo and map bases.

2.2 Landsat imagery

Landsat images, spanning more than ten years, from the highly successful experimental series of NASA satellites (LANDSAT-1 (formerly ERTS-1), -2, -3, -4 and now -5) are providing and will continue to provide effective map bases for the GBR until the progressing schedule of accurate survey work is complete.

The optical scanner system carried by the Landsat satellites records data in four bands - one in the green, one in the red and two in the near infra-red. The green band (band 4) covers the region of maximum penetration of light into coastal waters (Jerlov, 1976). Blue is not recorded and therefore no information is available on the blue to green ratio (or colour index) which is a basis for optical classification of oceanic water types. Landsat data do, however, provide a large area, synoptic coverage of the GBR of great value.

CSIRO Division of Water and Land Resources, GBRMPA and ASO have cooperated on studies which investigated the value and application of Landsat data for GBR planning and management.

Methods and computer programs realizing them (Jupp et al., 1984a) were developed to construct interpretations of reef covers based on the physical and biological zonations of reef tops (Jupp et al., 1984b). These interpretations provide a standard set of thematic images as a base for planning in the initial stages of the GBR Marine Park management plan.

The difficulty of establishing ground control on reefs led to the development of image rectification methods which maximized the value of each control point (Jupp et al., 1982c). The ASO is integrating this analysis with traditional survey to maximize the benefits of field survey. Reefs are being chosen for survey in order to maximally improve the overall rectification of the GBR Landsat image set. Based on this work, a complete cover of rectified standard images and thematic interpretations at 1:250,000 and 1:100,000 map scales will have been completed for the GBR by December 1984.

Landsat data were also transformed and developed to provide shallow bathymetric and reef morphological information. Although the accuracy of depth measurements from single images was low, it was improved by using several images taken at different times and choosing images which occurred with the best combinations of environmental conditions (Jupp and Mayo, 1982).

It is also planned in the future to set up specifications and develop a production program similar to that in operation at the Defense Mapping Authority in the USA (Shiver, 1981; Naylor and LaFollette, 1983) for Landsat based depth mapping, in which Landsat data are used as preliminary plans for more detailed investigations. This, together with research into the possible improvement of Landsat based depth mapping by using multiple images is underway at CSIRO. This, combined with the planned program will help define the shallow water bathymetry of the GBR until more sophisticated remote sensing devices such as the LADS (Laser Airborne Depth Sounding) system (Calder and Penny, 1981; see also Hoge et al., 1980; O'Neil, 1981, 1983; Anderson et al., 1983) become operational in the GBR region within the next 10 years.

2.3 The gaps in the current data base

Remote sensing in the form of Landsat data has has had immediate application to the planning needs of the GBRMPA. These have been largely cartographic and have provided bathymetric and reef morphological information as well as interpretations of shallow reef zonation. All of these are fixed inventory data types which are essential for planning but insufficient for operational management.

The GBR is a multilevel dynamic system. It can be considered a significant boundary for the Coral Sea and Pacific Ocean or, at the other extreme a medium for microscopic biota. Within this system the needs of operational management require far more knowledge about

(i) the movement of water, including currents, internal waves and fronts,

(ii) shelf circulation and the dynamics of suspended sediments and pollution, and

(iii) the amount of direct biological productivity of the waters and degree of inter-reef and reef-coast communication.

Without these data the GBR data base, and management decisions based on it, are restricted to a static fixed-reef inventory which, despite providing a sound basis for many of the decisions faced by planners in the GBR region, neglects the essential interdependancy of the reef environments and the communities which exist within and between them.

This report therefore addresses the scope of remote sensing technology which might be applicable to research and monitoring of the dynamics of coastal and ocean systems.

3. REMOTE SENSING OPPORTUNITIES FOR THE GBR

The remote sensing opportunities for the GBR depend on a match being made between the needs of management and research and the available methods and technology which comprize remote sensing.

3.1 Platform and sensor coverage

Figure 2 plots, on the same axes as Figure 1, the space and time resolution of the main existing remote sensing platforms. Together, satellites, aircraft, ships and buoys cover most of the range depicted in Figure 1 (Esaias, 1981). There are some gaps, but a sampling scheme like that recommended by the OCS Working Group (1982) in which an ocean colour scanner similar to the Coastal Zone Color Scanner (CZCS) carried on the NIMBUS-7 satellite (see section 4.3) is combined with ship cruises and moored and floating buoys would seem to effectively cover the space and time structure of (i), (ii) and (iii) above.

Each of the platforms has advantages and disadvantages as vehicles for covering the range of space and time scales involved.

Ships provide the distinct advantage of supplying detailed and fully controlled data using complex equipment measuring over a wide range of depths at every location. However, considerable time (and therefore money) is needed to cover areas with any extent and at reasonable resolution. It has been quoted (Simpson, 1981) that one day of ship time is needed to survey a 40 Km square at 5 Km resolution. For larger area surveys significant evolution of environmental parameters will have occurred and results cannot be treated on the same time basis.

Aircraft can cover much greater areas in less time but cannot carry the complexity of equipment nor manage the data flow to the extent possible on board ship. Also, the data are remote and generally no data from within the water column nor water samples can be taken. Nevertheless, aircraft provide the most flexible of the available platforms for obtaining remotely sensed data.

The main limitations for both ships and aircraft are defined by ship or flying time. In a given time (or cost range) the platforms may either concentrate the area of study to get good space and time resolution or extend the area at the cost of time resolution.

Satellite system design, on the other hand, is limited mainly by the technical limits to recording, transmitting and processing digital data. Large area synoptic survey with a rapid repeat time is usually matched with large pixels (low space resolution). Satellites with high

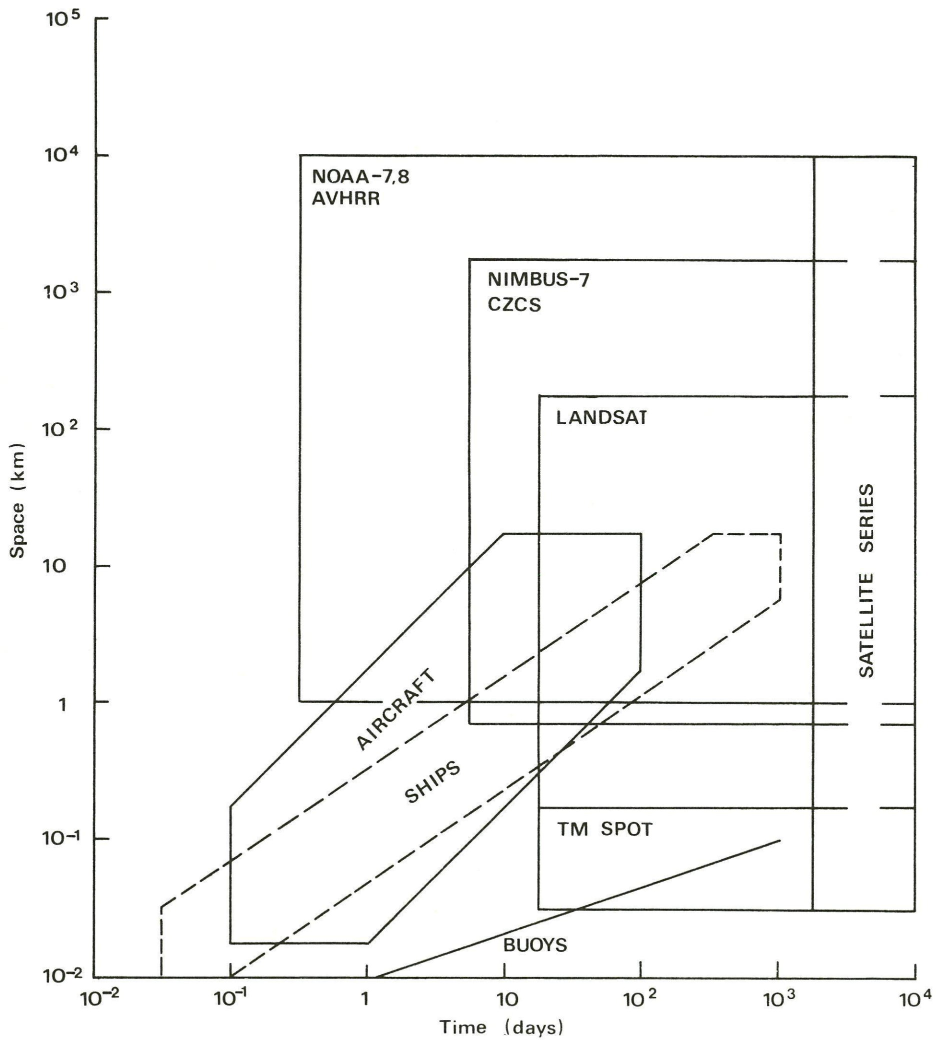

Figure 2. Resolution and extent of data platforms in time and space dimensions.

space resolution (small pixel size) generally cover smaller regions and visit them less frequently (see Figure 2) which reduces their effective time resolution. This different form of trade-off, in which the cost effectiveness of satellite systems increases as their operational lifetime, allows satellites to provide another degree of freedom in the design covering the full space and time range of the phenomena of interest in the GBR.

However, the total value of a sensor deployed on any of these platforms depends on its spectral resolution and extent and the intrinsic ability of spectral data to define the physical parameters of interest.

Spectral resolution refers to the width of the spectral region over which an observation is integrated and spectral extent to the range of wavelengths involved. Useful remotely sensed data come from many spectral bands ranging from the Ultra-violet to radio frequencies. Individual sensors, however, can only handle a limited combination of spectral resolution and extent.

3.2 The instruments available

Table 1 lists the most important of the instruments available at the present time and some of their proven applications. These instruments can be carried as sensors by a number of platforms, including satellites, aircraft, ships and even buoys. Moreover, matching sensors from Table 1 with platforms from Figure 2 may form a basis for designing a set of remote sensing applications to cover the phenomena plotted in Figure 1.

Some of the wide ranging uses to which these sensors have been put in oceanic and water quality measurement can be found in the Cited References and Additional Reading lists of this report and in Middleton (1983).

3.2.1 Optical remote sensing

Optical remote sensing sounds the Euphotic (or photo-productive) zone. In the GBR this may be the first 20 metres depth near the reefs and much less near the coast.

Generally speaking, the optical properties (or 'colour') of water depend on the underlying appearance of pure water (blue) modified by dissolved substances, inorganic and organic suspended particles as well as water depth and the nature of the sea floor. It is still not established whether an analysis of multispectral data can resolve all of these effects at a single point. However, it is well established that in restricted circumstances multispectral data can be used to resolve some of them, and that instruments may be flown from spacecraft to do it (Gower (Ed), 1981).

TABLE 1

Instrument	Description	Applications
Ocean Colour Instrument (OCI)	Selected visible and thermal bands or chlorophyll mapping	Primary production shelf processes. Chlorophyll and suspended sediment
Multispectral Scanner (MSS)	Wide set of bands for general applic- ations. Flexible spectral extent.	Coastal zone(incl wetlands) mapping and shallow water applications
Imaging Spectrometer (ISS)	Like MSS but using solid state tech- nology.	As for MSS but having better rectification
Camera System (AC,MSC, LFC)	Film based, possibly Multispectral (MSC) or Large format (LFC). recording, but low sensitivity.	Similar to MSS better rectification, cheaper data
Infra-red Radiometer (IR)	Thermal emission from sea surface.	Sea surface Temp, upwelling, fronts water masses.

Laser Fluorosensor (LIDAR)	Single wavelength laser to induce fluorescence. Emission measured over many bands.	Chlorophyll A and pigments. light attenuation, oil type.
Laser Depth Sounder (LIDAR)	Multi-wavelength laser profiler to measure time delay between sea floor and surface.	Bathymetry Turbidity
Microwave Radiometer (MR)	Microwave emission from sea surface.	Sea surface Temp and salinity. Oil slick thick-ness.

Instrument	Description	Applications
Altimeter (ALT)	Very precise nadir radar sensing height of satellite.	Surface current velocities, shear convergence and divergence.
Scatterometer (SCAT)	Off nadir back scattered radar.	Wind driven zones of convergence and divergence.
Synthetic Aperture Radar (SAR)	Off nadir radar with high (processed) resolution.	sea surface effects (eg swell, internal waves), bathymetry and surveillance.

In shallow waters, when suspended particles are not disturbing the signal, and water depths are of the order of 25 metres and less, then multispectral instruments can map bathymetry with fair accuracy (Bukata et al., 1981; Jain et al., 1981; Shiver, 1981).

For deep waters where organic suspended particles form the main factor modifying colour, Morel and Prieur (1977), Austin and Petzold (1981) and Clark (1981) have derived algorithms which measure ocean chlorophyll from spectral bands with specific resolution and extent. When the data are sensed from space, successful application of their methods also depends on careful correction for atmospheric and sea surface effects.

More generally, Moore (1980) and Johnson and Harriss (1980) describe how aircraft and spacecraft flown multispectral data can resolve a variety of ocean parameters more or less quantitatively depending on the complexity of the situation.

The relationship between fluorescence and chlorophyll A concentration has been used to measure phytoplankton for many years (Yentsch and Menzel, 1963; Strickland and Parsons, 1968; Kiefer, 1973a). With highly sensitive instruments, the natural fluorescence of chlorophyll may be used to infer phytoplankton abundance from airborne imaging systems (Neville and Gower, 1977; Gower, 1980; Gower and Borstad, 1981). This fluorescence may also be usefully induced with a laser as described below.

3.2.2 Thermal remote sensing

Optical remote sensing records the light which is scattered and reflected by the water column, the sea floor and any other components of the image. The signal is modified by the selective absorption of light by the different scene components to give them their characteristic signatures.

As well as reflecting and absorbing incident radiation, materials also emit radiation in various wavebands to balance the absorption and other energy inputs. The most important of these is thermal emission which occurs from every material above absolute zero temperature. The higher the temperature the shorter the wavelength of the maximum radiant energy so that the sun emitts most strongly in the visible region and the earth re-radiates most strongly in the infra-red region (3 microns to 1 mm) and weakly in the microwave (radio wave) region.

Reflected radiance is insignificant above about 4 microns and the atmosphere is reasonably transparent to radiation emitted in the 'windows' bounded by 3 to 5 and 8 to 14 microns. Therefore, remote sensing of this emitted radiation allows the temperature of the earth or sea surface to be sensed, even at satellite altitudes.

The temperature of the sea has great biological and physical significance. Temperature and salinity provide an oceanic index for different water masses and thermal gradients in the sea are both an indicator and mechanism for mixing and energy exchange between masses. Cool upwelling waters with high nutrient contents are often associated with highly productive areas (Walsh et al, 1977), and the 'warm core rings' of the Gulf Stream - as well as the East Australia Current - can form cells which transport biota over great distances.

Detectors for the major thermal emission band for the sea surface (8 to 14 microns) are well developed for all of the platforms used for remote sensing (Bernstein, 1982), and (unlike optical sensing) data may be taken at night as well as during the day. With multi-channel data, temperature and emissivity variations may be separated - with some significance for pollution mapping where emissivity variations represent significant components in the observed data.

Emission in the microwave region may also be used in conjunction with infra-red sensors (Thomann, 1975) to measure sea surface temperature and salinity (see also Blume et al., 1981).

3.2.3 Active lidars and radars

The previous instruments provide what is termed 'passive' remotely sensed data. That is, the source of energy is the sun and (in the case of thermal sensing) natural dynamic processes. When the source of energy is supplied by the instrument the method is said to be 'active'. Laser pulses and radar are the most widely used active energy sources used to date.

Active systems have the great advantage of being able to operate with cloud cover and during day or night - both significant advantages in the difficult GBR environment. It could be argued that for natural resources management in an area like the GBR a program based on remote sensing would be incomplete without the inclusion of some active remote sensing systems.

The LADS (Laser Airborne Depth Sounder, Calder and Penny, 1981) system is an active system which will, within 10 years, play a significant role in mapping GBR bathymetry. This system sounds depth by measuring the time difference between signals reflected from the surface and the sea floor providing an airborne replacement for the traditional echo sounder. The backscatter parameter is an additional measurement available from the data which can be used to measure turbidity (see Gordon, 1982; Phillips and Koerber, 1984; Phillips et al., 1984).

Laser induced fluorescence (emission) with a peak emission wavelength at 685 nm can be directly attributed to chlorophyll concentration (Bristow et al., 1979; O'Neil et al., 1980; Hoge and Swift, 1981a, 1983). This effect can be maximized by pumping with a laser beam in the blue region (440 nm) where chlorophyll A exhibits strong absorption. The developments outlined by Bristow et al (1981) have made this tool operational with high quality and reliability. Water has a natural fluorescence peak (Raman Fluorescence) defined by the input energy wavelength. Chlorophyll concentrations may be measured even in the presence of turbidity by using the Raman peak to normalize the measurement (Bristow et al., 1981).

By altering the frequency of the laser pulse a similar instrument may be used to unambiguously identify oil type in oil spills (O'Neil et al., 1981), and oil slick thickness (Hoge and Swift, 1983). Again, the Raman fluorescence is used to normalize the measurement. In this case the results are more reliable than chlorophyll concentration as oil has none of the feed-back mechanisms which living organisms use to avoid laser excitation (see Kiefer, 1973a and 1973b).

Sea state and wave spectra can be measured with Laser profilers, as well as the concentration of tracer dyes (Hoge and Swift, 1981b) and the location of estuarine fronts (Hoge and Swift, 1982).

Radar altimeters and Synthetic Aperture Radar (SAR) have applications for mapping surface winds, wave structure, internal waves and upwelling (Ross et al., 1970; Paniker, 1974) through an analysis of the energy backscattered from the rough sea surface. SAR is also a possible tool for general surveillance and detection of oil spills which may be separated from the general sea signal through the smoothing effect of the oil on the water.

The Seasat satellite's global coverage demonstrated how satellite borne radar, especially SAR, could measure sea surface topography, wave spectra, surface currents and even (indirectly) sense bathymetry (Born et al., 1979). The SIR-A experiment (Ford et al., 1983) confirmed this potential, and the SIR-B experiment (to be run in late 1984) may cover areas of the GBR - in which case more direct assessments of the potential of SAR may be available.

It would be very expensive, however, to monitor wave climates (for example) in the GBR region using radar based remote sensing. Such data would be occasional, but very useful, additions to data from a strategically located system of moored buoys.

Among the types of radar which might be considered for operational work is shore-based radar (Dexter et al., 1982) which could play a similar role to moored buoys in an integrated data system.

4. EXISTING DATA OPPORTUNITIES

Within the scope of the useful and feasible types of remotely sensed data which may be applied to the research and management needs within the GBR system there already exists a significant base of largely unexploited data.

4.1 Aerial photography and sunglint

Existing aerial photography of reefs contains interesting information on micro-flows of water around and over reefs. Where sunglint occurs within the frame, extensive slick and shear patterns can be seen (cf Stilwell, 1969). Cox and Munk (1954, 1956) have also used the glint area to infer wind speeds and spectra near the sea surface. At spacecraft altitudes, the areas of extensive calm within the sunglint can be mapped and related to frontal areas in the wind and current systems (McClain and Strong, 1969). Even simple hand-held panchromatic photography could be gleaned for important wave information, such as dominant wave length, wave direction and refraction around shallow reef areas. However, the lack of quantitative multispectral information in a photograph generally limits the use of this opportunity.

4.2 Landsat data

Landsat combines good spatial resolution with a large area mapping capability (80 metre resolution element - or pixel, and a 180 Km swath width). This enables it to detect broad scale ocean and shelf circulation and suspended sediment flow patterns throughout the GBR system on an opportunistic basis dependent on the 18 day repeat cycle and the degree of cloud cover. Such data have been successfully used (Thomson and Carpenter, 1981; Wolanski et al., 1984a, 1984b) in oceanographic applications to investigate the large area context of current mixing and island wakes and thereby to optimize the data from expensive ship based survey.

Oceanic and near coast fronts occur between water masses with quite different dynamics (such as tidal currents) or properties (such as river outflows). The fronts are the areas where material or energy exchanges are occurring and represent highly significant features in GBR studies. Klemas (1980) has shown how frontal systems, which can be delineated in Landsat imagery, are highly significant in pollution dynamics as oil and even fish eggs are entrapped by the fronts. Such oceanic fronts are some of the most dynamic areas of the ocean and growth of phytoplankton is often associated with them (Pingree et al., 1979). The Landsat image base provides one means for locating and investigating persistent frontal systems in the GBR region.

Landsat images sense different water masses and associated fronts since the different masses hold different amounts of suspended particles. This difference is also associated with different temperatures, salinities and chlorophyll contents (Mueller and LaViolette, 1981).

Alfoldi has applied algorithms developed in Canada (Alfoldi and Munday, 1978; Amos and Alfoldi, 1979; Munday et al., 1979; Alfoldi, 1982) to map suspended sediment concentration for selected rivers of the Queensland coast. The technique, called the 'Chromaticity' method, uses colour ratios of Landsat bands and a method for standardizing between different dates to obtain quantitative estimates of suspended solids concentration. With more ground data for calibration the chromaticity method could be applied to the complete historical set of images available and help research the dynamics of the plumes of terrigenous sediment which move along the Queensland coast. (cf Lindell, 1983 for applications in Sweden). The chromaticity technique has also been applied to mapping, on an opportunistic basis, oil slicks which it is able to separate from sediment plumes.

Landsat does not, however, have sufficient spectral resolution to separate inorganic and organic suspended solids and also lacks the time resolution (a repeat time, assuming no cloud, of 18 days) to investigate shelf circulation, suspended sediment plumes and pollutants on any more than an opportunistic basis (Klemas and Philpot, 1981). It is feasible (for example) that, due to the effective time resolution of the Landsat MSS, if an oil-spill occurred in the GBR region it might never be imaged, even if cloud free Landsat scenes were available, since the oil could be spilled and disperse between overpasses.

4.3 Coastal Zone Color Scanner (CZCS)

An instrument with much better spectral and time properties - but having low space resolution - is the CZCS which has been imaging the oceans from the NIMBUS-7 satellite platform since 1978 (Hovis et al, 1980; see also Carpenter, 1982)

CZCS has a range of sensors for spectral bands in the blue (443 nm), the green (520 nm and 550 nm) and the red (670 nm) regions of the spectrum as well as one on the boundary between the red and near infrared (700 to 800 nm) and one in the thermal infrared region (10.5 to 12.5 microns). These sensors were designed with high sensitivity and optimized for water property mapping. The CZCS bands are about 60 times as sensitive as the corresponding Landsat bands. CZCS is a large area mapping tool with a pixel size of 800 meters and a swath width of some 1000 Km. CZCS has a 6 day repeat coverage of any area - assuming cloud free days - with consecutive day overlap to improve the chance of attaining its basic period.

CZCS is designed to assess marine biomass (Hovis et al., 1980; Gordon et al., 1980) by detecting variations in concentrations of phytoplankton pigments. It has been shown that optical measurements using well placed spectral bands in the blue (high chlorophyll absorption) and green (low chlorophyll absorption) regions can give quantitative estimates of chlorophyll and related pigments concentration (Gordon and Clark, 1980; Smith and Baker, 1982; Gordon et al., 1983) in ocean regions where organic suspensions dominate.

Considerable data of opportunity exist over the GBR in the CZCS archive. The thermal channel senses Sea Surface Temperature (SST) to the same spatial resolution and is co-registered with the optical bands. These data represent a prime source for opportunistic mapping of GBR biological dynamics - including general communications between reefs and the estuaries of the Queensland coast (cf Smith and Eppley, 1982).

4.4 Advanced Very High Resolution Radiometer (AVHRR)

The energy distibution in the sea which is displayed by thermal gradients comes from absorption of the sun's energy and through the tidal forces of the sun and moon. The turbulent mixing in the ocean expesses the interaction of these physical forces through the energy balance and can be sensed as temperature differences in the upper layers of the ocean.

To the extent that the temperature of the sea surface (SST) mirrors temperature of the upper layers, the AVHRR instrument carried on the NOAA 6 and 7 satellites represents another large area data opportunity (Kidwell, 1981; Bernstein, 1982) for detecting frontal systems in the waters of the GBR and the Coral Sea.

The AVHRR has five spectral bands (one visible, one near infra-red and three thermal bands). The most important bands for SST studies are two thermal infra-red bands in the 8 to 14 micron atmospheric window. The use of this pair allows measurement of absolute SST to within 1.0 degree Celsius. With two satellites in operation up to four images may be obtained in a day (one morning, one afternoon and two at night) giving this instrument excellent time resolution.

The sensor transmitts data in two modes, a high resolution mode (HRPT or High Resolution Picture Transmission) and a lower resolution mode (APT or Automatic Picture Transmission). HRPT data has a pixel size of about 1.1 Km and APT data a pixel size of about 4 Km. APT data for the whole earth is able to be collected by NOAA but HRPT data, because of the volume of data generated, has only been collected for specific areas by NOAA or by local receiving stations.

Unfortunately, few high resolution images of the GBR exist, and historical data are limited to low resolution SST data (based on AVHRR-APT data). As AVHRR-HRPT data becomes routinely recorded in East Australia by local receiving stations (Carroll, 1982; Nilsson, 1982) these data will be significant in GBR very large area research. It is worth investigating the establishment of a local receiving station for this purpose as a station so located would effectively cover the Coral Sea and Northern Australia in a way not available through currently planned receivers in Southern Australia.

Of particular value will be the application of these data in fisheries research and applications (cf Borstad et al, 1982) where the rapid availability of data will enable many of the large area factors in fish population dynamics to be investigated.

4.5 Depth of penetration

While optical and thermal sensors provide significant data from the ocean and coastal region, it must be borne in mind that the information contained in the data concerns the uppermost layers of water.

The depth of penetration by optical sensors such as the first four CZCS bands is maximum in the blue for clear water at about 20 to 40 metres with the peak of penetration shifting to the green and red accompanied by rapidly decreasing depth as suspended particle concentrations increase. There is no water penetration in the thermal band and the AVHRR measures only the temperature of the surface skin of the water mass. The relationship between this surface temperature and optical depth penetration is also complex as the optical depth defines the extent to which the sun's radiation reaches different depths.

This has two implications. The first is that different bands provide information on different sections of the water column and should be used in conjunction to assess the homogeneity of the column. Mixing, for example, may be visible in one band and not in others. It is especially important also, when using sea surface temperature, to assess the homogeneity of the water mass beneath the surface. The blue and green bands can do this.

The second implication is that supplementary data, taken at the sea surface and from the water column, are necessary to interpret and fully utilize remotely sensed data. A balanced integration of ship, aircraft and satellite borne measurements is therefore necessary to fully study the GBR water mass.

Remote sensing provides an ideal frame in which to embed traditional survey data and conversely, the ground truth provided by traditional survey and a variety of measuring tools is essential to obtain full value from remotely sensed data. However, existing (historical) data lacks the ability to integrate with other data in this way and the greatest benefits from future remote sensing will come when the remotely sensed and field based data types are combined in a well planned design.

5. FUTURE REMOTE SENSING OF GBR DYNAMICS

In the future, the flow of data from satellites, aircraft and sensors mounted on ships and buoys will increase dramatically.

5.1 Meteorological satellites

The fundamental role of the ocean temperature and the ocean climate in weather prediction and monitoring means that global coverage by meteorological satellites will continue and grow.

This provides an opportunity for GBR studies as satellites such as the NOAA series with the AVHRR sensors provide extremely valuable oceanographic data.

Future plans indicate that an AVHRR with a smaller pixel size (possibly as low as 100 metres or less than 400 metres) may be developed which would provide data of great value for research into dynamic inter-reef flows.

To assure data availability it could well be the time to assess this opportunity and construct a facility to access this and similar data for the GBR region from Townsville, or some other convenient location in Northern Australia.

5.2 High resolution satellite data

Satellites carrying higher resolution instruments like Landsat-5 with the TM (Thematic Mapper) instrument (which has a 30 metre spatial resolution and 7 bands) and the French SPOT satellite (20 metre spatial resolution for 3 bands and 10 metre for the single panchromatic band) offer the prospect of significant data opportunities to help map and survey the GBR. However, their spectral and time resolutions and extents are generally not ideal for fine scale dynamic water property mapping.

It is expected that within 10 years there will be a large number of high resolution optical scanning satellites in orbit, including the commercial successor to the NASA Landsat experiment. These satellites will almost certainly address the needs of the oceanic marketplace. For a discussion of future plans in this area see ALCORSS (1982).

5.3 Multispectral scanners

Multispectral scanners and imaging spectrometers on aircraft platforms sensing natural radiation provide a new dimension in flexible assessment of the properties of the waters in and around reefs. Although they are not new in remote sensing of water properties (Clarke et al., 1970; Arvesen et al., 1973; Hovis and Lueng, 1977), instrumentation and recording technology have developed considerably in recent years. (cf Hoge and Swift, 1981a; Edel et al., 1982).

It is important to note that despite advances in data analysis such as the development of algorithms for chlorophyll and suspended sediment mapping from passive multispectral data (Zwick et al., 1981), the actual limits and abilities of multispectral data to resolve significant water parameters are not fully established. Any actual data collection by multispectral instruments over GBR waters needs to be made initially in a research framework, be based on careful planning and utilize in-water measurements (cf Anderson, 1976; Smith et al., 1979).

Scanner data is becoming more common in Australia as commercial groups offer scanner data as an (expensive) option. As sensors and data logging develop and more companies provide scanners these costs can only decrease.

5.4 Active scanners

Active scanners carried on aircraft platforms can also map at spatial scales relevant to reef lagoon dynamics and local variations in phytoplankton populations. The laser fluorosensor (Campbell and Thomas, 1981) is among the most discriminating of the instruments available for deployment and such instruments are becoming available for research or commercial applications in the USA and Canada (EPA, 1981).

As with any aircraft flown instruments, the time resolution is poor and they lack the ability to make routine biological measurements with depth. Therefore, collateral data from moored buoys or ships are needed to fully utilize the remotely sensed data. The use of fluorescence to construct a biological analogue of the current meter, and provide such collateral data, is described by Whitledge and Wirick (1982).

5.5 Camera systems

The presence of camera systems as opportunities in Table 1 should not be neglected. Camera systems lead to film products which have good rectification and which are easily accommodated within existing survey systems.

A camera system is a basic complement to any aircraft based remote sensing system. It provides a record of the flight and data collection and may range from a hand held 35mm camera to a battery of fixed and free cameras with a variety of formats, films and filters.

Modern filters and films can provide narrow band data and multispectral cameras may be used to separate the bands during flight. Even at spacecraft altitudes, the high resolution, large format metric camera deployed on space shuttle by NOAA-NOS provides a data opportunity of great value for GBR mapping and inventory.

The main limitation to film is that the data are not radiometric, cannot be directly analysed by computer and its dynamic range (maximum measurable contrast) is poor. In water this problem is significant although film digitizing, in which the photogaphy is converted into digital form, with subsequent computer enhancement may improve matters (Munday and Zubkoff, 1981). The effectiveness of film digitizing and computer enhancement in this context should be researched as a significant means of providing future remotely sensed data for the GBR.

5.6 Radars

In the next 10 years there will be a dramatic increase in the number of radars flown by satellites. Following the (brief) success of SEASAT, radars (mainly SAR) will be flown on the Japanese Marine Observation Satellite (MOS-1), the Canadian RADARSAT and the European Space Agency's Earth Resources Satellite (ERS-1).

The USA plans to launch a satellite with an accurate altimeter called TOPEX and this, as well as those listed above, will provide data of great value for oceanographic and near reef current studies.

The main impetus for operational radar sensors on satellite platforms has been the benefits of their use for mapping and monitoring sea ice. Oceanography generally, however, will benefit from their data.

6. DISCUSSION

The types of instruments available for deployment are listed and described in Table 1. These instruments currently have the capability of mapping water and sediment movements, primary productivity and even bioluminescence. In addition to providing a basic research complement for the GBR this set of instruments provides possibly the most realistic set of tools for monitoring and mapping pollutants - such as oil-spills.

The design task is therefore to assess how the planned combinations of remote sensing platforms and sensors apply in the GBR system for research, planning and management. Where significant gaps exist the task is to assess how the needs of GBR management might promote research into specific combinations of platforms and sensors.

Table 2 lists the available data platforms and sensors together with potential sensors by scale of application. The abbreviations used for the sensors are from Table 1.

At the whole GBR scale the NIMBUS-7 CZCS, the NOAA AVHRR and Landsat MSS data provide a significant data set for general definition of biological productivity and the movement of water masses. Taken together, the variations in the pattern of suspended sediment, phytoplankton and sea surface temperature over space and time provide indirect measurements of ocean structure and movement as well as being significant direct parameters in themselves (Gower et al., 1980).

One problem is that CZCS is an experimental instrument. Data continuity will depend on an OCI (Ocean Color Instrument, see Stewart, 1981) being flown in the mid 1980's on board the NOAA series of satellites, or on the availability of data from the Japanese Marine Observation (MOS-1) satellite or the European Space Agency's ERS-1, each of which may carry a set of ocean mapping instruments including an optical scanner.

At the regional reefs scale, there is scope for using high resolution satellite data in conjunction with the existing satellite data. Further radar missions on the Space Shuttle (such as SIR-B), the Canadian RADARSAT and the MOS-1 and ERS-1 satellites referred to previously could provide significant wave and current data at this scale.

At the reef-to-reef and within-reef scales the remote sensing tools must be flown from high resolution satellites, from aircraft or deployed from boats and buoys. It is at this level and the point events level that the major deficiencies in data availability exist for the GBR at this time.

One example of a point event is an oil spill. To assess and model oil-spills it is necessary to combine rapidly collected data about a detected oil slick (oil type and quantity) with environmental data such as surface winds and currents. Oil thickness information is also important for planning cleanup and containment activities. Microwave radiometers, SLAR and Laser fluorosensors mounted on aircraft platforms provide the most practical instrument systems for detecting, monitoring and assessing the fate of oil slicks (Klemas, 1982; O'Neil et al., 1980; Hoge and Swift, 1983). They also may be used at other times for more general remote sensing purposes. However, no aircraft equipped in this way is available for the GBR region. A separate list of references outlining the range and abilities of remote sensing tools for oil spill detection and assessment has been appended to this report.

TABLE 2

Scale	Platform(s)	Existing(+) Systems	Potential(+) Sensors
Oceanic |1,000 Km	Satellite	NIMBUS-7 OCI, MR NOAA-6,7 MSS, IR	ALT, SCAT, SAR
Whole Reef |500 Km	Satellite	NIMBUS-7 OCI, MR NOAA-6,7 MSS, IR LANDSAT-5 MSS	ALT, SCAT, SAR
Regional reefs |100 Km	Satellite	NIMBUS-7 OCI, MR NOAA-6,7 MSS, IR LANDSAT-5 MSS LANDSAT-5 TM	ALT, SCAT, LFC, MSC, SAR, ISS
reef-to- reef |10 Km	Satellite Aircraft Ship	LANDSAT-5 TM AC -	MSS, MR, IR MSC, LIDAR, ISS, SAR
Within- reefs |1 Km	Aircraft Ship	AC -	MSS, MR, IR, MSC, LIDAR, ISS, SAR
Point Events 1 Km	Aircraft Ship	AC -	MSS, MR, IR MSC, LIDAR, ISS, SAR

(+) Abbreviations from Table 1.

The full value of the available tools and future space and aircraft platforms for GBR research, planning and management will only come when adequate research and development has been done. A series of research and development projects which will assess and modify the existing opportunities must therefore be of prime importance.

7. CONCLUSIONS

Remotely sensed data from satellite and aircraft platforms are providing, and can continue to provide, operational information about GBR structure and dynamics of value to Marine Park management.

In the context of the whole of the GBR a design for research and application is feasible using existing and planned satellite data which could improve the overall information base on fronts, water circulation and general biological productivity of the GBR waters. At the finer, and possibly more important, scale of coast-reef, inter-reef or within-reef communication and flows there is a range of tools available and at present under development which with effective research could be immensely valuable for research, management and planning in the GBR region. These tools could map and monitor suspended sediment and biological dynamics within the space and time scales occupied by these phenomena. They would also be at hand in the event of spillage of oil or other pollutants for monitoring and assessment.

To accomplish this there is a need to research the essential limits to spectral resolution of GBR phenomena and events and to develop an operational system encompassing broad scale satellite data, aircraft based data as well as instruments deployed on ships and buoys. This system could be similar to (but with greater emphasis on fine scale data from aircraft platforms) the OCS Working Group's (1982) MAREX sampling strategy.

In the initial stages research could be started using existing satellite data and an airborne multispectral camera or spectroradiometer in company with in-water measurements. The most useful piece of equipment for such a project would be an airborne MSS with adjustable band widths and locations. Such an aircraft based system could be used in a number of ways. The pilot projects should also investigate an optimum deployment of such an aircraft based monitoring system.

On the basis of such research a designed, rather than ad hoc, approach to fine scale remote sensing of the GBR may be developed and applied to fill data needs for GBR management.

To summarize, the major conclusions from the report are that:

(i) Remote sensing technology exists to address many of the remaining information acquisition problems faced in the GBR region,

(ii) there is a range of currently available satellite data (AVHRR, CZCS and Landsat) which should be incorporated into the current GBR data base,

(iii) future satellite data, and even more especially, airborne scanner data from a variety of instruments, have a significant ability to address the GBR data needs if developed carefully through applied research,

(iv) in order to take advantage of the data provided by remote sensing they need to be integrated with data from other instruments and from ground survey, and

(v) among the remote sensing tools of greatest future potential are the active Lidars and Radars which are under development in a number of overseas research centres.

8. RECOMMENDATIONS

Corresponding to the conclusions of the report the following recommendations can be made:

(i) The range and scope of available remote sensing methods be actively promoted among groups likely to benefit by them,

(ii) the available data opportunities which are not fully used be investigated and incorporated into the planning process as soon as possible, and if feasible the possibility of developing receiving and processing facilities in North Queensland be addressed,

(iii) a series of studies and projects, which can provide basic research into the spectral properties of the GBR system and features occurring within it, and a remote sensing survey and monitoring system, which realizes the significant benefits of modern scanner technology, be designed,

(iv) projects be defined and designed to integrate remotely sensed and ground survey data to maximize the benefits of each data type, and

(v) the Authority encourage Australian research and development in active remote sensing by Lidars and Radars with operating characteristics relevant to applications in the GBR region.

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