Figure 3.1. ArcView interface views of a sidescan sonar mosaic (left) and resulting interpretation (right) of a portion of the Big Creek Ecological Research Reserve. Interpretation of the sidescan data was based on the application of the Greene et al. system that characterizes this site as: a flat marine megahabitat on continental shelf in shallow water depths (0-30 m). Mesohabitats include sand waves, sand stringers and cobble patches interspersed with rock outcrops and reefs; isolated boulders and pinnacles are examples of macrohabitats.

4. DATA ACQUISITION METHODS

In Section 3, we described those physical and biophysical parameters important in determining the distribution and abundance of many benthic and nearshore species, and around which a habitat classification system must be organized. It follows therefore, that for a classification scheme to be applied, data from the region of interest must be acquired for these parameters at the appropriate scale and resolution. Here we present a review of the methods currently in use for acquiring habitat data as well as new technologies that hold great promise for increasing both survey coverage and data resolution in shallow marine environments. We focus primarily on methods appropriate for collecting data at various scales and resolutions on water depth, substrate type, rugosity, slope and aspect.

There are two main reasons for reviewing the capabilities, advantages, limitations and costs of these systems. First, although the most cost-effective means for obtaining habitat data is to make use of existing data sets, we have found that there is a great scarcity of suitable data available for the shallow nearshore marine environment along most of the California coast (Section 7). This situation will necessitate the acquisition of new data for most fine grain habitat mapping applications. Our hope is that this review will enable those responsible for planning, conducting or contracting for habitat mapping studies to make a more informed decision on the types of methods to be employed. The other reason for this review is to help those needing to evaluate the suitability of previously collected data for habitat mapping based on the performance characteristics of the acquisition methods used.

4.1. DEPTH AND SUBSTRATE DATA TYPES

Bathymetry data

As stated above, our primary focus here is to review the technologies available for mapping water depth and seafloor substrate. Depth or bathymetry data is usually recorded as x,y,z point data, and can be used to generate depth contours (line and area vector data) as well as digital elevation models (DEM) (Fig. 4.1).

Depending on the horizontal spacing of the depth data, DEM of sufficient resolution can be developed for determining the values for other parameters important in classifying habitat types such as exposure, rugosity, slope and aspect (Fig. 4.1). Bathymetry data can be collected using a wide variety of sensors including: lead lines, singlebeam and multibeam acoustic depth sounders, as well as airborne laser sensors (LIDAR). Each of these systems has its inherent advantages and limitations that will be discussed in the following sections. The range of sampling scales for these instruments is presented in Table 2.2.

The utility of bathymetric data depends on the resolution at which it is collected. Until recently most bathymetry data was collected as discrete point data along survey vessel track lines with singlebeam acoustic depth sounders.

The introduction of swathmapping and multibeam bathymetry systems has dramatically improved our ability to acquire continuous high-resolution depth data (See section 4.3 below). Bathymetric data with horizontal postings of less than 1m are now routinely collected over wide areas using multibeam techniques (Fig. 4.2). Comparable data resolutions are also now possible with some of the new LIDAR laser topographic mapping systems, although water clarity generally limits their application is to the very nearshore environment (< 20m) (see section 4.3 below).

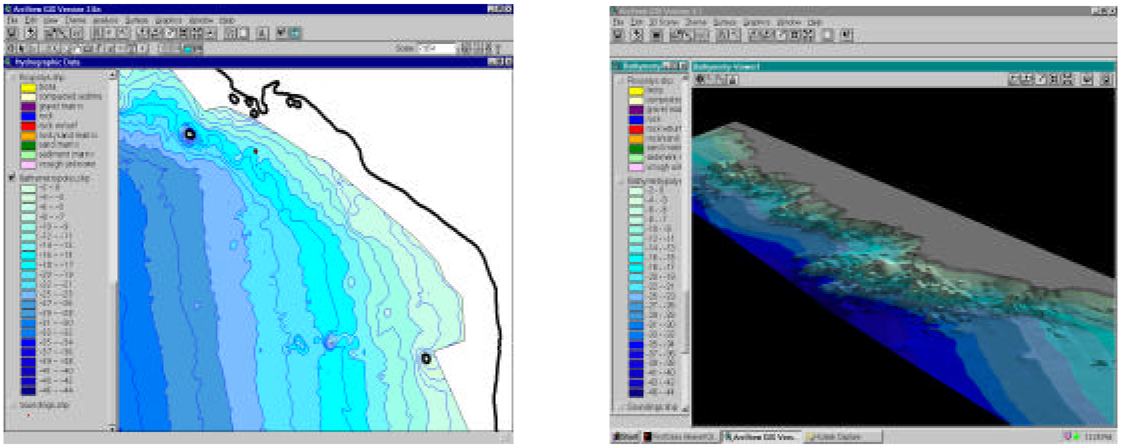


Figure 4.1 GIS products displayed in ArcView created for Big Creek Marine Ecological Reserve from x,y,z bathymetry data. Left) Two dimensional depth contour polygons can be used to stratify the site by water depth. Shoreline vectors (black lines) including offshore rocks can be used to define the "zero" depths when constructing the gridded bathymetry prior to contouring. Right) DEM of the same location shown in shaded relief and draped with depth polygons is used to illustrate slope, aspect, depth, and sea floor morphology simultaneously (Kvitek et al. unpublished data).

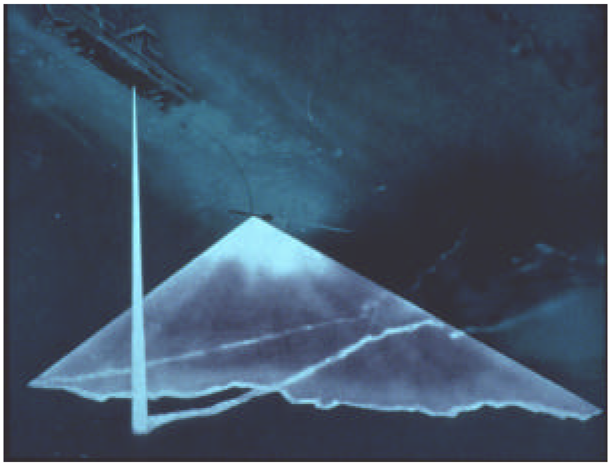


Figure 4.2. Illustration showing difference in coverage between singlebeam versus sidescan sonar and multibeam acoustic depth sounders (courtesy S. Blasco, Geologic Survey of Canada).

Seafloor substrate point data

Information on substrate type and texture can be collected as either point (x,y,z) data or as broad coverage raster imagery analogous to aerial photographs. Point data on substrate composition can come from georeferenced grab or core samples or even underwater photographs and video. Spatial resolution from this type of sampling, however, tends to be very limited due to the effort and cost required to increase data density while maintaining the spatial extents of the survey area. Point data on substrate type can also be acquired through co-processing or post-processing depth sounder data. For example, RoxAnn and Quester Tangent products make use of the multiple returns from echo sounders to classify seafloor substrates according to roughness and hardness parameters. This technology is similar to that applied in acoustic fishfinders, making use of the character and intensity as well as the timing of the return signal. With these add-on devices, it is possible to acquire information on the character of the substrate at each bathymetric sounding position. Similar approaches are now being developed for application to multibeam data. However, rigorous groundtruthing to verify that the resulting classifications are accurate is essential, because the results from this "automated" approach to seafloor substrate classification can vary widely between sites and with environmental conditions.

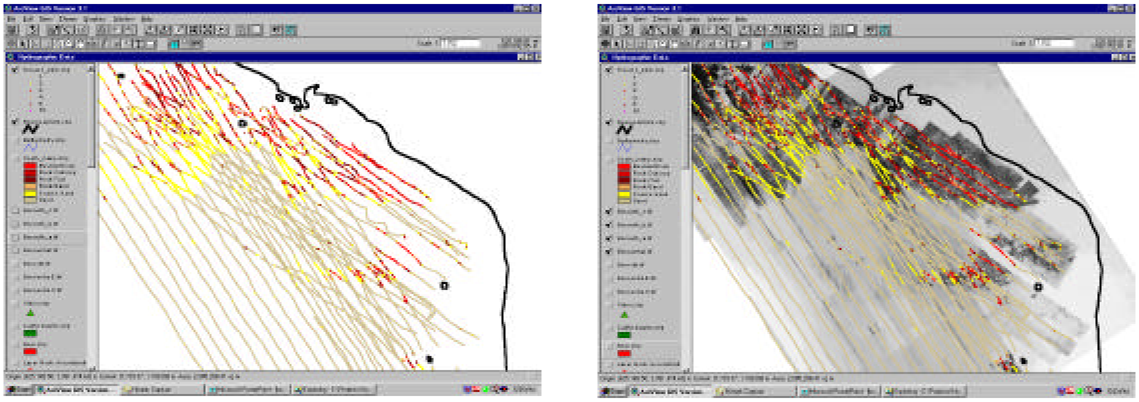


Figure 4.3 Left) RoxAnn substrate classification data collected in conjunction with bathymetry data at the Big Creek Ecological Research. Red = rock, Yellow = cobble, Tan = sand. Right) Same RoxAnn classifications varified against sidescan sonar imagery. (Kvitek et al. unpublished data).

Seafloor substrate raster data – acoustical methods

Seafloor substrate information can also be collected as continuous coverage raster imagery from reflected acoustic or optical backscatter intensity values. Because reflected intensities vary with substrate hardness, texture, slope and aspect, sidescan sonar has been used widely for over 30 years to create detailed mosaic images of seafloor habitats at resolutions as fine as 20 cm (Fig.

4.3). In recent years, this same approach has been applied to the backscatter values of multibeam bathymetry data (Fig. 4.4).

While multibeam backscatter images generally lack the resolutions and detail found in conventional sidescan images, they can be corrected for distortion resulting from unintended sensor motion (e.g. role, pitch, and heave due to waves). This type of correction has not yet been developed for sidescan sonar systems. As a result, shallow water sidescan sonar operations are generally restricted to days with relatively calm sea states, a rarity in may open coast areas. Multibeam systems equipped with motion sensors can be used under a much wider range of sea conditions. One other advantage multibeam systems have over sidescan sonar is continuous coverage directly below the sensor. Sidescan sonar systems have two side-facing transducers that do not ensonify the seafloor directly beneath the towfish.

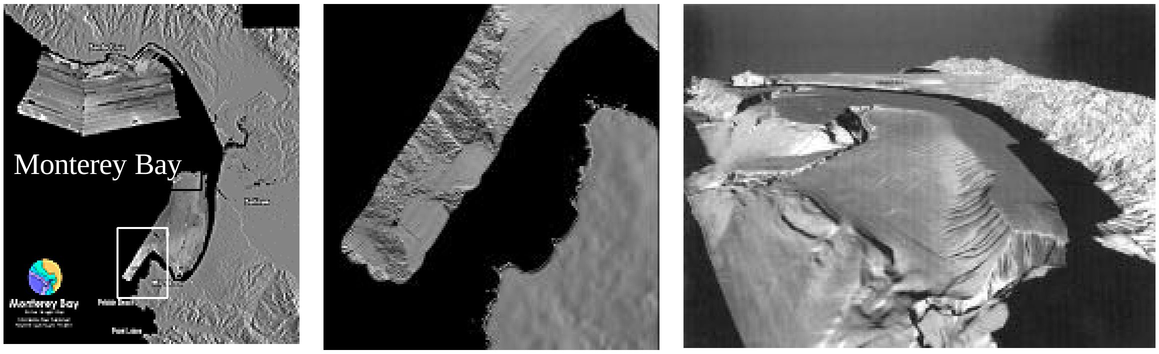


Figure 4.4 USGS high resolution bathymetry coverage in Monterey Bay, Ca. (a). Panel (b) shows multibeam bathymetry imagery from the inset. Panel (c) shows 3D digital terrain model fusion of offshore multibeam and terrestrial DEM data. Note the black "data gap" zone (0-100m water depth) between the terrestrial and USGS data coverage restricted to the offshore habitats.

Seafloor substrate raster data – electro-optical methods

Optical techniques are also being developed for seafloor substrate mapping, including laser linescanner and multispectral imaging. Few of these instruments are in service at this time, in part due to their high cost and the still experimental nature of the technology. For this reason there is a scarcity of examples for comparison in terms of cost, quality, resolution, scale, etc. Nevertheless, these instruments show great promise; laser linescanners for their potential to dramatically increase image resolution over broad survey areas; and airborne multispectral systems for their ability to rapidly map habitat and vegetation types at meter resolution over vast areas in depths too shallow for survey vessel operations. As with all optical sensors, however, both of these technologies are limited in their depth range by water clarity. Below, we discuss the performance characteristics and costs associated with each of these new optical methods in greater detail.

Limitations to acoustic substrate acquisition techniques

Despite the high-resolution seafloor imagery obtainable using acoustic backscatter systems, their application can be limited by several factors including resolution, survey speed, swath width, and water depth.

The relatively slow survey speeds (4-10 knots) required for acoustic surveys can make mapping large areas at high resolution a long and costly enterprise. This situation is especially true in shallow water habitats due to the limitations imposed on swath width by water depth. For sidescan and multibeam systems, the closer the sensor is to the seafloor, the narrow the swath coverage. For most sidescan systems, swath width is limited to no more than 80% of the transducer altitude above the seafloor. Although multibeam systems can have very wide beam angles, data from the outer beams are usually of questionable value, especially in high relief areas where much of the seafloor at the edges of the swath is block from “view” due to acoustic shadowing by the relief. Survey track line spacing for shallow water surveys must therefore be closer than for deeper water work, where wider swath ranges can be successfully used. Even where wider swaths can be used, however, there is a trade off with resolution, which is directly and inversely proportional to swath width. (A sidescan sonar resolution of 20 cm at the 50 m range, drops to 40 cm at the 100 m range.)

Data acquisition in the very nearshore (0-10 m)

Although acoustic methods are not theoretically limited to a given depth range, several practical considerations generally preclude survey boat operations in the very nearshore (0-10 m). Wave height, submerged rocks, kelp canopy and irregular coastlines all make boat based survey operations difficult to impossible within this depth zone along the open coast. While a new technique has been developed for conducting acoustic surveys in kelp forests (see below), the other factors still argue for more efficient, safe and reliable means of mapping California’s extensive intertidal to shallow subtidal habitat. Airborne techniques including lasers and multispectral sensors, while limited to shallow water applications by their optical nature, may be the ideal tools for rapidly collecting elevation, depth, substrate and time series data along this vast and essentially unmapped zone.

4.2. CONSIDERATIONS IN SELECTING DATA ACQUISITION METHODS

A variety of remote and direct methods are available for acquiring depth and substrate data including: acoustic, electro-optical, physical and observational. Selection of which methods to use will be based on geographic extent of the project (scale) and the resolution required (data density), which in turn, are based on the purpose and goals of the project. Identifying the correct scale and resolution for a project in advance is important for two reasons. First, survey costs scale directly with each of these parameters, and there is generally a direct trade-off between scale and resolution if cost is to be held constant. As the aerial extent of a survey increases, resolution must decrease or survey time and costs will increase proportionally. Identifying the scale and resolution required for a given project is also an important consideration for selecting appropriate survey methods. If, for example, the goal is to simply map the aerial extent and depth of sandy versus rocky areas at mega- or meso-scales (1-10km) in moderate water depths (20-80m), then relatively low cost, low resolution techniques such as widely space acoustic survey lines would be adequate. Much higher resolution techniques would be required if the goal was to characterize the complexity of rocky reef habitats by quantifying the relative cover of specific substrate types (e.g. bolder fields, pinnacles, cobble beds, rocky outcrops, algal cover and sand channels), as well as sub-meter relief and the abundance of cracks and ledges because each of these meso- and macro-habitats supports a different species assemblage.

Once the scale, data resolution and budget for the project have been determined given the overall goal, it is then possible to move on to the selection of appropriate methods and tools.

In the following section we present a description of specific technologies commonly used or showing promise in the acquisition of depth and substrate data for nearshore benthic habitats. Wherever possible, we also present sample imagery and products as well as relationships between resolution, scale and cost.

4.3. ACOUSTICAL METHODS

Single-beam Bathymetry

The utility of bathymetric data is highly dependent on the resolution at which it is collected. Until recently most bathymetry data was collected as discrete point data along survey vessel track lines with singlebeam acoustic depth sounders. These sounders work on the principle that the distance between a vertically positioned transducer and the seabed can be calculated by halving the return time of an acoustic pulse emitted by the transducer. All that is required is an accurate value for the speed of sound through the intervening water column. The speed value can be back calculated by adjusting the sounder to display the correct depth while maintaining a known distance between the transducer and an acoustically reflective object (e.g. seafloor measured with a lead line, or calibration plate suspended at a known depth).

The horizontal resolution, or posting, of singlebeam acoustic data is defined by the sampling interval along the track lines and the spacing between track lines. Because it is generally impossible or too costly to space survey lines as close together as the interval between soundings along the track lines, most older bathymetry data sets tends to have much higher resolution along track than across track. This situation necessarily leads to considerable interpolation between track lines when constructing contours or gridded DEM. As a result, the DEM are generally either too course (postings at > 50m) or inaccurate for fine grain mapping at macro- or micro-habitat scales.

One advantage of single beam depth sounders however, is the ability to interface them with acoustic substrate classifiers. These co-processors correlate the intensity values from the single beam echo returns with seafloor substrate hardness and roughness.

Acoustic Substrate Classifiers

The most accurate method of bottom classification is that of *in situ* testing. Direct observations by SCUBA divers, drop or ROV video, or submersible provide substrate classifications with very high confidence levels, as do grab samples or cores; the latter two methods are especially useful for classifying sediments. However, application of these high-resolution, high-confidence methods of substrate classification in large area mapping projects can be quite costly in terms of money and effort. While *class* resolution of core and grab samples can be extremely high, the samples must be very closely spaced in order to give appreciable *spatial* (x,y) resolution. Similar obstacles exist for application of direct visual observation or video imagery to large areas; because of the limitations imposed by visibility underwater, cameras and/or observers must be placed in close proximity to the seabed that is to be classified, and achieving good bottom coverage becomes logistically difficult. In essence, drop camera samples are analogous to cores and grabs in that they are *point* samples, while ROV and submersible observations and video surveys may provide *swath* or *area* information within the visibility and physical range limits of their traveled course. Logistical constraints (in terms of cost, equipment required, support, etc.) can be quite high for ROV and especially submersible work. Towed camera systems may offer a considerably lower cost alternative to ROV or submersible observations while giving greater aerial coverage than drop cameras, but are also difficult to deploy in complex bathymetric settings, owing to the fact that they must be "flown" quite near the bottom due to visibility limitations. Over relatively flat bottom, or with very good visibility, however, these systems may be quite useful. All of these factors make direct observation of bottom type a much more appropriate tool for *groundtruthing* classifications derived from a remote sensing method with higher efficiency in covering large areas and lower cost per unit effort. Indeed, groundtruthing using the above methods is crucial when employing remote sensing techniques. In addition to providing greater coverage efficiency, bottom classifiers can help automate the classification process to some degree, especially relative to the human interpretation that must be applied to sidescan sonar or video imagery in order to map large areas. The primary means of remotely sensing and classifying substrate in the marine environment are acoustic methods.

The following text discussing acoustic substrate classifiers is drawn primarily from "Bottom Sediment Classification In Route Survey" (Mike Brissette, Ocean Mapping Group, Department of Geodesy and Geomatics Engineering, University of New Brunswick, http://www.omg.unb.ca/~mbriss/BSC_paper/BSC_paper.html#Bottom Sediment Classification). Additional text has been added, but the bulk of this section is quoted directly from that report.

This section will discuss two such sonars, namely Marine Micro System's 'RoxAnn', and Quester Tangent's 'QTC View'. Each discussion will look at the theory of operation behind each sonar as well as performance size requirements and costs.

ROXANN

Theory of Operation

RoxAnn is manufactured by Marine Micro Systems of Aberdeen Scotland. RoxAnn uses the first and second echo returns in order to perform bottom sediment classification. The first echo is reflected directly from the sea bed and the second is reflected twice off of the seabed and once off of the sea surface (Fig. 4.4). This method was first used by experienced fishers using regular echo sounders [Chivers et al, 1990]. The fishers observed that the length of the first echo was a good measure of hardness in calm weather.

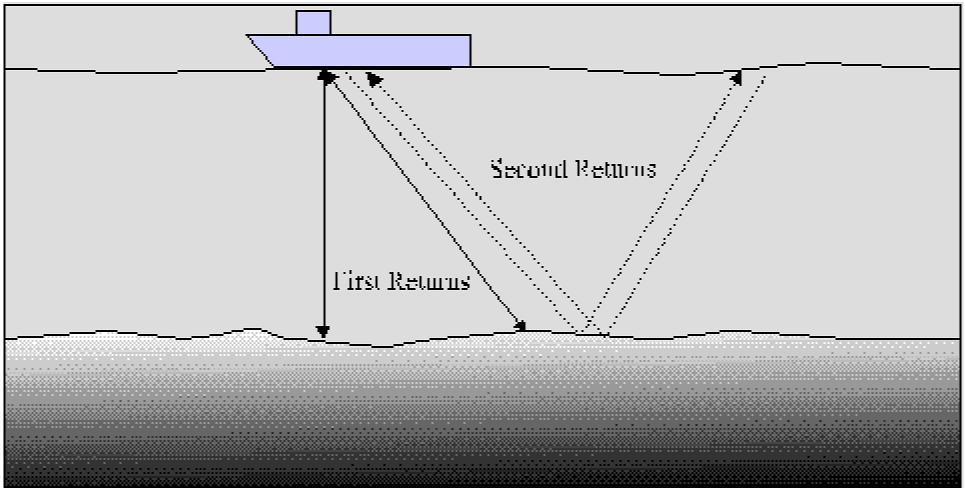


Figure 4.4. Diagrammatic representation of first and second returns (from Chivers et al, 1990).

The second echo, which mimicked the first echo, was much less affected by rough weather. RoxAnn uses two values, E1 and E2, in order to estimate two key parameters of the sea floor, namely roughness and hardness. The first echo contains contributions from both sub-bottom reverberation and oblique surface backscatter from the seabed. It has been shown that oblique backscattering strength is dependent on the angle of incidence for different seabed materials. At 30 degrees there is almost a 10 dB difference in scattering level between mud, sand, gravel and rock [Chivers et al, 1990]. The first part of the first echo contains ambiguous sub-bottom reverberations and is therefore removed (Fig. 4.5). Most or all of the remaining portion of the first echo is then integrated to provide E1, the measure of roughness. The exact parameters within which E1 is integrated are difficult to estimate and is therefore based on empirical observations in a number of different oceans [Chivers et al,1990]. The entire second echo is integrated, which is the relative measure of hardness and is designated E2 [Schlagintweit, 1993]. A processor is used to interpret E1 and E2 such that bottom characteristics may be determined [Rougeau, 1989]. Looking at E1, on a perfectly flat sea floor, non incident rays would be expected to reflect away from the transducer. As the sea floor is not perfectly flat, the returning energy from non incident rays coincides and interferes with the incident rays and indicates the roughness of the sea floor [Chivers et al, 1993]. The specular reflection of the sea floor is a direct measurement of acoustic impedance relative to the sea water above it. Hardness can be estimated using E2 because the acoustic impedance is a product of the density and speed of longitudinal sound in the sea bed [Chivers et al, 1990].

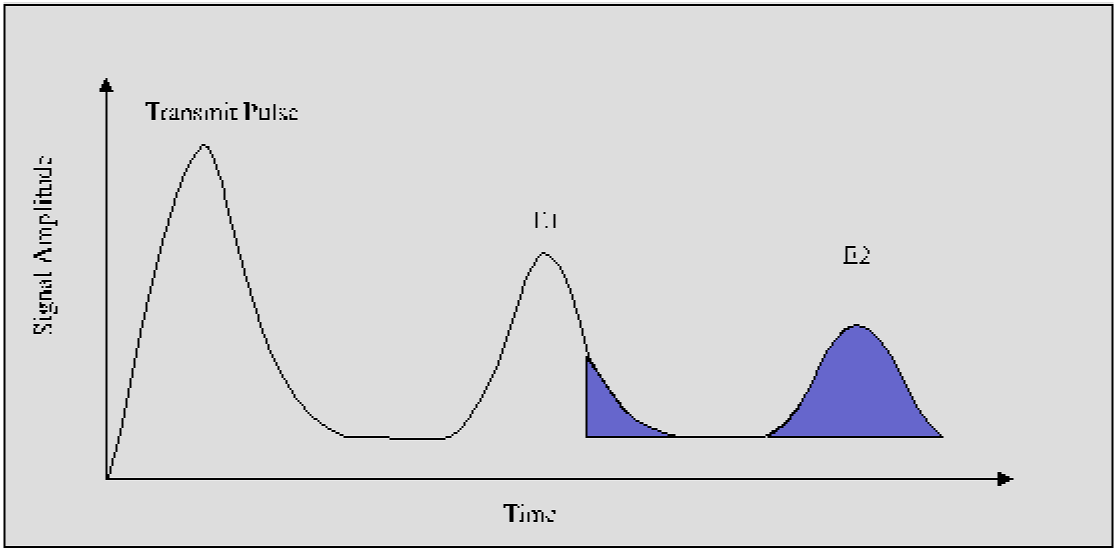


Figure 4.5. First and Second Return Waveforms (from Schlagintweit, 1993)

Test Results

Schlagintweit [1993] conducted a field evaluation of RoxAnn in Saanich Inlet off of Vancouver Island using two frequencies, 40 kHz and 208 kHz. RoxAnn was deployed over a ground-truthed area that had been previously inspected by divers. A supervised classification method was used and a "modest" correlation was found at both frequencies. Classification differences between the two frequencies were due to the different sea bed penetration depths of these frequencies on various sea floor types. That is, the frequency dependent penetration factor into the sea floor depended on the local sea floor itself. Schlagintweit felt that the frequency should be chosen according to the application. Schlagintweit believed that an unsupervised classification method would be the best alternative, i.e., let the system select the natural groupings and then look at ground truthing. Both the Chivers et al [1990] and Rougeau [1989] articles support this method of an initial calibration. In separate tests, Kvitek et al [in press] found quite good agreement between classes created from sidescan sonar interpretation and those created using unsupervised classification of RoxAnn E1 & E2 values at the Big Creek Ecological Reserve in Big Sur, CA (Fig. 4.3). Using sidescan imagery and video groundtruthing, Kvitek et al found that RoxAnn successfully classified sand, rock, and coarse sand/gravel between 6-30m depth in a 2-3 sq. km area in this study.

RoxAnn Equipment

The RoxAnn system is very compact. The entire unit consists of a head amplifier (not shown) which is connected across an existing echosounder transducer in parallel with the existing echo sounder transmitter, and tuned to the transmitter frequency. The parallel receiver accepts the echo train from the head amplifier [Schlagintweit, 1993]. The installation requires no extra hull fittings, simply room for the processing equipment. The required processing equipment includes an IBM compatible computer and an EGA monitor [Rougeau, 1989]. Software which is specifically written to handle RoxAnn data must then be installed on the computer for processing analysis. The RoxAnn Seabed Classification System retails for about $15,000 US and the additional RoxAnn software costs about $10,000 US. Other programs such as Hypack, which retails for US$ 11,000, are also compatible with the RoxAnn hardware [Clarke, 1997]. These prices do not include taxes, installation expenses or services of a technician for calibration and sea trials.

QTC VIEW

Theory of Operation

QTC View is manufactured and distributed by Quester Tangent Corporation of Sidney, BC [Quester Tangent Corporation, 1997]. Like RoxAnn, Quester Tangent's QTC View uses the existing echo sounder transducer; however, QTC View does not examine two different waveforms. Instead, analysis is performed on the first return only. Quester Tangent's other classification system ISAH-S (Integrated System for Automated Hydrography) is also available, and uses the same approach as QTC View in wave form analysis. However, ISAH-S offers multiple channels for multi-transducer platforms, integration with positioning and motion sensors, and helmsman displays. QTC View is more of a standalone system accepting GPS input for georeferencing of echo sounder data. QTC View operates in the following manner. First, both the transmitted echo sounder signal and return signals are captured and digitized by QTC View. Second, the sea bed echo is located (bottom pick), and an averaged echo from several consecutive returns is computed [Prager 1995]. Next, the effects of the water column and beam spreading are removed such that the remaining wave form represents the seabed and the immediate subsurface [Collins et al, 1996]. Quester Tangent's echo shape analysis works on the principle that different sea beds result in unique wave forms. Through principal component analysis, complex echo shapes are reduced into common characteristics. Each wave form is processed by a series of algorithms which subdivides it into166 shape parameters [Collins et al, 1996]. A covariance matrix of dimension 166 x 166 is produced and the eigen vectors and eigen values are calculated. In general, three of the 166eigenvectors account for more than 95 per cent of the covariance found in all the wave forms. The 166 (full-feature) elements of the original eigen vector are reduced to three elements ("Q values"). These reduced feature elements will cluster around locations in reduced feature space corresponding to a sea bed type [Prager, 1995]. Test Results QTC View was designed to operate in both the supervised and unsupervised classification modes. If no ground-truthing has taken place in an area of interest, QTC View will still cluster-like areas such that some type of calibration or ground truthing may be performed after the survey. In a test conducted by the Esquimalt Defense Research Detachment, QTC View was found to have produced very good results. QTC View was used over the same area where the RoxAnn tests were conducted off of Vancouver Island in the unsupervised classification mode. QTC View was able to discriminate between eight different seabed types. After a calibration, QTC view was found to agree with each ground truthed area and showed good transition from seabed type to seabed type [Prager, 1995].

QTC View Equipment

QTC View is comprised of a head amplifier and PC with a DX2/66 processor. The head amplifier is connected in parallel across the existing transducer and to the PC via a RS232 cable. The PC also accepts the GPS data in NMEA-0183 standard GGA or GGL format for georeferencing of data [Collins et al, 1996]. The PC displays three windows: one for the reduced vector space, one for the track plot and classification and the third for seabed profile and classification. Figure 4.6 illustrates the QTC View screen output.

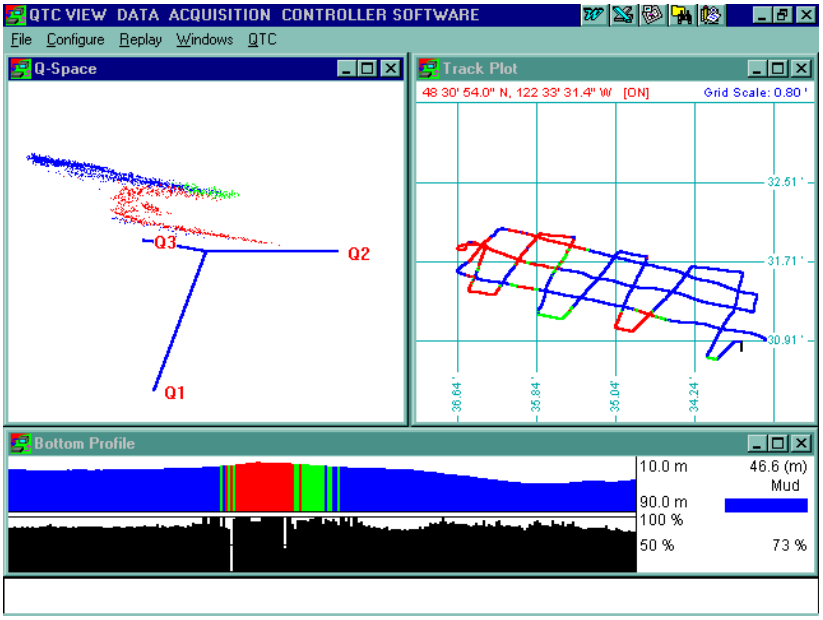


Figure 4.6. QTC View Screen Display (from Quester Tangent, 1997)

QTC is presently working with Reson, Inc. on adaptation of QTC View for use with multibeam depth sounders. This development will greatly increase survey efficiency by supplying substrate class data over most or all of the multibeam swath, but it is unknown when this product will be available. At present, however, QTC View will work with the Reson 8101 multibeam head, although it uses only the nadir beam data. QTC View retails for approximately US $15,000 [pers com J. Tamplin] [Lacroix, 1997] whereas ISAH-S retails for approximately $35,000 [Collins, 1997]. Unlike RoxAnn, the QTC View purchase price includes the software, and like RoxAnn the user must supply the computer. Hypack is not yet capable of acquiring raw QTC View data, but Coastal Oceanographics has provided support for recording the reduced dataset (3 “Q” values) processed in realtime by QTC view. The above prices do not include taxes or installation.

Summary

Both products discussed above have been shown to be useful tools for acoustic bottom substrate classification. The levels of success achieved in past studies using these tools is a function of the inherent qualities of the tools themselves, the operator and processor/analyzer expertise of those involved, the methods used, and the specific conditions of the areas studied. For this reason, true between-product comparisons are difficult. By far the most important fact to remember when using either of these tools (or any remote sensing method, for that matter) is that classifications created using these methods *must* be groundtruthed using one of the direct observation methods discussed above. Only with independent verification can confidence be placed in remotely sensed data.

Multi-Beam Bathymetry

During the last 10-15 years, use of multibeam bathymetry in hydrographic mapping has become increasingly common and accepted. Initially fraught with considerable accuracy and precision issues, multibeam sonar technology has improved vastly and rigorous testing has established its reliability. The ability to acquire *denser* sounding data while surveying *fewer* tracklines (with greater spacing between lines), and simultaneously acquiring backscatter imagery using the same sensor, has made multibeam a popular tool. Using this technology, however, requires attention to a number of considerations that are less crucial when using single-beam technology.

Multibeam depth sounders, as their name implies, acquire bathymetric soundings across a swath of seabed using a collection of acoustic beams (Fig. 4.7 right), as opposed to a single beam, which ensonifies only the area directly below the transducer. The number of beams and arc coverage of the transducer varies among makes and models, and determines the swath width across which a multibeam sounder acquires depth measurements in a given depth of water (Fig. 4.7 and 4.8). It is important to note that effective swath width is often somewhat less than potential swath width, as data from the outer most beams is often unusable due to large deviations induced by ship roll and interference from bottom features such as pinnacles. The potential swath width shown in Figure 4.8 may only be realized under calm conditions over a relatively flat bottom. Swath width is depth dependent, requiring closer line spacing in shallower water if full coverage is to be maintained. The mechanics and physics of how the beams are formed varies as well among makes and models, and may be a consideration of importance if extremely high resolution, precision, and accuracy are required.

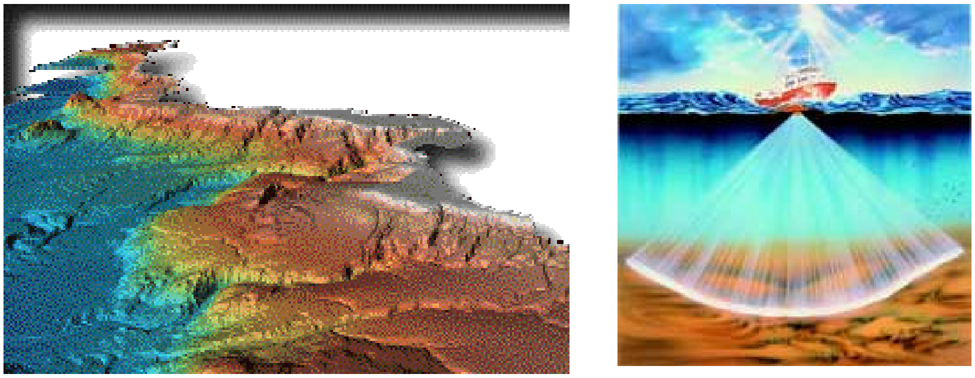


Figure 4.7. (Left) Multibeam generated DEM of central California coast from shore to abyssal depths. Monterey Bay is at center right. (NOAA National Data Centers NDGC, http://web.ngdc.noaa.gov/mgg/bathymetry/multibeam.html). (Right) Conceptual drawing of multibeam ensonification of seafloor (Kongsberg Simrad AS, http://www.kongsberg-simrad.com)

In order for the multibeam system to calculate accurate x, y, and z positions for soundings from all off-nadir (non-vertical) beams (every beam other than the center beam), precise measurement of ship and transducer attitude is required. This includes measurement of pitch, roll, heading, and (preferably) vertical heave. Thus, a motion sensor must be interfaced to the unit, so that its output may be used to adjust and correct the multibeam data in either real time or post-processing.

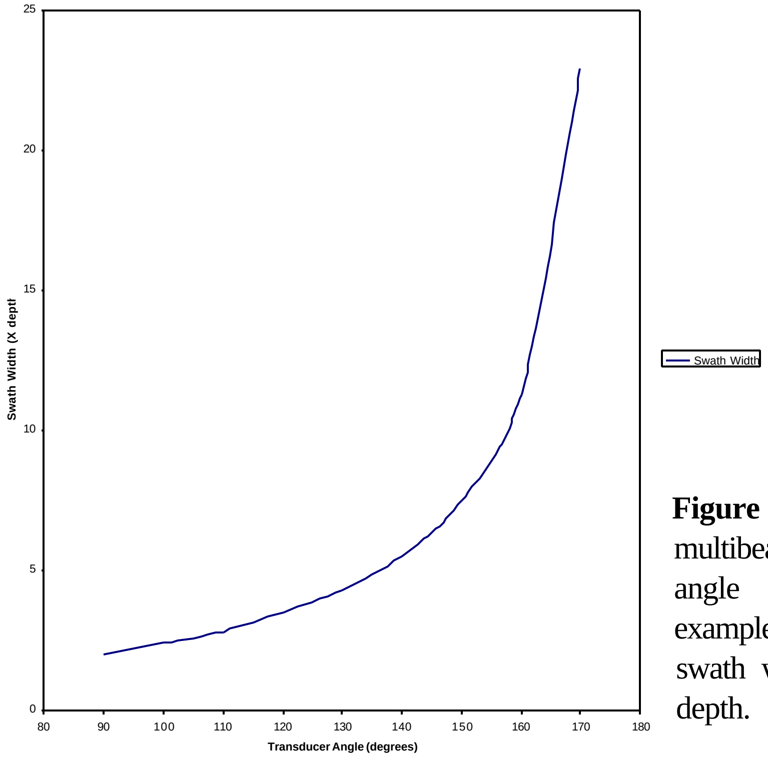


Figure 4.8. Relationship between multibeam bathymetry transducer beam angle and swath coverage. For example: with a 90 degree beam angle swath width will be twice the water depth.

In addition, because of longer travel times for off-nadir beams, variations in the speed of sound in water (SOS) can induce relatively large errors in these beams; especially if temperature stratification exists in the water column. For this reason, sound velocity profiling should be conducted on site during a survey, and the SOS data used to adjust depth soundings. Controlling for variations in SOS is of increasing importance as depth increases. Multibeam surveying also requires more rigorous system calibration to account for systemic variations in, and improve the accuracy of, heading, roll, and pitch sensor values, as well as any adjustment to navigation time tags that will reduce timing errors between navigation and sonar data. This calibration, known as a “Patch Test”, is typically conducted by running a series of survey lines over the same area with relative orientations that allow assessment of the variables listed above.

Multibeam bathymetric surveying generates orders of magnitude more data than single-beam surveying, resulting in greater storage requirements, longer processing times, and the need in some cases for greater processing power. Gigabytes of data may be generated daily, (as opposed to megabytes in single-beam surveys), especially if backscatter imagery is being recorded as well. The removal of bad sounding data during the editing process is, accordingly, a much larger task in multibeam than in single beam surveys, although some processing packages allow some degree of automation of this process.

The considerations and requirements listed above make multibeam surveying a much more complex and expensive undertaking relative to single beam, but the benefits in cost per unit effort and resolution can well outweigh the hardships, especially if extensive surveying is planned. Survey speeds of up to 30 knots are now possible with some systems. Minimal costs for setting up a multibeam system range from $75,000-$150,000 US for equipment alone, not including vessel, installation, and maintenance costs. Higher precision equipment with greater capabilities and more features can cost substantially more.

Sidescan Sonar

Sidescan sonar is the only technology capable of producing continuous coverage imagery of the seafloor surface at all depths. (Blondel and Murton [1997] give an excellent and comprehensive review of sidescan sonar theory, technology, imagery and application in their recent book, Handbook of Seafloor Sonar Imagery.) These systems transmit two acoustic beams, one to each side of the survey track line. Most sidescan systems use transducers mounted on a towfish pulled behind the survey boat (Fig. 4.2 & 4.9), but some are hull mounted. Because towfish can be deployed well below the water's surface, they can be used in deeper habitats than hull mounted systems.

Sidescan sonar beams interact with the seafloor and most of their energy is reflected away from the transducer, but a small portion is scattered back to the sonar where it is amplified and recorded. The intensity of the backscatter signal is affected by the following factors in decreasing order of importance:

- Sonar frequency (higher frequencies give higher resolution but attenuate more quickly with range than lower frequencies)
- The geometric relationship between the transducer and the target object (substrate slope)
- Physical characteristics of the surface (micro-scale roughness)
- Nature of the surface (composition, density)

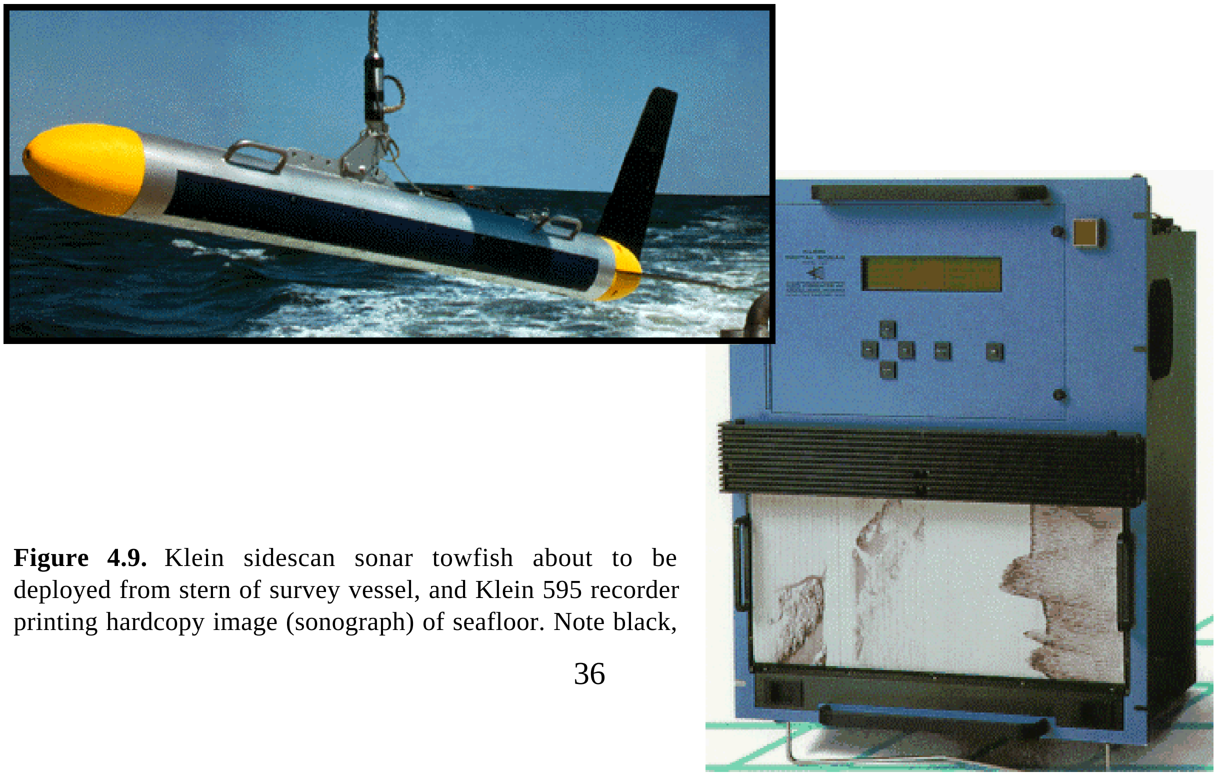


Figure 4.9. Klein sidescan sonar towfish about to be deployed from stern of survey vessel, and Klein 595 recorder printing hardcopy image (sonograph) of seafloor. Note black,

port transducer running down the left side of the towfish (Klein Associates).

For each sonar pulse or ping, the received signal is recorded over a relatively long-time window, such that the backscatter returned from a broad swath of seafloor is stored sequentially. This cross-track scanning is used to create individual profiles of backscatter intensity that can be plotted along track to create a continuous image of the seafloor along the swath (Fig. 4.9).

Swath width is selectable but maximum usable range varies with frequency. High frequencies such as 500kHz to 1MHz give excellent resolutions but the acoustic energy only travels a short distance (< 100 m). Lower frequencies such as 50kHz or 100kHz give lower resolution but the distance that the energy travels is greatly improved (>300 m). Typical systems used for nearshore mapping have frequency ranges from 100 to 500 kHz with resolution as fine as 20 cm. Resolution also varies with swath width. Thus, while a 500 kHz system set at range of 75m will cover a 150m swath at 20 cm resolution, a 100 kHz system set at a range of 250m will cover a 500m swath but at a resolution closer to 1m. There is also a direct relationship between maximum allowable survey vessel speed and range. The shorter the range, the slower the speed and the more survey lines required to cover a given area. (Typical sidescan sonar survey speeds are around 4-5 knots, but with newer systems have been increase to 10 knots.) Thus, the trade-offs between swathwidth, resolution, survey speed, and financial resources must be considered when planning a survey. The choices will depend on: 1) the size of the area to be surveyed, 2) what resolution of substrate definition is required, and 3) how much time and money is available for the survey. Interactive survey time estimate calculation tables such as the Hydrographic Survey Time Estimate Worksheet shown below can be easily constructed in a spreadsheet program such as Microsoft Excel. These tables can be used to construct what-if scenarios to explore the relative time requirements and costs for different survey parameters.

Another variable important to survey time is the amount of overlap desired between adjacent track lines. Most sidescan sonar systems cannot “see” the seafloor directly beneath the towfish. (Klein’s new multibeam sidescan system is an exception.) As a result, if complete coverage of the seafloor is required, it will be necessary to have up to 100% overlap of the sidescan swaths, such that the port side of swath along one track line is completely covered by the starboard side of the swath from the adjacent track line. In this manner, the outer range of one swath can be used to “fill-in” the missing inner-range of the adjacent swath during post-processing.

HYDROGRAPHIC SURVEY TIME ESTIMATE WORKSHEET	
Client: CDF&G	**Project description:**
Project Name: Big Creek Reserve Kelp Forest Survey	Map & classify kelp forest/rockfish habitat
Preparation date: 18 April, 1996	Bathymetry, sidescan sonar, RoxAnn
Prepared by: Rikk Kvitek (831) 582-3529	

Survey area specifications	Plan A	Plan B	Plan C	Plan D
Survey area width (m)	1,000 m	10,000 m	100,000 m	100,000 m
Survey line length (m)	1,000 m	10,000 m	100,000 m	100,000 m
Line spacing (m)	50 m	50 m	50 m	500 m
Survey speed (knots)	4 knots	4 knots	4 knots	10 knots
Survey estimates				
Number of lines	20	200	2000	200
Minutes per line (+1 for turn)	9 min	84 min	834 min	334 min
Total survey time (hours)	3 hr	281 hr	27811 hr	1114 hr

An additional advantage of designing overlap into the survey is to provide different views of the seafloor. This approach is especially important in areas of high relief, where features such as rock pinnacles may block the acoustic beam from striking and reflecting off that part of the seafloor hidden from towfish view. This interruption of the acoustic beam will create shadows or blind spots in the record, which can be filled with information from adjacent tracklines if there is sufficient overlap. Running track lines at different angles over the survey area can also be used to give a more complete picture of what the habitat looks like. For example, the acoustic appearance of canyons, pinnacles and exposed rock strata can vary greatly with approach angle.

Once the survey is completed, the swath images or sonographs can then be combined into a composite image or mosaic of the entire area surveyed (Fig. 4.10). Traditionally, these sonographs were created as hardcopy originals by the sidescan recorder, but are now more often recorded in digital form. As a result, all post-processing, including image enhancement, mosaicking and GIS product creation can be done electronically. Interfacing the sidescan with a differential GPS navigation system can produce georeferencing and imaging accuracy at submeter resolutions. To obtain this accuracy, however, requires that the off-set or "layback" between the sidescan sonar transducer and the GPS antenna is accurately determined and recorded throughout the survey.

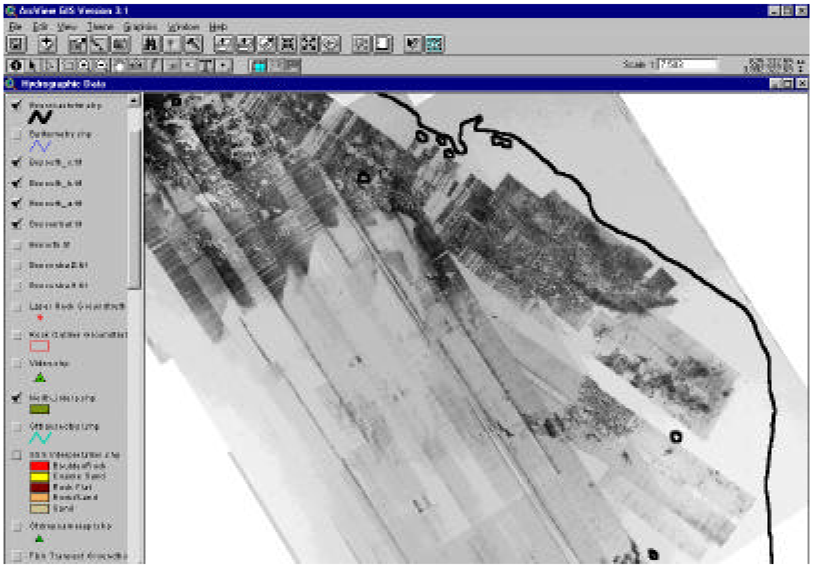


Figure 4.10. Sidescan sonar mosaic of Big Creek Ecological Reserve, Big Sur, California produced with an EG&G 260 100 kHz towfish sidescan

sonar system (authors' unpublished data).

The sonographs and mosaics are used to create what is know as a sidescan interpretation. This process involves tracing polygons around regions of similar substrate as identified on the sonograph (Fig. 4.11). While it is relatively easy to differentiate between rock and sediment on the sonograph, caution must be exercised in the interpretation of the substrate based solely on the sidescan imagery if finer division of the substrate type is required (e.g. cobble, gravel, coarse sand, fine sand, silt, clay, etc.). As a result, it is often necessary to augment the sidescan data with some form of direct sampling (scuba, video, ROV, bottom grabs, etc.) in order to groundtruth the interpretation.

Groundtruthing is especially critical when image analysis software first developed and refined for use with satellite imagery is used to automate the classification and interpretation of the sidescan imagery. Classification involves identifying different features or classes in an image based on their reflectance characteristics. There are two principal methods for performing a classification of an image. "Unsupervised classification" is a method for grouping pixels in an image into classes or "clusters", based on their statistical properties, without the user supplying any prior information on the classes. Once the unsupervised classification has been performed, the clusters that the classifier has identified can be examined and labeled according to what class they represent in the real-world as determined via groundtruthing.

"Supervised classification" involves the user first "training" the system in recognizing different classes by selecting representative samples of each class or habitat type from the image: these samples are known as training sets and should be groundtruthed prior to performing the supervised classification. The system then assigns each pixel in the image to one of these pre-determined classes. Some groundtruthing is essential for accurate classification results regardless of the method used. While highly effective in processing aerial imagery of terrestrial habitats, development of classification techniques is still in its infancy for application to acoustically derived images of marine habitats. These classification routines are available in stand-alone image processing software packages such as ERDAS and DIMPLE, as well as accessories or modules for some GIS software packages including those offered by ESRI and MicroImages.

Once processed and correctly georeferenced, the sidescan imagery and interpretations can also be draped over DEM's to give a 3D representation of the seafloor (Fig. 4.12).

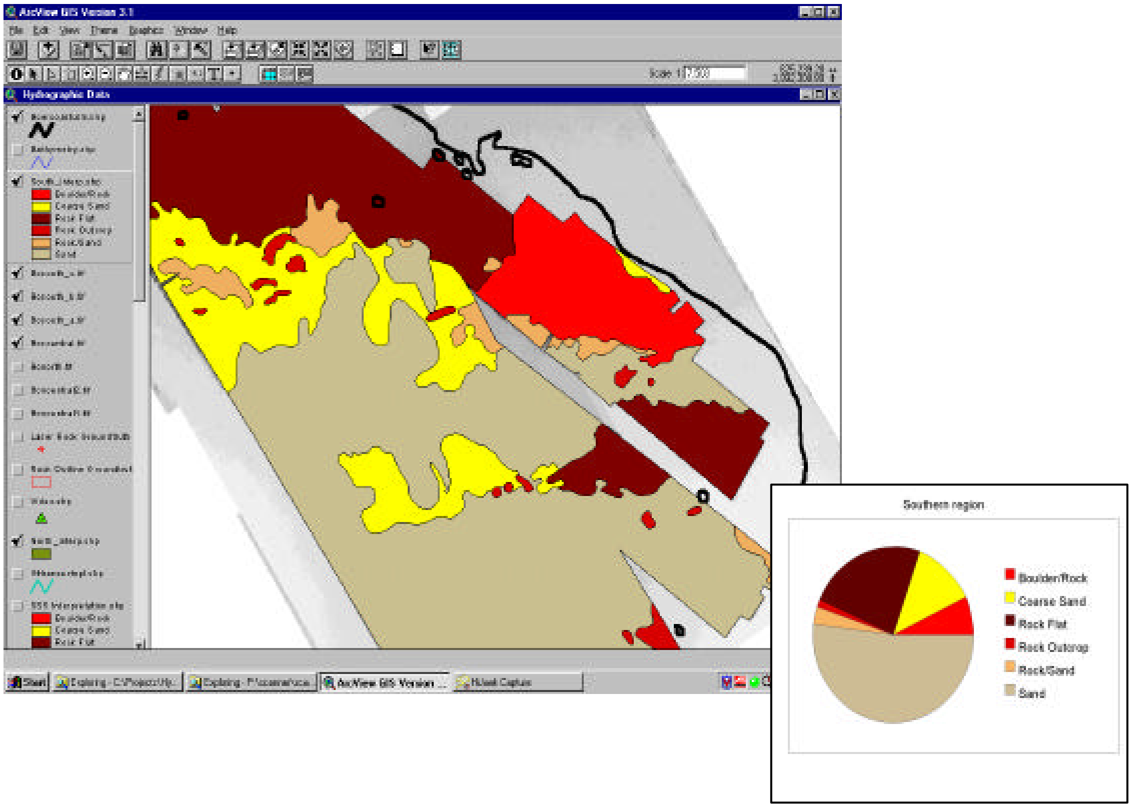


Figure 4.11. Sidescan sonar interpretation created from mosaic shown in Figure 4.10 of the Big Creek Ecological Reserve, (authors' unpublished data).

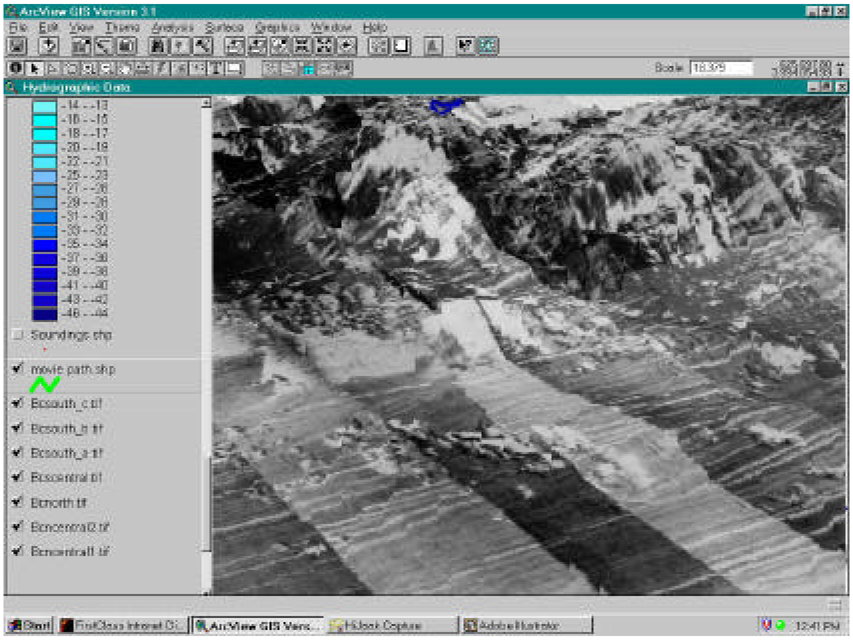


Figure 4.12. Sidescan sonar mosaic draped over DEM of Big Creek Ecological Reserve, (authors' unpublished data).

SPECIAL CHALLENGES TO SIDESCAN SONAR SURVEYS IN SHALLOW WATER

Challenges specific to shallow water nearshore marine habitats make sidescan sonar surveys in these areas more difficult, and costly than for deep water offshore surveys. Close to shore, waves are often higher and small vessels must be used where larger ones will serve in deeper waters. These factors combined with the shorter cable lengths required for shallow water surveys mean that under a given set of conditions, there will be more wave induced vessel motion transferred to the towfish during a shallow water versus a deep water survey. Any towfish motion other than along track movement (e.g. pitch, yaw and heave) will create distortion in the sonograph. While motion sensors are available for single beam and multibeam bathymetry systems, they have not yet been developed to remove motion induced distortion from sidescan sonar data. For this reason, shallow water sidescan sonar surveys conducted when seas are > 2m produce results of little value.

Geohazards

Geohazards are also more of a consideration in shallow waters because towfish altitude above the seafloor is often limited by water depth. Towfish altitude should be kept between 10% and 40% of the range if full coverage of the selected swath width is desired. Less than 10% will result in loss of signal from the outside part of the range, and greater than 40% will produce a large gap in coverage directly below the fish. In water depths of > 40m a towfish could be kept up to 40m off the bottom while still maintaining a range of 100m on a side. This margin of safety is not available, however, in water depths of 10 to 30 m, where the towfish must be kept at least 10m off the bottom but cannot be raised more that the water depth. Thus, a 20m pinnacle in 30m of water presents a very serious hazard to sidescan operations. For this reason, it is always advisable to conduct a bathymetric survey prior to the sidescan work in areas of uncertain seafloor morphology.

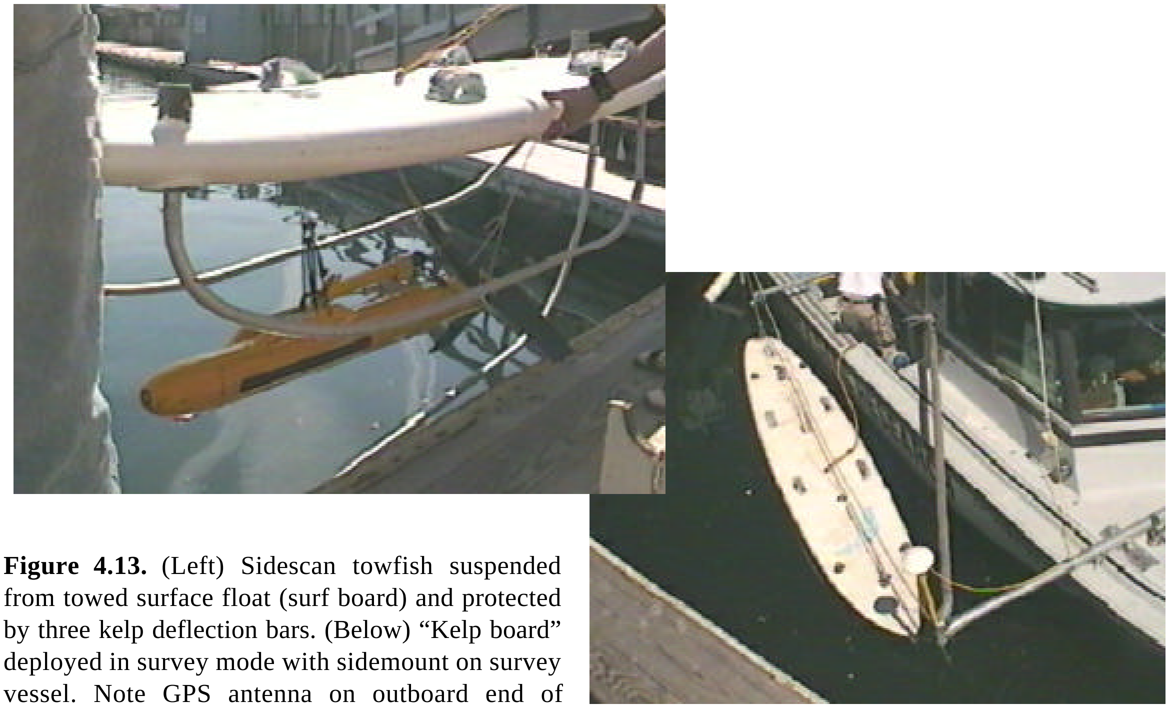


Figure 4.13. (Left) Sidescan towfish suspended from towed surface float (surf board) and protected by three kelp deflection bars. (Below) “Kelp board” deployed in survey mode with sidemount on survey vessel. Note GPS antenna on outboard end of sidemount arm.

Kelp

Kelp canopy presents another hazard for shallow water sidescan work. Although a survey vessel may be able to motor through a sparse kelp canopy, even the smallest amount of kelp that snags on the towfish will result in distortion of the sidescan record due to erratic motion of the towfish. The seafloor mapping group at California State University Monterey Bay has developed a system for shielding their towfish from kelp as it is towed through canopy cover, and are now routinely surveying in area previously off limits to sidescan (Fig. 4.13).

In summary, the advantages of sidescan sonar for habitat mapping are that these systems can produce continuous coverage georeferenced digital imagery of the seafloor substrate at resolutions on the order of decimeters. This technology is analogous to the use of aerial photography for mapping habitats in terrestrial systems. The constraints imposed by the aquatic medium, however, make sidescan sonar a costly endeavor. Vessels are slower than aircraft, sidescan systems are more expensive than cameras, sound energy attenuates more rapidly in water than light does in air, and airplanes need not fly through tree canopies to get their imagery. Costs for complete sidescan sonar systems including dGPS navigation interface and digital data acquisition and processing start at over $150,000.

4.4. ELECTRO-OPTICAL MAPPING TECHNIQUES

In recent years, several new technologies have emerged that may be applied to coastal marine habitat mapping; these tools rely upon the electro-optical, rather than the acoustic, spectra to make measurements and create imagery. Three main types of electro-optical tools show great potential for use in habitat mapping: CASI, LIDAR, and laser line scan (LLS). Two of these tools (CASI and LIDAR) are aircraft-deployed, offering great improvements in vessel speed and survey efficiency (but with lower resolutions in some cases), while the third (LLS) is typically deployed in a towed body similar to sidescan sonar systems. Each tool has specific capabilities, limitations, and considerations, which will be addressed in detail below.

Compact Airborne Spectrographic Imager (CASI)

The Compact Airborne Spectrographic Imager (CASI) system, developed by ITRES Research Ltd., is an imaging system with a two-dimensional CCD array and reflection grating to provide spectral dispersion of the incoming optical signal. The CASI instrument is described in detail in the account of its use in the BOREAS project (Earth Observations Laboratory, http://www.eol.ists.ca/projects/boreas/) and consists of five modules: Sensor head, Instrument Control Unit, Keyboard, PowerSupply Module and Monitor (Fig. 4.14). The following text is directly paraphrased from that document.

Figure 4.14 CASI-2 system manufactured by Itres Research, Ltd.

Total instrument weight is 55 kg. Power requirements are 110 volts at 2.4 amps and with a suitable inverter the CASI can be operated from the 28 volts DC power found on many aircraft. Designed to be compact enough to be flown on light aircraft, the CASI has been flown on quite small aircraft such as the Piper Aztec and Cessna Citation. With no moving parts to the optics, the CASI is a "push broom" imaging spectrograph with a reflection grating and a two-dimensional CCD (charge coupled device) solid-state array detector.

The CCD sensor is a P86520 series frame transfer device (EEV Inc. Chelmsford, UK). The array is thermoelectrically cooled to 2 C to reduce dark current. The imaging area of the array is 578 x 288 pixels with each element measuring 15.5 by 22 um. The instrument operates by looking down and imaging a line perpendicular to the aircraft line of flight. A two-dimensional image is created as the forward motion of the aircraft allows the imaging of successive lines under the aircraft (Anger et al. 1990). The reflection grating provides spectral dispersion of the incoming optical signal. CASI has a nominal spectral range of 391 nm to 904 nm with a spatial resolution of 512 pixels across the 35-degree field of view (FOV). Ground resolution depends on the aircraft altitude and ranges from one to ten meters. The spectral resolution is nominally 2.5 nm FWHM (full width, half-maximum), with 288 spectral channels centered at 1.8 nm intervals. This bandwidth increases with wavelength. The CCD sensor is read and digitized to 12 bits by a programmable electronics system, which is controlled by an internal single-board computer. Data are recorded on a built-in digital tape recorder (Exabyte) which uses 8 mm cassettes, or to other removable or hard disk media. This low cost, standardized, data storage medium greatly facilitates post processing of the data. Each tape can store up to one gigabytes of data or depending on the frame-rate up to one hour of imagery. A representative value for the frame rate under typical conditions is 20 frames (lines) /sec for eight spectral channels in imaging mode. Due to the high data rate of the CASI sensor, three user selectable operating modes have been developed. Each mode maximizes the information content while keeping the data rate at a manageable level.

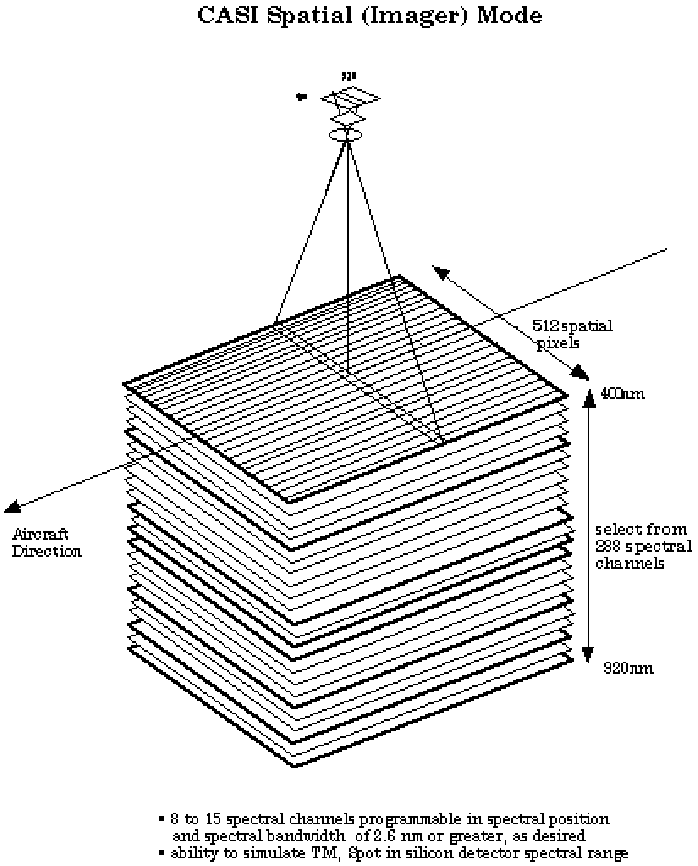


Figure 4.15 Diagram of CASI in Imaging Mode (IM), showing spatial and pixel coverage (Earth Observations Laboratory, http: //www.eol.ists.ca/projects/boreas/)

The three operating modes are Imaging mode (IM), multispectral mode (MS), and Full-frame mode (FFM). In IM, full spatial resolution of 512 spatial pixels across the 35 degree swath is achieved (Fig. 4.15).

Channel wavelengths and bandwidths are user specified (up to 15 bands). In imaging mode, the image width is 512 pixels, and the image length is determined by the length of time that the imager is allowed to operate. Each picture element records radiance values in up to 15 bands between 391 and 904 nm, the spectral location of the bands being selectable by the operator. The pixel size is approximately 1 m by 2 m, when the aircraft is flown at 2000 m above the target surface. Slowing the aircraft substantially may be able to reduce pixel size to as little as 60 cm, but to accomplish this one must reduce the number of bands to about 10 or use band averaging to 16 nm wide bands. Imaging mode is also sometimes called spatial mode.

In multispectrometer mode (MSM, Figure 4.16), full spectral resolution of 288 channels for up to 39 look directions across the 35 degree swath are possible. Look direction spacing and location are user specified to sample the array. This sampling produces an image rake or comb.

A single channel, full spatial scene recovery channel can be selected. In multi-spectrometer mode, the image width is up to 39 pixels, the image length is determined by the length of time that the imager is allowed to operate, and each picture element records the radiance values at up to 288 wavelength intervals in the region from 391 nm to 904 nm. The pixel width is the same as that in imaging mode, however adjacent pixels on the image represent ground points separated by approximately 20 m. The pixel length is approximately 6 to 8 m, and depends on the speed of the aircraft, and on the integration time selected. When the imager is operated in multispectrometer mode, it produces a second image, called the "track recovery row", which consists of only one spectral interval, but is at the spatial resolution of the imager when operated in spatial mode. This track recovery image is usually used solely for locating the multispectrometer image, although it could be included as part of the data stream. This mode is also sometimes called spectral mode.

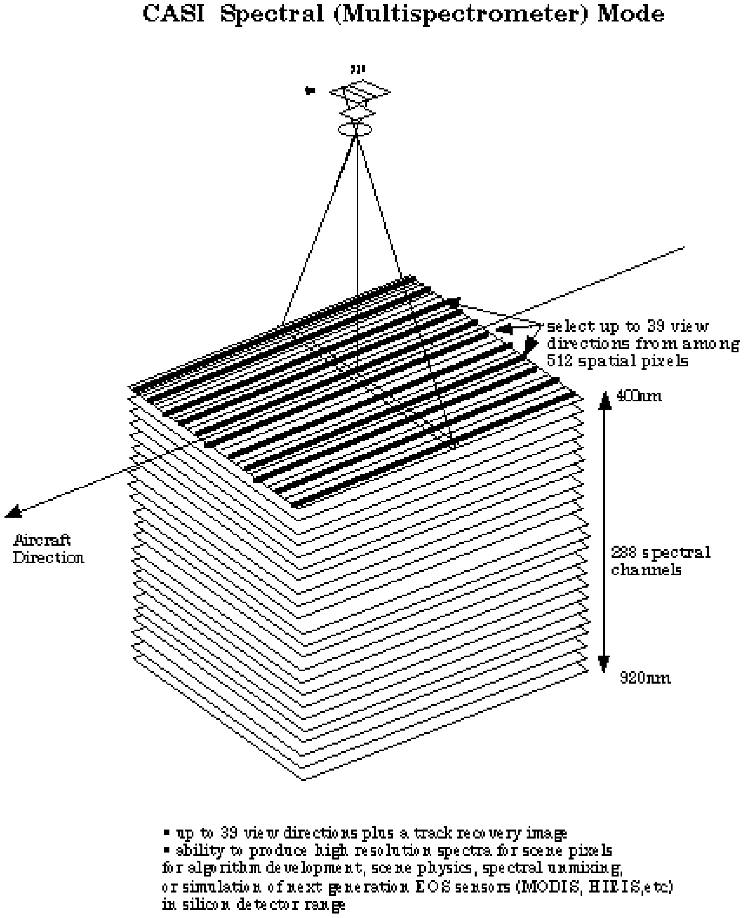


Figure 4.16. Diagram of CASI in Multispectrometer Mode (MSM), showing spatial and pixel coverage (Earth Observations Laboratory, http:// www.eol.ists.ca/projects/ boreas).

In full-frame mode (FFM, sometimes called calibration mode, CASI outputs all the 288 spectral channels for all 512 spatial pixels (i.e. the whole array). This mode requires long data readout times, in the order of one second or more. In airborne operation the first two modes are typically used in successive flights of the same target area. The full-frame mode is used for calibration and ground measurements. CASI has been used successfully in terrestrial, freshwater, and marine settings, to map vegetation, substrate, phytoplankton abundance, thermal and pollution plumes, and other features. By imaging reflectance in different spectral brands, vegetation can be distinguished taxonomically, to species in some cases. In the marine environment, CASI has been used to map benthic algae and substrate type in one of the largest airborne mapping projects to date, to map benthic habitats in shallow coastal waters in Port Phillip Bay, Australia (Anstee et al., 1997, Figs. 4.17 and 4.18).

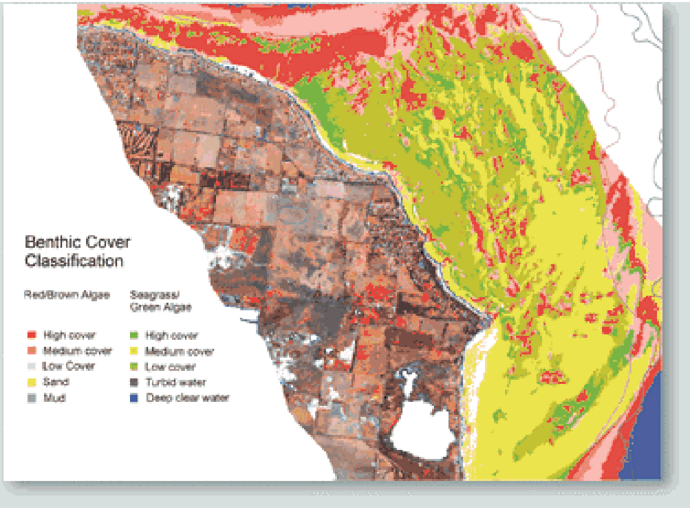


Figure 4.17 Benthic cover classification using CASI (Anstee et al., 1997, http://www.clw.csiro.au/research/environment/remote/australia.html).

This large embayment adjacent to Melbourne has an area of about 1,950 km2. It is relatively shallow with over half the area being less than 10 m deep. Urban population and industrial development on its shores has been increasing, creating growing pressures on the bay's ecology and water quality.

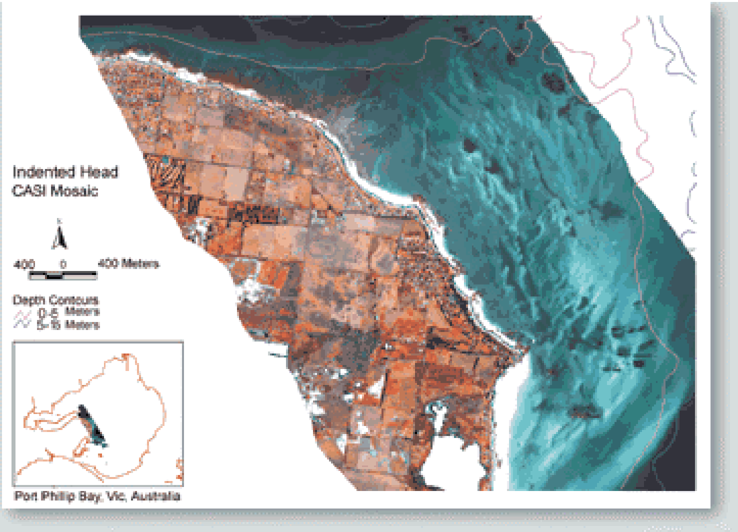


Figure 4.18 Color image mosaic created using CASI (Anstee et al., 1997, http://www.clw.csiro.au/research/environment/remote/australia.html).

The CASI was used to map the whole of the bay to a depth of 15 m (the major portion of the bay), to derive maps of benthic type and cover to 1:25,000 map accuracy, and to help develop objective ecological categories to provide a base for monitoring. Starting with 6 GB of raw CASI data (72 flightlines) at 5 m pixel resolution, laboratory and field methods were developed for mapping spectrally distinguishable benthic materials and optical water quality in the bay. The major breakthroughs of this work, conducted by CSIRO, included the ability to treat the data as physical reflectance, to use large mosaics on a consistent physical basis as 'single' images, and (through physical modeling) to abolish the need for coincident in-water data collection.

An important consideration when using CASI, as with other electro-optical methods, is water clarity. Turbid or otherwise poor-visibility conditions reduce the depth capabilities and resolving power of CASI. A rule of thumb is that CASI is generally effective only within approximately the secchi depth, typically 5-15 m in coastal California waters < 30m deep. Positional accuracy of CASI data is dependent upon type of GPS positioning used (i.e. differential or RTK GPS) and accuracy of aircraft attitude sensor used (as with all airborne data collection methods, aircraft pitch, roll and yaw must be accounted for). Accuracies of ± 2m are common with dGPS. CASI may be deployed simultaneously with LIDAR, achieving greater survey efficiency by simultaneously collecting two types of complementary data (see below).

LIDAR

LIght Detection And Ranging (LIDAR) technology has been used to map topography and bathymetry, and to detect objects (mines, fish schools, etc.) in the water column in marine and freshwater bodies of water. As with CASI, LIDAR is deployed from an aircraft, either fixed-wing or helicopter. Systems for hydrographic mapping typically use a blue-green laser (532 nm) to optimize penetration depth. One such system, the SHOALS (Scanning Hydrographic Operational Airborne LIDAR Survey system) (Fig. 4.19), operated by USACE, is capable of mapping both coastal topography and nearshore bathymetry simultaneously, by the addition of a dual-frequency IR laser.

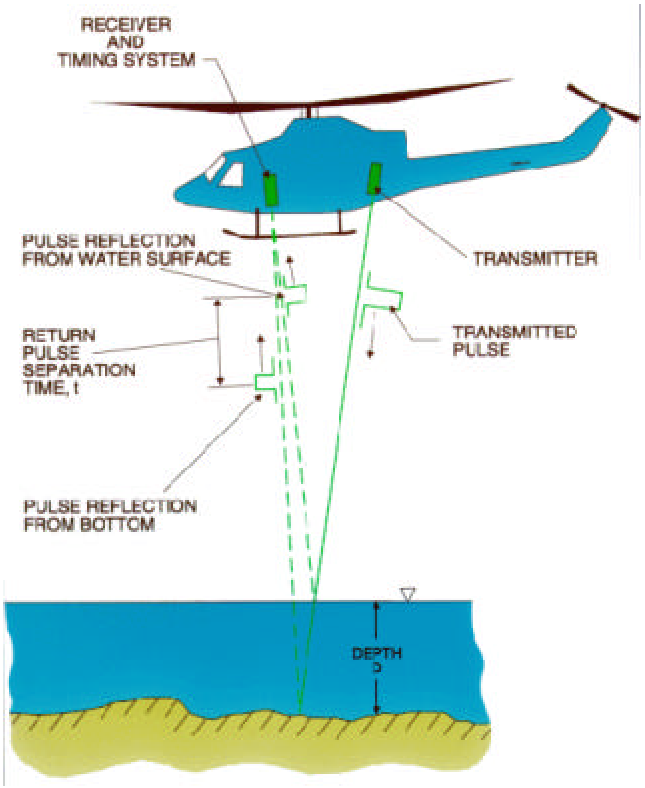


Figure 4.19 SHOALS LIDAR system (http://shoals.sam.usace.army.mil/).

One half of the altitude-dependent swath-width must be over water for this to function; at normal altitude (200m), this allows a 50 m portion of the terrestrial coastline to be mapped.

Other LIDAR systems optimized for terrestrial mapping might then be used if terrestrial elevation data beyond this 50 m swath are desired. Under normal operating conditions (an altitude of 200 meters and a speed of 60 or 120 knots) the system can survey up to 8-32 square kilometers in one hour, collecting depth soundings on a 4 meter horizontal grid. Using dGPS, SHOALS references each depth measurement to a horizontal position accurate to 3 meters and a vertical position accurate to 15 centimeters. RTK GPS can increase the horizontal accuracy to the sub-meter level. Water clarity affects the depth capabilities of LIDAR; under ideal conditions, up to 60 m penetration is possible. In a project in Redondo Beach, CA, 20-25 m penetration was achieved.

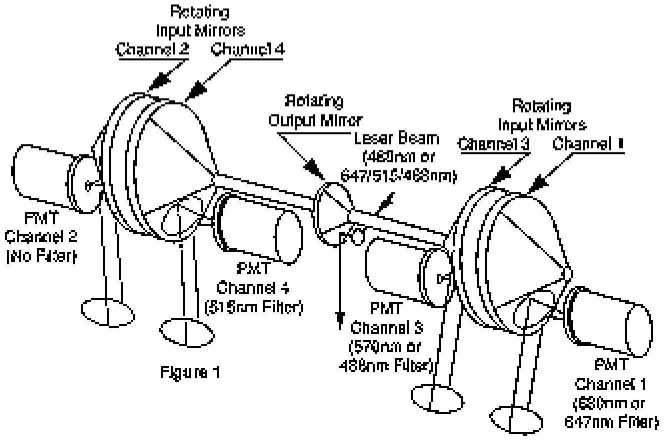
Georeferenced video is recorded simultaneously with the SHOALS LIDAR depth & elevation data. This imagery may be used to help interpret data inconsistencies and to construct mosaics of aerial imagery. As mentioned above, LIDAR may be co-deployed with CASI. Use of the SHOALS system costs $8,000-$10,000 US per square mile (approximately $3100-$3900 per square km), depending on whether dGPS or RTK GPS is used. For this price, both raw and processed x, y, z data are provided on a CD-ROM, as well as raw video imagery if desired (CASI is not included and must be arranged separately).

Laser Line Scanner (LLS)

Unlike the previous two tools, laser line scan (LLS) systems are deployed either in towed bodies similar to a sidescan sonar fish, or on submersibles. This tool, originally developed by the military for mine hunting applications, uses laser light to create high-resolution seafloor imagery (Fig. 4.18). LLS systems were used recently in the search for the TWA 800 and Swissair 111 air disaster remains. A solid state blue-green laser is continuously scanned across a 70º field of view illuminating only a pencil diameter spot at any one time. This spot is tracked by a highly sensitive narrow beam sensor, thereby vastly reducing the effects of backscatter from waterborne particles. The data from the receiver are digitized in real time and stored in an image buffer for display, line by line, on a conventional video monitor, and stored on computer disk for further processing. Data volumes generated are dependent upon resolution, but are substantial (GBs). Potential resolution is much better than that provided by sidescan sonar, as fine as 1 mm. LLS thus provides a resolution midway between that provided by video and still imagery, but at a much higher coverage rate and with much better penetrating capabilities (up to four or five times that of video, Table 4.1). As with video, water clarity limits viewing altitude, and thus swath width and resolution possible (Tables 4.2, 4.3). Survey speeds of 1 to 6 knots are possible, in water from 3 to 1500 m deep. At present, systems manufactured by Northrop-Grumman (formerly Westinghouse) and Raytheon Corporation are available, although high purchase price and related costs may make contracting survey companies offering LLS services (such as SAIC) a more viable option. Additionally a single multi-spectral LLS system exists, owned and operated by the U.S. Navy. At present, it can be deployed only on a submersible. This system and its uses are described in Strand et al., 199X, (http://www.ncsc.navy.mil/css/papers/oceanopeoid.htm). The fundamental difference between this sensor and more conventional laser line scan systems, such as the CSS/Raytheon EOID

Sensor or the Raytheon LS-4096, is the fact that this sensor has four separate receivers (Fig. 4.20).

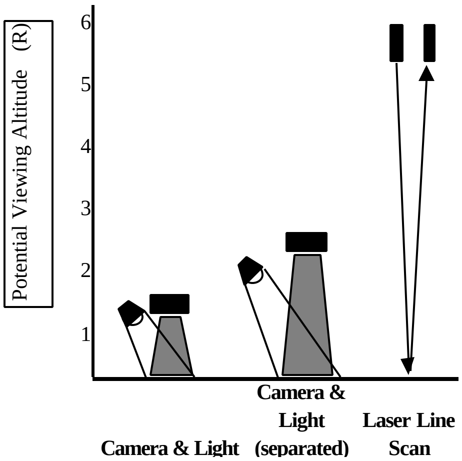
Figure 4.20. Multi-spectral LLS system owned by U.S. Navy and used in the CoBOP Program (Strand et al., 199X).



Each receiver consists of a rotating optical assembly, a controllable aperture assembly, a photo-multiplier tube (PMT), a preamplifier and signal conditioning electronics, and an analog-to-digital converter (ADC). Each of the receivers' rotating optical assemblies can be fitted with optical interference filters and other optical elements, such as polarization analyzers, which allow various aspects of the reflected light field to be evaluated. In a conventional laser line scan system, the receiver is used to measure the magnitude of the reflected light field and the receiver is therefore fitted with no filter or with a filter whose center wavelength matches the wavelength of the outgoing laser light. The use of an optical filter in this case helps reduce the undesirable energy due to ambient sunlight or auxiliary luminaries that may be mounted on the deployment platform. During the CoBOP Program (Strand et al., 199X, http://www.ncsc.navy.mil/css/papers/oceanopeoid.htm) the multi-receiver laser line scan system was used to investigate biological fluorescence by using a short wavelength laser and fitting the receivers with optical filters whose center wavelengths correspond to known fluorescence wavelengths. An Argon Ion laser whose output was tuned to 488nm was used as the stimulating light source and three of the receivers were fitted with interference filters. A 680nm (20nm FWHM) filter was installed in channel #1, a 570nm (40nm FWHM) filter was installed in channel #3, a 515 nm (20nm FWHM) filter was installed in channel #4, and channel #2 was left open without any filter. When the system is used to create color images the Argon Ion laser is replaced with an Argon/Krypton mixed gas laser which provides simultaneous outputs at 647nm (red), 515nm (green), and 488nm (blue). Matching filters, with 6nm FWHM bandwidths, are then added to three of the four receivers and the data required to produce RGB color images can be collected. The images presented in Strand et al. (199X) demonstrate that the quantity and quality of target related information produced by a laser line scan system can be increased dramatically by evaluating other linear and non-linear, or elastic and inelastic, characteristics of the light field.

Table 4.1. Comparison of potential range (or viewing altitude, expressed in terms of R, the range of video camera & light systems), resolution, and search rate for camera and laser line scan systems. Source: SAIC.

	Camera & Light	Camera & Light (separated)	Laser Line Scan
Range	R	2R	5R
Resolution	Excellent	Excellent	Good
Search Rate	Poor	Poor	Excellent



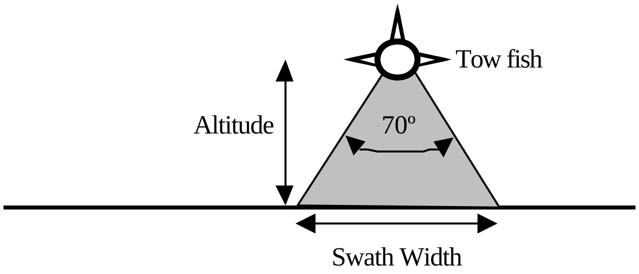
Colorful RGB images, for example, can be produced by illuminating the object with a multi-colored laser and simultaneously monitoring the magnitude of the reflected light at three coordinated wavelengths (Figs. 4.21-4.24). The color images produced in this manner have been shown to be very realistic and could be produced at a range that was 8-10 times greater that the range at which a three chip color CCD television camera was able to produce useful color information. These images also demonstrate conclusively that inelastic, or trans-spectral, phenomena such as fluorescence can also be used to great benefit. Fluorescence maps can be produced that describe, on a point-by-point basis, the fluorescent characteristics of large and small individuals within a relatively large, panoramic field of view. While the importance and application of these fluorescence maps is just beginning to be explored, the intimate connection of fluorescence with key biological processes makes the potential utility of FILLS imagery appear to be particularly tantalizing. Possible applications of these new image forms include wide area evaluation and assessment of specie diversity and distribution, the study of inter-relationships between species and individuals, evaluation and mapping of the health and biological vigor of coral reef communities, and the possible localization and identification of pollutants and other negative stress factors.

Table 4.2. Comparison of resolution, positional accuracy, coverage rate, and sea bottom impacts for sidescan sonar, camera, and laser line scan systems. Source: SAIC.

	Sidescan Sonar	Video/ROV	Laser Line Scan
Resolution	Low	High	High
Positional Accuracy	< 5 m	< 5 m	< 5 m
Rate of Coverage	Very High	Low	High
Sea Bottom Impact	None	Low-Medium	None

Table 43. Effect of water clarity on potential imaging altitude, swath width, coverage rate, and resolution for laser line scan systems. Source: SAIC.

Water Clarity	Typical Imaging Altitude	Swath Width	Area Coverage Rate (@ 3 kts)	Sampling Resolution (@ 2048 Samples)
Very Clear (Hawaii)	45m	65m	346,000 m^2/hr	3 cm
Clear (Eolian Islands)	22 m	30 m	161,000 m^2/hr	1.5 cm
Moderate (WA State, MA Bay)	9 m	13 m	69,000 m^2/hr	0.6 cm
Poor (Boston Harbor)	3 m	4 m	23,000 m^2/hr	0.2 cm



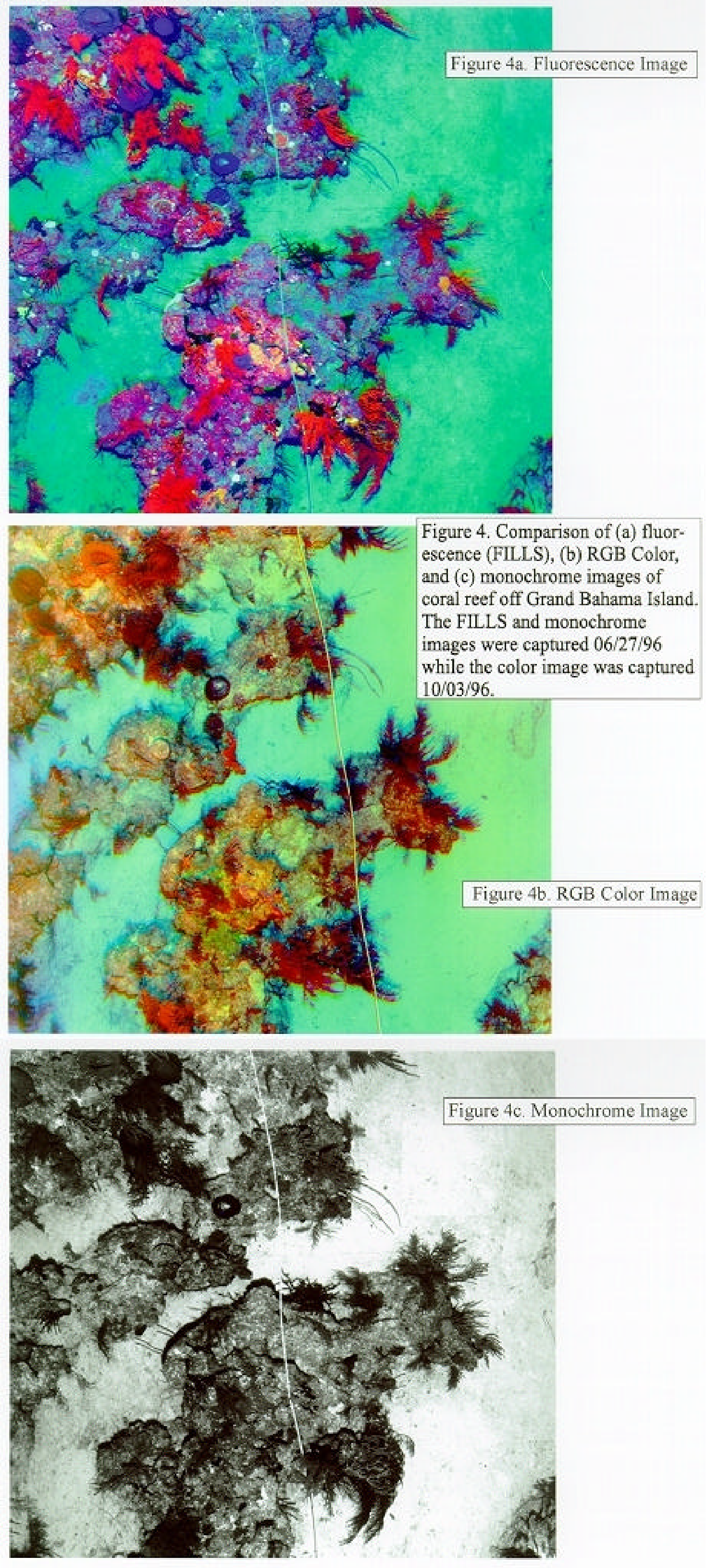


Figure 4. Comparison of (a) fluorescence (FILLS), (b) RGB Color, and (c) monochrome images of coral reef off Grand Bahama Island. The FILLS and monochrome images were captured 06/27/96 while the color image was captured 10/03/96.

Figure 4.21. Comparison of LLS Fluorescence, RGB Color and Monochrome Images. (Source Strand, et al. 199x).

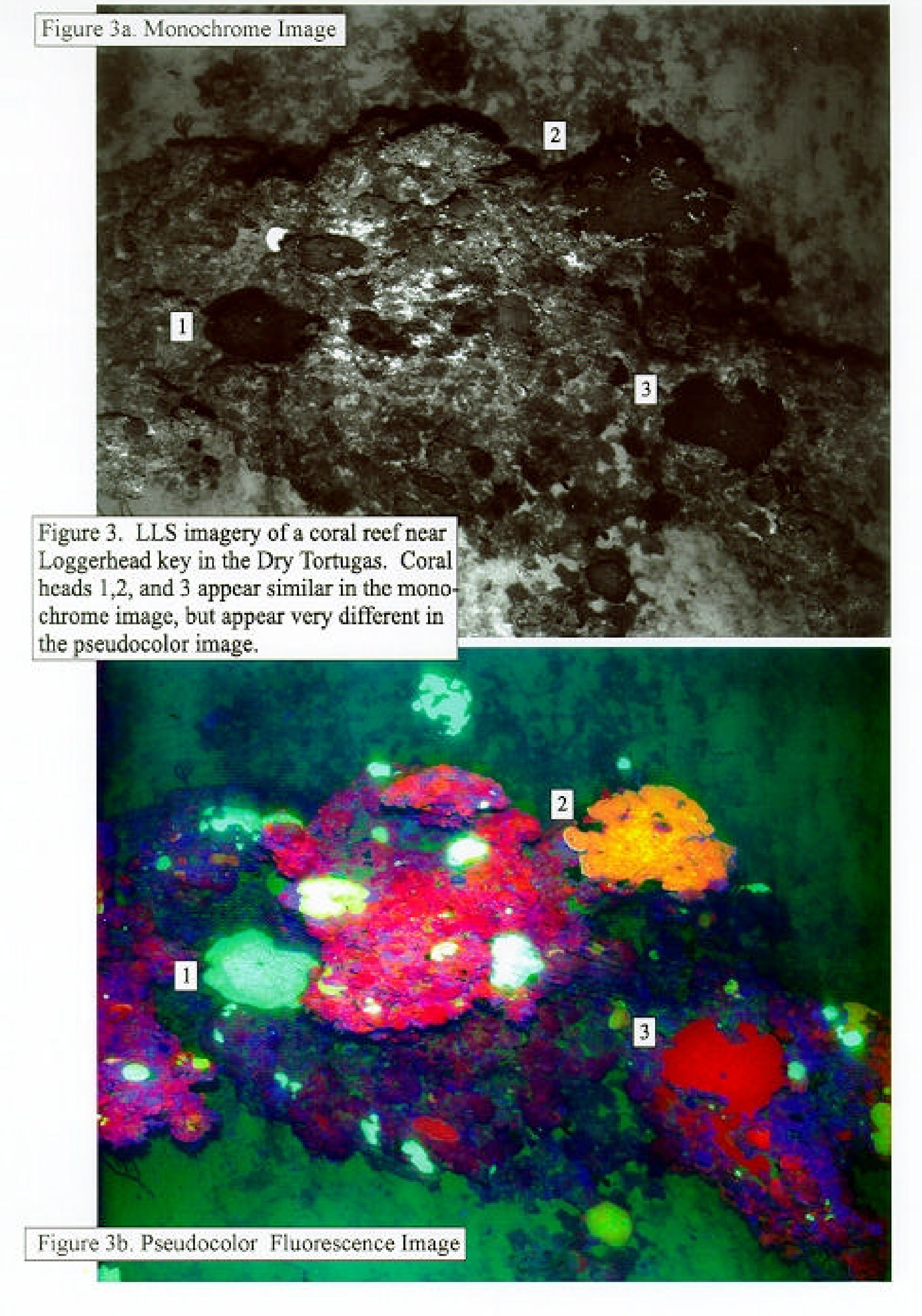


Figure 3a. Monochrome Image

Figure 3. LLS imagery of a coral reef near Loggerhead key in the Dry Tortugas. Coral heads 1,2, and 3 appear similar in the monochrome image, but appear very different in the pseudocolor image.

Figure 3b. Pseudocolor Fluorescence Image

Figure 4.22. Comparison of LLS Monochrome and Pseudocolor Fluorescence Images. (Source Strand, et al. 199x).

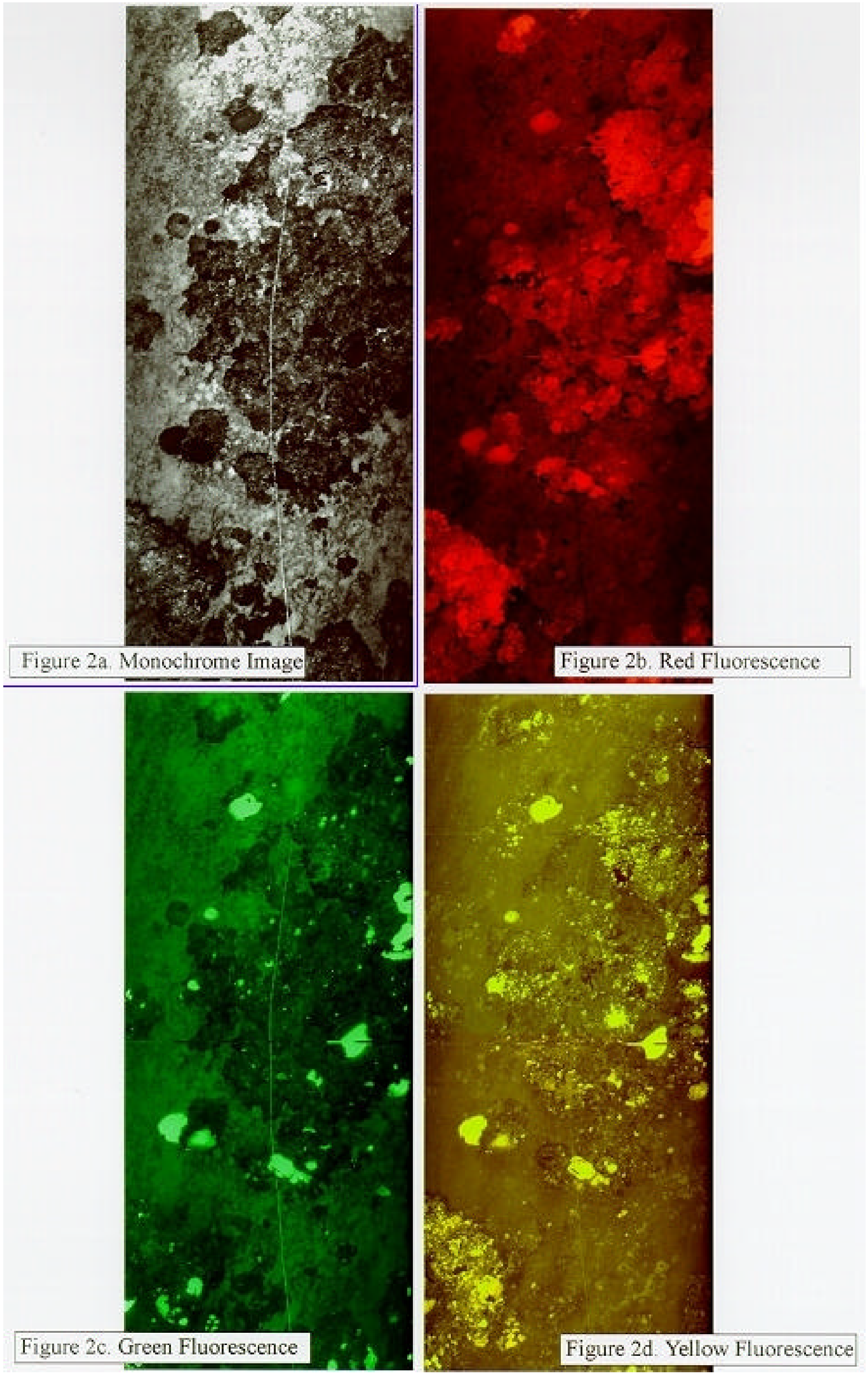


Figure 2a. Monochrome Image

Figure 2b. Red Fluorescence

Figure 2c. Green Fluorescence

Figure 2d. Yellow Fluorescence

Figure 4.23. Comparison of Monochrome LLS Image, Red Fluorescence, Green Fluorescence, Yellow Fluorescence. (Source Strand, et al. 199x).

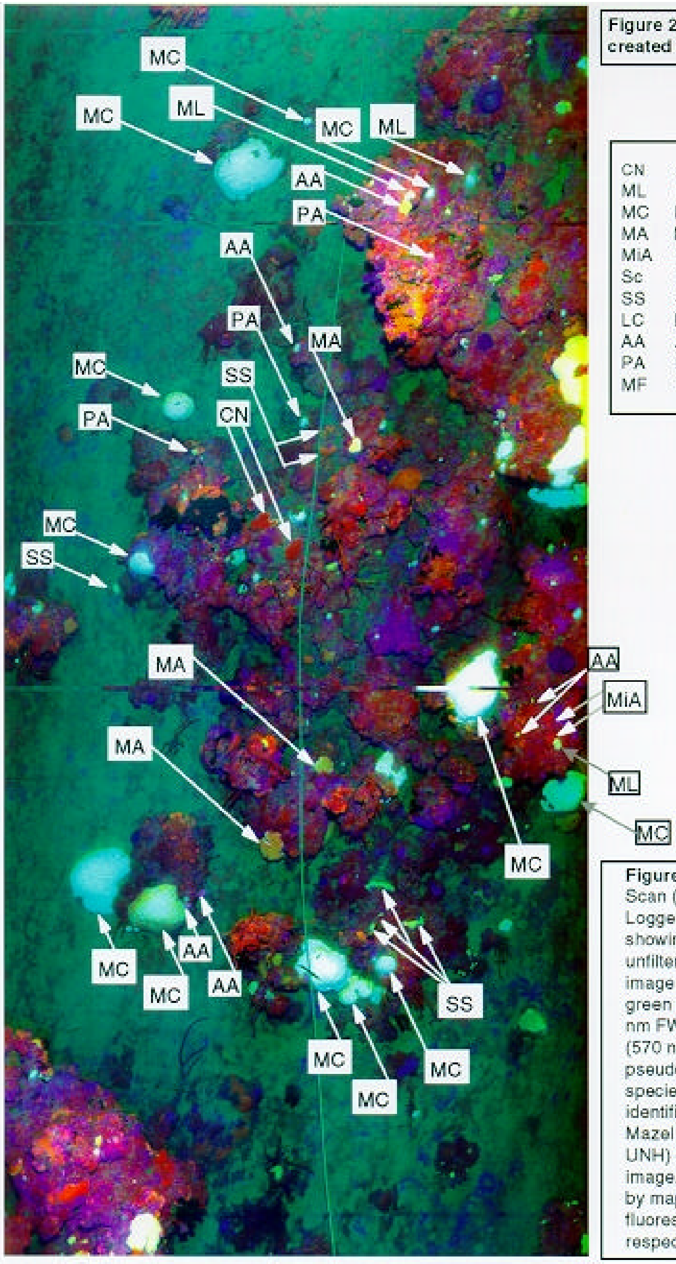


Figure 2e. Pseudocolor fluorescence image created by combining figures 2b, 2c, and 2d.

CN	Colpophyllia natans
ML	Mycetophyllia lamarckiana
MC	Montastrea cavernosa
MA	Montastrea annularis
MiA	Millipora alcicornis
Sc	Scolymia sp.
SS	Siderastrea siderea
LC	Leptoseris cucullata
AA	Agaricia agaricites
PA	Porites asteroides
MF	Mycetophyllia ferox

Figure 2. Fluorescence Imaging Laser Line Scan (FILLS) imagery of a coral reef near Logger Head Key in the Dry Tortugas, showing (a) monochrome image from the unfiltered channel, (b) red fluorescence image (680 nm filter, 20 nm FWHM), (c) green fluorescence image (515 nm filter, 20 nm FWHM), (d) yellow fluorescence image (570 nm, 40 nm FWHM), and (e) pseudocolor fluorescence image, with coral species identification. The species identification was by divers (Dr. Charles Mazel of MIT and Dr. Michael Lesser of UNH) guided by the FILLS pseudocolor image. The pseudocolor image was formed by mapping the red, green, and yellow fluorescence signals to red, green, and blue, respectively.

Figure 4.24. Pseudocolor LLS Image created by combining Red Fluorescence, Green Fluorescence, Yellow Fluorescence (Source Strand, et al. 199x).

4.5. DIRECT 1:1 SAMPLING METHODS

Groundtruthing

Despite the remarkably fine resolution now achievable using acoustic and electromagnetic remote sensing techniques, direct or 1:1 sampling (scuba observation, cores, video, etc.) is still critical to the success of any subtidal mapping program for at least three reasons. First, while remote sensing technologies are capable of submeter resolution, much of the habitat detail important to the biotic communities can occur on the scale of centimeters. Grain size, small cracks, pits and mounds that may be below the resolving capabilities of remote sensing systems can be sampled using direct techniques. Secondly, some types of biotically important features, such as void spaces between rocks, can be difficult or impossible to accurately quantify in terms of size and distribution using acoustic techniques. Finally, if accurate habitat maps are to be produced from remotely sensed data, the results need to be groundtruthed using direct methods. For example, a white area on a sidescan sonograph is the result of no or very low reflected signal. Without directly sampling the area, the operator may not be able to determine whether the light patch is a region of very soft sediment which reflected little of the signal, or a shadow cast behind an object projecting up into the water column. Although this is an extreme case, the issue remains that sonographs are merely spatial patterns of acoustic reflectance which often have to be "spot-checked" with direct techniques if the true nature of the substrate is to be identified (e.g. grain size, rock type, biotic cover, etc.).

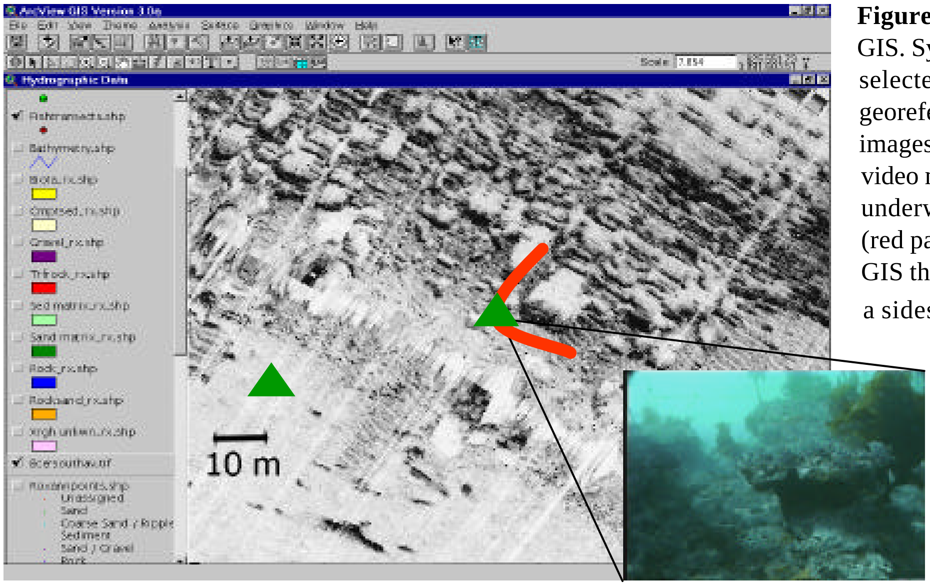


Figure 4.25. Multimedia GIS. Symbols can be selected to display georeferenced digital still images (green triangle) or video movie clips from a underwater video transect (red path) embedded in a GIS theme displayed over a sidescan sonograph.

Underwater positioning and georeferencing

A variety of methods are available for groundtruthing and 1:1 sampling of the seafloor including: direct observations by scuba divers, diver operated still and video cameras, sediment cores and grabs, drop cameras deployed from a vessel, submersibles, and remotely operated vehicles (ROV) guided by a pilot from a deployment vessel. Common to all of these methods, however, is the need for accurate georeferencing of where the samples are collected. Again, there are a variety of methods for determining the x, y, z location of were a sample is taken. The simplest methods for geolocating sampling locations involve determining the surface position of the deployment vessel using GPS and assuming the location of the sample is directly below the boat or float. This approach is most successful for cores, grabs, and drop-cameras used in areas of low current and wind, such that the cable or tether remains nearly vertical.

Under circumstances where there may be significant horizontal displacement of the sampling device away from the deployment vessel, such as with divers and ROV's, some type of underwater tracking will be required if meter level resolution is required. Acoustic tracking systems, such as DiveTracker from Desert Star and Track Point II® from ORE International, can be used for underwater tracking and navigation in real-world coordinates when interfaced with dGPS. Using these systems, divers, submersibles and ROVs equipped with video cameras can be precisely guided along pre-determined transect lines. These georeferenced video images can be incorporated directly into GIS products as snap shots or "move clips" to illustrate what the habitat actually looks like (Fig. 4.25) (Bretz, Kvitek and Iampietro 1998). Also, when equipped with paired reference lasers set a known distance apart, video transects and quadrats can be used to quantify the size, distribution and abundance of many habitat features as well as species. Vertical images of the seafloor, if precisely georeferenced, can even be mosaicked to produce continuous, highly detailed views of larger areas (Fig. 4.26). Furthermore, with the advent of digital video imagery, these mosaic images can be greatly enhanced to reveal much detail normally obscure in conventional analogue imagery (Howland et al. 1999).

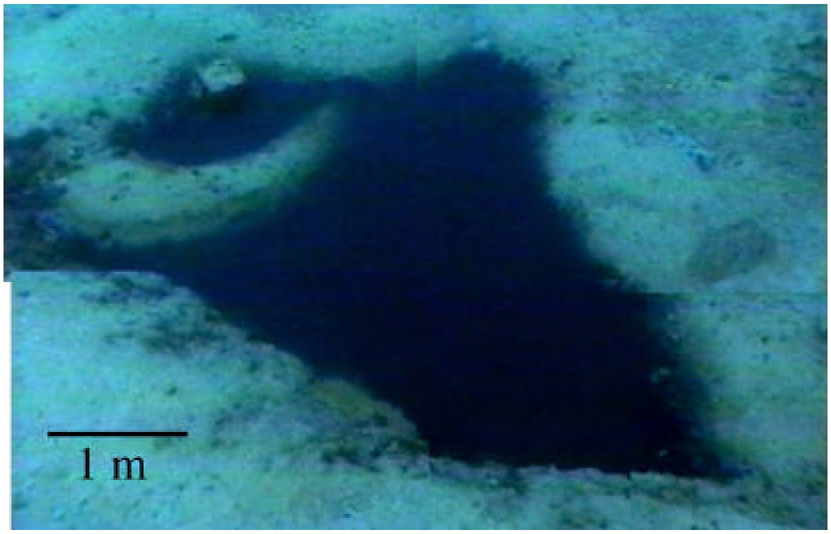


Figure 4.26. Example of georeferenced seafloor video mosaic. Image is of hypoxic brine pool found at 10m water depth in Resolute Bay, Canada. Picture was created from four digital video stills images (Kvitek et al. 1998).