TOOLS AND TECHNIQUES FOR THE ACQUISITION OF ESTUARINE BENTHIC HABITAT DATA

FINAL REPORT

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1.0 INTRODUCTION

This paper will present and review the wide range of methods available for the acquisition of estuarine benthic habitat characterization data. Most managers who ultimately control project budgets and many scientists who may review and analyze benthic data may not have a strong survey background or be well-versed in the variety of techniques available to acquire benthic habitat data. Though many references exist outlining a myriad of available seafloor characterization and mapping techniques, there are not many papers that focus primarily on mapping estuarine benthic habitats or that collectively address all of the available techniques.

The characterization or classification of benthic habitats may be based on a wide variety of seafloor (e.g., topography, composition, complexity, etc.) and water column (salinity, temperature, turbidity, dissolved oxygen, etc.) physical parameters, as well as the actual observed biological structure. The physical characterization of the seafloor is undoubtedly one of the most important elements in any comprehensive benthic habitat classification scheme, and will be the primary focus of this paper. In the more widespread terrestrial remote sensing and habitat mapping applications, the physical description of the land area is often referred to as "cover." Within the marine environment it is far more common to refer to the seafloor itself as the "habitat." For the purposes of this paper, the term "benthic habitat" will be viewed synonymously with the physical characterization of the seafloor.

Though the tools and techniques that are presented herein are applicable to a wide variety of seafloor characterization applications, the primary emphasis of this paper will be on the effective mapping of shallow-water, estuarine environments. This paper will try to provide the framework for evaluating the potential applicability of the wide variety of benthic habitat mapping data acquisition tools based on numerous project-specific considerations (e.g., data requirements, general environment, habitat scales, budgetary constraints, complexity of the survey area, availability of existing data, etc.). Because the acquisition of benthic habitat data is typically a costly and time-consuming effort in the initial stages of any benthic mapping project (and has a major impact on the value of any subsequent analyses), it is important that the selection of the data acquisition techniques be based on a well-informed review.

1.1 Overview

Any comprehensive seafloor characterization effort will generally rely on some combination of broad-scale, lower resolution, physical characterization data (e.g., multibeam bathymetry, side-scan sonar imagery, etc.) as well as fine-scale, higher resolution sampling data (e.g., sediment grabs, sediment-profile imaging, underwater video, etc.). The broad-scale techniques are intended to provide a general physical overview (e.g., bottom topography, changes in surface sediments, etc.) of the seafloor over the entire area of interest. The fine-scale techniques are used to generate the higher resolution, ground-truth data that will improve and/or confirm the broad-scale interpretation. Within this context, the term "ground-truth" implies that the fine-scale data will be used to assist with a manual interpretation of the broad-scale data or to help "train" an automated interpretation of the broad-scale data. This use of the term is somewhat different than in the terrestrial remote sensing realm, where the term "ground-truth" most often refers to some type of discrete sampling data that is used to help assess the accuracy of an automated remote sensing data interpretation.

In an ideal situation, the broad-scale characterization would be completed first, and then used to help define the preferred sampling plan for the follow-on fine-scale survey. This type of approach will help to ensure that each of the distinct regions or habitat types that can be delineated within the broad-scale data will be sufficiently sampled with a fine-scale technique to enable a complete physical characterization of the area. If a strong correlation cannot be made between the broad-scale characterization and the discrete sampling data, then higher resolution broad-scale data or more densely sampled discrete data may be required. The ultimate goal is to create a full-scale physical characterization of the seafloor over the study area.

When the primary focus of the seafloor characterization effort is on some particular benthic communities (rather than just the benthic habitat), then the fine-scale sampling data may also be used to establish a direct relationship between the broad-scale physical characterization and the benthic communities of interest. Because direct benthic sampling techniques require greater resources for both acquisition and analysis, most large-scale benthic habitat mapping efforts are focused mainly on providing a complete physical characterization of the seafloor. For smaller survey areas or for projects with larger budgets, direct benthic sampling may enable a full-scale physical *and biological* characterization of the seafloor over the entire study area. If extensive direct benthic sampling is not feasible, it is then up to the benthic biologist to infer the link between the physical seafloor characterization data and the likely benthic communities that inhabit those areas. Evaluating the nature of the relationship between the physical characterization data and the biological communities of interest is the focus of a companion paper (Diaz and Solan 2003).

The initial section of this paper provides a broad overview and discussion of the numerous techniques available for the acquisition of benthic habitat mapping data. The initial grouping of these techniques distinguishes between those that provide mainly broad-scale characterization data and those that provide fine-scale (or ground-truth) data. Within each of these two main categories, the techniques are further grouped based on their primary data measurement parameter (i.e., acoustic, electro-optical, etc.). Though the initial review of the various data acquisition tools and techniques is relevant to a wide range of potential mapping applications and includes references covering a broad range of seafloor environments, the subsequent sections focus primarily on physical characterization issues related to "typical" estuarine environments. For this paper, a "typical" estuarine environment is broadly defined as one that is shallow (less than 25 m), generally turbid, and comprised primarily of soft and/or fine-grained sediments.

The mention of specific equipment and manufacturers is generally avoided throughout the body of this paper. However, many of the references cited provide greater detail on individual systems and most of the overview figures generated for each of the main techniques addressed in this paper do provide website addresses for a variety of relevant sources. In addition, Kvitek et al (1999) provides a relatively comprehensive list of vendors and suppliers for many of the data acquisition tools discussed in this paper.

2.0 DATA ACQUISITION TOOLS FOR BENTHIC HABITAT DATA

Because of the technical complexity of the numerous techniques available for the acquisition of seafloor characterization (or benthic habitat) mapping data, the following discussion does not intend to provide detailed descriptions of how the various systems work. Instead, the focus is on the types of data that the various techniques can provide and also the major operational considerations (limitations, complexity, costs, etc.) associated with their use. Numerous references are cited within each subsection to provide greater technical detail on the various techniques.

The two main categories of techniques generally used to provide broad-scale seafloor characterization data are boat-deployed acoustic methods and aircraft-deployed electro-optical methods. The two main categories of techniques used to generate fine-scale characterization data are boat-deployed electro-optical methods and boat-deployed physical sampling methods. Although the primary distinction within this section is between the broad-scale and fine-scale data acquisition techniques, the initial subsection addresses some of the navigation and data acquisition software issues that are applicable to any of the subsequent seafloor characterization methods.

2.1 Position Control and Data Acquisition Software

Regardless of which of the numerous techniques are employed for data acquisition, it is critical that all aspects of the data acquisition process are well controlled with accurate and consistent time and position data. Accurate position control (along with consistent horizontal and vertical datums) for each sampling element is critical for subsequent data analyses and time-series data comparisons. (A more in-depth discussion of datums is provided in Section 3.3.) The following discussion is applicable primarily to the boat-deployed data acquisition techniques. All of the aircraft-deployed techniques have their own suite of specialized acquisition and processing software that is outside the realm of the following discussion.

2.1.1 Global Positioning System (GPS)

Because of its reliability, accuracy, and ease of use, the Global Positioning System (GPS) has become the overwhelming choice for providing accurate position control during most field survey operations. It is widely used throughout the surveying industry and has essentially revolutionized that profession. Instead of the labor- and equipment-intensive methods (microwave, optical, etc.) formerly needed for obtaining survey-quality position control, the use of differential GPS (DGPS) enables a navigator or surveyor to obtain comparable (or in many cases better) positioning accuracy without having to establish any local control stations. Although GPS coverage can be impacted by vertical obstructions (e.g., tree canopy, buildings, etc.), there are few marine applications (perhaps narrow estuarine rivers) where GPS would not be the overwhelming choice for position control. The U.S. Coast Guard's (USCG) differential beacon network provides extensive coverage over the coastal U.S. and is being expanded to eventually provide coverage throughout the entire U.S. (http://www.navcen.uscg.gov/). In those areas without existing USCG beacon coverage, comparable differential correctors can be obtained through longer-range commercial differential service providers over an FM radio link.

In addition to providing accurate horizontal positions, kinematic GPS processing also can be used to provide accurate vertical tracking data. The vertical tracking applications require the use of dual-frequency GPS receivers and generally entail the establishment of a separate GPS base station over a local vertical reference point; in some cases, data from a government-maintained continuous operating reference station (CORS) may be able to provide the GPS base station data. If the accurate vertical data is required in real-time (known as a real-time kinematic or RTK application), then a reliable radio link must also be established between the base station and the survey platform. Though the accurate vertical-tracking DGPS application is far more complex and costly to implement than standard horizontal-tracking DGPS, the technique has proven beneficial in instances (e.g., dredge monitoring and navigation hazard surveys) where vertical accuracy was critical and the true tidal (or water-level) impacts at the survey platform were difficult to measure from shore-based monitoring stations (USACE 2002, Wong 2001).

2.1.2 Automated Data Acquisition System

A variety of automated data acquisition and processing systems are employed throughout the marine surveying profession; some of these systems are available commercially and are widely used by both government and private surveyors, while others have been developed for specific internal applications only. In general, the commercial systems will have been integrated with a wide array of external sensors, including positioning systems, single and multi-beam echosounders, side-scan sonars, sub-bottom profilers, and magnetometers. Most of these data acquisition systems typically operate on any standard personal computer (PC) and interface with the different sensors through multiple serial ports.

The data acquisition software should have survey planning and layout tools and be capable of displaying a wide variety of user-supplied background layers, including raster nautical chart files, CADD drawing files, geo-referenced image files, or xyz data files. During data acquisition it should simultaneously time-tag, display, and log incoming data from multiple sensors. In addition to receiving incoming data, the system should also be able to generate user-defined outgoing data strings that may be needed as input into other specialized data acquisition platforms.

One important (and often complicated) aspect that must be adequately addressed by the data acquisition software is the physical relationship (or offsets) between the different sensors being employed. Although it is best to co-locate sensors if possible, it is often necessary to separate the GPS antenna from the other sensors being used. For an acoustic bathymetric survey, it is critical that the offset between the GPS antenna and the transducer is accurately measured before the survey and then properly applied during (or after) the survey. The potential offset issues become even more difficult to address when towed systems (e.g., side-scan sonars or sub-bottom profilers) are being used. Assuming that an independent towfish tracking system is not employed, then the data acquisition software should have the ability to estimate a towfish position based upon the offset from the GPS antenna to the tow point and the amount of cable deployed.

Though the commercially available data acquisition software may be widely used for most bathymetric and discrete sampling applications, many other sensor types (e.g., side-scan sonar, sub-bottom profiling, underwater video, etc.) may require the use of their own vendor-supplied data acquisition system for display and logging of data. If multiple acquisition systems need to be used because of the types of hardware being employed, it is critical that the operations are based on a consistent time and position basis. When multiple data acquisition systems are required, it is often beneficial to designate one of the systems as the primary survey control system. The primary system can then be configured to output a consistent time and position record that will be used to control any of the secondary data acquisition systems.

Any of the data acquisition systems employed (whether commercial or internal) should have some initial data processing and exporting capability. The required level of data processing will be largely dependent on the type of data acquired, with the various types of acoustic data (particularly multibeam bathymetric data) generally requiring the greatest amount of post-processing. Specific data processing issues associated with each of the data acquisition techniques will be addressed in some of the following subsections. Regardless of the type of data acquired or the level of post-processing required, ultimately it is most important that the data can be exported into a format that is compatible with whatever system (typically a GIS) will be used to merge, analyze, and display all of the data.

2.2 Broad-Scale Characterization Techniques

As discussed previously, the broad-scale techniques addressed in this section are intended to provide a general physical overview (e.g., bottom topography, sediment composition, etc.) of the seafloor over the entire area of interest. In an ideal situation, the broad-scale characterization would be completed first, and then used to help define the preferred sampling plan for a follow-on fine-scale survey. The two main categories of techniques generally used to provide the broad-scale characterization data are boat-deployed acoustic methods (e.g., multibeam and single-beam bathymetry, side-scan sonar imaging, acoustic sub-bottom profiling) and aircraft-deployed electro-optical methods (e.g., aerial photography, LIDAR, hyperspectral imagery, satellite, imagery, etc.).

2.2.1 Boat-Deployed Acoustic Techniques

All of the acoustic systems presented here are boat-deployed, some via hull or pole-mounts and others via tow vehicles that are tethered to the survey platform (Figure 2-1). Generally, these techniques provide data on seafloor topography and/or sediment composition. As depicted in Figure 1, many of these techniques can be conducted concurrently from the same platform, thereby minimizing at-sea survey time. These acoustic techniques operate over a wide frequency band, from less than 1 kHz for some of the lower-frequency sub-bottom profiling systems to over 1000 kHz for some of the higher-frequency side-scan sonar systems. In all acoustic systems, increasing frequency leads to increases in resolution and decreases in range or depth of coverage. For each of the main acoustic techniques, the following discussion addresses the types of data generated, the resolution and coverage provided, and the complexity of both data acquisition and initial processing (Table 2-1). The summary information from Table 2-1 has been merged with representative figures of the sensors and examples of their data to provide a graphical overview of each of these techniques.

Echosounder Bathymetry

Of all the techniques addressed herein, the acquisition of acoustic bathymetric data is the most widely employed and also the best documented. Because of the importance of bathymetric data within the related fields of nautical charting, dredging, and navigation safety, NOAA, the USACE, and their numerous commercial contractors routinely acquire these data. Extensive technical guidance exists documenting the procedures that should be followed for the various portions of a bathymetric survey, and internationally accepted standards (http://chartmaker.ncd.noaa.gov/hsd/specs/specs.htm) have been developed to define different classes of accuracy requirements for the different elements (e.g., horizontal and vertical control) that comprise a bathymetric survey (USACE 2002, Finkbeiner et al. 2001). For instance, the highest established accuracy standards (Class 1) are normally followed for all inshore nautical charting and dredging-related bathymetric survey applications, primarily because of their importance to navigation safety.

Though a typical benthic habitat mapping application may not require strict adherence to the highest bathymetric accuracy standards, meeting these standards will help to ensure the usefulness of these data in comparisons with past or future bathymetric datasets. Comparisons between bathymetric datasets can help to highlight areas of seafloor change that may have important implications on the benthic habitat. However, the ability to make meaningful comparisons between two independent bathymetric datasets is very dependent upon the procedures that were used and standards that were met during each of the surveys. Though the procedures will likely vary between different surveys, if the same accuracy standards were not met by both surveys, then it is unlikely that the comparison will provide any realistic measure for evaluating seafloor change. Because the requirements to satisfy the Class 1 survey standards are not overly stringent, most bathymetric survey operations should strive to meet those standards.

Single-Beam/Multi-Transducer

For much of the last 50 years, single-beam bathymetry has been the primary method used for generating seafloor topography. Even with the relatively recent advances in shallow-water multibeam sounding technology, there are still many applications well suited for single-beam bathymetry and it will always be an accurate, low-cost, and relatively simple technique for generating seafloor topography. Especially in areas with gradual seafloor relief or shallow water depths, the single-beam results will likely be comparable to the multibeam results, and the single-beam surveys can be accomplished at a much lower overall cost. Using over-the-side transducer mounting hardware, the single-beam equipment can be quickly mobilized on almost any vessel of opportunity. Although several different transducer configurations are possible, a higher resolution standard single-beam survey will typically use a narrow-beam (3°), 200-kHz transducer. The use of a dual-frequency transducer (perhaps 25 kHz and 200 kHz) may provide additional insight into the seafloor composition, particularly in areas with soft surface sediments or patchy aquatic vegetation beds (Figure 2-2).

A multi-transducer system is essentially an offshoot of a traditional single-beam system in which multiple single-beam transducers are mounted along a boom extending across the survey platform (Figure 2-3). As opposed to multibeam systems where swath coverage is based on water depth, multi-transducer systems provide a fixed-swath coverage based on the overall length of the transducer boom. Though the multi-transducer systems can provide far greater bottom coverage than a single-beam system, the systems are far less portable and are typically mounted semi-permanently on designated boats. Because the transducer boom typically extends from both sides of the survey platform, boat maneuverability is restricted and the systems may be negatively affected by even moderate wave action. In general, most multi-transducer systems are used for conducting accurate navigation or dredging-related surveys in protected harbor and river environments.

Single-beam surveys are typically laid out, conducted, and processed using some form of commercial or internal software. After data acquisition, raw position and sounding data are edited as necessary to remove or correct questionable data, sound velocity and draft corrections are applied, and the sounding data are reduced to a vertical datum (often Mean Lower Low Water [MLLW]) based on tidal (or water-level) data obtained from local observations or from NOAA tide stations. After the bathymetric data are fully edited and reduced to a datum, cross-check comparisons on overlapping data should be performed in order to verify the proper application of the correctors and to evaluate the consistency of the data set. Ultimately, the fully edited and verified single-beam bathymetric data are exported to a GIS for additional analysis and integration with other data types.

Based on the lane spacing used during data acquisition, single-beam bathymetric survey data will usually cover only a small percentage of the total seafloor area (typically 5–10%). Subsequent analysis and gridding tools can still be used to generate a three-dimensional seafloor surface model with this relatively sparse data, though a large degree of interpolation between the discrete survey data points will be required. This interpolation generally works well in flat or gently-sloping areas, but in steep and irregular areas the interpolation of the seafloor surface can be very dependent upon the orientation of the survey lanes and the density of the data around the area. The lane spacing used for a single-beam survey should be based on the complexity of the underlying seafloor and may vary between different topographic areas within a survey area. While 100-meter single-beam lane spacing may be sufficient to accurately model flat or gently sloping areas, 10- to 25-meter spacing may be required to adequately model steep or irregular areas. If single-beam methods provide acceptable bathymetric resolution, then the operations could be supplemented with concurrent full-bottom coverage side-scan sonar data to provide a comprehensive acoustic image of the seafloor

Multibeam

The use of shallow-water multibeam technology to provide accurate, high-resolution, full-bottom coverage seafloor topography has grown rapidly over the last ten years. These systems are widely employed within both government and commercial survey entities and are used to address many different inshore hydrographic survey requirements (e.g., nautical charting, dredging, coastal structure assessment, etc.; see Basu and Saxena 1999, Chavez et al. 1999, USACE 2002, Finkbeiner et al. 2001). The acquisition and processing of multibeam bathymetric data is far more complex than comparable single-beam operations, and requires personnel who are experienced and well-trained in the techniques. At a minimum, multibeam operations require a multibeam echosounder, an accurate navigation device, a vessel motion sensor (for precise and rapid measuring of boat heave, pitch, and roll), a gyrocompass (for accurate boat heading), and an accurate measure of the water-column speed of sound. Although the multibeam systems are frequently installed on a semi-permanent basis on a designated survey vessel, multibeam systems can be temporarily mounted on a vessel of opportunity. Because of the additional sensors required and the complexity of the relationship between these sensors, a temporary multibeam installation is far more complex than a single-beam installation (Figure 2-4).

With high-resolution multibeam systems, it is possible to accurately detect and define features as small as one meter in diameter on the seafloor. In addition to greatly enhancing the spatial resolution of depth measurements, the expanded swath coverage will generally allow for wider survey lane spacing and may decrease at-sea survey time when compared to even a relatively sparse single-beam survey. Multibeam systems are capable of providing a total swath coverage that varies from 2 to 7 times the water depth, based on an overall array beam pattern that varies from 90° to 150°. Because the outer beams are far more affected by a variety of potential errors (e.g., roll and yaw biases, refraction, etc.), it is relatively common to restrict the use of the multibeam data to the inner 90° to 120°, thereby reducing the effective swath coverage.

Although the acquisition of multibeam data can proceed rapidly once the system is properly installed and calibrated, the processing of the data can be a more time-consuming effort, particularly in areas of high vertical relief. Similar to the single-beam processing operations, after the various multibeam sensor data have been edited and verified, the sounding data are reduced to a vertical datum (typically MLLW) using tidal data obtained from local observations or from NOAA tide stations. After the bathymetric data are fully edited and reduced to a datum, comparisons are then made on the extensive areas of overlap that are generally seen in multibeam datasets. Eventually, the multibeam data are gridded based on desired resolution and file size constraints, and then exported to a GIS for additional analysis and integration with other data types.

In addition to high-resolution bathymetry, some multibeam systems are capable of acquiring acoustic backscatter imagery data that can be used to provide side-scan sonar-like acoustic images of the seafloor. The multibeam backscatter data can be a useful tool for assisting with the determination of the seafloor composition and a good deal of ongoing research is involved in further evaluating the potential applicability of these data (Butman et al. 2000, Dartnell 2001, Dekeyzer et al. 2002). Although the resolution of multibeam backscatter data is somewhat lower than true side-scan sonar data, and image quality may be reduced because of steeper grazing angles, the positioning accuracy of the data is generally better because of the fixed location of the transducer. Because of its strong potential as a characterization tool, continued improvements in the applications of these data are likely into the foreseeable future. Instead of backscatter data, some other multibeam systems provide true side-scan sonar transducers co-located with the multibeam transducer. Because the multibeam side-scan sonar transducers are either hull- or pole-mounted, they cannot be lowered closer to the seafloor and may not be that effective in deeper water. However, in water depths shallower than 5 m, a pole- or hull-mounted system will likely be preferable because of the difficulty in towing the sensor behind a boat in shallow depths.

Ultimately, the decision between multibeam and single-beam bathymetry will come down to balancing the trade-offs between cost, complexity, and the need for high-resolution, full-bottom coverage bathymetric data. If a bathymetric survey is intended to cover large and complex seafloor areas, and there is a strong need to completely and accurately model these areas, then multibeam systems will likely offer significant time savings and resolution improvements over single-beam systems. If lower bathymetric resolution is acceptable, then a single-beam survey in conjunction with a full-bottom coverage side-scan sonar imagery survey may provide a lower cost and perhaps more qualitative view of the seafloor.

Side-Scan Sonar Imaging

Side-scan sonar imaging has been used extensively over the last 30 years to provide a relatively quick and complete acoustic image of the seafloor surface. In addition to providing an indication of broad-scale seafloor characteristics, side-scan sonar data can also reveal the size and location of distinct objects on the seafloor (Zajac et al. 1995, Barnhard et al. 1998, Cochrane and Lafferty 2002, USACE 2002). Side-scan sonar operates by measuring the strength of the acoustic backscatter seafloor returns from acoustic signals emitted from a towed side-scan transducer array. The side-scan sonar towfish normally has a pair of opposing transducers aimed perpendicular to and directed on either side of the vessel track. Dense objects (e.g., metal, rocks, coarse sand seafloor areas) will reflect strong signals and normally appear as darker areas on standard side-scan sonar images. Conversely, areas characterized by soft features (e.g., silt, mud, or fine sand sediments) that absorb sonar energy will appear as lighter areas on standard side-scan sonar records (Figure 2-5).

Because a side-scan sonar towfish is typically towed astern of the survey vessel, it is important that a reliable method for estimating the towfish position is applied. The survey control software should be able to generate a reliable estimate of towfish position based upon the offset between the GPS antenna (or other position control point) and the side-scan towing point and the amount of cable that is deployed. This recorded towfish offset (or layback) value should be updated whenever the amount of cable deployed is changed. In deeper water and on larger survey vessels, the towfish offset values could be quite large. If the offset values are not properly accounted for, then the accuracy of the resulting mosaic images will be impacted. For most shallow-water applications (less than 5 m water depth) either a bow-mount towing configuration or a fixed pole-mount is preferable because of better boat maneuverability and improved towfish control. Both the bow and pole-mount configurations also offer somewhat better control over the towfish positions.

Similar to bathymetric acoustic systems, side-scan sonar systems also offer trade-offs between frequency and resolution. The higher frequency systems (300 kHz and above) can provide high-resolution images, but at much reduced range coverage. Lower frequency systems (typically around 100 kHz) provide somewhat lower resolution, but much greater swath coverage, so that full-bottom coverage imagery can be obtained in a shorter amount of time. Several side-scan sonar systems offer dual-frequency capability and can simultaneously display and record both high- and low-frequency data. Typically, the lower resolution data will be used to generate broad-scale mosaics of the whole survey area, and the higher resolution data will be used to create a detailed acoustic image of a particular feature or area of interest. Because of the large spatial area covered by each survey lane, side-scan sonar is an effective technique for quickly providing a comprehensive qualitative picture of a large area of the seafloor.

During data acquisition, continuous real-time positioning of the survey vessel and side-scan towfish should be provided within the topside data acquisition system. Position and time-tagged side-scan sonar data are generally logged and eventually processed with specialized digital image acquisition and processing software. Within the image processing software, the side-scan data can be re-processed using a variety of user-defined adjustments to optimize the image for its intended purpose (e.g., creating broad-scale mosaics or identifying individual targets). Eventually, the individual side-scan lines are merged to create a full-coverage mosaic that can be saved as a geo-referenced TIFF (Tagged Image File Format) file and then exported to a GIS for additional analysis and integration with other data types.

Sub-Bottom Profiling

Sub-bottom profiling is a lower frequency acoustic technique used for distinguishing and measuring various sediment layers that exist below the sediment/water interface. Sub-bottom systems are able to distinguish these sediment layers by measuring differences in acoustic impedance between the layers. Acoustic impedance is a function of the density of a layer and speed of sound within that layer, and is affected by differences in grain size, roughness, and porosity. Sound energy transmitted to the seafloor is reflected off the boundaries between sediment layers of different acoustic impedance. A sub-bottom system uses the energy reflected from these boundary layers to build the image (Figure 2-6).

As with other acoustic systems, the range (depth of seafloor penetration) and resolution of a sub-bottom system depends on the frequency and pulse width of the acoustic signal, as well as the characteristics of the various layers encountered. For the purposes of benthic habitat characterization, a review of the relevant sub-bottom techniques is limited to the higher frequency systems (generally 2 to 20 kHz) that provide higher resolution data of the upper seafloor surface layers. Other lower frequency acoustic seismic systems (e.g., boomers, sparkers, water guns, etc.) are intended to provide much deeper seafloor penetration for various geophysical, engineering, and gas/oil exploration applications (Mosher 2000). In some configurations, a sub-bottom sonar and a side-scan sonar are co-located within the same tow body.

For the higher frequency systems, the depth of penetration may extend as deep as 50 m below the seafloor surface, and is largely dependent on the hardness of the overlying layers and the presence of surficial gas deposits. Particularly in estuarine environments, the presence of methane gas in the surface sediment is relatively common and may be associated with organic loading, biological decomposition, and other natural and manmade sources. Any large-scale sub-bottom survey effort should probably include a provision to perform some initial broad-coverage reconnaissance lines to assess the surface gas impacts throughout the planned survey area. If the interference from a surface gas layer is found to be widespread, then it is unlikely that the acoustic sub-bottom data will provide much value. In addition, although higher frequency sub-bottom systems can theoretically provide vertical resolution of around 10 cm, because of the strength of the acoustic return signal normally associated with the seafloor reflector it is often difficult to clearly distinguish sub-bottom horizons that are very near the seafloor surface (SAIC 2002a).

High-resolution sub-bottom data have been used to provide broader area coverage to supplement geotechnical coring information, to define the basement (or bedrock) layer for potential confined aquatic disposal (CAD) sites, to detect and measure the thickness of various dredged material deposits, to identify buried objects (e.g., debris, cables, pipelines, etc.) below the seafloor, and to detect harder substrate that has been covered by sedimentation (Davies and Austin 1997, Smith and Greenhawk 1998, SAIC 2001a). As with the other acoustic characterization techniques, ground-truth sampling data are necessary to improve the reliability of the sub-bottom interpretation. Because the sub-bottom interpretation extends well below the seafloor surface, coring samples provide the only relevant data for verifying a sub-bottom interpretation.

During data acquisition, continuous real-time positioning of the survey vessel and sub-bottom towfish is provided through the top-side data acquisition system. As noted in the side-scan sonar discussion above, it is important that a reliable method for estimating the sub-bottom towfish position is employed. The survey control or navigation software should be able to generate a reliable estimate of towfish position based upon the offset between the GPS antenna (or other position control point) and the sub-bottom towing point and the amount of cable that is deployed. If the towfish offset values are not properly accounted for, then the accuracy of the resulting sub-bottom data will be impacted. For most shallow-water applications (less than 5 m water depth) either a bow-mount towing configuration or a fixed pole-mount is preferable because of better boat maneuverability and improved towfish control. Both the bow and pole-mount configurations also offer somewhat better control over the towfish positions.

Position and time-tagged sub-bottom data are generally logged and eventually processed with specialized digital image acquisition and processing software. Within the image processing software, the sub-bottom data can be re-processed using a variety of user-defined adjustments to optimize the extent of the sub-bottom coverage for its intended purpose. Sub-bottom layers are manually or automatically tracked and digitized for each survey lane and then merged to create geo-referenced data files that define each sub-bottom horizon. These merged, geo-referenced digital sub-bottom data files can then be exported into a GIS for additional analysis and integration with other data types. Sub-bottom data, when viewed in conjunction with the geotechnical analyses performed on just a relatively small sample of representative sediment cores, can provide a comprehensive picture of the often complex stratigraphy that exists below the seafloor surface.

Acoustic Seafloor Classification

A final class of data acquisition technique involves the use of the acoustic return signal from a bathymetric echosounder to make qualitative estimates of the seabed composition. Another specialized acoustic classification system has also been developed that is intended to provide an indication of the presence (and type) of submerged aquatic vegetation (Guan et al. 1999). Because the commercially available acoustic seabed classification systems are intended to work in line with any standard single-beam echosounder, these systems do not require specialized acoustic instruments; they generally require only an acoustic signal amplifier, a standard PC, and specialized interpretation software (Figure 2-7). The software performs a detailed analysis of the waveform associated with the acoustic return signal from the initial seafloor echo and attempts to group these waveforms by common characteristics (Tsemahman et al.1997); in some cases, the classification system may also examine the waveform associated with the second return signal (Greenstreet et al. 1997, Kvitek et al. 1999).

In all cases, the link between the acoustic waveform analysis and the seafloor classification scheme must be based upon extensive ground-truth data (e.g., grab samples, video, etc.) that is acquired over the different seafloor types that are likely to be encountered. This established relationship between the acoustic waveform and the seafloor type is very dependent on both the echosounder settings (e.g., power, gain, etc.) and the seafloor types. This relationship would need to be re-established for each new project area or anytime the echosounder settings have been modified.

Ongoing development is presently underway to integrate the acoustic seabed classification tools with multibeam backscatter and side-scan sonar return signal data in an effort to dramatically increase the spatial coverage of these systems. Similar to the single-beam acoustic bottom classification systems already in use, these backscatter and side-scan sonar classification systems may be able to provide full-bottom coverage seafloor composition data based on the relationship developed between the acoustic waveform of the return signal and ground-truth sampling data. Similar acoustic classification systems are also being developed for sub-bottom profile and other types of seismic data. The intent of these classification systems is to identify the composition of the various sub-bottom horizons that are acoustically detected beneath the seafloor surface. As with the other acoustic classification systems, the critical element is establishing a positive correlation between the acoustic waveform and the ground-truth coring data.

2.2.2 Aircraft-Deployed Electro-optical Techniques

This section addresses the main aircraft-deployed (planes, helicopters, or satellites) electro-optical data acquisition techniques used to assist with the broad-scale physical characterization of the seafloor (Figure 2-8). Where they are applicable, these techniques can generally provide broad coverage data on seafloor topography and/or benthic habitat conditions. Most of these techniques are limited to use primarily in generally clear and shallow water, because water rapidly absorbs or reflects most wavelengths of electromagnetic energy. Most of the airborne electro-optical techniques operate within the visible portion of the spectrum (400–700 nm) that is able penetrate water to certain depths. Ten meters of clear ocean water can transmit almost 50% of the incident blue and green wavelengths (400–600 nm) and less than 10% of the red light (600–700 nm) (Sabins 1997). For each of the these techniques, the following discussion addresses the types of data generated, the resolution and coverage provided, the complexity of both data acquisition and initial processing, and the advantages and disadvantages associated with each technique (Table 2-1).

Aerial Photography

Aerial photography has been used for well over 100 years to help support a wide range of mapping applications (Sabins 1997). Though its use to support land-based surveying and mapping applications is obvious and widespread, it is only in the last few decades that aerial photography has become a useful tool for certain broad-scale benthic habitat mapping applications (Figure 2-9). In nearshore estuarine and marine environments it is used primarily for identifying and delineating habitats within the photic zone. Though the depth of the photic zone will vary with water clarity it is generally within a range of 2 to 30 m (Finkbeiner et al. 2001).

Diverse benthic habitats have been successfully mapped using aerial photography (Sheppard et al. 1995; Hopley 1978). Habitats that can be mapped with aerial photography include seagrass meadows (patchy or continuous), coral reefs, unconsolidated sediments, shellfish beds (oyster and mussel), hard-bottom areas, soft corals, macro algal beds, and drift algal accumulations. Aerial photographs can reveal the spatial extent and distribution of a habitat, habitat fragmentation (expressed as a percent bottom-cover value), and, in the case of submerged aquatic vegetation, qualitative measures of biomass. Habitats or characteristics that are more difficult to map with aerial photography include low biomass submerged aquatic vegetation (SAV), clam beds, bacterial mats, worm tubes, habitat health, species composition, and sediment texture (Finkbeiner et al. 2001).

Traditional land-based aerial photography mapping applications often relied on the use of land-surveyed photo-targets to enable geographic rectification (and subsequent mapping) of the aerial photographs. Because photo targeting over most estuarine environments is not practical, other techniques need to be used to ensure that the photographs can be geo-referenced. In most cases, the widespread use of airborne GPS to control the flight operations will enable the photographs to be rectified. Ideally, the aerial photographs would be processed digitally to produce geo-referenced images that can later be brought into a GIS for benthic analysis. Within the GIS, geo-referenced images can be combined to produce a photomosaic of a large area.

There are several advantages to this technique as summarized by NOAA (Finkbeiner et al. 2001). First, the technique provides a wide area of data coverage (several square kilometers of ground) at constant resolution. Second, aerial photographs are readily obtainable from federal, state, and private sources, and there is a historical archive of data. Third, it is easily integrated into the coastal management process. Furthermore, though the data must be obtained when environmental conditions (i.e., tides, weather, sun angle, etc.) are favorable, sufficient aircraft/camera services are usually available so that a mission can be held on standby until the required conditions are met. Finally, the technique provides sufficient spectral and superior spatial resolution for detecting subtle submerged features and can resolve features smaller than 1 m.

The limitations associated with the aerial photography technique are common among nearly all electro-optical data acquisition techniques. They include water turbidity, water depth and tidal variation, sun angle (sun glint or shadows), clouds and haze, and wind and waves. In addition, there are also problems with rectification of aerial photographs that are not geo-referenced. If the photographs are not collected in a digital format, it also may be more time consuming to process the images (i.e., develop the film) after data collection. Finally, the relatively coarse information collected in traditional aerial photography can limit the utility of automated mapping techniques.

Hydrographic LIDAR

Hydrographic LIDAR (LIght Detection and Ranging) has been used successfully for numerous inshore, high-resolution, bathymetric mapping projects, although the technique is highly dependent on water-clarity (Irish and Lillycrop 1997, USACE 2002). LIDAR technology utilizes the reflective and transmissive properties of water and the sea floor to enable measurement of water using a laser (USACE 2002). When a light beam hits a column of water, part of the energy (the infrared pulse) is reflected off the surface and the rest (the blue-green pulse of the visible spectrum), unless absorbed by particles in the water, is transmitted through the column. As the light (blue-green) travels through the water column and reflects off the seafloor, scattering, absorption, and refraction all combine to limit the strength of the bottom return, and therefore the system's maximum extinction depth (a function of water clarity). The infrared (IR) pulse reflection off the water surface is a very strong return, while the blue-green pulse bottom return is much weaker. The water depth is calculated (to the centimeter) from the time difference between the IR surface return and the blue-green bottom return (Figure 2-10).

Hydrographic LIDAR is able to compliment acoustic survey techniques in several ways. While acoustic multibeam systems have revolutionized bathymetric data acquisition in medium and deep waters, they are much less effective in generally shallow water (less than 5 m). In contrast, LIDAR systems have been specifically designed for use in such challenging environments and can provide uniform and dense data in even the shallowest water. Unlike multibeam systems, the LIDAR swath coverage is independent of the water depth. Because of its ability to achieve coverage rates several orders of magnitude higher than any of the acoustic methods, LIDAR will likely be a cost-effective tool for surveying large and shallow areas with generally good water clarity. Hydrographic LIDAR systems are capable of collecting a large volume of data in a single flight; however, data processing software exists that has the capability to process such an enormous data set (USACE 2002).

Despite its ability to rapidly collect dense survey data over large areas, the technique is highly dependent on water clarity. In clear water it can be effective to depths over 50 m, but in turbid water it is only successful to depths of 2–3 times the visible depth (USACE 2002). In general, LIDAR systems will not be applicable in areas with chronic moderate to high turbidity. In areas where the turbidity may be variable over a wide range of values, it is critical to schedule LIDAR operations during a period when the conditions are most favorable.

Ongoing research is presently focused on enhancing the capability of the hydrographic LIDAR systems to provide topographic as well as hydrographic data. Although this capability has been demonstrated, it is not yet in widespread use. This technique offers a strong potential for being able to efficiently map many complex surf zone, nearshore, and intertidal areas that are very difficult to survey with traditional land and hydrographic survey techniques.

Airborne Hyperspectral Imaging

Airborne Hyperspectral Imaging is an emerging technology that has recently been used to classify benthic habitats in coastal zones. Hyperspectral sensors are one type of a remote sensing instrument that can collect several hundred spectral bands of data at a high-spatial resolution (Anger et al. 1994, Larsen and Erickson 1998). These sensors are generally airborne sensors mounted to light aircraft (Figure 2-11). Data are collected at contiguous, narrowband wavelengths for a specifically defined portion of the electromagnetic spectrum (usually between 400 and 900 nm). In order to determine what the reflectance represents, the reflected spectral data obtained by the hyperspectral sensor is compared, and matched, to spectral data of known absorption features. While spatial resolution depends on the altitude of the aircraft and usually ranges between 1 and 20 m, the spectral bands measured and the bandwidths used are all programmable to meet user specifications and requirements. The resulting product of this surveying technique is a high-resolution, geo-referenced image, which can be imported into a GIS.

The technique has been successfully used to classify tropical benthic habitats including coral reefs, seagrass, macroalgae (fleshy and turf), unconsolidated sediments, uncolonized hard-bottom areas, and encrusting algae (Chauvaud et al. 1998, Warner et al. 2000, Goodman and Ustin 2001, Analytical Laboratories of Hawaii 2002). Where aerial photography may fail, airborne hyperspectral imaging can be useful for SAV mapping. It can provide potential detail on species composition in addition to biomass estimates. Hyperspectral Imaging also has its limitations. It has low availability and may not be cost effective. Also, because of its ability to collect several hundred bands of data at high resolution, somewhat advanced software is needed to process and analyze these data. In addition, it is primarily useful in shallow, non-turbid waters, as are most electro-optical techniques. However, hyperspectral sensors can achieve far better resolution than multispectral instruments, which are discussed in the following section.

Satellite Multispectral Imaging

Satellite Multispectral Imaging is a surveying technique that has been used to map the land and sea for military, commercial, and environmental purposes (Figure 2-12). Several different types of satellites and systems obtain multispectral images to identify military targets, detect hazardous wastes, map renewable and non-renewable resources, measure ocean productivity, and track weather patterns, among other applications. Satellite Multispectral instruments can create multiple images of a scene or object using light from different parts of the spectrum. If the proper wavelengths are selected, multispectral images can be used to detect bathymetric features and benthic habitats (Meinesz et al 1991). The blue-green band provides the greatest penetration of water.

With optimal conditions, the nearshore, shallow seafloor can be mapped using Satellite Multispectral Imaging. This technique is especially useful for mapping of shallow shelf areas where deposition, erosion, and growth of coral reefs can change bottom topography over the period of a few years (Sabins 1997). Water penetration increases with decreasing wavelength (from IR to blue), so the blue-green wavelengths will likely penetrate deepest in clear water. Shorelines are difficult to define on the visible bands because those wavelengths penetrate the shallow water and are reflected from the bottom to produce signatures that are similar to signatures of the adjacent land (Sabins 1997). The resulting data product is an image showing general bathymetry (without data points) and possibly the general benthic habitat of a nearshore environment.

The greatest limitations to the collection of multispectral images are atmospheric conditions (cloud cover), water turbidity, water depth, sun glint from the sea surface, and reflectance of sediment and vegetation on the seafloor. In addition, despite the satellite's ability to cover an extremely large area (several km), the resulting image resolution is low (sometimes on the order of several hundred meters). Multspectral systems record only a few bands of the electromagnetic spectrum, unlike hyperspectral systems that can collect several hundred bands. However, this can be an advantage over hyperspectral imaging, because the acquisition of more moderate data streams requires less-specialized software to process and analyze these data. Finally, satellite multispectral data has limited availability. Although data that have already been collected can be obtained from various sources, there may be licensing and/or security issues for data access. Some of the satellite imagery products now becoming available are due to a relaxation of many of the strict security measures that restricted the past use of various military-related satellite products.

2.3 Fine-Scale Characterization Techniques

The fine-scale techniques presented in this section are generally used to generate the ground-truth data that will improve and/or confirm the broad-scale physical interpretation. The two main categories of techniques used to generate fine-scale characterization data are boat-deployed electro-optical methods and boat-deployed physical sampling methods (Figure 2-13). An overview of these techniques is presented in Table 2-2.

2.3.1 Boat-Deployed Electro-Optical Techniques

This section will address the main optical data acquisition techniques used to assist primarily with the detailed characterization of small areas of the seafloor. Some of these techniques (e.g., sediment profile imaging, plan-view photography) provide individual still images over discrete sample points on the seafloor and other techniques (e.g., underwater video, laser line scan) provide video or video-like footage over small swaths of the seafloor. All of these techniques provide high-resolution data over a generally limited spatial extent. With the exception of sediment profile imaging (which is imaging of the seafloor surface cross-section), all of these optical techniques are negatively impacted by reduced water clarity. For each of these techniques, the discussion will address the types of data generated, the resolution and coverage provided, and the complexity of both data acquisition and initial processing.

Sediment-Profile Imaging (SPI)

Sediment-profile imaging (SPI) is a benthic sampling technique that produces undisturbed, vertical cross-section photographs (*in situ* profiles) of the upper 15 to 20 cm of the seafloor surface. Employing a specially designed camera and frame, SPI is a discrete sampling technique used for rapid collection, interpretation, and mapping of data on physical and biological seafloor characteristics (Figure 2-14). As opposed to all of the other optical techniques (both boat and aircraft deployed), SPI is not negatively impacted by poor water clarity. Rapid computer-aided analysis of each sediment profile image yields a suite of standard measured parameters, including sediment grain size major mode, camera prism penetration depth (an indirect measure of sediment bearing capacity/density), small-scale surface boundary roughness, depth of the apparent redox potential discontinuity (RPD, a measure of sediment aeration), infaunal successional stage, and Organism-Sediment Index (OSI, a summary parameter reflecting overall benthic habitat quality) (Rhoads and Germano 1982).

SPI high-quality images provide a clear and effective method for assessing the biological and physical condition of the uppermost layer of the seafloor surface. From physical, chemical, and biological features observed in sediment profile photographs, marine scientists are able to evaluate the status of benthic biological activity and recruitment (Valente 2002). In addition, subtle differences in sediment grain size and bedforms detected by SPI can be used to make inferences about the erosional or depositional characteristics of an area (Rhoads and Germano 1990). Additionally, the SPI photographs are valuable visual aids at public symposiums and related events because they provide benthic information in a form that is easily presented and readily understood by the general public. It has been a prominent benthic monitoring tool for over 20 years and has been widely used in support of numerous site-selection projects and long-term environmental monitoring programs (Germano et al. 1989, Diaz 1995, SAIC 1995, SAIC 2001b).

Though not in wide use yet, the use of digital images instead of standard 35 mm slides has the potential to improve the efficiency of standard sediment profile survey operations by providing immediate feedback on image quality and eliminating the need for field slide processing. Though image resolution was a concern with some of the initial digital sediment profile cameras, newer digital camera technology will be able to satisfy the high-resolution requirements. Another potential sediment profile enhancement under review is the development of a deeper penetrating camera that may enable imaging much deeper below the seafloor than the 20 cm presently possible. Sediment profile images have proven very useful for evaluating cap integrity and thickness in confined aquatic disposal (CAD) projects (Valente et al. 2001). Because the design cap thickness for a typical CAD project may be as great as one meter, a deeper penetrating camera would provide a much stronger monitoring tool.

Plan-View Photography

Plan-view photography is another discrete sampling technique that employs a frame-mounted downward looking camera to obtain plan-view photographs of a small patch (typically 2 m^2) of the seafloor surface (Figure 2-15). The plan-view images provide an undisturbed view of the seafloor surface and are useful for indicating sediment composition and surface biological activity. A plan-view camera is often added to the SPI frame to provide a seafloor surface image of the SPI sampling area (Valente et al. 2001). The addition of the plan-view image can greatly enhance the SPI interpretation of benthic habitat, particularly when a harder substrate may restrict the SPI camera penetration.

For deeper-water applications, the plan-view camera and strobe is typically mounted on a large frame, usually in conjunction with some other remote sampling operation (like SPI). For shallow-water applications the camera and strobe can be mounted on a much lighter PVC frame for use on a smaller vessel. The camera is triggered with a remote surface-mounted shutter/strobe trigger that is connected to the camera via an electrical cord following the hoisting line. In addition to numerous SPI applications, plan-view photography has also been employed to help monitor SAV restoration projects and to assess shellfish beds.

Underwater Video Imaging (Towed, Diver, or ROV)

There are a wide variety of deployment techniques for obtaining underwater video data, including boat-deployed drop, towed, or remotely operated vehicle (ROV) systems, as well as diver hand-held systems (Figure 2-16). Although the value of the underwater video data is very dependent upon water clarity, the video data can provide valuable insight into the qualitative water column and seafloor conditions. The video data are most often used to assist with the detailed assessment of water-column and seafloor biological conditions or to search for specific items on the seafloor. Depending on the quality of the video, as well as the nature of the assessment, the detailed interpretation of underwater video can be a labor-intensive effort, particularly over long transects. Many biological characterization or monitoring surveys, particularly over reefs and harder substrates, are based on detailed analyses of video footage (Greene et al. 1993, SAIC 2000).

Trade-offs between site conditions (water depth, water clarity, size of survey area), intent of the survey (biological assessment, item search), and operating costs generally help to determine the technique that will be used to obtain the video data. Because of the costs associated with video operations and the generally limited spatial coverage that they provide, it is usually worthwhile to review prior broad-scale characterization data (e.g., side-scan sonar mosaics, bathymetry, etc.) to help select the specific video sampling areas. As with other field sampling tasks, all video operations need to be closely time and position controlled, so that these data can be correlated with other sampling data. Though drop or towed video can be controlled based upon approximate offsets between the survey platform and the video camera, for diver and ROV operations accurate tracking of the video may require the use of a separate sea-based acoustic tracking system. In some cases, planned video transects can be laid-out beforehand by the survey platform using tag lines and survey buoys to mark the beginning and end of the transect. The diver or ROV video operations would then be conducted along the established tag line transects.

Laser Line Scan Imaging

The Laser Line Scan (LLS) system is a towed laser-light system that produces high-resolution “picture quality” panoramic image surveys at rapid coverage rates. The basic system consists of the towed underwater optical sensor and the topside control console. Display options include video, frame-grabbed stills, and photographic hard copy. The LLS functions by illuminating a small spot on the target plane with a laser beam and recording the reflected energy with a photo-multiplier tube on a synchronous scanner. The transmitted and reflected laser beams are swept through a 70° sector using a rotating pair of prisms, building an image pixel by pixel in each scan line. The resultant scan lines are viewed as a waterfall display on a standard black and white video monitor and are recorded as an analog video signal (Figure 2-17).

Although the LLS provides much higher resolution images than side-scan sonar, its effective swath coverage is much lower, generally making it an inefficient tool for any large-area characterization. It has proven useful for ground-truthing selected portions of a broad-scale side-scan sonar data set over a variety of applications, including habitat and fisheries assessments, and underwater search and recovery operations (Greene et al. 1995, Coles 1997, Kvitek et al. 1999). Though the LLS provides somewhat lower resolution than video or still photography, it is capable of providing a coverage range that may be up to four or five times greater than video. Similar to the coverage provided by multibeam and side-scan sonar acoustic systems, the swath range illuminated by the 70° LLS sector scan is determined by the altitude of the towfish above the seafloor. Establishing the proper LLS towfish altitude (and therefore swath range) during survey operations is primarily dependent upon water clarity (and how far the laser can penetrate), though the steepness of the surrounding seafloor topography will also have an impact. Although LLS is not a widely available technique, it does offer strong potential as a useful discriminator of species and habitat types.

2.3.2 Physical Sampling Techniques

This section addresses the main physical sampling techniques used to assist primarily with the detailed characterization of small areas of the seafloor. The primary intent from the sediment and water sampling operations is to obtain representative samples of the areas for subsequent laboratory physical, biological, and chemical analyses. Fishery samples can be used to assess tissue chemical and toxicity levels and also as a tool for estimating stock levels. For each of the these techniques, the discussion addresses the types of data generated, the resolution and coverage provided, the complexity of both data acquisition and initial processing, and the relative costs. As with the other field acquisition tasks, the sampling operations must be closely time- and position-controlled, so that the sampling data can be correlated with other characterization data.

Sediment Sampling

There are a wide variety of tools available for obtaining representative physical samples of sediment from the seafloor. Grab sampling is a basic technique commonly used to help characterize the physical, chemical, or biological properties of the surface (10–15 cm) sediments within a survey area (Figure 2-18). A grab sampler is typically lowered to the seafloor on a single wire; upon touching the bottom, the sampler penetrates the sediment-water interface and then closes to retain an intact sediment sample. Once retrieved, the sediments contained within the device are physically described then extracted in one of a variety of ways to facilitate additional analysis. If the benthic or biological community structure is of interest, then the collected sediment is washed through a sieve, the retained organisms are preserved in solution, and the samples are sent to experts for taxonomic identification and enumeration. The selection of a specific sampler from the wide variety available is usually dependent on the type of substrate being sampled (soft or hard) and the size of the sample required.

Sediment cores are used to penetrate the substrate and provide a deeper vertical cross-section of the seafloor to examine the composition and thickness of discrete layers of sediment. Though grab sampling is far more prevalent in most benthic habitat applications, coring results provide the only useful ground-truth data for acoustic sub-bottom profiling interpretation. Sediment cores are somewhat more time and gear intensive and expensive to collect, but can yield a great deal of information about the composition of the sediment column in a study area. Typically a hollow tube is driven into the sediment and then withdrawn to provide a continuous, undisturbed cross-section of the seafloor. A variety of coring techniques (e.g., hand cores, gravity cores, piston cores, vibracores, etc.) are available offering a range of penetration depths from 10 cm to 6 m (Figure 2-19). These different methods are employed based on substrate type, interval of interest, and volume of material required. In addition to physical and chemical analyses of the different sediment horizons, sub-samples of the coring sediments can also be analyzed for benthic community structure as outlined in the preceding paragraph.

Water-Column Sampling

Though outside the realm of the main seafloor characterization techniques that are the focus of this paper, water-column sampling is addressed briefly here because it may represent an important field measurement component for a benthic habitat characterization project. Several common water column characteristics (e.g., salinity, temperature, currents, suspended sediment, etc.) are recommended measurement parameters within different benthic habitat classification schemes (Kvitek et al. 1999). The acquisition of discrete vertical profile water column data for temperature, salinity, turbidity, total suspended solids (TSS), dissolved oxygen, and other physical parameters is an important component in evaluating water quality and perhaps providing a better understanding of the benthic habitat potential. Most of these parameters can be measured in situ by any number of vertical profile sampling devices. TSS is usually obtained through laboratory analysis of water samples obtained at various depths in the water-column (Figure 2-20). Often, a site-specific calibration equation can be derived that will allow in situ turbidity readings to be correlated with expected TSS values.

Water column currents are usually measured with an acoustic Doppler current profiler (ADCP), though other types of current sensors and water following drogues are also deployed. Wave height and period can be measured with burst-sampling pressure gauges or a variety of different strain-type gauges. Sometimes current sensors, wave height sensors, and other water column sampling devices are installed on specialized moored arrays to provide periodic measurement of these parameters over longer time periods. In addition to short-term project-specific moorings, several different federal and state agencies have established semi-permanent, automated water quality-monitoring stations within various estuaries to provide a long-term record of the temporal variations in several of the common water-column parameters (http://www.epa.gov/owow/estuaries/).

In addition to their value as a tool for evaluating water quality and benthic habitat, some water column parameters (i.e., speed of sound, tidal height, etc.) are important factors that have a significant impact on several of the acoustic characterization techniques addressed in this paper. Because the water-column speed of sound is a critical parameter for any acoustic bathymetric survey, periodic speed of sound casts should be taken during each survey day to account for any variability in this parameter. This is particularly true in many estuarine environments, where the speed of sound variability due to river flows and tidal mixing may be more pronounced.

Accurate and consistent measurement of the tidal height (relative to the project datum) is an equally important measurement that will greatly impact the vertical accuracy of a bathymetric survey. Though NOAA primary tide gauges may provide adequate tidal coverage in some survey areas, additional water-level measurements may be required in other areas. Supplemental tidal height measurements can be acquired from either moored or shore-based pressure or acoustic sensors that are established during periods of bathymetric surveying. Ultimately, local tidal data are closely compared and analyzed with verified tidal data from the nearest operating NOAA tide gauges (Wong 2001). If either the speed of sound or tidal height measurements are not properly measured and applied, then the vertical accuracy of the bathymetric survey will be greatly compromised.

3.0 PLANNING CONSIDERATIONS FOR BENTHIC HABITAT DATA ACQUISITION

Although benthic habitats may be influenced by numerous water-column characteristics, for the purposes of this paper, a benthic habitat mapping effort has been viewed synonymously with a comprehensive physical characterization of the seafloor; and the two primary parameters of interest in this physical characterization are the bottom topography and the surface sediment composition. As presented in the preceding section, there are a wide variety of techniques that are capable of providing physical seafloor characterization data. However, for a particular benthic habitat mapping effort, it is likely that only a small subset of these techniques may be applicable. In most cases, an initial consideration of the basic requirements and the general environment of the planned survey area should quickly narrow the focus of the applicable techniques.

In relatively clear, shallow-water environments, it is likely that many of the aircraft-deployed electro-optical techniques would be the preferred method for efficiently acquiring the broad-scale survey data. For instance, aerial photography and/or hyperspectral imaging may be the best tools for identifying and delineating SAV or coral beds and hydrographic LIDAR may be the most effective tool for generating high-resolution bathymetry over broad, nearshore survey areas (Figures 3-1 and 3-2). Where they are applicable, it is likely that the aerial techniques will satisfy most of the data requirements and at a much more rapid data coverage rate. Even in areas where the aerial techniques are applicable, some boat-based acoustic or sampling operations may be necessary to fill-in coverage gaps or to generate ground-truth comparison data. However, although one of the aerial techniques may provide the most effective method for data acquisition over broad areas of reasonably clear, nearshore waters, these same techniques will generally be of limited value in providing broad-scale physical seafloor characterization data in a "typical" estuarine environment (i.e., one that is shallow, generally turbid, and comprised primarily of soft and/or fine-grained sediments). Though the boat-deployed acoustic techniques provide much slower survey coverage rates, they are the only means for reliably acquiring the required broad-scale physical characterization data over a wide range of environments.

If a majority of the focus of the broad-scale characterization is focused on softer and/or fine-grained sediments, then most of the fine-scale (or ground-truth) sampling will also be limited to only a few of the techniques presented in the preceding section. Many of the boat-deployed optical techniques will be useful for imaging rock, sand, coral, or other hard-bottom areas and enabling the characterization of surface biological activity over these areas (Figure 3-3). However, most of these optical techniques have limited value over softer and/or fine-grained sediments; this is especially true in areas where the water clarity is low, as is frequently the case in these fine-grained environments. Generally, most of the fine-scale sampling within these types of estuarine environments will rely on either grab sampling or sediment profile imaging. Most of the remaining discussion within this paper focuses on those techniques that will be of primary use for completing a seafloor characterization in a typical estuarine environment.

Although the identification of data requirements is often listed as a critical first step in the development of a plan for acquiring benthic habitat data, in most cases the data acquisition tools available to meet the data needs in an estuarine environment will not vary a great deal between projects. For this discussion, it is assumed that a benthic habitat mapping project will entail some combination of broad-scale characterization data and fine-scale sampling data. As addressed in more detail in the sections below, the selection of specific techniques within each of these two main categories will depend on the type of general environment, the availability of existing data, the variability of the habitat, the habitat scales to be delineated, the spatial extent to be covered, and the budgetary constraints. Ultimately this section is intended to provide a general framework for selecting the most appropriate data acquisition techniques based on numerous project-specific considerations.

3.1 Data Requirements

One emerging trend within the seafloor characterization realm is the generally improved resource and data coordination that is evolving between federal, state, and local groups conducting similar programs. With the advent of internet-based data repositories, the reasonably widespread use of Metadata standards, and better regional resource coordination there seems to be much better understanding of some of the common areas of interest that exist between various marine-related agencies that often have very different mandates. Groups such as NOAA's Coast Survey that formerly focused on seafloor characterization issues solely from a nautical charting or navigation safety perspective, are now considering how their abundant and routinely updated marine survey datasets can also be used by coastal resource managers and researchers to help assess and manage critical marine habitats. Continued improvement in the level of coordination among the various agencies involved in coastal resource management, should lead to continued improvement in the quality and availability of coastal benthic habitat mapping data.

Before embarking on a major seafloor characterization data acquisition effort, the availability of prior applicable datasets covering the area of interest should be investigated. At a minimum, NOAA nautical charts should be available covering the entire survey area. Raster versions of all NOAA nautical charts are commercially available and are often useful as a GIS project-planning tool and as a base map during survey operations. In addition, the more detailed hydrographic surveys that were used in the compilation of the nautical chart are also available directly from NOAA as either a survey smooth sheet (http://chartmaker.ncd.noaa.gov/hsd/hsd-2.html) or as digital xyz sounding data (http://www.ngdc.noaa.gov/mgg/geodas/geodas.html). These prior hydrographic surveys may span a wide time period (from the 1800s to present day) and the sounding techniques employed will vary from lead-line to multibeam. Obviously, in the older vintage surveys, the data will be more sparse and less relevant for describing the current conditions. Although the digital xyz sounding data may be the preferred product since it can be easily incorporated into a GIS or other survey planning package, the paper smooth sheet will provide more useful seafloor composition data reflecting the fairly extensive bottom sampling operations that are a routine component of most nautical chart surveys. In many cases, this historical smooth sheet bottom sampling data may provide the most comprehensive view of the likely seafloor composition over a broad area.

The USACE (http://corpsgeo1.usace.army.mil/) and the USGS (http://mapping.usgs.gov/) are other government sources with data that may be relevant to a particular benthic habitat mapping project. In general, most USACE hydrographic survey data will provide limited coverage and will be focused primarily in and around federal navigation and dredging projects (USACE 2002). The USGS data may provide more comprehensive broad-scale characterization data (often including multibeam, backscatter, and side-scan sonar data), although the areas of coverage are somewhat limited and are generally focused in deeper, offshore environments (as opposed to estuarine environments). Other potential sources for estuarine benthic habitat data include state, local, educational, and non-profit institutions. NOAA (http://www.csc.noaa.gov/crs/bhm/index.html) maintains a partial listing of the status of various NOAA-sponsored benthic habitat initiatives underway across different regions of the country.

Several of the planning decisions that need to be made regarding survey techniques will be based on the expected variability in the topography and habitat types that are likely to be encountered within the survey area. If a good deal is not already known about the planned survey area, then the evaluation of habitat variability will need to be based on available prior survey area. One of the key issues that need to be addressed in this initial planning phase is how to balance the available resources between the broad-scale and fine-scale sampling effort. In general, if the topography and/or the composition of the seafloor is likely to vary a great deal within a survey area, then the broad-scale characterization will be important to accurately delineate the extent of this variability. Follow-on fine-scale sampling operations will be used to selectively describe different habitats identified in the initial broad-scale characterization (Figure 3-4). If, however, the seafloor is flat or gradually sloping and comprised mostly of similar fine-grained sediment types, then it is unlikely that even the higher-resolution acoustic techniques will provide enough information to clearly distinguish these different areas. In these types of less dynamic environments, a greater emphasis on fine-scale sampling (particularly sediment profile imaging) will probably provide more useful data for differentiating subtle differences in habitat type (Figure 3-5). For any seafloor environment, the development of a comprehensive fine-scale sampling plan is necessary to establish a positive relationship between the benthic communities of interest and the physical seafloor habitat (Cutter et al. 2001, Diaz and Solan 2003).

Another data requirement issue that needs to be considered during the initial planning is the intent of the fine-scale sampling data. If the main intent of these data is simply to provide a physical description of the sediment type (i.e., a general habitat description) to verify or ground-truth the broad-scale interpretation, then a relatively straightforward grab sampling operation with a field description of samples would likely suffice. However, if more detailed information is needed from the fine-scale sampling data, then sediment profile imaging may provide a more useful dataset for conducting in-depth physical and biological analyses. Grab samples can also be retained in the field and sent to appropriate laboratories for various physical, biological, and chemical analyses. Not only does this increase the field handling requirements for the grab samples, but the costs associated with the laboratory analysis, particularly the sediment chemistry, may be quite high.

3.2 Spatial and Temporal Scales

Prior to selection of specific data acquisition techniques, the desired scale (or resolution) of the habitat characterization needs to be considered. Although the usual reality is that every researcher or coastal manager would prefer optical image quality resolution across the entire area of interest, this is not practical due to time, resource, and physical constraints. As discussed above, the manager will have to balance the available resources among the various aerial or acoustic broad-scale characterization techniques and the fine-scale sampling techniques. A basic understanding and knowledge of the habitat variability and complexity within a study area will define the habitat scale and ultimately help determine how best to use the available survey resources. Andrews (2003) and Kvitek et al (1999) provide a more in-depth definition and discussion of specific scale-related issues. The intent of this section is to relate how some of these scale issues may help to determine the selection of specific survey data acquisition techniques.

Since all of the fine-scale sampling techniques typically provide very high-resolution data (though over a limited area of coverage), most of the scale-related issues that need to be addressed for these data primarily relate to coverage (Table 2-2). In general, more complex and diverse habitats will require much more extensive fine-scale sampling data to adequately categorize the different habitats. This is especially true when these different habitat types cannot be clearly differentiated within any of the broad-scale acoustic or optical data products. For instance, broad-scale acoustic techniques can generally clearly distinguish between rock, sand, and silt/clay bottom types, and extensive fine-scale sampling may not be required it these broad physical classifications were adequate tothen define the benthic habitat. If however, more subtle differences in the characteristics (e.g., sand fraction, shell fragments, etc.) of the soft-bottom material were important for the benthic habitat classification, then it is likely that more extensive fine-scale sampling data would be required. Evaluating the nature of the relationship between the physical characterization data and the benthic habitat (or biological communities of interest) is the primary focus of a companion paper (Diaz and Solan 2003). This relationship can be a key component when considering the balance between the broad-scale characterization effort and the fine-scale sampling effort.

Because there is not a great deal of difference in the data resolution provided by the different broad-scale acoustic sensors (Table 2-1), many of the acoustic data issues will also relate more to coverage than to resolution. For instance, assuming it is properly acquired and post-processed, a single-beam bathymetric data point is usually very accurate. However, single-beam surveys typically provide only 5 to 10% coverage of the seafloor, and the resulting data models will be based on a large degree of interpolation. If this degree of interpolation (and uncertainty) is unacceptable for the bathymetric element of the habitat characterization, then a multibeam survey or more tightly spaced single-beam survey will need to be conducted.

Many recent examples of high-resolution multibeam and backscatter datasets have been published that clearly illustrate the benefits of those data. If a bathymetric survey is intended to cover large and complex seafloor areas and there is a strong need to completely and accurately model these areas, then multibeam systems will likely offer significant time savings and resolution improvements over single-beam systems (Figure 3-6). However, examples also exist outlining the use of single-beam bathymetry (particularly in flat or gradually sloping areas) to generate a useful topographic characterization of the seafloor (Figure 3-7). If lower bathymetric resolution is acceptable, then a single-beam survey, in conjunction with full-bottom coverage side-scan sonar data and acoustic classification data, may provide a lower cost and perhaps more qualitative view of the seafloor. Although full-bottom coverage, high-resolution bathymetry may be a desired broad-scale characterization goal for any benthic habitat project, ultimately the researcher will need to determine how important this aspect may be relative to the other components of the habitat characterization. Because multibeam survey operations are relatively expensive, other desired sampling elements may need to be curtailed.

Although the habitat scale does need to be considered when evaluating applicable acoustic data acquisition techniques, many of these scale-related issues become more important during subsequent analysis and visualization efforts (Andrews 2003). Because many desktop GIS analysis and visualization systems may have a difficult time handling the dense datasets produced mainly by the multibeam and side-scan sonar techniques, much of the final post-processing for these large datasets entails the systematic merging and thinning of the data. Extensive research has been conducted to develop efficient thinning algorithms (primarily for multibeam and LIDAR data) that will greatly reduce the density of these datasets while still maintaining an accurate and comprehensive depiction of the seafloor (USACE 2002). Even the single-beam bathymetric data can be greatly reduced in the along-track direction and still provide a representative view of the seafloor topography.

For side-scan sonar data, individual lanes are typically merged and thinned to create acoustic imagery mosaics that will cover much broader survey areas. Because of the size of each individual side-scan sonar lane data file, the creation of the digital mosaic typically requires a reduction in the resolution of the imagery data. The extent of the reduction in image resolution is dependent on the size of the area being mosaiced and the power and capacity of the computing system. Although the side-scan mosaic may be useful for delineating broad-scale seafloor differences over larger areas, the reduction in resolution may mask finer-scale elements that were evident in the full-resolution raw imagery data (Figure 3-8). If these finer-scale habitat elements are important in the benthic habitat characterization, then the proper processing procedures must be employed to ensure that these elements are properly represented during later analyses. Both the thinning of large bathymetric datasets and the mosaicing of multiple side-scan sonar lanes essentially reduces the resolution of the original dataset to improve the efficiency of the subsequent analysis and visualization tasks.

Although potential temporal scale issues will not usually have a direct impact on the selection of specific data acquisition techniques, they may have a direct bearing on the scheduling of the field data acquisition operations. Because of seasonal or event-driven (i.e., storms, man-made impacts, etc.) fluctuations in almost all biological activity (including shellfish, finfish, and SAV) within any estuarine area, any direct benthic or biological sampling should account for these variations. The biological sampling events may need to be conducted during specific time periods or they may need to be scheduled in response to specific events, such as low dissolved oxygen conditions or excessive run-off events. Although temporal scale issues should have less impact on any seafloor characterization data, the topography and composition of some dynamic estuarine areas (e.g., surf zones, tidal inlets, etc.) will be affected by seasonal changes in the sediment transport regimes. In addition, storm-driven effects have the potential to greatly alter both the topography and composition of the seafloor, particularly in shallow-water environments. Post-storm bathymetric surveys to assess the impacts from major storms are often conducted to ensure navigation safety, to evaluate the integrity of underwater structures, and to assess the impacts to the overall benthic habitat.

3.3 Data Integration

For the data acquisition portion of a benthic habitat project, the primary data integration concerns will primarily focus on the ability to consistently merge data originating from different sensor types. As initially addressed in section 2.1, for most of the boat-based operations a centralized survey-control system should help to ensure that a consistent position and time basis is used during all data acquisition operations. Even those external sensors that may require their own topside data acquisition platform (often side-scan sonars, sub-bottom profilers, video systems, etc.) should be able to receive external position and time messages from the survey control system. Although the positioning function may be more complicated when dealing with towed or remotely operated sensors, these offset effects can typically be addressed through the survey control software, particularly in shallower water where shorter cable lengths will be used. With the robust performance of DGPS for providing reliable survey-quality positioning data and the multi-function capability of various survey control systems, successfully integrating multi-sensor data from the same survey platform should be a relatively straightforward endeavor (Figure 3-9).

The data integration problems can become more complex when trying to merge data from different sources and of different vintages within a benthic habitat mapping framework. Although many of these data integration issues are more relevant within the analysis and visualization realm, some of the main concerns are important to address before embarking on a major data acquisition effort. Probably the single most common data integration problem across different survey datasets is the use of inconsistent horizontal and vertical datums. Because of the widespread reliance on GPS (and the WGS-84 or NAD83 datum) for position control, horizontal datum issues are not usually a major concern for most recent datasets. Older survey datasets may have been based on the NAD27 datum, but a variety of utilities exist for performing the relatively straightforward conversion between different datums and grid systems (http://www.ngs.noaa.gov/products_services.shtml). If the datum information has not been provided along with an external dataset, then datum issues will not be detected until that dataset is merged within a GIS project environment. However, because the position offset differences between the NAD27 and NAD83 datums may only be on the order of 10 to 20 m horizontally, it may be difficult to detect these differences, particularly at small-scale views.

Although vertical datums are generally only an issue with bathymetric datasets, they are probably the most frequent source for data integration problems. Particularly for nearshore, shallow-water surveys, where tidal effects are more important, the use of inconsistent vertical datums can present a major obstacle when trying to make any meaningful comparison between two different surveys. Generally, most current navigation and charting-related bathymetric surveys are reduced to the Mean Lower Low Water (MLLW) vertical datum based on project-specific tidal information acquired during the period of the survey. The use of area-specific water-level based vertical datums for bathymetric surveying is different than most land surveying applications where a fixed and consistent vertical datum is employed (typically NAVD88). The relationship between MLLW and NAVD88 varies throughout the U.S. and is primarily a function of the mean tidal range associated with a particular area.

Probably the preferred method for obtaining the tidal information required to reduce a bathymetric survey would be to rely on observations from a nearby primary NOAA tide station (http://www.co-ops.nos.noaa.gov/data_res.html). If the survey area is large or far from the primary tide station, then phase and range offset correctors will need to be applied to the observed tide values to transfer those observations to various zones that need to be established within the survey. These zones can often be based on offset correctors provided by NOAA for generating predicted tides over different areas (http://www.co-ops.nos.noaa.gov/tp4days.html). As addressed briefly in section 2.1.1, some kinematic GPS applications also have the ability to accurately track the vertical water-level movement of the survey vessel during survey operations.

The establishment of an accurate water-level based datum and then the use of this datum to generate tidal correctors and to accurately reduce a bathymetric survey to MLLW can be a complex issue and a full discussion is outside the realm of this paper (Wong 2001). Depending on the goals of a specific benthic habitat mapping project, an accurate reduction of the bathymetric data to a valid MLLW datum may not be critical. However, if the ability to evaluate localized seafloor change (through meaningful comparisons between repetitive bathymetric surveys) is a project goal, then it is critical that an accurate and consistent vertical datum is used.

3.4 Cost Considerations

Obviously the cost considerations that may impact a benthic habitat project are diverse and there is no definitive or encompassing cost model that can be derived to accurately predict those costs. Because field data acquisition and initial data processing is typically an expensive component of any project, some cost compromises will likely be necessary when selecting from the wide-range of field techniques and determining how to balance resources between the broad-scale and fine-scale surveying efforts. Assuming that the project is government-sponsored, then the availability of internal resources (including personnel, equipment, vessels, aircraft, etc.) to meet all or some of the requirements will likely have a significant impact on the total costs associated with a project. In addition, the region of the country and the availability of local resources to support the project will also have an impact on the costs. The following discussion is intended to address the cost considerations associated primarily with the boat-deployed data acquisition techniques, as well as some of the initial post-processing efforts. Significant costs are also likely to accrue during subsequent analysis and visualization efforts.

Assuming that the cost implications will be an important consideration in the eventual selection of a survey plan, then the cost elements are generally reviewed in tandem with the development of a field survey approach. Assuming in-house resources will not be used to conduct the survey, the individual costs associated with any of the boat-deployed techniques will generally fall within one of three main categories—boat costs, equipment costs, and personnel costs. In addition, the initial post-processing costs associated with a particular data element may also be included within the costs to acquire the data. Frequently, the various costs associated with a particular field survey element are lumped together to provide a lump sum day rate for that element. Because several of the acoustic techniques can be conducted concurrently, a daily rate can be developed that may combine several techniques.

For instance, the daily rate for conducting a combined single-beam bathymetric, acoustic classification, and side-scan sonar survey would include the cost of the boat (and crew), the cost of all the required equipment, and the cost of the technical survey personnel (to conduct the survey and initially process the day's data). Although boat rates vary widely depending on size and geographic location, a reasonable cost for a 35-foot inshore survey vessel with an operator may be around $1000 / day. The required survey equipment (and approximate daily costs) would include a DGPS receiver ($50), a survey control and data acquisition system ($50), a single-beam echosounder ($100), a speed of sound profiler ($75), an acoustic classification system ($250), a side-scan sonar towfish, cable, and topside acquisition system ($400), and perhaps a portable tide gauge unit ($30). Based on these estimates total equipment costs may approach $900 / day. The combined costs for one senior and one junior survey technician to operate the equipment during a 10-hour survey day would likely approach $1000 / day and the subsequent costs associated with the initial processing of the data would probably approach $500 / day. Based on these costs assumptions, a daily rate of $3455 may be estimated for these operations. It should be a relatively straightforward process to develop similar daily rates for each combination of data acquisition techniques being considered.

The next step is to then consider how long (or how many days) it will take to meet the desired data goals based on an assumed level of productivity for each of the planned elements as well as the extent of the data coverage. For track-line type data (e.g., bathymetry, side-scan-sonar, sub-bottom profiling) the extent of the data coverage may be indicated by the total number of linear nautical miles required and for the sampling data the extent of the coverage will normally be indicated by the number of discrete samples required. The time estimates are then multiplied by the projected daily costs to generate an expected total cost for each of the different elements. Based on the initial cost estimates, it is likely that the desired survey coverage requirements will need to be revised to meet budgetary constraints.

For instance, perhaps the combined single-beam, acoustic classification, and side-scan sonar survey used as an earlier example was initially envisioned to be run based on 100 m lane spacing over a 10 km by 10 km survey area. This spacing would provide 200% side-scan sonar imagery bottom coverage and reasonably dense bathymetric and acoustic classification coverage. Based on an assumed track-line survey productivity of around 40 linear nautical miles/day, this portion of the survey would take approximately 16 days to complete at a projected estimated cost of $55,000. If these costs are too high, especially considering the extensive fine-scale sampling effort required to ground-truth the acoustic classification data, then the broad-scale coverage will probably need to be reduced. Reducing the planned line spacing to 200 m would cut the projected costs for this element in half, while still providing full-bottom side-scan sonar coverage. This iterative process of evaluating the trade-offs between expected costs and survey coverage can be easily conducted within a project-specific spreadsheet designed to reflect the relationship. However, the use of realistic cost and productivity estimates is critical to this process.

Besides the projected daily survey data acquisition costs addressed above, mobilization and planning costs will also need to be accounted for to cover survey planning and management, evaluation of prior data sources, and the mobilization of the specific survey equipment. These costs should typically be no more than 10% of the planned data acquisition costs. In addition, if any laboratory analyses (e.g., physical, biological, or chemical) are planned for the discrete grab samples then these potentially large lab analysis costs will also need to be accounted for within the data acquisition cost estimate (unless this element will be reflected within the analysis and visualization budget). Finally, potential weather-related contingencies may also need to be addressed within the data acquisition cost estimate. Particularly for extended survey operations in areas that may be impacted by weather, the potential standby costs associated with weather down-time may be significant.

4.0 SUMMARY AND CONCLUSIONS

This paper has attempted to provide a reasonably in-depth examination of the wide range of tools and techniques available for the acquisition of benthic habitat mapping data. Because of the technical complexity of many of these techniques, this presentation was not intended to provide a complete description on how these various systems work. Instead, the discussion focused on the types of data that the various techniques can provide and also the major operational considerations (limitations, complexity, costs, etc.) associated with their use.

Though the classification of benthic habitats may be based on a variety of water-column parameters (i.e., salinity, dissolved oxygen, temperature, etc.) for the purposes of this paper the benthic habitat was viewed synonymously with the physical seafloor characterization; and any comprehensive seafloor characterization effort will generally rely on some combination of broad-scale, lower resolution, physical characterization data (e.g., multibeam bathymetry, side-scan sonar imagery, etc.) as well as fine-scale, higher resolution sampling data (e.g., sediment grabs, sediment profile imaging, underwater video, etc.).

The broad-scale techniques are intended to provide a general physical overview (e.g., bottom topography, changes in surficial sediments, etc.) of the seafloor over the entire area of interest. The fine-scale techniques are used to generate the ground-truth data that will improve and/or confirm the broad-scale interpretation. In an ideal situation, the broad-scale characterization would be completed first, and then used to help define the preferred sampling plan for the follow-on fine-scale survey. If a strong correlation cannot be made between the broad-scale characterization and the discrete sampling data, then higher resolution broad-scale data or more densely sampled discrete data may be required. The ultimate goal is to create a full-scale physical characterization of the seafloor over the study area. Assuming extensive direct benthic sampling is not feasible, it is then up to the benthic biologist to infer the link between the physical seafloor characterization data and the likely benthic communities that inhabit those areas.

Because of the importance of seafloor characterization across numerous nationally important applications (e.g., nautical charting, navigation safety, dredge monitoring, commercial fishing, coastal engineering, and benthic habitat assessment) there is a good deal of ongoing government-funded research and development underway to improve various aspects of the acquisition and interpretation of seafloor characterization data. Some of the relevant emerging technologies and trends have been presented within the sections addressing the specific technique. When developing an approach for a planned benthic habitat mapping project, a knowledge of some of these ongoing developmental initiatives may have a bearing on the selection of specific survey data acquisition techniques.

The selection of specific data acquisition techniques within each of the two main categories (broad-scale and fine-scale) will depend on the wide variety of project-specific considerations. Though no set formula exists for determining the best mix of data acquisition techniques, a framework for selecting the most appropriate data acquisition techniques based on the numerous project-specific considerations (e.g., type of environment, availability of existing data, the variability of the habitat, the habitat scales to be delineated, the spatial extent to be covered, and the available resources) has been provided. Initially, a careful consideration of the general habitat environment (e.g., water depths, clarity, variability, etc.) and the basic data requirements (i.e., seafloor composition, SAV delineation, etc.) should help to narrow the focus to only a limited number of applicable techniques. Ultimately, the selection of specific data acquisition tools and techniques and an overall survey approach will be an iterative process in which the budget constraints will be weighed against the costs associated with the different techniques and their ability to best meet the overall data objectives.

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Valente, R. 2002. The Role of Seafloor Characterization and Benthic Habitat Mapping in Dredged Material Management: A Review. SAIC Report 621 prepared for NOAA Coastal Services Center, Charleston, SC.

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TABLES AND FIGURES

Table 2-1.
Broad-Scale Techniques

Type	Technique	Application	Data Coverage	Resolution			Key Points
				Vertical	Horizontal	Image	
Boat-Deployed Acoustic techniques	**Single Beam**	Bathymetry	Along-track/ Point Data	cm	m	N/A	Point Dataset Simple to mob, use, process; low-cost for acquisition and processing Accurate and reliable bathymetry Provides sparse data coverage
	Acoustic Classification	Sediment Classification	Along-track/ Point Data	cm	m	N/A	Point Dataset from single beam acoustic return Descriptor in dataset indicates sediment type Requires extensive ground-truth Moderate complexity and cost for acquisition and processing
	Multi-transducer	Bathymetry	Along-track/ multiple lanes Point Data	cm	m	N/A	Point Dataset Multiple single-beam transducers, greater bottom coverage Accurate and reliable bathymetry Boat maneuverability restricted
	Multi-beam	Bathymetry	Medium Swath 2-7 times water depth Point Data	cm	m	m	Point Dataset, dense data Far greater coverage than single beam, higher resolution Backscatter data can be used to characterize sediment Coverage limited in shallow water Acquisition and processing complex and high-cost
	Side-scan Sonar	Imagery	Wide Swath 5-15 times water depth Imagery Data	m	N/A	cm - m	Geo-referenced composite image Trade-offs between resolution and swath coverage Characterize surface sediment and identify objects Moderate complexity and cost for acquisition and processing
	Seismic Reflection or Sub-bottom	Sub-bottom imagery	Imagery Data	10's cm	N/A	cm - m	Stratigraphy image or point data Detection of subsurface sediment horizons Trade-offs between resolution and penetration depth Susceptible to methane interference Moderate complexity and cost for acquisition and processing
Aircraft-Deployed Electro-optical techniques	**Aerial Photography**	Imagery	Several km	N/A	m	cm - m	Digital Orthophoto, Stereo Pairs of Photographs, Photomosaics Identification and delineation of nearshore habitats within the photic zone Wide area of coverage with constant resolution; data readily available data collection limitations: water turbidity, water depth and tidal variation, sun angle, clouds and haze, and wind and waves
	Hydrographic LIDAR	Bathymetry	Several km	cm	m	cm	Point Dataset, very dense data Measurement of water depth using a laser but highly dependent on water clarity Collection of data possible in challenging areas: shallow water, boat hazards, etc. Cost-effective in shallow areas in support of acoustic data
	Airborne Hyperspectral Imaging	Imagery	Several km	N/A	m	m	Geo-referenced image Collection several hundred spectral bands of data at a high-spatial resolution Classification of benthic habitats in coastal zones Dependent on water turbidity; low availability, complex, not cost-effective
	Satellite Multispectral	Imagery	Several km	N/A	m	m - 100's m	Satellite Image, Image Mosaic Detection of nearshore bathymetric features and benthic habitat mapping Dependent on atmospheric conditions (cloud cover), water turbidity; low resolution High complexity and cost; limited availability

N/A - Not Applicable

Table 2-2.
Fine-Scale Characterization Techniques

Type	Technique	Application	Data Coverage	Resolution			Key Points
				Vertical	Horizontal	Image	
Electro-optical Techniques	**Sediment-Profile Imaging (SPI)**	Benthic Imagery	Point Data	m	m	cm	Detailed photographic cross-section image of upper 20 cm of seafloor Rapid measurement of physical and biological parameters Not impacted by water clarity Discrete sampling technique Moderate complexity and cost for acquisition and processing
	Plan View Photography	Benthic Imagery	Point Data	m	m	cm	Discrete Benthic Image, plan view snapshot of 2 m^2 of seafloor surface Used in conjunction with SPI, but impacted by water clarity Discrete sampling technique Moderate complexity and cost for acquisition and processing
	Underwater Video Imaging (Towed, Diver, ROV)	Benthic Imagery	Narrow Swath	m	m	cm	Benthic Image, geo-referenced digital images or video Impacted by water clarity, limited coverage Variable complexity and cost for acquisition and processing
	Laser Line Scan Imaging	Benthic Imagery	Narrow Swath	m	m	cm	Benthic Image, geo-referenced video or images High-resolution panoramic laser images at rapid coverage rates Limited swath coverage, but better than video Provides strong ground-truth for acoustic side-scan sonar data High complexity and cost for acquisition and processing
Physical Sampling	**Grab Sampling**	Benthic and Sediment Samples	Point Data	m	m	cm	Sediment Sample Used for benthic characterization Can be used for physical, chemical or biological testing Discrete sampling technique Variable complexity and cost for acquisition and lab analyses
	Sediment Coring	Sediment Samples	Point Data	m	m	cm	Sediment Sample Used to provide a deeper vertical cross-section to describe sediment horizons Can be used for physical, chemical or biological testing Time consuming, discrete sampling technique Variable complexity and high cost for acquisition and lab analysis (chemical)

N/A - Not applicable

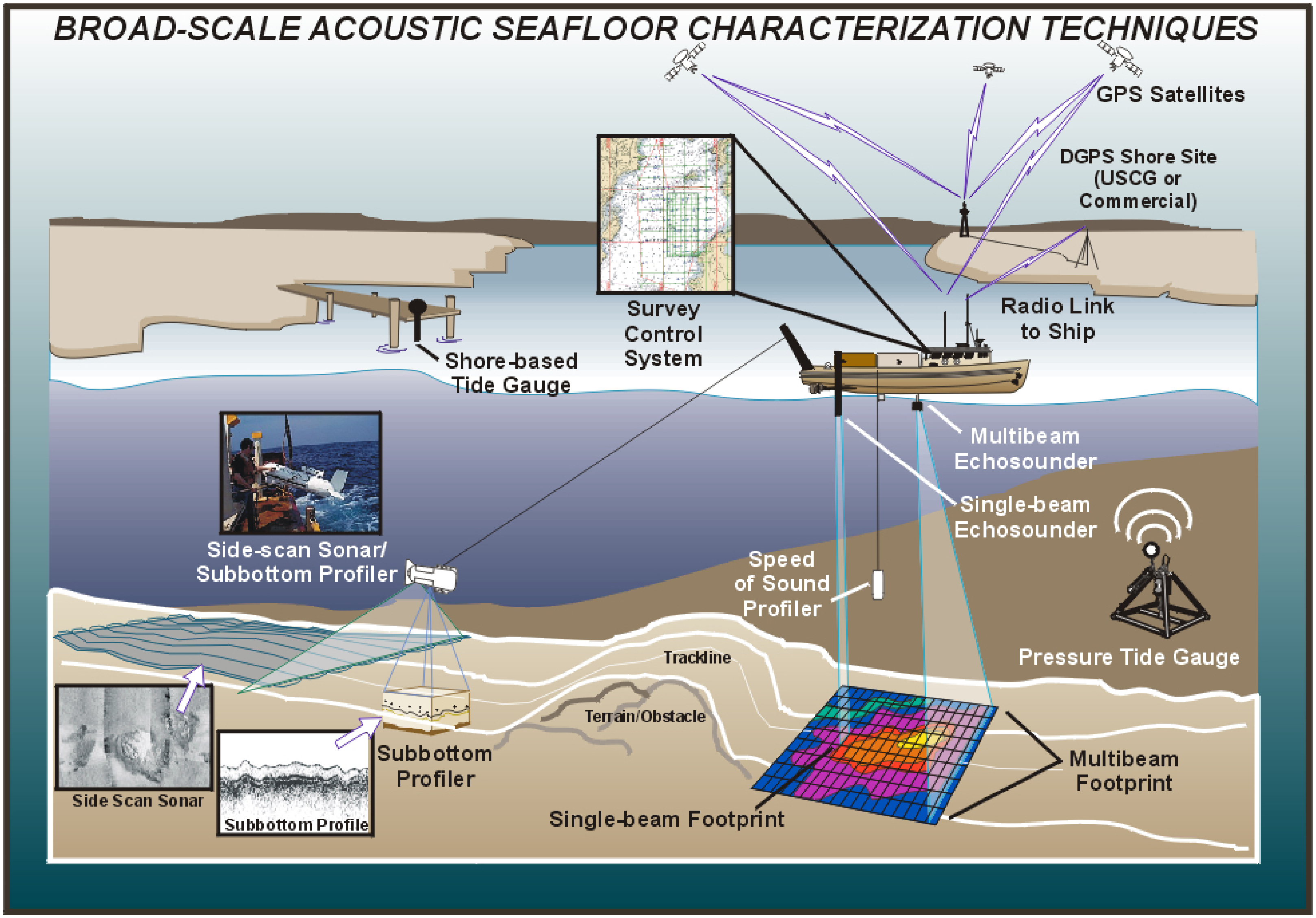
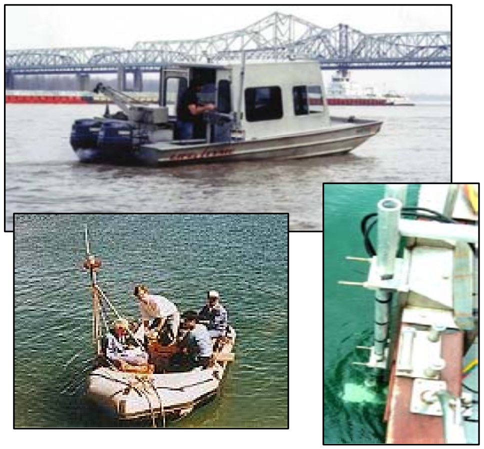
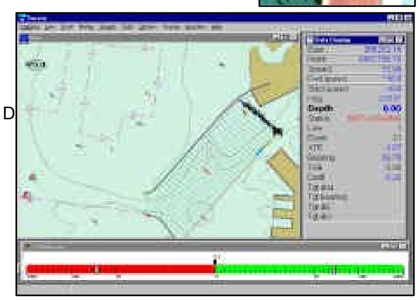
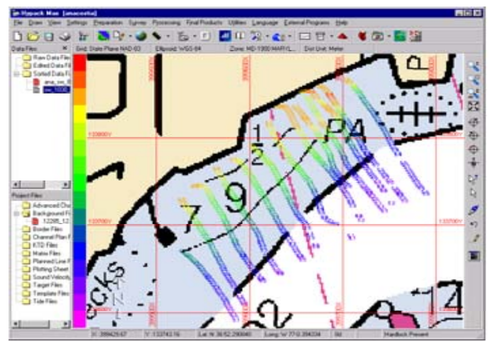
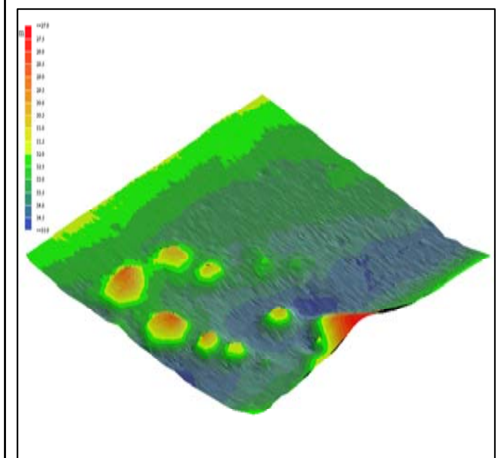


Figure 2-1. Schematic overview of several of the broad-scale acoustic seafloor characterization techniques

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
SINGLE BEAM	Bathymetry	Along-track Point Data	cm	m	N/A	Point Dataset Simple to mob, use, process; low-cost for acquisition and processing Accurate and reliable bathymetry Common Frequency Ranges: 20 kHz - 400 kHz Provides relatively sparse data coverage / requires greater degree of interpolation

Data Collection[1]	Raw Data[1]	Processed Data[2]
 Onboard D Display  Single beam transducers can be temporarily pole-mounted on a survey vessel of opportunity.	 Bathymetric Trace  Digital display of bathymetry collected in the Anacostia River, Washington, DC. Single beam bathymetry traces are printed on a thermal printer; bathymetric data can also be recorded digitally with survey software.	 TIN Surface Model generated from single-beam bathymetry conducted in the summer of 2001 at the Western Long Island Sound Disposal Site (WLDS).

N/A Not applicable

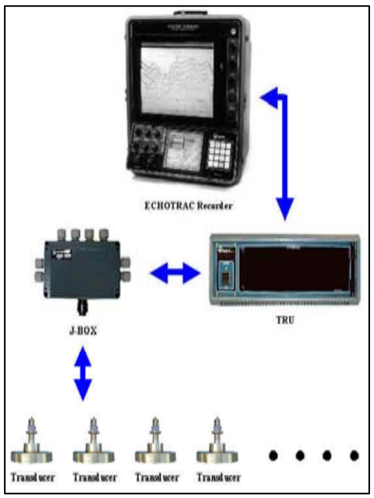
[1]Digital data and software examples produced by Coastal Oceanographic's HYPACK software system (http://www.coastalo.com/hypack.htm)

[2]Processed data image provided by SAIC (2001).

Figure 2-2. Summary view of single-beam survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
MULTI-TRANSDUCER	Bathymetry	Along-track multiple lanes Point Data	cm	m	N/A	Point Dataset Multiple single-beam transducers, greater bottom coverage Accurate and reliable bathymetry Boat maneuverability restricted / more difficult to mob on temporary vessel

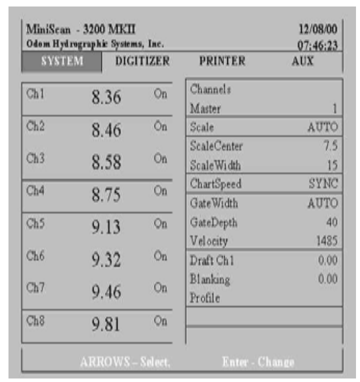
Data Collection[1]



Multi-transducer echosounders are mounted on a long boom that extends across the survey vessel.

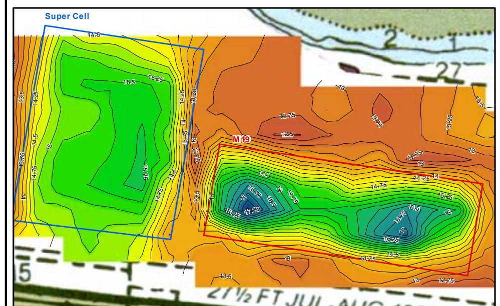
Raw Data[1]

Output example per channel

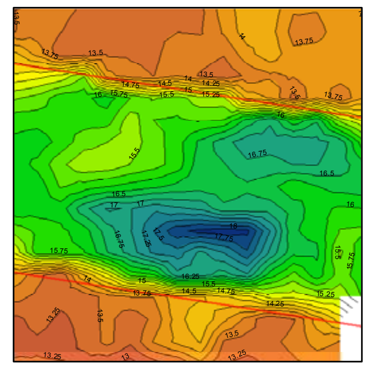


Multi-transducer bathymetry traces are printed on a thermal printer; bathymetric data can also be recorded digitally with survey software.

Processed Data[2]



The two bathymetric images are from Boston Harbor and show detailed bathymetry of some of the confined aquatic disposal (CAD) cells.



Multi-transducer bathymetric surveys are commonly conducted in harbors and protected shallow-water areas.

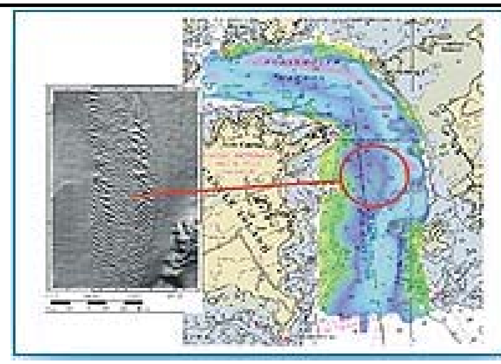
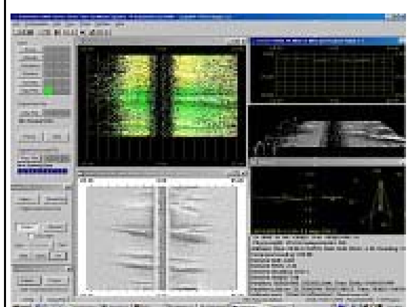
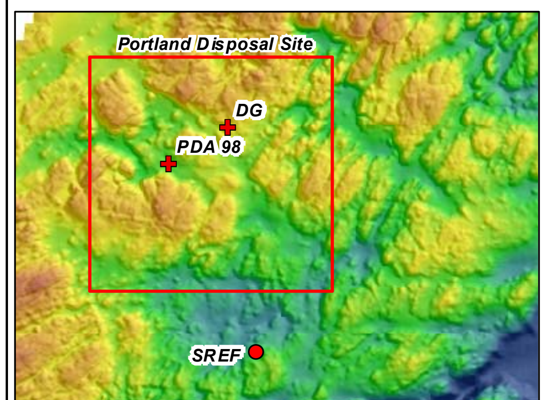
N/A = Not applicable

[1]Data collection and raw data examples from Odom Hydrographic Miniscan (http://www.odomhydrographic.com/newpage1.htm).

[2]Processed data images provided by SAIC (2002).

Figure 2-3. Summary view of multi-transducer survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
MULTI-BEAM	Bathymetry	Medium Swath 2-7 times water depth Point Data	cm	m	m	Point Dataset, dense data Far greater coverage than single beam, higher resolution Backscatter data can be used to characterize sediment Common Frequency Ranges: 200 kHz - 450 kHz Coverage limited in shallow water High costs and complexity for acquisition and processing

Data Collection[1]	Raw Data[1]	Processed Data[2]
 Multi-beam systems can be semi-permanently hull-mounted or temporarily pole-mounted.	  Multi-beam bathymetric data can be processed digitally and displayed in real time.	 Hill-Shaded surface model generated from multi-beam bathymetry acquired at the Portland Disposal Site (2001).

[1]Data collection and raw data examples from L3 SeaBeam Instruments (http://www.seabeam.com/), Odom Hydrographic (http://www.odomhydrographic.com/newpage1.htm) and Reson (http://www.intnlind.com/Reson/sb6042.htm).

[2]Processed data image provided by SAIC (2002).

Figure 2-4. Summary view of multibeam survey technique

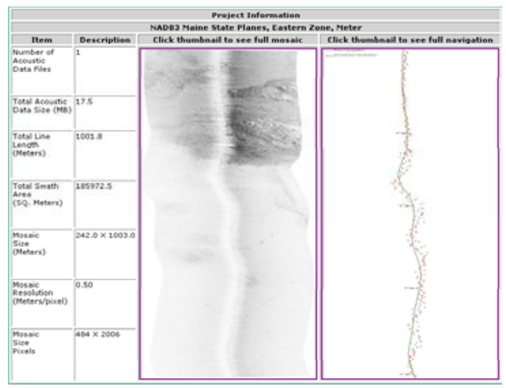
Technique	Application	Data Coverage	Resolution			Key Points
			Vertical	Horizontal	Image	
SIDE-SCAN SONAR	Imagery	Wide Swath 5-15 times water depth Imagery Data	m	N/A	cm - m	Geo-referenced composite image Trade-offs between resolution and swath coverage Common Mapping Frequency Ranges: 100 kHz - 500 kHz Characterize surface sediment and identify objects Moderate complexity and cost for acquisition and processing

Data Collection[1]

The side-scan towfish is usually towed astern of the survey vessel; in shallow-water, a bow or pole towfish mount may be useful.

Raw Data[2]

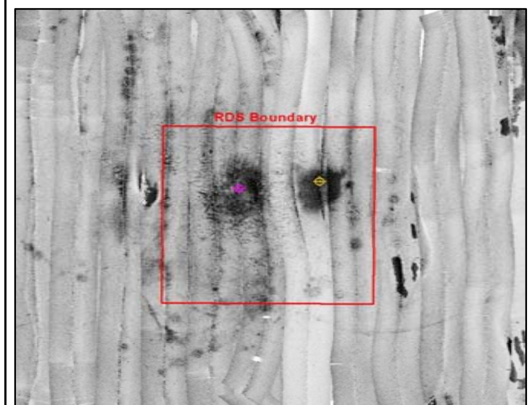
Raw Data



Processing raw data

Side-scan sonar data can be processed digitally and displayed in real time as it is collected.

Processed Data[3]



100 kHz Side-scan sonar mosaic from the Rockland Disposal Site clearly indicating the presence of past disposal operations around prescribed buoy locations as well as a prominent rock outcrop over the mostly soft seafloor.

N/A = Not applicable

[1]Data collection examples from SAIC, EdgeTech Sonar Products Group (http://www.edgetech.com/ss%20pl.html) and Klein Sonar (http://www.kleinsonar.com/specs.html).

[2]Raw data examples provided by SAIC (2002); SonarWeb Pro (Chesapeake Technologies) used for processing software example.

[3]Processed data image provided by SAIC (2002).

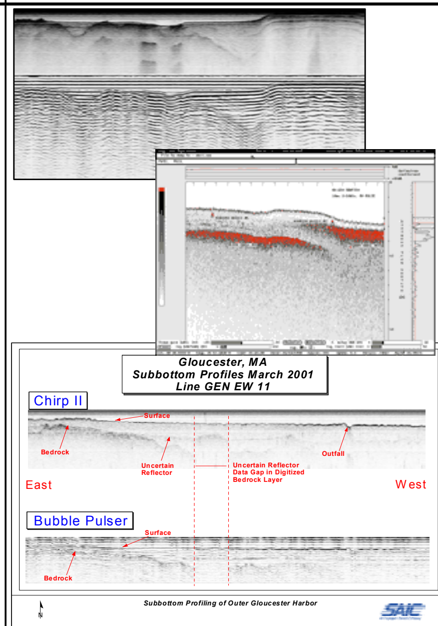
Figure 2-5. Summary view of side-scan sonar survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
SEISMIC REFLECTION OR SUB-BOTTOM	Sub-bottom imagery	Imagery Data	10's cm	N/A	cm - m	Stratigraphy image or point data Detection of subsurface sediment horizons Trade-offs between resolution and penetration depth Common Frequency Ranges: 400 Hz to 20 kHz (for higher resolution systems) Susceptible to surficial gas interference+H29 Moderate complexity and cost for acquisition and processing

Data Collection[1]

Send and receive elements for higher frequency sub-bottom systems are usually housed in a single towfish. Lower frequency systems (e.g., boomers, sparkers, etc.) generally use a separate sound source with a towed hydrophone array.

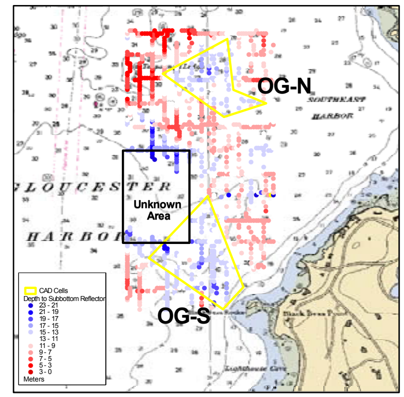
Raw Data[2]

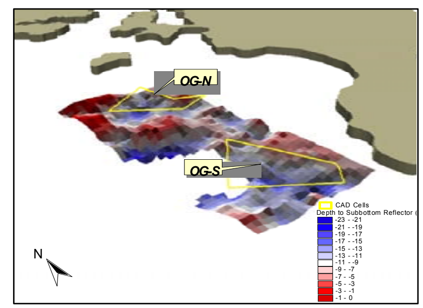


Interpretation of high and low frequency sub-bottom profiling data for potential confined aquatic cell (CAD) investigation in outer Gloucester Harbor

Sub-bottom profiles can be displayed in real-time when collected and processed digitally.

Processed Data[3]





Determination of depth to bedrock from sub-bottom data collected around the potential confined aquatic (CAD) cells in the outer Gloucester Harbor. Top image is point data, bottom image is grid of point data.

N/A = Not applicable

[1]Data collection examples from SAIC, Edgetech, Benthos, and the USGS Woods Hole Seafloor Mapping Group (http://woodshole.er.usgs.gov/operations/sfmapping/default.htm).

[2]Raw data examples provided by SAIC (2002) Edgetech; SonarWeb Pro (Chesapeake Technologies) used for processing software example.

[3]Processed data images provided by SAIC (2002).

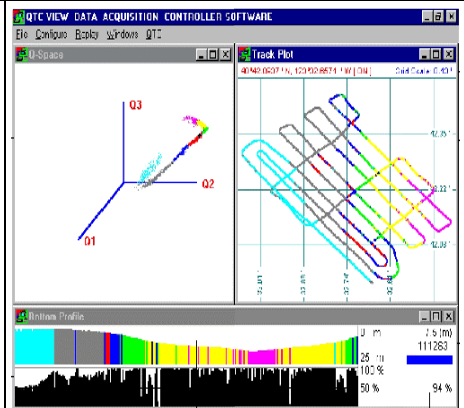
Figure 2-6. Summary view of sub-bottom survey technique

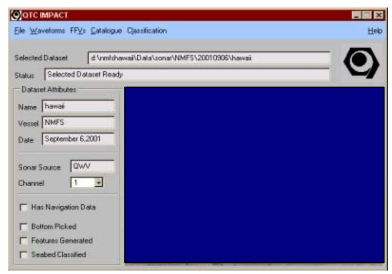
Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
ACOUSTIC CLASSIFICATION	Sediment Classification	Along-track Point Data	cm	m	N/A	Point Dataset from single beam acoustic return Descriptor in dataset indicates sediment type Requires extensive ground-truth Moderate complexity and cost for acquisition and processing

Data Collection[1]

Acoustic classification systems generally work in conjunction with a standard acoustic echosounder.

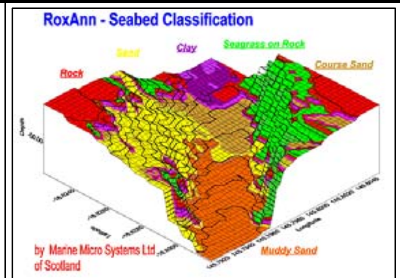
Raw Data[2]





Acoustic classification data can be processed digitally by specialized software.

Processed Data[3]



Example of Seabed Classification near Scotland, UK

Example of Shallow Water Classification near Galveston, Texas

N/A = Not applicable

[1]Data collection hardware examples from Quester Tangent (http://marine.questertangent.com/m_qv_display.html)--QTC VIEW™ system, and Marine Microsystems (http://www.intnlind.com/Roxann/roxindex.html)--RoxAnn system.

[2]Raw data processing examples regarding QTC VIEW™ and QTC IMPACT™ provided by Quester Tangent (http://marine.questertangent.com/m_imp.html).

[3]Processed data images obtained from Marine Microsystems--RoxAnn (http://www.intnlind.com/Roxann/roxindex.html) and Quester Tangent (http://marine.questertangent.com/m_qtc5.html). Image courtesy of James Hinson, Parson's Engineering, Austin, Texas. Data collected by QTC VIEW™.

Figure 2-7. Summary view of acoustic classification survey technique

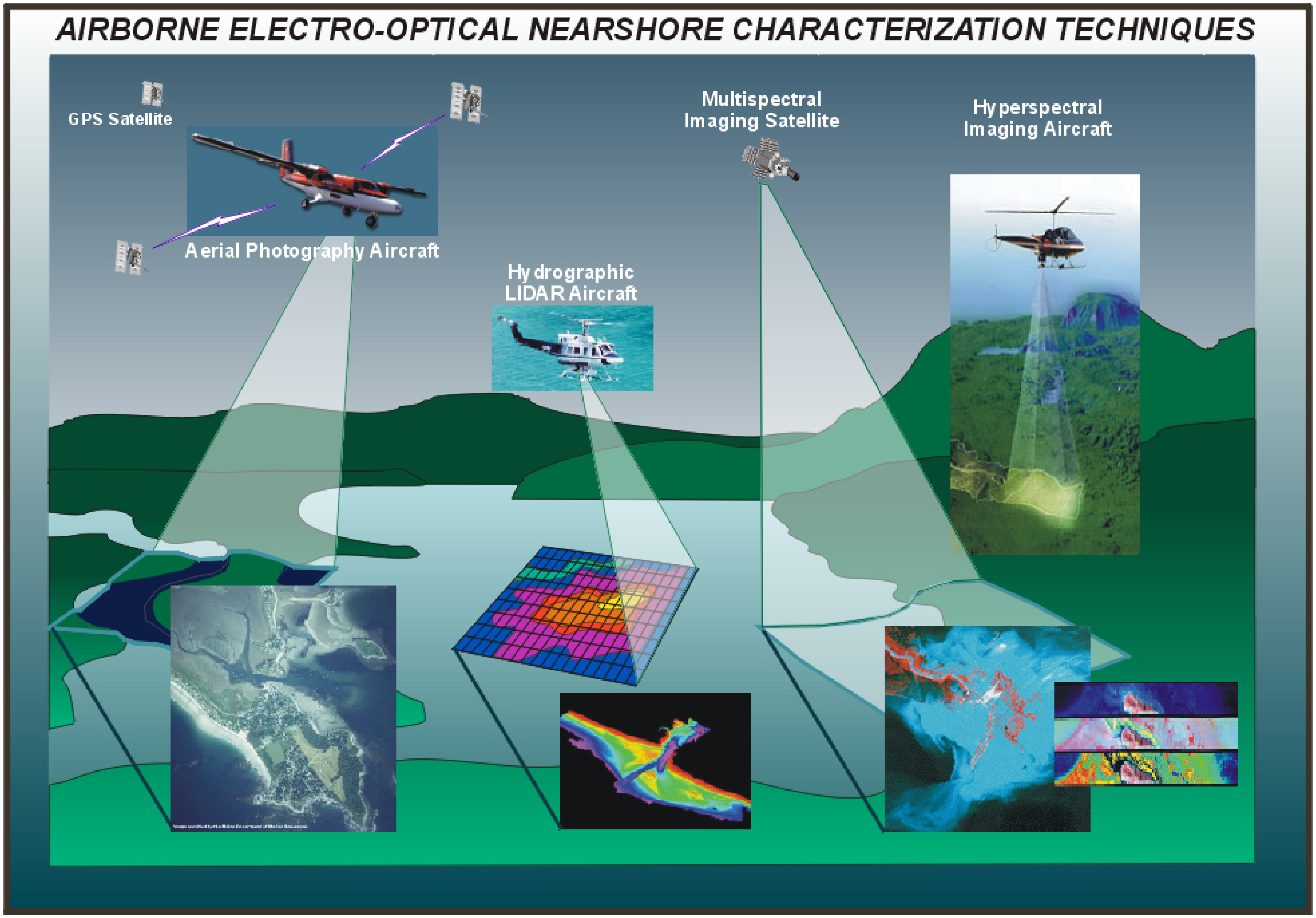


Figure 2-8. Summary view of airborne electro-optical nearshore characterization technique

Technique	Application	Data Coverage	Resolution: Vertical	Resolution: Horizontal	Resolution: Image	Key Points
AERIAL PHOTOGRAPHY	Imagery	Several km	N/A	m	cm - m	Digital Orthophoto, Stereo Pairs of Photographs, Photomosaics Identification and delineation of nearshore habitats within the photic zone Wide area of coverage with constant resolution; data readily available Data collection limitations: water turbidity, water depth and tidal variation, sun angle, clouds and haze, and wind and waves

Data Collection

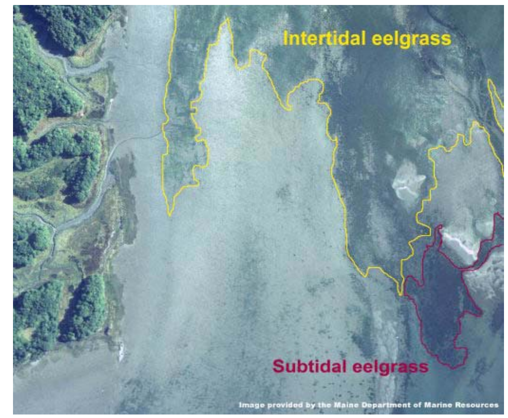
Camera

Equipment mounted on aircraft

Raw Data[1]

True color aerial photograph of SAV habitat from Maine (1:24000).

Processed Data[1]



SAV Mapping. True color aerial photograph (Maine). Interpretation of subtidal and intertidal eelgrass beds from photograph.

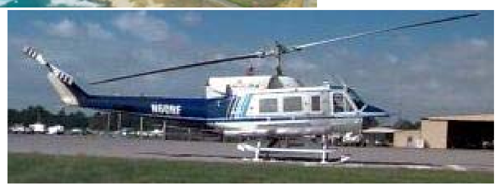
N/A = Not applicable

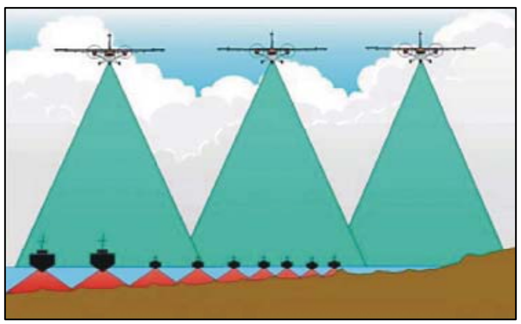
[1]Raw data and processed data photographs obtained from the NOAA SAV image gallery (http://www.csc.noaa.gov/crs/bhm/sav_cd/html/image.htm)

Figure 2-9. Summary view of aerial photography survey technique

Technique	Application	Data Coverage	Resolution: Vertical	Resolution: Horizontal	Resolution: Image	Key Points
HYDROGRAPHIC LIDAR	Bathymetry	Several km	cm	m	cm	Point Dataset, very dense data Measurement of water depth using a laser but highly dependent on water clarity Collection of data possible in challenging areas: shallow water, boat hazards, etc. Cost-effective in shallow areas in support of acoustic data

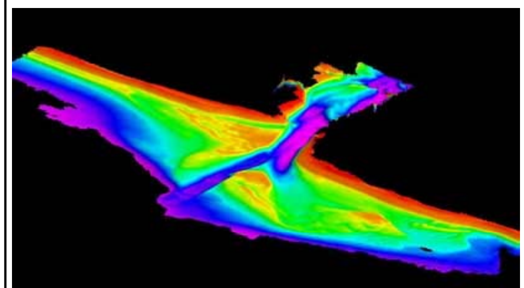
Data Collection[1]



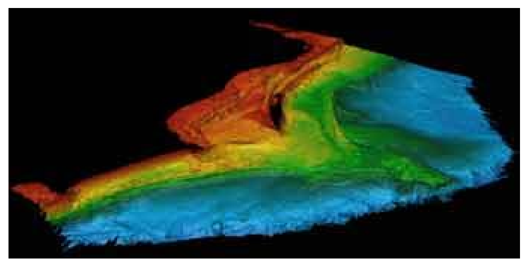


Aircraft-deployed LIDAR equipment can collect more nearshore and shallow-water data than boat-deployed sonar equipment

Raw Data[1]

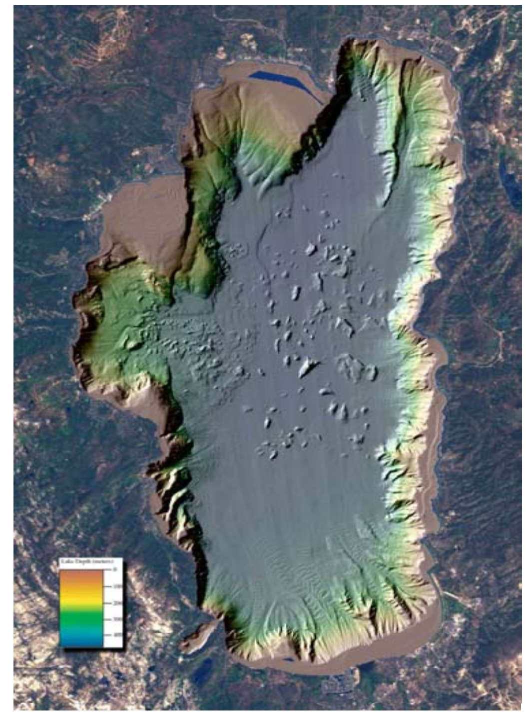


New Pass, Florida was one of the first locations surveyed by the SHOALS Hydrographic LIDAR system. The survey was conducted in March 1994.



In early 1996, SHOALS performed its first international mission offshore of Cancun, Mexico to chart the waters and identify any potential navigation hazards.

Processed Data[2]



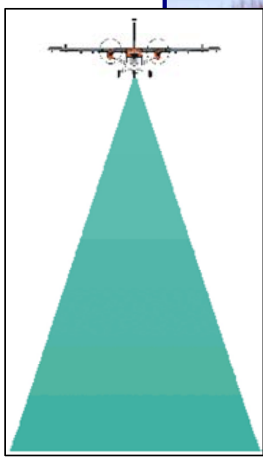
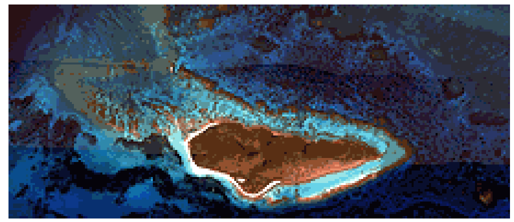
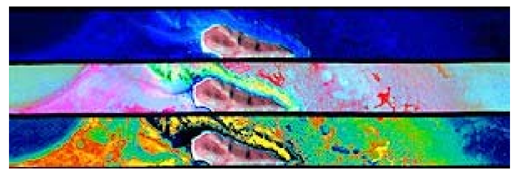
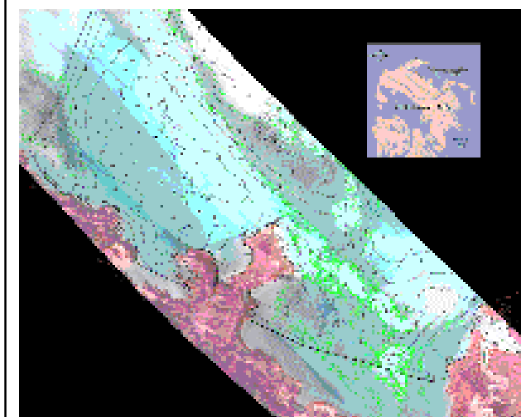
Lake Tahoe Bathmetry. Shaded relief image of combined LIDAR and multibeam bathymetry over Landsat-7 imagery (surrounding land).

[1]Data collection images obtained from USACE SHOALS (http://shoals.sam.usace.army.mil).

[2]Processed data imagery obtained from USGS Western Region Coastal and Marine Geology (http://walrus.wr.usgs.gov/pacmaps/lt-shoal.html). USACE SHOALS Lidar survey of Lake Tahoe.

Figure 2-10. Summary view of hydrographic LIDAR survey technique

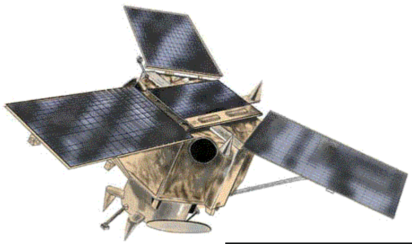
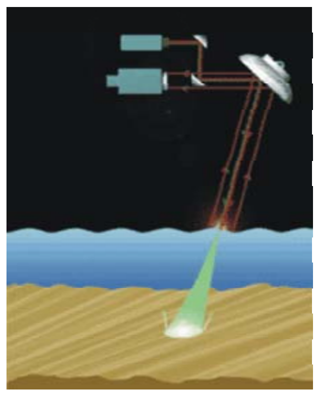
Technique	Application	Data Coverage	Resolution: Vertical	Resolution: Horizontal	Resolution: Image	Key Points
AIRBORNE HYPERSPECTRAL IMAGING	Imagery	Several km	N/A	m	m	Geo-referenced image Collection several hundred spectral bands of data at a high-spatial resolution Classification of benthic habitats in coastal zones Dependent on water turbidity; low availability, complex, not cost-effective

Data Collection	Raw Data[1]	Processed Data[1]
   Sensor Example Aircraft-deployed hyperspectral sensors can collect wide swaths of data.	  Coral Reef identification and habitat health assessment, Buck Island Coral Reef National Park, USVI (March 1999). The bottom image composite shows the false color image (top), the raw data (middle), containing 29 discrete spectral bands of information, and scope of information in only one band (bottom).	 SAV Classification around Smith Island, MD (1998).

N/A = Not applicable

[1]Raw data and processed data images obtained from the 3Di Corps Hyperspectral Imaging page (http://www.3dicorp.com/rem-hyperspectral.html).

Figure 2-11. Summary view of airborne hyperspectral imaging survey technique

<table>
<tr><th rowspan="2">Technique</th><th rowspan="2">Application</th><th rowspan="2">Data Coverage</th><th colspan="3">Resolution</th><th rowspan="2">Key Points</th></tr>
<tr><th>Vertical</th><th>Horizontal</th><th>Image</th></tr>
<tr><td rowspan="5">SATELLITE MULTISPECTRAL</td><td>Imagery</td><td>Several km</td><td>N/A</td><td>m</td><td>m - 100's m</td><td>Satellite Image, Image Mosaic
Detection of nearshore bathymetric features and benthic habitat mapping
Dependent on atmospheric conditions (cloud cover), water turbidity; low resolution
High complexity and cost; limited availability</td></tr>
<tr><th colspan="3">Data Collection[1]</th><th colspan="2">Raw Data[2]</th><th>Processed Data[2]</th></tr>
<tr><td colspan="3">
Remote sensing satellite example

Satellite-deployed multispectral sensors can provide lower-resolution images of the seafloor.</td><td colspan="2">
Raw image of Cape Canaveral, Florida, 0.7 meters per pixel resolution.</td><td>
SAV Mapping, Cape Canaveral, Florida, 0.7 meters per pixel resolution. Classifying vegetation based on spectral signatures of given species has been successfully utilized as a mapping and monitoring tool. This technique eliminates hours of field work in remote sites.</td></tr>
</table>

N/A = Not applicable

[1]Remote sensing satellite example obtained from The Tech website sponsored by Lockheed Martin (http://www.thetech.org/exhibits/online/satellite/home.html)

[2]Raw data and processed data images obtained from the Airborne Data Systems, Inc. website (http://www.airbornedatasystems.com/environment.htm)

Figure 2-12. Summary view of satellite multispectral imaging survey technique

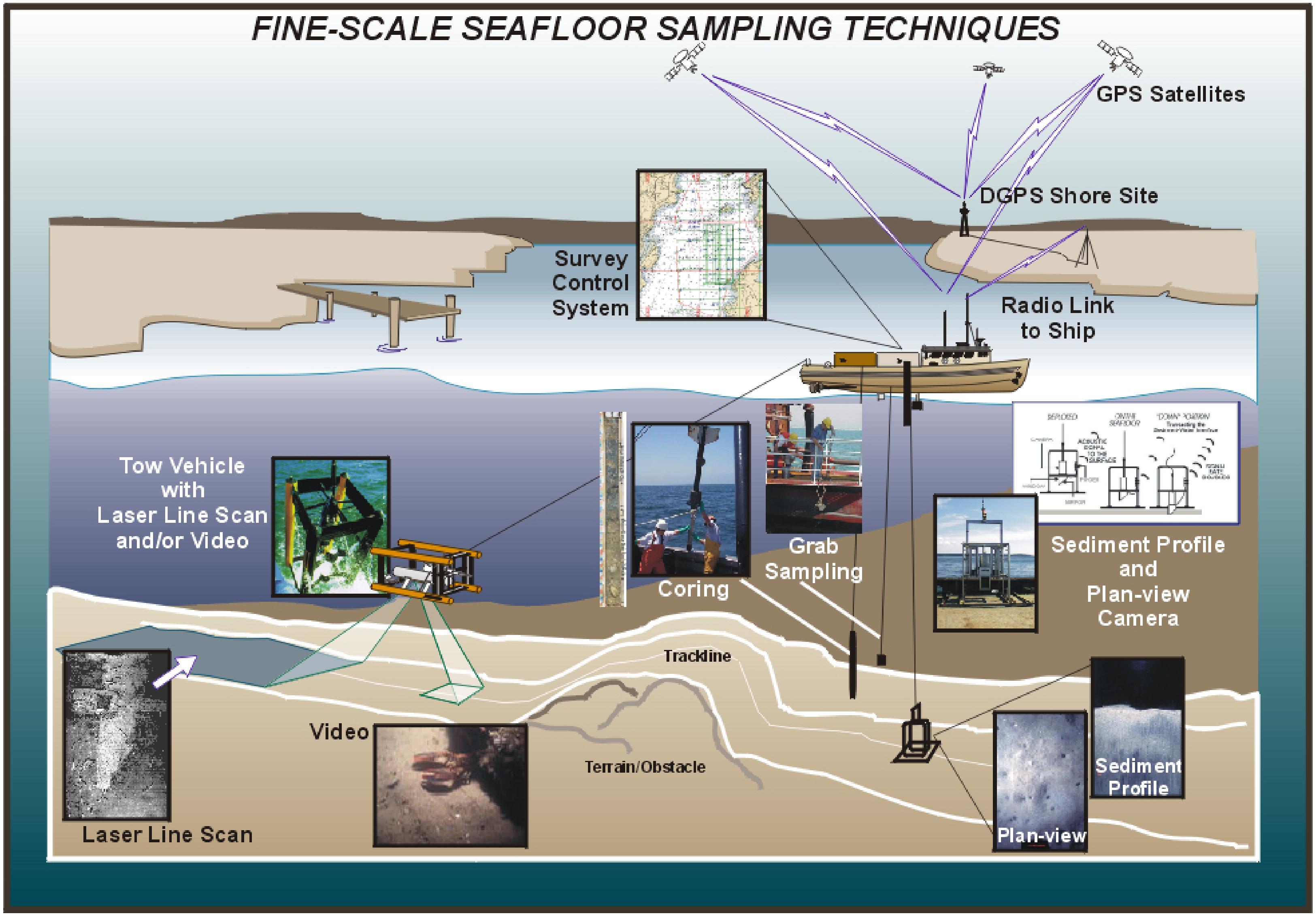
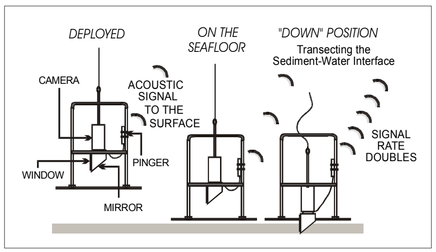


Figure 2-13. Schematic overview of several of the fine-scale seafloor sampling techniques

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
SEDIMENT-PROFILE IMAGING (SPI)	Benthic Imagery	Point Data	m	m	cm	Detailed photographic cross-section image of upper 20 cm of seafloor Rapid measurement of physical and biological parameters Not impacted by water clarity Discrete sampling technique Moderate complexity and cost for acquisition and processing

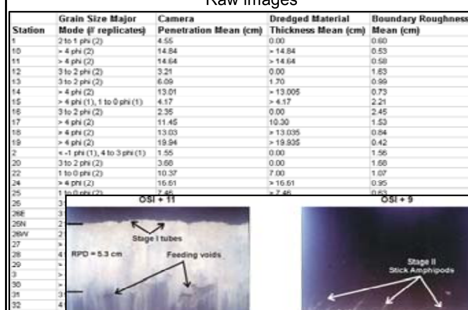
Data Collection[1]



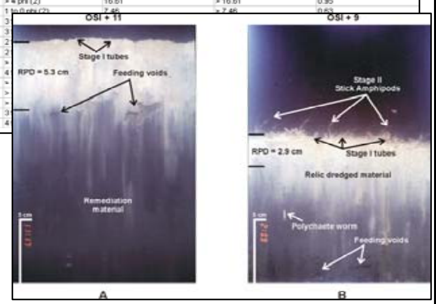
The sediment-profile imaging camera is boat-deployed.

Raw Data[1]

Raw images



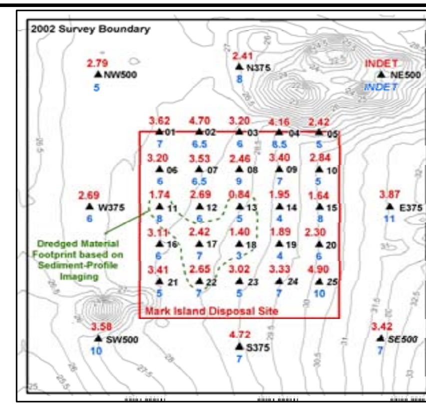
Station	Grain Size Major Mode (# replicates)	Camera Penetration Mean (cm)	Dredged Material Thickness Mean (cm)	Boundary Roughness Mean (cm)
1	2 to 1 phi (2)	4.55	0.00	0.60
10	> 4 phi (2)	14.84	> 14.84	0.53
11	> 4 phi (2)	14.64	> 14.64	0.58
12	3 to 2 phi (2)	3.21	0.00	1.63
13	3 to 2 phi (2)	6.09	1.70	0.99
14	> 4 phi (2)	13.01	> 13.005	0.73
15	> 4 phi (1), 1 to 0 phi (1)	4.17	> 4.17	2.21
16	3 to 2 phi (2)	2.35	0.00	2.45
17	> 4 phi (2)	11.45	10.30	1.53
18	> 4 phi (2)	13.03	> 13.035	0.84
19	> 4 phi (2)	19.94	> 19.935	0.42
2	< -1 phi (1), 4 to 3 phi (1)	1.55	0.00	1.56
20	3 to 2 phi (2)	3.68	0.00	1.68
22	1 to 0 phi (2)	10.37	7.00	1.07
24	> 4 phi (2)	16.61	> 16.61	0.95
25	1 to 0 phi (2)	7.46	> 7.46	0.63
26				
26E				
26N				
26W				
27				
28				
29				
3				
30				
31				
32				



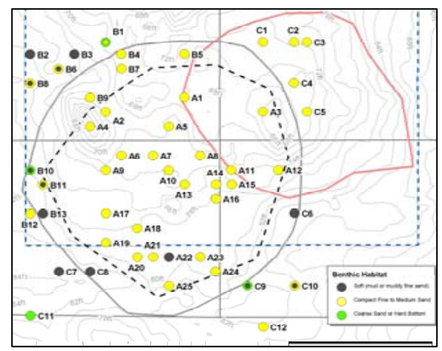
Processing raw data

Discrete photographs of the benthic community are taken and analyzed visually and digitally.

Processed Data[1]



Redox potential discontinuity (RPD) depths and organism sediment index (OSI) values for sediment-profile imaging stations at the Mark Island Disposal Site (MIDS), 2002.

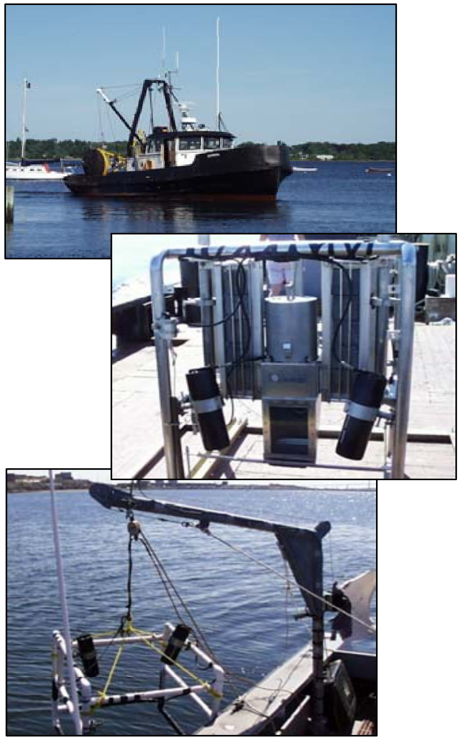
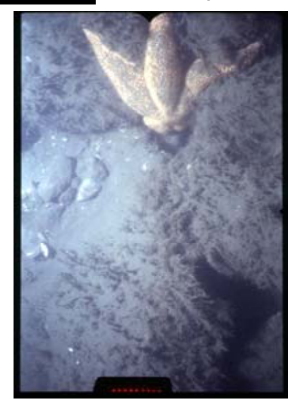
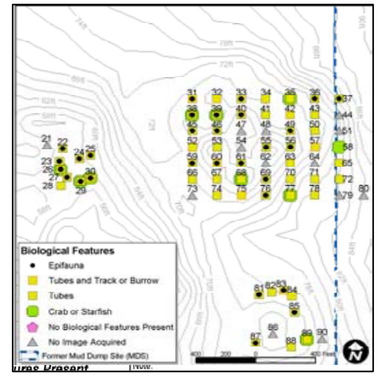
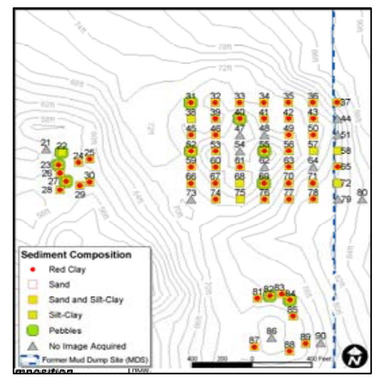


Benthic habitat at sediment-profile imaging stations at the Historic Area Remediation Site (HARS), 2002.

[1]Data collection, raw data, and processed data examples and images provided by SAIC.

Figure 2-14. Summary view of sediment-profile imaging (SPI) survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
PLANVIEW PHOTOGRAPHY	Benthic Imagery	Point Data	m	m	cm	Discrete Benthic Image, plan view snapshot of 2 m^2 of seafloor surface Used in conjunction with SPI, but impacted by water clarity Discrete sampling technique Moderate complexity and cost for acquisition and processing

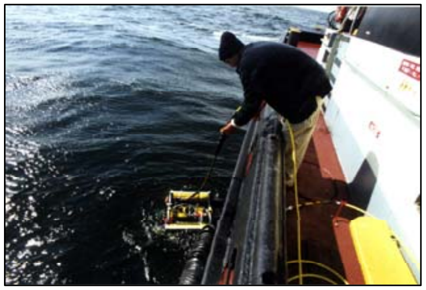
Data Collection[1]	Raw Data[1]	Processed Data[1]
 The downward looking plan-view camera may be mounted onto a sediment profile image frame; it can also be mounted on its own light-weight frame for small boat and/or shallow-water work.	 Raw images  Discrete photographs of the benthic community at the sediment surface are taken and analyzed visually and digitally.	 Biological features present in planview photography images at the Red Clay area of the Historic Area Remediation Site (HARS), 2002.  Sediment composition at planview photography stations at the Red Clay area of the HARS, 2002.

[1]Data collection, raw data, and processed data examples and images provided by SAIC.

Figure 2-15. Summary view of plan view photography survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
UNDERWATER VIDEO IMAGING (TOWED, DIVER, ROV)	Benthic Imagery	Narrow Swath	m	m	cm	Benthic Image, geo-referenced digital images or video Impacted by water clarity, limited coverage Interpretation of video data can be a labor and time intensive effort Variable complexity and cost for acquisition and processing

Data Collection[1]

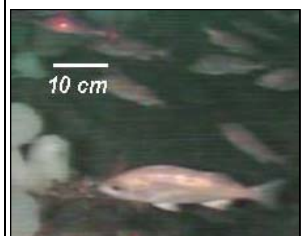


ROV Video System being deployed from the USACE Vessel GELBERMAN during biological assessment survey at Ambrose Shoal.

Towed video sled deployed by CR Environmental.

Raw Data[1,2]

feather stars, basket stars, sea cucumber

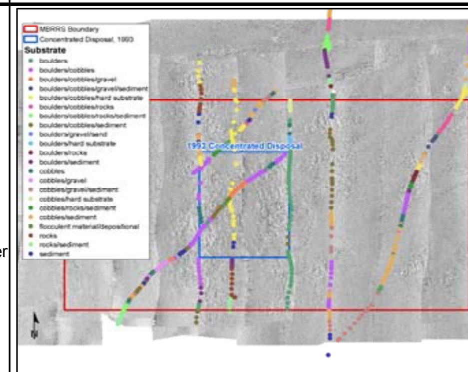


widow rockfish

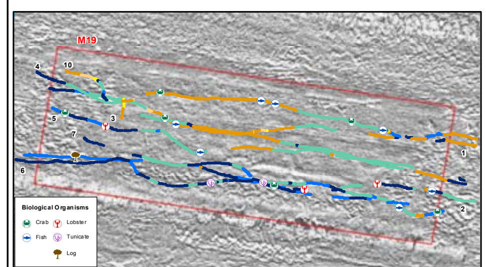
Boston Blue Clay (BBC) nodules and oxidized silty clay

Video of the sefloor surface allows for sediment and biological characterization. Water clarity can be a factor.

Processed Data[1]



Substrate classification based on towed video over the Massachusetts Bay Rock Reef Disposal Site (MBRRS), 2002.



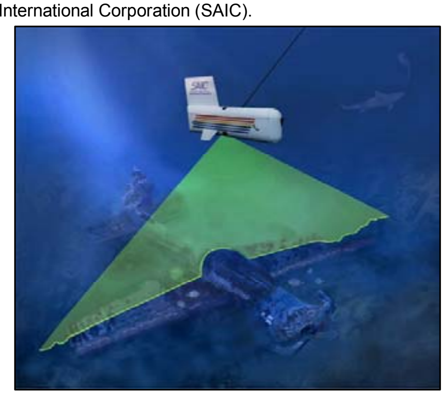
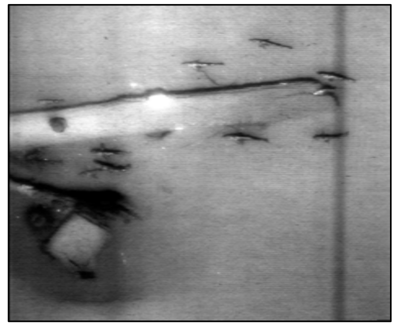
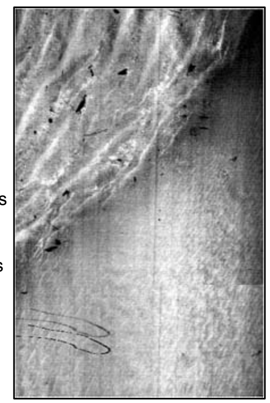
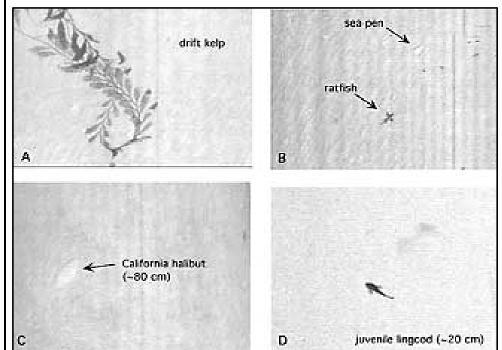
Sediment and biological characterization of the seafloor based on towed video data in Cell M19 of Boston Harbor, 2002.

[1]Data collection, raw data, and processed data examples and images provided by SAIC.

[2]Some raw data images from NOAA (http://oceanexplorer.noaa.gov/).

Figure 2-16. Summary view of underwater towed video imaging survey technique

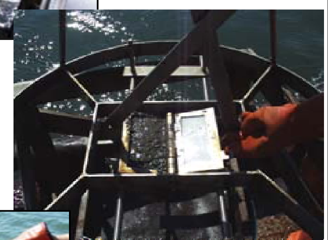
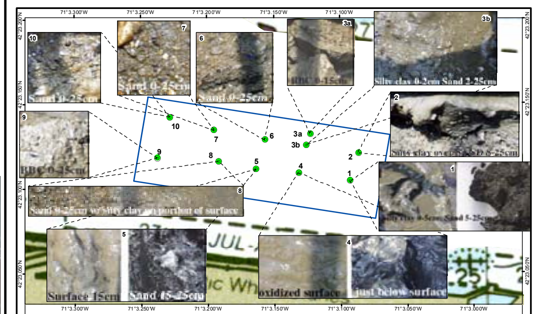
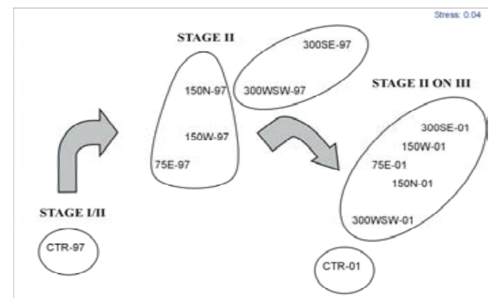
Technique	Application	Data Coverage	Resolution			Key Points
			Vertical	Horizontal	Image	
LASER LINE SCAN IMAGING	Benthic Imagery	Narrow Swath	m	m	cm	Benthic Image, geo-referenced video or images High-resolution panoramic laser images at rapid coverage rates Limited swath coverage, but better than video Provides strong ground-truth for acoustic side-scan sonar data High complexity and cost for acquisition and processing

Data Collection[1]	Raw Data[1]	Processed Data[1]
 A Northrup-Grumman SM-2000 monochrome laser line scan integrated with a McCartney Underwater Technology FOCUS tow body, owned and operated by Science Applications International Corporation (SAIC).  Laser line scanning systems are towed below the surface.	 Snap shot of a section of Laser Line Scan video showing fish behavior and species density near a disposal site in turbid conditions.  Laser image of a sharp boundary between sand waves (top left corner) and smooth seafloor. Dark objects in the area of sand waves are pieces of drift kelp.	 Identification of biological features by NOAA. Laser line scan images of (A) drift kelp at 45 m water depth, swath width 2.7 m; (B) sea pen (arrow) and ratfish in water depth 90 m; (C) California halibut, swath width 4.3 m; and (D) juvenile lingcod over sand bottom (based on swath width, fish is about 20 cm). Data collected by laser line scanning allows for sediment and biological characterization of the seafloor.

[1]Data collection, raw data, and processed data examples and images provided by SAIC or NOAA (http://www.oar.noaa.gov/spotlite/archive/spot_laser.html).

Figure 2-17. Summary view of laser line scan imaging survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
GRAB SAMPLING	Benthic and Sediment Samples	Point Data	m	m	cm	Sediment Sample Used for benthic characterization Can be used for physical, chemical or biological testing Discrete sampling technique Variable complexity and cost for acquisition and lab analyses

Data Collection[1]	Raw Data[1]	Processed Data[1]
 Deployment of the Young-modified Van Veen Grab sampler 	 Grab samples   Seiving a grab sample  Subsampling a composite grab sample for chemical analysis	 Images of the sediment acquired within the individual grab samples relative to the sampling locations within CAD cell M19 at Boston Harbor..  Infaunal successional pattern underlying the 1997–2001 differences in benthic community structure seen in grab samples collected over the Seawolf Mound at the New London Disposal Site (2001).

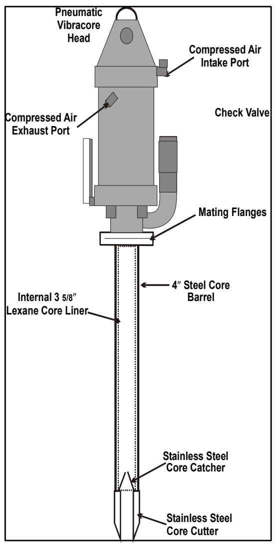
[1]Data collection, raw data, and processed data examples and images provided by SAIC.

Figure 2-18. Summary view of grab sampling survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
SEDIMENT CORING	Sediment Samples	Point Data	m	m	cm	Sediment Sample Used to provide a deeper vertical cross-section to describe sediment horizons Can be used for physical, chemical or biological testing Time consuming, discrete sampling technique Variable complexity and high cost for acquisition and lab analysis (chemical)

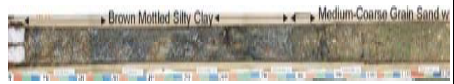
Data Collection[1]

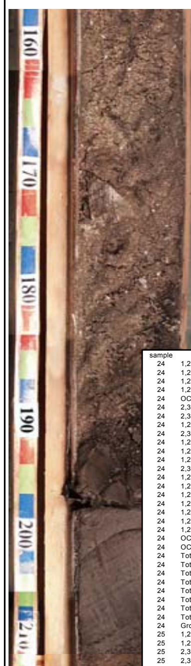
Shallow-water vibra-coring operations



Vibra-core Diagram

Raw Data[1]





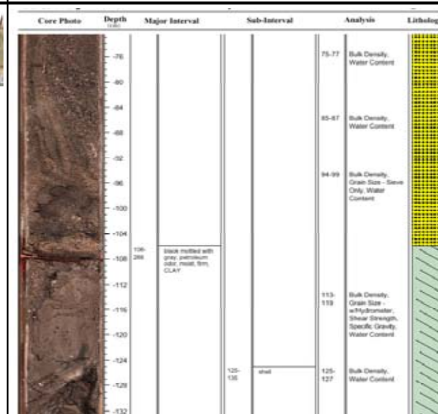
Composite images showing split cores with varying sediment type.

Core chemistry sub-sample values

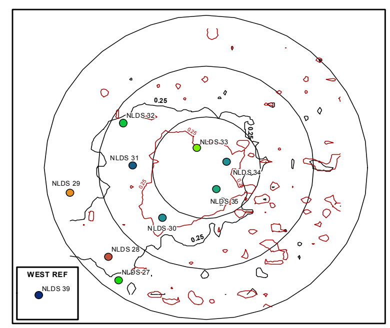
sample	Compound Name	Concentration	LOD	Units	% Recovery
24	1,2,3,4-TCDD-13C	140	0	ng/Kg	77
24	1,2,3,7,8,9-HxCDD-13C	130	0	ng/Kg	70
24	1,2,3,4,7,8,9-HpCDF-13C	120	0	ng/Kg	66
24	1,2,3,4,6,7,8-HpCDD-13C	130	0	ng/Kg	69
24	OCDD-13C	210	0	ng/Kg	59
24	2,3,7,8-TCDF	ND	0.18	ng/Kg	
24	2,3,7,8-TCDD	ND	0.18	ng/Kg	
24	1,2,3,7,8-PeCDF	ND	0.91	ng/Kg	
24	2,3,4,7,8-PeCDF	ND	0.91	ng/Kg	
24	1,2,3,7,8-PeCDD	ND	0.91	ng/Kg	
24	1,2,3,4,7,8-HxCDF	ND	0.91	ng/Kg	
24	1,2,3,6,7,8-HxCDF	ND	0.91	ng/Kg	
24	2,3,4,6,7,8-HxCDF	ND	0.91	ng/Kg	
24	1,2,3,7,8,9-HxCDF	ND	0.91	ng/Kg	
24	1,2,3,4,7,8-HxCDD	ND	0.91	ng/Kg	
24	1,2,3,6,7,8-HxCDD	ND	0.91	ng/Kg	
24	1,2,3,7,8,9-HxCDD	ND	0.91	ng/Kg	
24	1,2,3,4,6,7,8-HpCDF	ND	0.91	ng/Kg	
24	1,2,3,4,7,8,9-HpCDF	ND	0.91	ng/Kg	
24	1,2,3,4,6,7,8-HpCDD	ND	0.91	ng/Kg	
24	OCDF	ND	1.8	ng/Kg	
24	OCDD	ND	1.8	ng/Kg	
24	Total TCDF	ND	0.18	ng/Kg	
24	Total TCDD	ND	0.18	ng/Kg	
24	Total PeCDF	ND	0.91	ng/Kg	
24	Total PeCDD	ND	0.91	ng/Kg	
24	Total HxCDF	ND	0.91	ng/Kg	
24	Total HxCDD	ND	0.91	ng/Kg	
24	Total HpCDF	ND	0.91	ng/Kg	
24	Total HpCDD	ND	0.91	ng/Kg	
24	Group 1 PeCDF	ND	0	ng/Kg	
25	1,2,3,4-TCDD-13C	2.2	0	ng/S	109
25	1,2,3,7,8,9-HxCDD-13C	1.6	0	ng/S	80
25	2,3,7,8-TCDD-37Cl4	0.19	0	ng/S	97
25	2,3,7,8-TCDF-13C	1.5	0	ng/S	74
25	2,3,7,8-TCDD-13C	1.5	0	ng/S	75
25	1,2,3,7,8-PeCDF-13C	1.7	0	ng/S	83
25	2,3,4,7,8-PeCDF-13C	1.6	0	ng/S	82
25	1,2,3,7,8-PeCDD-13C	1.7	0	ng/S	85
25	1,2,3,4,7,8-HxCDF-13C	2	0	ng/S	99

Sediment cores are usually visually described and photographed before being sampled for grain size and chemical analysis.

Processed Data[1]



LogPlot exerpt showing composite core photograph, depth in core, core description, sub-intervals, sample analysis completed, and graphic of general lithology.

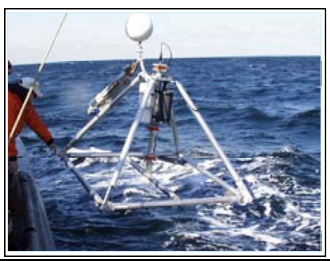
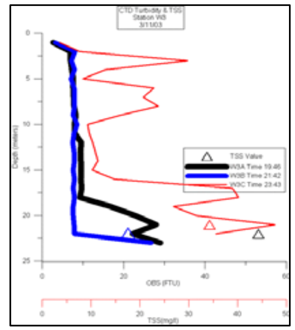
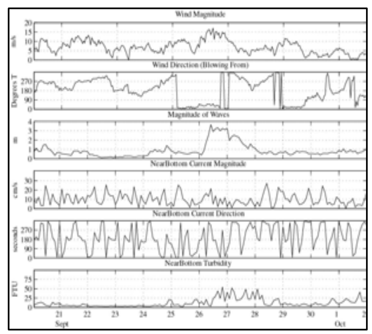
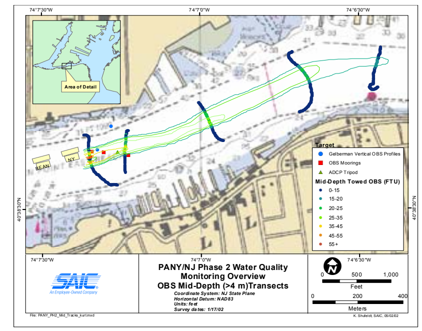
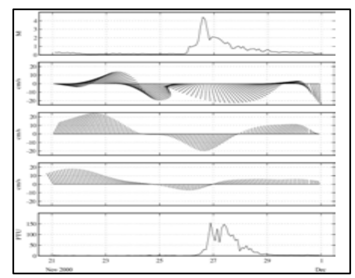


Total PAH concentrations found in the upper 50-cm composite samples of the 2001 NLDS Seawolf Disposal Mound short cores and WESTREF.

[1]Data collection, raw data, and processed data examples and images provided by SAIC.

Figure 2-19. Summary view of sediment coring survey technique

Technique	Application	Data Coverage	Resolution Vertical	Resolution Horizontal	Resolution Image	Key Points
WATER COLUMN SAMPLING	Water quality monitoring, speed of sound, tidal height	Point data, time-series data	cm - m	m	N/A	Speed of sound and tidal height measurements are critical for acoustic bathymetric survey Many water column parameters (salinity, DO, temperature, etc.) may be useful for benthic characterization Vertical profiling instruments measure continuously throughout the water column Discrete sampling to collect water from certain depths for subsequent physical and chemical analysis Moored instrument arrays are deployed to acquire long-term time-series data on specific parameters

Data Collection[1]	Raw Data[1]	Processed Data[1]
 Combined water sampling and CTD profiling with a large rosette sampler Water sampling and CTD profiling on small wire  Deploying ADCP and wave/tide gauge mooring with acoustic release 	Vertical profile plot correlating CTD data (turbidity, density, etc.) with discrete water sample TSS results   Oceanographic mooring time-series data on waves, currents (magnitude and direction), and turbidity	 Depiction of dredging-related turbidity plume as defined by towed and moored sensor data, as well as discrete water sampling data  Time-series depiction of wave height, averaged water-column currents (cm/s), and near-bottom turbidity (FTUs)

[1]Data collection, raw data, and processed data examples and images provided by SAIC.

Figure 2-20. Summary view of water-column sampling survey technique

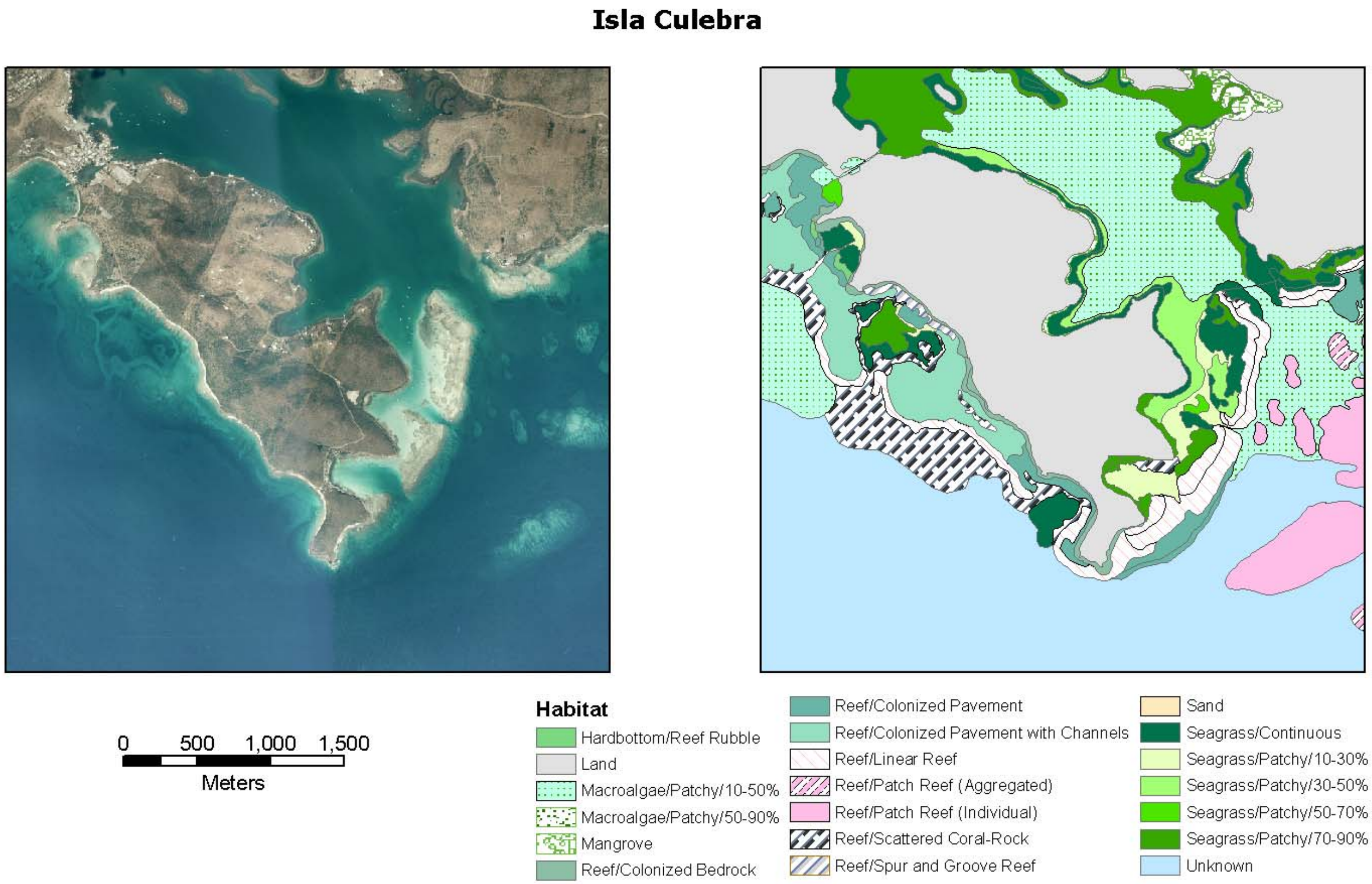


Figure 3-1. Aerial photography over Culebra Island, Puerto Rico was used to generate detailed physical seafloor characterization over a large and diverse nearshore area. The photography was used to clearly differentiate between the numerous types color reef types and also to provide an estimate on the extent of the seagrass cover. To derive a similar interpretive map from boat-based acoustic or optical survey techniques would be a far more labor intensive effort and would likely be less accurate.

Data Source: NOAA/NOS Biogeography Program, http://biogeo.nos.noaa.gov/projects/

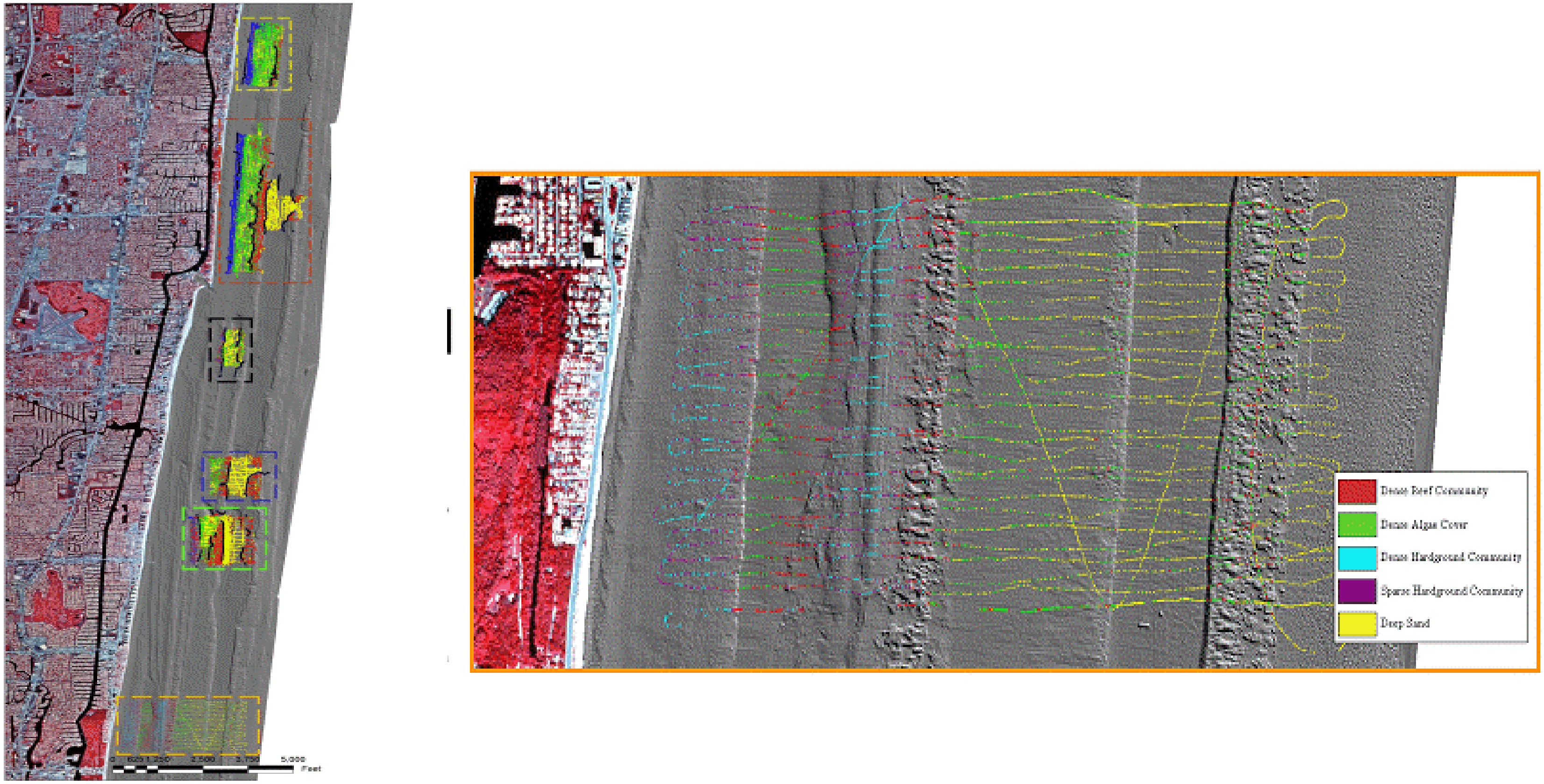


Figure 3-2. A combination of airborne hydrographic LIDAR data (LADS) and boat-based acoustic bottom classification data was used to provide high-resolution physical seafloor characterization of numerous potential sand borrow areas off of the Broward County coastline in southern FL. The LIDAR data was used to generate the high-resolution hill-shade relief model for the broad survey area that clearly delineated distinct areas of seafloor relief. The acoustic bottom classification data was then used in conjunction with ground-truth sampling data to clearly categorize the different benthic habitat areas as high diversity reef, low diversity reef, rubble, or sand.

Source: "Coral Reef Habitat Mapping in Broward County, Florida", Bernhard Riegl, Ryan Moyer, Brian Walker, Richard Dodge. National Coral Reef Institute , Dania Beach, FL.

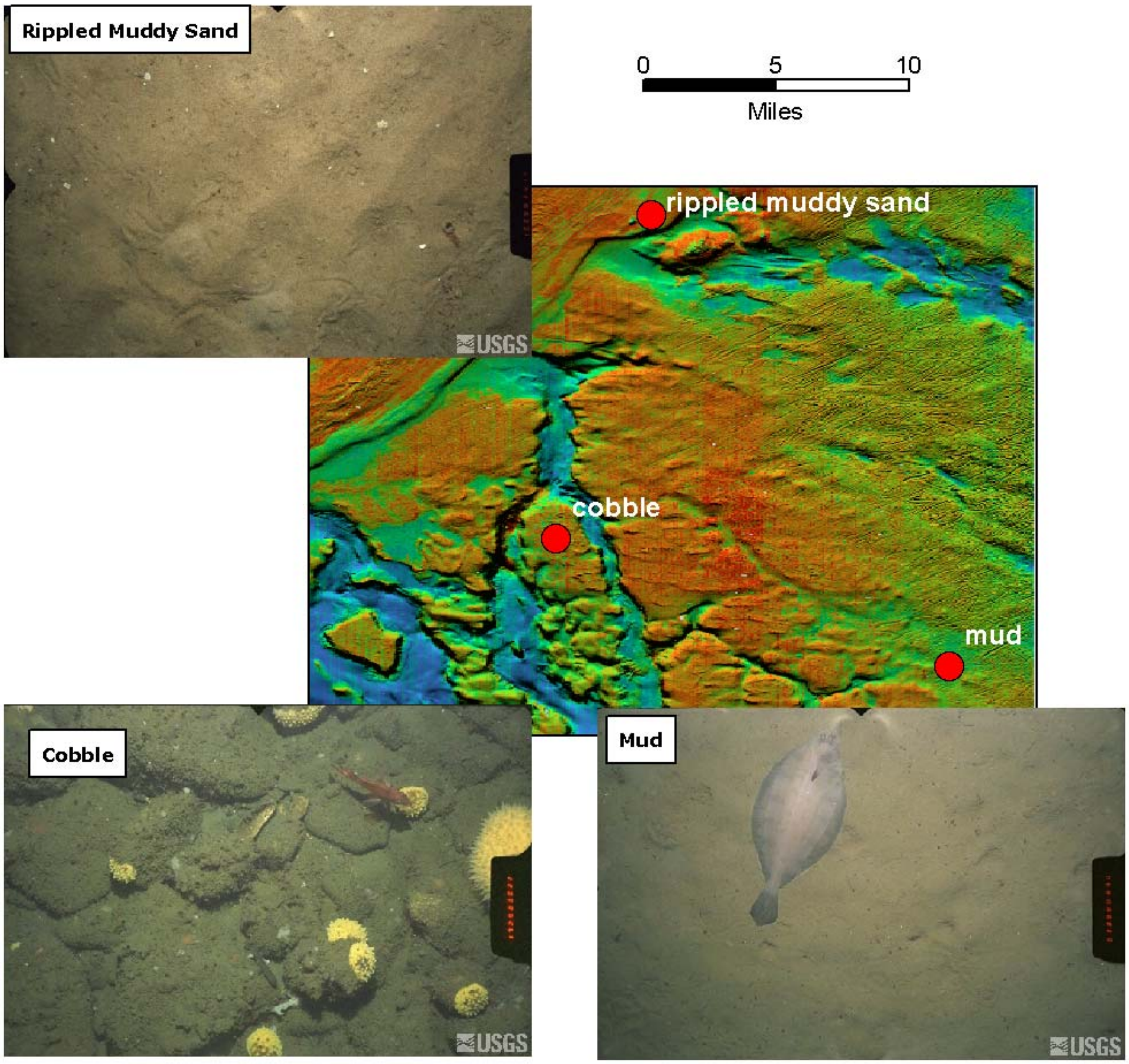


Figure 3-3. An example of fine-scale optical data acquired over several different seafloor types in the Massachussets Bay Disposal Site. The underlying high-resolution multibeam backscatter data clearly differentiates areas of the seafloor based on the intensity of the backscatter return. The still images of the seafloor surface can then provide a high-resolution depiction of the physical characteristics of the seafloor within each of the unique backscatter areas. The relationship between the broad-scale acoustic backscatter data and the fine-scale optical data can then be used to characterize the rest of the survey area. The usefulness of the optical data is very dependent on water clarity.

Data Source: USGS Woods Hole Field Center, http://woodshole.er.usgs.gov/project-pages/stellwagen/

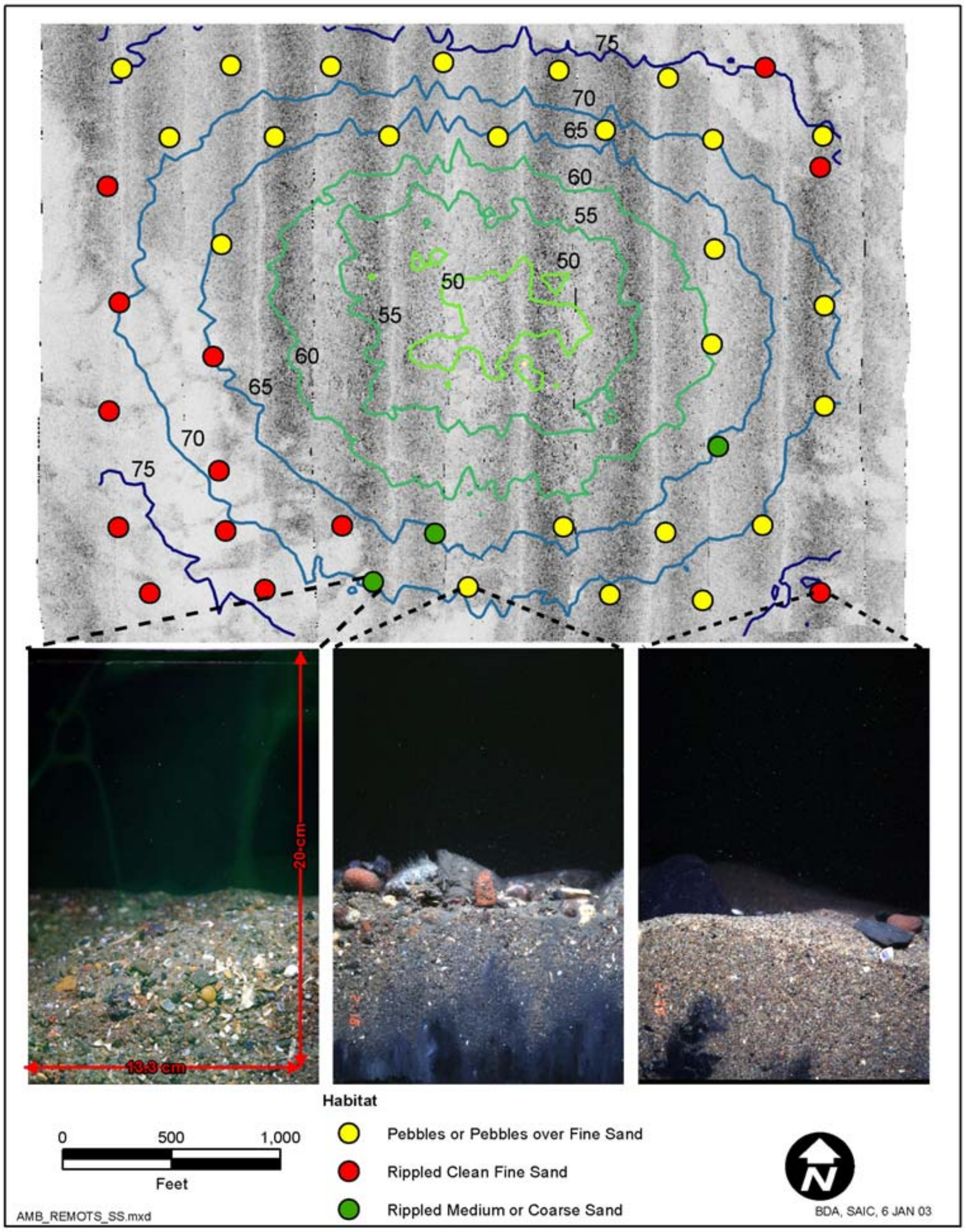


Figure 3-4. A side-scan sonar mosaic and sediment profile imaging characterization of the Ambrose Shoal. These data were part of a full physical and biological characterization of this prominent shoal area near the New York Harbor entrance channel that was a permit requirement prior to dredging operations to reduce the extent of the shoal. The primary objectives of this multidisciplinary survey were to assess the potential environmental impacts that the dredging would have on the local marine community. The initial phase entailed bathymetric, side-scan sonar, and sub-bottom operations that provided the initial broad-scale characterization of the site. These data were used to establish the fine-scale sampling plan for the subsequent sediment profile imaging and ROV video operations. These fine-scale data were used to ground-truth the broad-scale physical interpretation and to assess the benthic and biological communities.

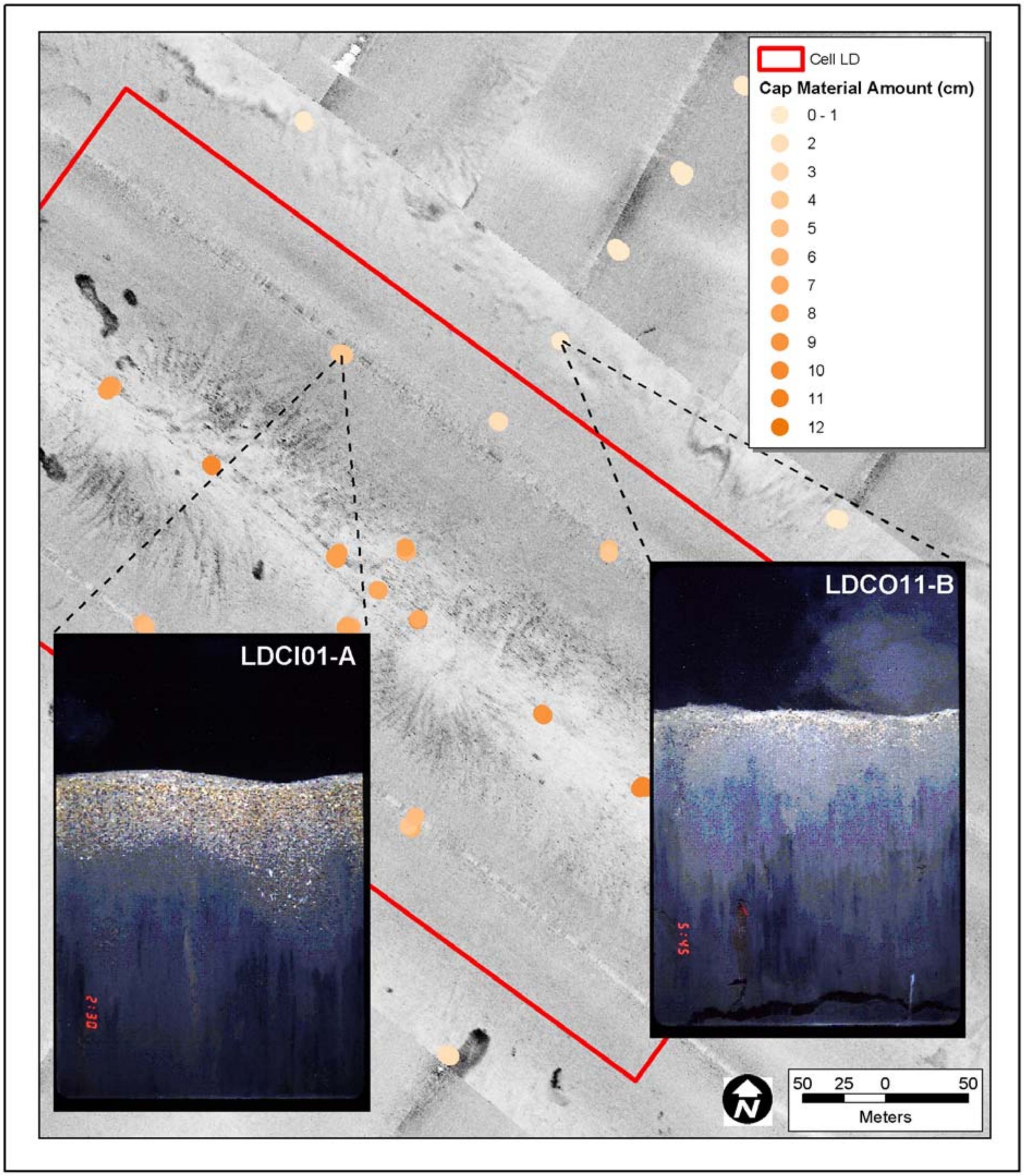


Figure 3-5. PV Side-scan sonar mosaic and representative sediment profile images within Disposal Cell LD off of the Palos Verde Shelf. These data were acquired during a demonstration capping project that used a low impact spreading technique to place the cap material from a hopper dredge onto the seafloor. Because the seafloor surface disturbance was minimized with this technique, the presence of cap material could not be reliably detected with the side-scan sonar imagery. As shown in the two nearby sediment profile images, the thin layer of medium sand cap material was quite different than the ambient fine-grained silty sand.

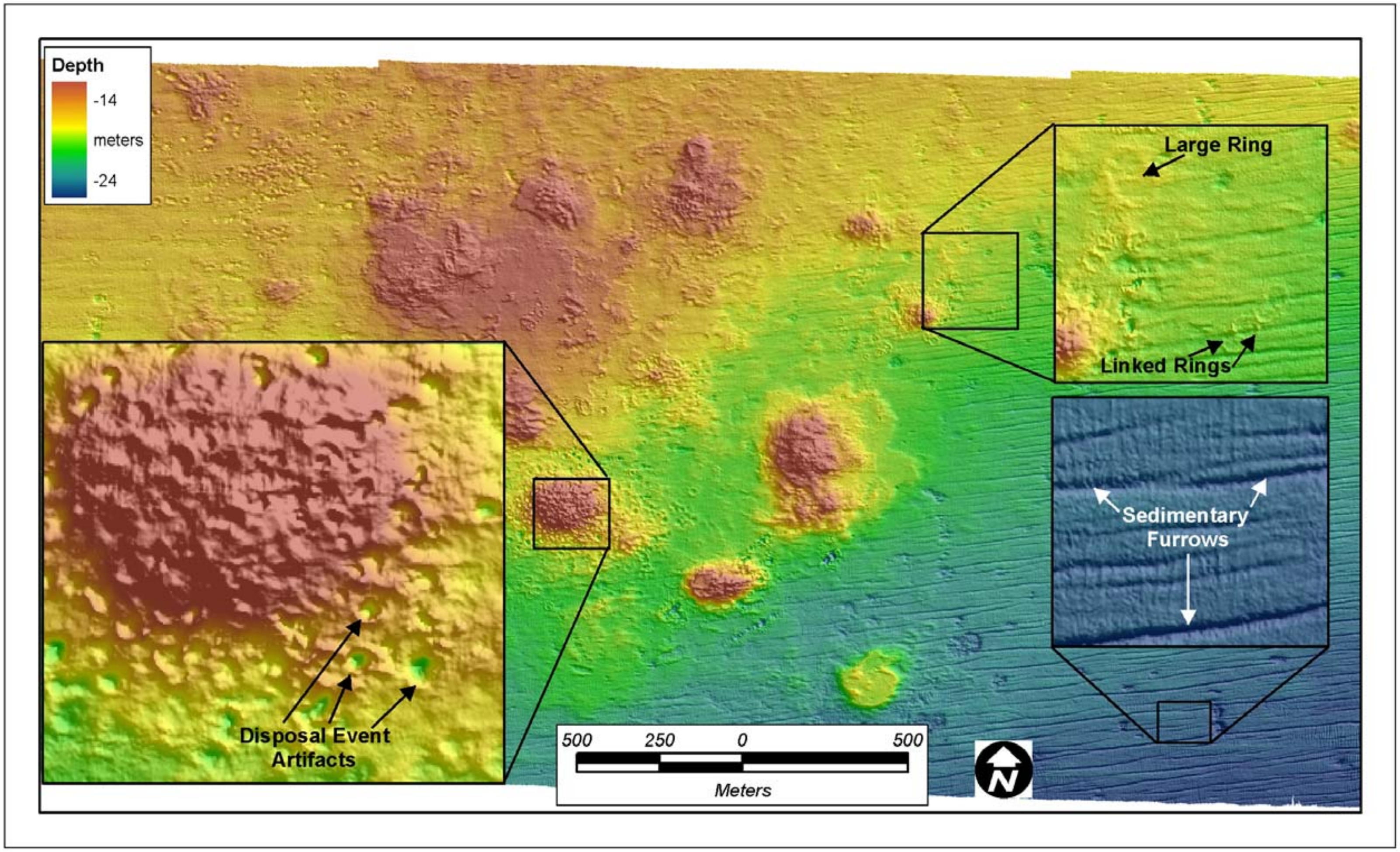


Figure 3-6. A color, hill-shaded model view of a high-resolution multibeam data set acquired in the vicinity of the Central Long Island Sound Dredged Material Disposal Site (CLIS). Applying hill shade and color to this 1m x 1m dataset highlights numerous small-scale vertical relief features, including circular, individual placement event artifacts (vertical relief of 10 to 20 cm) clustered around the disposal mound areas, as well as naturally occurring sedimentary furrows (vertical relief 20 to 40 cm) that occur in the deeper depths to the southeast. Even in this relatively benign soft-bottom habitat, the multibeam data are able to detect subtle bathymetric change that may be important to the benthic habitat characterization.

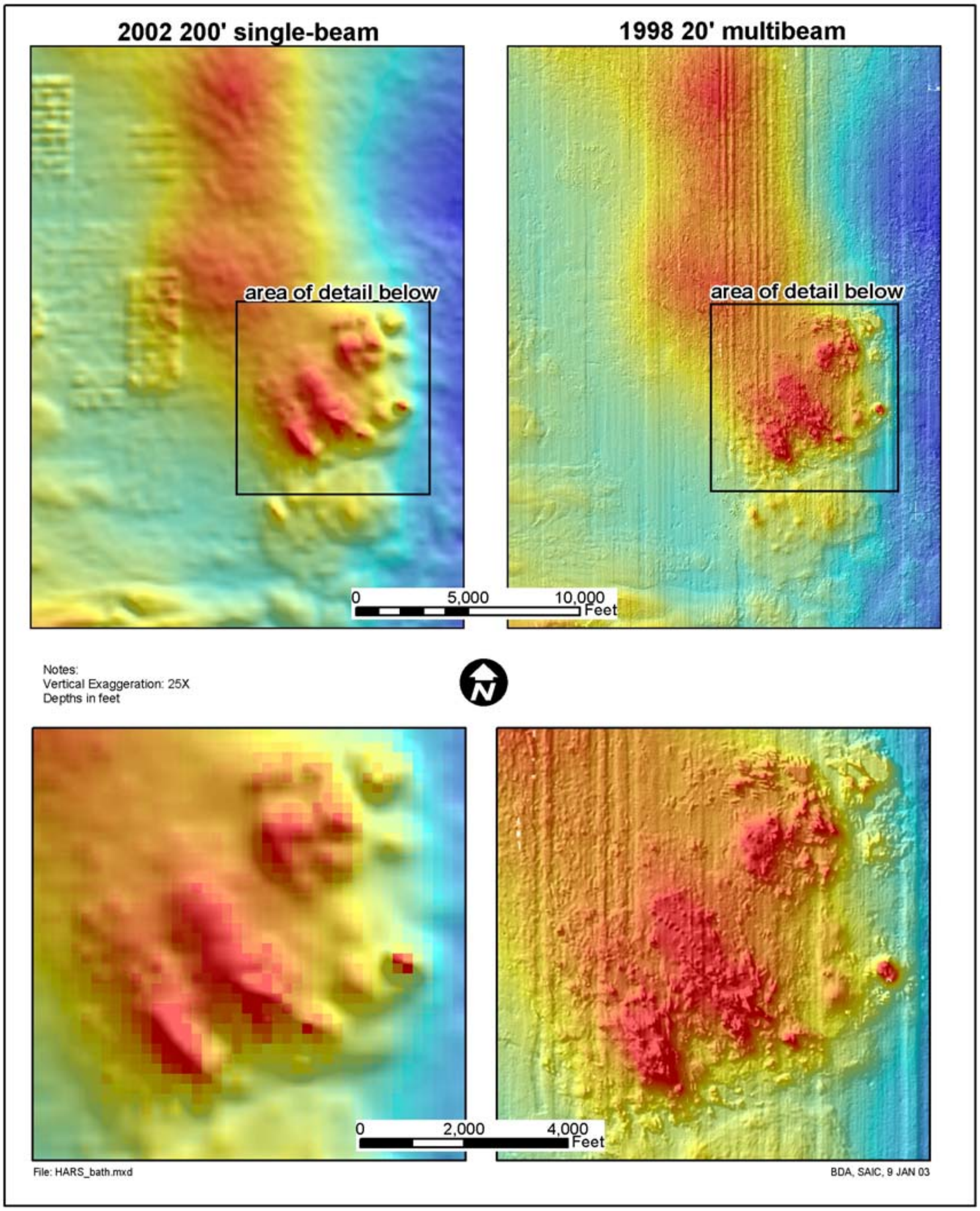


Figure 3-7. Color, hill-shaded model views of both a 2002 single-beam bathymetric dataset and a 1998 multibeam bathymetric dataset over a dredged material disposal site in the New York Bight (Historic Area Remediation Site). The significant volumes of dredged material that have been placed at the site between these two surveys is clearly evident in the northwest quadrant of the 2002 survey. These data also show that single-beam bathymetry can be used to generate model views that are similar to multibeam bathymetry, particularly at smaller scales. At a larger-scale view, the differences in the lower resolution single-beam model are more apparent.

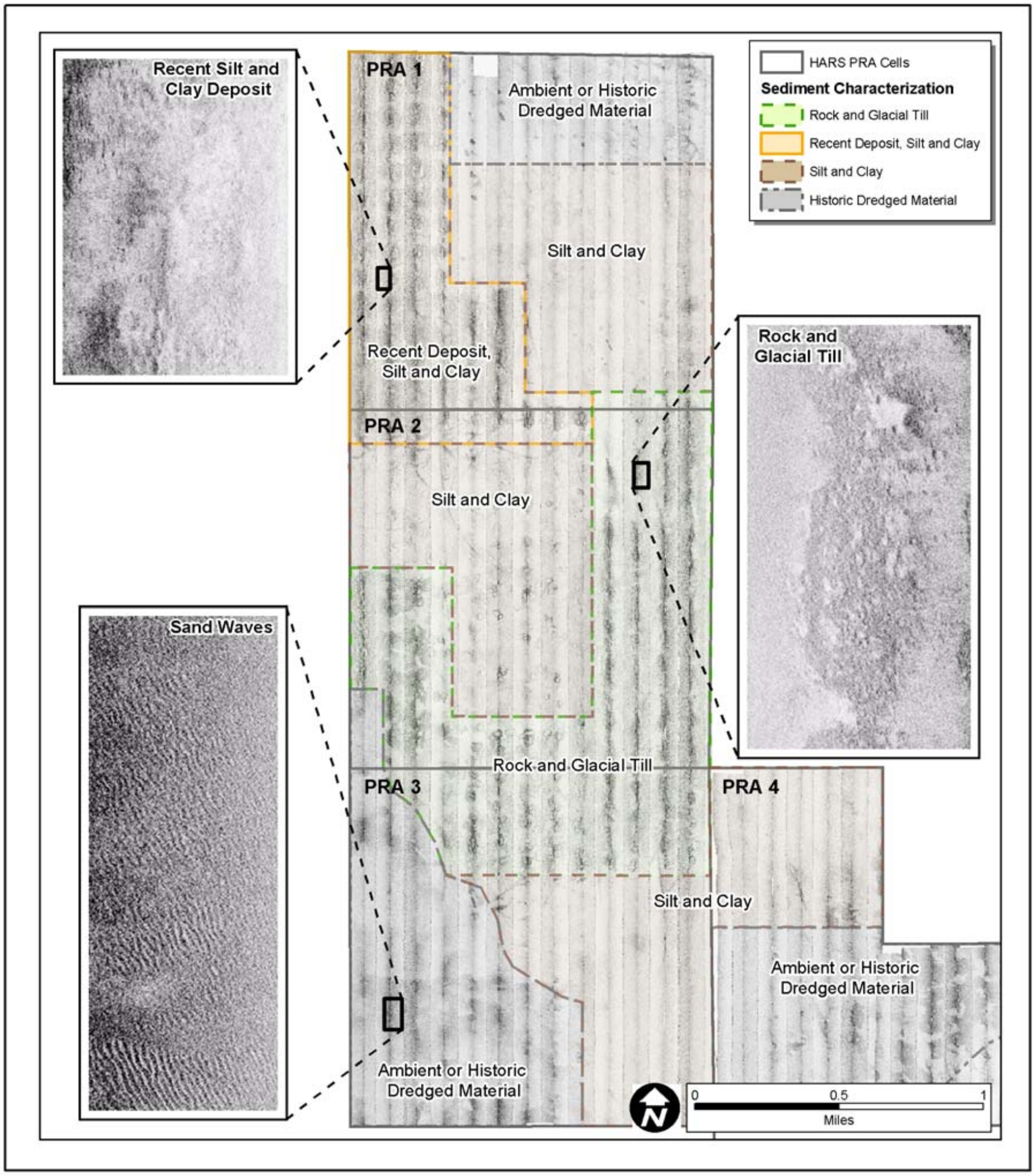


Figure 3-8. Imagery mosaic within the eastern portion of the Historic Area Remediation Site (HARS) generated from 100-kHz side-scan sonar data. The original 14 lanes of raw side-scan sonar imagery represented almost 1.5 gigabytes of digital data and the resulting georeferenced TIFF mosaic file was 54 megabytes. The resulting mosaic was useful for detecting broad-scale seafloor differences and it correlated well with the known composition of the seafloor based on detailed dredged material disposal records maintained for this site. However, various smaller-scale features that were evident in the raw imagery data were smoothed over during the mosaic creation. Many of these smaller scale features will likely be important for characterizing smaller scale benthic habitats.

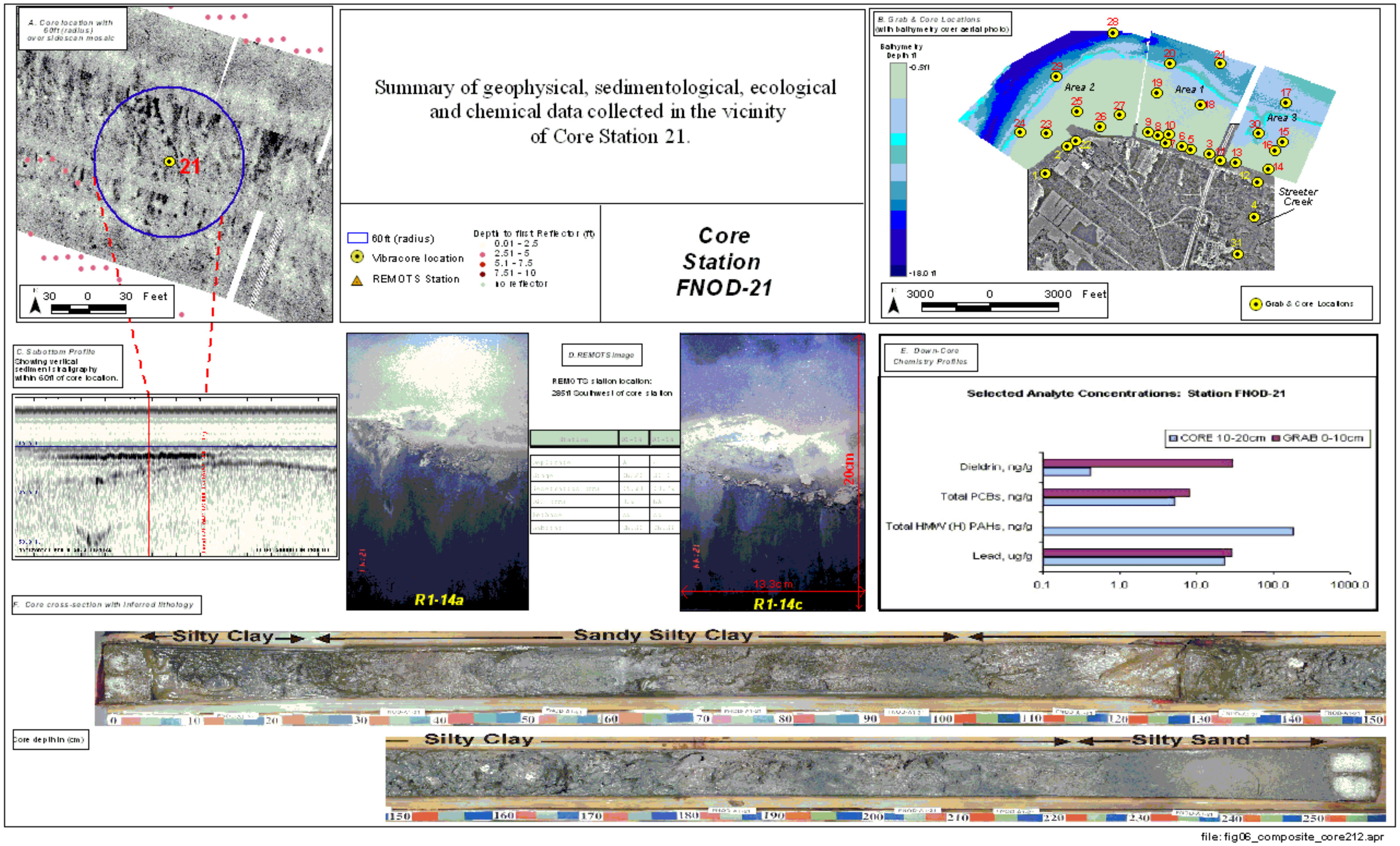


Figure 3-9. A composite GIS depiction of numerous physical, biological, and chemical characterization data that were acquired in the nearshore areas of the U.S. Navy's Formerly-used Nansemond Ordnance Depot (FNOD) on the James River near Norfolk, VA. In this figure, a single sediment core and its accompanying chemical analyses results have been shown with the co-located bathymetric, aerial photograph, side-scan sonar, sub-bottom profile, magnetic anomaly profile, and sediment profile image data from the same location in the basin. The consistent use of an accurate time and position basis during all broad-scale surveying and discrete fine-scale sampling operations is critical to enable this type of multi-sensor integration.