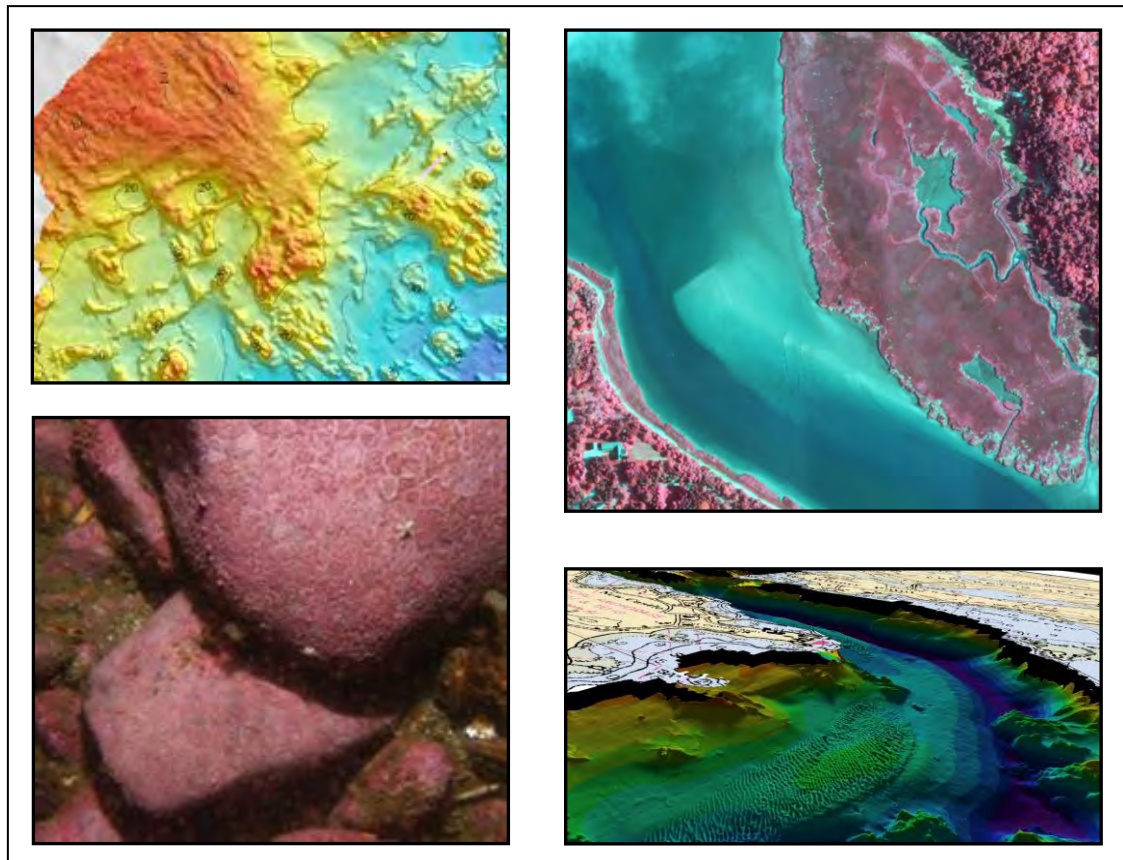




Survey Methods for Shallow Water Habitat Mapping in Northeast National Parks, Wildlife Refuges, and Estuarine Research Reserves

Workshop Proceedings

Natural Resource Technical Report NPS/NER/NRTR—2010/145



ON THE COVER

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Survey Methods for Shallow Water Habitat Mapping in Northeast National Parks, Wildlife Refuges, and Estuarine Research Reserves

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Natural Resource Technical Report NPS/NER/NRTR—2010/145

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January 2010

U.S. Department of the Interior
National Park Service
Northeast Region
Philadelphia, Pennsylvania

The Northeast Region of the National Park Service (NPS) comprises national parks and related areas in 13 New England and Mid-Atlantic states. The diversity of parks and their resources are reflected in their designations as national parks, seashores, historic sites, recreation areas, military parks, memorials, and rivers and trails. Biological, physical, and social science research results, natural resource inventory and monitoring data, scientific literature reviews, bibliographies, and proceedings of technical workshops and conferences related to these park units are disseminated through the NPS/NER Technical Report and Natural Resources Report series.

Natural Resources Reports are the designated medium for information on technologies and resource management methods; "how to" resource management papers; proceedings of resource management workshops or conferences; and natural resource program descriptions and resource action plans.

Technical Reports are the designated medium for initially disseminating data and results of biological, physical, and social science research that addresses natural resource management issues; natural resource inventories and monitoring activities; scientific literature reviews; bibliographies; and peer-reviewed proceedings of technical workshops, conferences, or symposia.

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Survey Methods for Shallow Water Habitat Mapping in Northeast National Parks, Wildlife Refuges, & Estuarine Research Reserves

WORKSHOP PROCEEDINGS

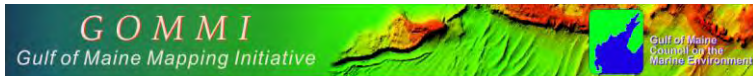
September 30, 2009
Durham, New Hampshire

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This publication and corresponding workshop were made possible through support and funding contributions from the National Park Service (NPS) [North Atlantic Coast Cooperative Ecosystem Studies Unit](#) (CESU)

Coordinator:

The workshop and proceedings were produced by the [Gulf of Maine Mapping Initiative](#) (GOMMI). Established in 2001, GOMMI is a subcommittee of the Gulf of Maine Council on the Marine Environment, and a voluntary partnership of U.S. federal and state agencies, Canadian government agencies, and academic institutions working together to accelerate the availability and use of seafloor mapping products for Gulf of Maine ocean management. The [Gulf of Maine Council on the Marine Environment](#) was established in 1989 by the Governments of Nova Scotia, New Brunswick, Maine, New Hampshire, and Massachusetts to foster cooperative actions within the Gulf watershed. The Council's mission is to maintain and enhance environmental quality in the Gulf of Maine to allow for sustainable resource use by existing and future generations.



Host: The University of New Hampshire [Center for Coastal and Ocean Mapping- Joint Hydrographic Center](#), Durham, NH, generously hosted this workshop and provided coordination support

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Introduction

On September 30, 2009, thirty-six participants convened at the University of New Hampshire Center for Coastal and Ocean Mapping (UNH CCOM) for a workshop focusing on *Survey Methods for Shallow Water Habitat Mapping In Northeast National Parks, Wildlife Refuges & National Estuarine Research Reserve*. The aim of this workshop was to provide federal natural resource managers with an opportunity for collaborative training on methods to increase understanding of nearshore natural and cultural resources in the Northeast region. The focus of the workshop was related to a primary data need to develop seamless geologic framework and habitat maps extending from land and offshore extents of Park, Refuge, and Reserve holdings in this region. A series of prior multi-agency efforts (see Section III) have identified the need for benthic nearshore data as a top priority need.

The specific objectives of the workshop were to provide regional scientists and managers from the National Park Service (NPS), U.S. Fish and Wildlife Service (USFWS), and National Estuarine Research Reserve (NERRS) with:

- An overview of shallow water habitat mapping techniques, including their capabilities, limitations, and costs specific to the environmental conditions represented in this region;
- An opportunity to assess the regional resource management, monitoring, research, outreach, and education applications of shallow water benthic data;
- A technical foundation enabling informed interactions with collaborators; and
- An opportunity to interact with technical experts and initiate agency and multi-agency collaboration

The event was supported by the National Park Service North Atlantic Coast Cooperative Ecosystem Studies Unit (CESU) and coordinated by the Gulf of Maine Mapping Initiative (GOMMI), in cooperation with a multi-agency steering committee. UNH CCOM hosted the workshop and coordinated additional learning opportunities including a tour of the Center's [visualization lab](#)¹ and a [GeoWall](#) demonstration.

Workshop presentations were divided into two sections (See Agenda, Appendix A). Park, Reserve, and Refuge representatives provided an initial overview of the needs, objectives, capacity and specific challenges for shallow water mapping within the Northeast (Section II and III). These presentations provided context for a set of technical presentations on the capabilities, advantages, and disadvantages of the suite of technologies available for shallow water seabed mapping. Speakers from the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), academia (UNH CCOM, Coastal Carolina University, the University of Rhode Island, and Rutgers University), NPS, and NERRS used case-study examples to review the latest techniques for mapping shallow subtidal areas just beyond mean low water to 10 meter depths. These presentations outlined the cost-effectiveness of various technologies and their suitability for use in conditions and water depths specific to this region.

¹ See also http://www.ccom.unh.edu/index.php?page=research/data_visualization.php

Presentations were followed by a discussion focusing on the agencies' potential next steps to address benthic mapping priorities.

The following is a summary of information conveyed during this workshop. These proceedings outline:

- the need for shallow water mapping (Section II);
- the specific shallow water inventory and mapping interests of the Parks, Refuges, and Reserves in this region (Section II & III);
- a comparative review of the technologies (Section IV);
- recommendations (Section V);
- additional resources including speaker abstracts, a sampling of presentations, references, and a list of participants (Appendices).

Need for Shallow Water Seafloor Mapping

The thin edge where land meets sea is rich in natural resources and supports critical habitats, but also attracts disproportionately high human use. The valuable but vulnerable nature of these nearshore marine and estuarine areas makes them an important focus of pressing resource management issues. Shallow water mapping data are sought to inform a wide range of modern-day decisions related to beach erosion and nourishment, alternative energy development, sustainable shellfish industries, storm impacts and recovery, resource protection, sea-level rise, and mitigation of coastal hazards, to name a few.

Large portions of the coastal protected areas in the Northeast region (i.e. Parks, Refuges, and Reserves) consist of ocean and estuarine shorelines and submerged lands. For example, each coastal National Park in this region includes between 64 and 262 miles of shoreline and/or submerged habitat, totaling between 51% and 75% of the total park area. The prominence of nearshore resources within Northeast federal holdings highlights the need for improved understanding of these areas in order to address overarching regional resource planning and management objectives.

Despite the extent and importance of shallow water habitats within Northeast Parks, Reserves, and Refuges, these areas remain poorly inventoried and mapped. While geophysical and habitat mapping are an integral part of the resource management framework for terrestrial portions of these natural areas, comparatively little mapping has been completed of the submerged lands within their boundaries. Extensive mapping products often exist for terrestrial areas, including elevation, topography, soils, geology, water table, vegetation, land use, rare species, non-native species, and breeding area maps. In the nearshore realm, seagrass bed data and some shoreline change data exists, but very little mapping and characterization has been completed within other

habitats. There is an overall paucity of current shallow water bathymetry, substrate type, geology and habitat mapping data. Data for very shallow water areas (less than 10 m) are largely lacking.

The primary reason for the scarcity of nearshore data is that these areas are inherently difficult to map. Shallow waters pose unique challenges for mapping due to variable currents, turbidity, challenging wave conditions, large temperature and salinity fluctuations (which can affect sensors and readings), limited clearance for mapping vessels, and navigational hazards that may limit vessel access or operation.

Additionally, seafloor mapping in shallow areas can be an expensive endeavor. Shallow water depths pose limitations on the survey capabilities and efficiencies of a number of technologies. Acoustic mapping in shallow areas, for example, is more costly due to the effect of shallow depths on the swath widths of acoustic instruments. The closer the sensor is to the seafloor, the narrower the swath width, requiring more tracklines, greater cost, and more time to achieve required coverage.

Fiscal and logistical challenges exist, but there is growing recognition nationally and regionally that a lack of high resolution seabed maps compromises our ability to effectively manage a variety of key issues in the marine and coastal realm. A mapping technology review for the California Department of Fish and Game summarizes that, “High use and data scarcities have made the 0-30 meter depth zone a high priority for habitat mapping over the next decade” (p. 5). The same need is highly relevant to the northeastern U.S. coast.

There is interest in expanding inventory and mapping within the ocean and estuarine extents of park, refuge and reserve holdings in the Northeast to enhance our knowledge-base for these areas and to support effective resource planning and management. Seamless elevation, geology, and habitat maps are sought to comprise a basic inventory of submerged marine resources as a complement to data sets that are available for terrestrial areas. The list of data needs is extensive (Table 1), including coastal topography, bathymetry, substrate characterization, sediment contaminants, hydro-geologic framework (shallow stratigraphy, surface and groundwater paths), extent and density of submerged aquatic vegetation, structure of intertidal areas, and mapping and characterization of specific submerged habitats (including shellfish beds, macroalgae, sand and cobble, mud/anoxic sediments, etc.). The management applications identified for these data are equally diverse. Workshop participants defined wide-ranging applications for high-resolution seabed and coastal maps to support the efforts of Northeast Parks, Refuges, and Reserves (Table 1).

Table 1. Data needs and applications for shallow water inventory and mapping. Information presented in this table was derived from presentations and discussion during the workshop.

DATA THEME	MANAGEMENT AND RESEARCH APPLICATIONS
GEOPHYSICAL	
Bathymetry	• Dredge planning and management • Facilities design and placement • Identify threats (e.g., prop scars, trawl scars) • Support of hydrodynamic and sediment models
Basic Hydrography (e.g., wave climate, tide, currents)	• Assist with oil/contaminant spill response • Facilities design and placement • Dredge planning and management • Habitat characterization, restoration planning • Support of hydrodynamic and sediment models
Substrate (e.g., grain size, surficial geology, organic content, contaminants)	• Dredge planning and management • Facilities design and placement • Evaluate vulnerability to contaminants • Assist with oil/contaminant spill response • Habitat characterization, restoration planning • Support sediment transport models
Sub-bottom Geology or Hydro-geologic Framework	• Evaluate groundwater discharge to coastal zone • Quantify reservoirs of sand for beach nourishment or natural transport processes
WATER CHEMISTRY (e.g., temperature, salinity, pathogens, nutrients)	• Habitat characterization and understanding species occurrences • Documenting freshwater inputs and nutrient loading • Assessing environmental quality
BIOLOGICAL HABITATS	• Natural resource damage assessment baseline • Evaluate coastal development proposals • Identify critical fish spawning areas • Identify shellfish beds of recreational and commercial importance • Habitat characterization and restoration planning • Identify resource threats (e.g., invasive species, macroalgal blooms) • Evaluate responses to climate change variables

Shallow Water Inventory and Mapping: An Interagency Collaborative Need

Several efforts served as precursors and impetus for this workshop and the inter-agency collaboration that it represents:

- ❖ A national-level agreement was signed in August 2006 by NPS, USFWS, NERRS, and NOAA National Marine Sanctuary (NMS) Program to establish a seamless network of ocean parks, refuges, and sanctuaries and increase interagency collaboration and interaction. Known as the “Seamless Network Agreement,” this MOU outlined a shared common goal to conserve sensitive coastal and marine resources and ecosystems through greater sharing of knowledge and expertise among the agencies ([NOS Agreement Code: MOA-2006-036/7196](#)). The agreement’s implementation plan specifically highlights the need for boundary mapping, marine habitat mapping, and marine resource characterization;
- ❖ In response to this MOU, a series of seamless network workshops were convened, including: (1) a Gulf of Maine workshop hosted by the Wells NERR at the Rachel Carson NWR in March 2008; and (2) a workshop focused on the New York-New Jersey Bight hosted by the Jacques Cousteau NERR and Rutgers University in May 2008. The goal of these workshops was to improve ocean stewardship through a seamless network of enhanced regional collaboration among the agencies. Workshop participants representing the NPS, USFWS, and NERRS Northeast offices and NOAA-NMS identified common resource management issues among Northeast protected areas and opportunities for cooperation in meeting research, monitoring, and outreach needs. The need for benthic mapping was identified consistently as a high priority need;
- ❖ In June 2007, the NPS-Northeast region developed a regional marine conservation strategy as part of the NPS ocean stewardship initiative, which was launched in response to the 2004 President’s U.S. Ocean Action Plan. The strategy document [Conserving Ocean and Marine Resources: Northeast Region Ocean Park Strategic Plan](#) points to enhanced regional interagency collaboration in mapping protected coastal habitats.
- ❖ The [Ocean and Coastal Activities Implementation Plan: From Continental Divide to Continental Shelf \(FY 2009-2011\)](#) was outlined by the Department of the Interior (DOI) Senior Ocean Policy Team in 2008. This document provides the framework for DOI agencies to “work collaboratively among its bureaus in a concerted effort to develop policies and coordinate ocean, coastal, and Great Lakes efforts and activities.”

Together, these efforts and others provide the framework for greater inter-agency collaboration on the exploration and protection of coastal habitats. Additionally, these efforts define a common interest in greater knowledge about the submerged resources in the Northeast region.

The NPS North Atlantic Coast Cooperative Ecosystem Studies Unit invited USFWS and NOAA NERRS representatives to participate in this workshop in the spirit of collaboration defined by these prior efforts and in an effort to advance the seamless network concept. Agency representatives on the workshop steering committee identified a number of common interests and objectives that would be served by this workshop:

- Knowledge of Techniques--enhance understanding of methods/techniques for shallow water inventorying and mapping;
- Agency Collaboration--facilitate collaboration among land management entities and technical experts in the Northeast;
- Resource Conservation & Protection--promote landscape-scale conservation initiatives, addressing ecological connectivity between terrestrial and submerged marine landscapes;
- Research--promote the identification of research opportunities to improve our understanding of submerged habitat functions and controlling processes;
- Education--enrich science education, using the appeal and challenges of shallow water mapping to bridge the diverse interests of the student, public, professional, and research communities.

Comparison of Technologies: An Overview

The workshop included technical presentations on shallow water mapping techniques using aerial optical imagery (light detection and ranging systems (LIDAR), aerial and satellite sensors), acoustic instruments (single beam, sidescan, interferometric, and multibeam sonar), automated underwater and surface vehicles (AUV and ASV methods), and ground-truthing methods. Table 2 summarizes the main points discussed and presented on the use of these techniques in shallow depths. The purpose of this workshop report is not to describe each of these methodologies in detail; however, the reader is referred to the presenters' abstracts (Appendix B) and a listing of relevant references and web-links (Appendix D).

The workshop also resulted in the development of a MATRIX that documents the capabilities, advantages, limitations, and other considerations associated with the various shallow water techniques (Appendix E). The matrix represents the workshop organizers' best efforts to: (1) incorporate comments provided by participants during the workshop's final discussion; and (2) summarize the information presented on shallow water seafloor mapping technologies. Although the matrix includes some very limited information from peer reviewed literature, it is primarily a compilation of information presented and discussed during this workshop. The matrix is intended to serve as a tool for the participating agencies, not as a review and summary of scientific literature on these technologies.

Some limitations to the matrix are as follows:

- The matrix does not include any information about accuracy. This information is needed in order to make informed decisions from the mapping data, but is often dependent on the

specific model of the equipment, survey conditions, skill of the crew, etc. The principles for judging the quality of bathymetry data from hydrographic surveys are well developed. Further developments are needed to assess the accuracy of backscatter data, often collected with multibeam sonar. Limited data on accuracy is available for other techniques.

- There is a danger in including a cost per unit area for each technology because a general cost figure does not reflect specific survey factors such as accuracy, resolution, or minimum mapping unit of the data collected.
- Actual cost estimates can become quickly dated. Thus, instead of actual costs, the workshop participants suggested that the matrix present a “restaurant guide” approach in which the number of dollar signs denotes the comparative cost of each technology. The least expensive methods receive a single dollar sign, as do mapping configurations for lower resolutions and accuracies.
- There is a process to choosing mapping technologies that is driven by an assessment of objectives, environmental conditions, available time frame and fiscal resources. This process cannot be captured well in a matrix, although vitally important to mapping design.

Table 2. Primary advantages, capabilities, disadvantages, and limitations of benthic mapping techniques when applied in shallow depths. Information presented in this table was derived from presentations and discussion during the workshop.

Technology & Products	Primary Attributes Identified
LIDAR (coastal topography, sediment volume, shoreline position, land cover, saltmarsh & SAV mapping)	• Good for collecting coastal topography data over large coverage areas. Limited use for bathymetry mapping in the Northeast--algal blooms and turbidity in summer restrict the surveys to months when weather is poor, affecting flights, data quality, costs. • Portable side-looking LIDAR systems provide simultaneous bathymetry and topographic data. Quick, repeatable, and cheaper than airborne LIDAR, but there are vertical datum problems.
Aerial & Satellite Sensors (marsh structure & morphology, seagrass, shellfish beds <2 m., macroalgae, shoreline condition, accretion)	• Both can achieve broad coverage and capture the land/water interface, making them effective for mapping shallow complex landscapes (e.g., channels) that would be difficult to navigate via water-borne instrumentation. • Ineffective in deeper water and usage is limited by turbidity, cloud cover, sea state, sun angle, and tides. Planning can minimize these limitations, but at greater expense.
Acoustic Sonars (all)	• Highly turbid areas can necessitate the use of acoustic vs. aerial/optical approaches. • Shallow acoustic surveys can be long and costly due to slow survey speeds & the limitations imposed on swath width at shallow depths.
Single Beam Sonar (bathymetry, eelgrass mapping)	• Good choice for mapping bathymetry in very shallow water <3m. • For bathymetry mapping at very shallow depths, must consider the effects of crew weight and current on transducer elevation & eelgrass effects on signal return. Corresponding tide monitoring and high vertical accuracy is important. • Can be mounted on jet skis for rapid bathymetry mapping in surf zones.
Sidescan Sonar (backscatter intensity to classify substrate type; oyster bed mapping)	• Primary tool for regional substrate type mapping in shallow water because it has a wider swath than multibeam at shallow depths, and is therefore more time- and cost-efficient.
Interferometric Sonar Systems (bathymetry; seafloor morphology)	• Ability to acquire high quality bathymetry and backscatter image data simultaneously makes it the preferred technology for mapping geologic formations and substrates at shallow depths. • A preferred technique for shallow water bathymetry because swath width is 7-10 times water depth vs. 3-5 times water depth for multibeam. More cost- and time-efficient in depths <30 m. In very shallow water, swath width is equivalent to that of single beam. • Vertical datum problems and refraction artifacts are significant.
Multibeam Echosounders (slope, topography, backscatter)	• Commonly used in shallow waters 10-30 m. Multibeam echosounders are less efficient as the water depth decreases and not widely used at depths less than ~10 m. • Collects bathymetry and backscatter data, but backscatter is lower quality than interferometry & multibeam has limited dynamic range.
Groundtruthing Techniques (sediment grain size, stratigraphy, verifying acoustic data, substrate type, abundance & distribution data, biology)	• Underwater imagery techniques (i.e. sediment profile imagery (SPI) and video technologies) are appropriate for mapping attributes including substrate, rooted vegetation, water column attributes, faunal communities, and population patterns. • Characterizing habitat attributes that are highly dynamic (e.g., biotopes, biological assemblages, drift algae, etc.) requires grab sampling and high sampling effort. SPI cameras can also provide biological information.
AUV/ASV (Products depend on sensors. Possible: bathymetry, backscatter, surficial & subbottom geology, habitat classification, water quality)	• Can be equipped with a variety of sensors (e.g., sidescan, chirp subbottom, single beam, etc.) to collect multiple integrated data streams. Can reach hazardous or difficult areas more easily than manned platforms. • Range may be a limiting factor. Geohazards pose risks to the equipment in areas with high relief bottom if not equipped with an avoidance system. Aquatic vegetation poses entanglement/prop fouling hazards. • The number of sensors moderately influences survey time as function of power draw.
Seismic Reflection/ Subbottom Profiling (surficial sediment thickness, structure, and stratigraphy)	• Effective for evaluating the stratigraphy/structure from shallow waters to offshore. • Stratigraphy is important to visualize the stability of surficial substrates, an especially key consideration in shallow water because of the susceptibility of these areas to storm surge.

Workshop Recommendations and Future Directions

Several recommendations emerged from the workshop discussions that should help guide the design of shallow water inventory and mapping programs for parks, refuges and reserves in the Northeast region, and elsewhere.

Management and Research Objectives Must Drive the Selection of Mapping Technologies

Workshop participants emphasized that any consideration of mapping technologies must be framed within the context of primary management and research objectives. Decisions about which technologies to utilize are driven by the survey objectives, and influenced by mapping depths, environmental conditions (e.g., turbidity), and available financial resources. The process for choosing mapping technologies involves: (1) defining objectives, water depths, area coverages, and data types needed; (2) developing a plan to meet objectives including scale and resolution, survey days, costs, and technology choices; and (3) if the plan exceeds available resources, working to eliminate or reduce sections of the plan until it represents the best approach for meeting mapping objectives within financial constraints. Technology selections are ultimately made by determining which combination of techniques will furnish data that best meets the mapping objectives, within the available budget and time frame, and with acceptable tradeoffs.

In many cases a combination of technologies is necessary to accomplish mapping of sufficient spatial resolution and accuracy to meet the project objectives. A combination of techniques is often an extremely efficient approach. It may be most cost- and time-efficient to achieve all surveying that is needed at the same time. However, there are mobilization costs for each instrument, making it prudent to consider the tradeoffs of using fewer techniques and/or establish collaborative mechanisms to minimize mobilization costs.

Use CMECS to Guide Shallow Water Mapping Program Design

Workshop participants considered the use of CMECS III (NOAA Coastal and Marine Ecological Classification System) as a conceptual framework to guide shallow water mapping project design, including geophysical and biological components. It was suggested that a working group be assembled to: investigate the use of CMECS as a guide in drafting a list of common core data needs for the nearshore realm; identifying technologies to best achieve data priorities; and distinguishing data layers that can be gathered simultaneously to achieve economies of scale. CMECS could be effectively used to define shallow water mapping priorities and tie technologies to specific levels of the CMECS framework. Mapping program designers would need to; (1) consider how far down the CMECS hierarchy surveying would be required to meet project objectives; (2) assess which CMECS data levels could be achieved with the various technologies; and (3) determine the combination of the technologies that would provide a dataset sufficient to meet the program needs.

Conduct Geologic Framework Mapping

Workshop discussions emphasized the critical importance of developing an underlying geologic framework, even if biological objectives are the overarching driver of an inventory and mapping program for shallow waters. There are several parameters that are relatively easy to measure (e.g., bathymetry, grain size, substrate type, and subbottom profiles), which provide information fundamental to basic inventories and serve as a foundation for benthic habitat mapping. By focusing on simple measurable parameters that are minimally dynamic, a spatial database can be constructed that serves as the basis for other research and decision-making. While the data types needed for geologic framework mapping can inform future biological ground truth data collection, as well as hypothesis-based research, benthic biological samples (cores, grabs, photographs, etc.) can be collected simultaneously with the geological groundtruth effort for maximum cost efficiency.

As noted, management and research objectives should drive the selection of data needs; however, the workshop participants identified the following priority geophysical needs to serve as a starting point for the development of shallow water mapping programs:

- Bathymetry (identified as a premier data need)
- Sediment grain size/surficial geology
- Subbottom geology

A second mapping tier to focus on more dynamic and sampling intensive biological information could follow, or be conducted in conjunction with the geophysical data collection. Participants suggested a number of ways to develop a basic level of biological and habitat data necessary for effective resource planning and management, while minimizing the time and costs associated with biological sampling:

1. assess the type and accuracy of biological information that can be derived easily from geophysical mapping (e.g., seagrass and oyster bed spatial extent);
2. consider use of physical data as proxies to anticipate habitats and biological communities and determine minimal groundtruthing needs;
3. survey seagrass species (e.g., *Zostera marina* and *Ruppia maritima*) to develop the basis for hypotheses and further sampling effort;
4. measure dissolved oxygen and salinity to aid investigations of biologic drivers and help define biota breaks and minimum zones.

For the purpose of seamless data integration, there were also suggestions to target data layers for the nearshore realm that match terrestrial data sets, including elevation, topography, soils, geology, fresh water inputs, vegetation, land use, rare species, non-native species, and breeding area data.

Develop Interagency Partnerships

Establishing and maintaining partnerships among parks, refuges, and reserves, along with agency and academic technical experts will be essential to the development of efficient, professional and cost-effective shallow water inventory and mapping efforts. It was suggested that a working group be established to identify;

- opportunities for partnerships of adjacent or nearby protected areas (e.g., Cape Cod National Seashore, Monomoy National Wildlife Refuge; Gateway National Recreation Area, Forsythe National Wildlife Refuge, Jacques Cousteau National Estuarine Research Reserve);
- emerging prospects for developing multi-agency proposals and tying nearshore efforts to emerging initiatives (such as climate change initiatives);
- additional potential partners to invite into these efforts (e.g., NSF-funded Long-term Ecological Research Reserves such as the Parker River/Plum Island (MA) and Virginia coastal reserves; and the USFWS Landscape Conservation Cooperatives);
- potential partnerships to develop the pilot projects. Interagency pilots should be designed to demonstrate the importance of nearshore mapping for different types of protected areas and/or to evaluate the power of the CMECS mapping framework as a model for shallow water survey design.
- opportunities for engaging outreach and education applications of shallow mapping programs with the goal of enriching science education and building public support for large-scale mapping efforts.

APPENDICES

Appendix A: Agenda& Links to Presentations

Survey Methods for Shallow Water Habitat Mapping in New England Department of the Interior Holdings & Estuarine Research Reserves

WORKSHOP AGENDA

WEDNESDAY, SEPTEMBER 30, 2009

8:00 AM Registration & Continental Breakfast

8:30 AM Welcome

- WORKSHOP OVERVIEW & PARTICIPANT INTRODUCTIONS
Charles Roman, Coastal Ecologist, National Park Service, Northeast Region, RI

8:50 AM Overview of the Objectives, Needs, Capacity, and Specific Challenges of Shallow Water Mapping in the Submerged Extents of Park, Refuge, and Reserve holdings in New England

- NATIONAL PARK SERVICE (10 min.)
Charles Roman, Coastal Ecologist, National Park Service, Northeast Region, RI
- U.S. FISH & WILDLIFE SERVICE (10 min.)
Jan Taylor, Regional Refuge Biologist, U.S. Fish and Wildlife Service, NH
- NATIONAL ESTUARINE RESEARCH RESERVES (10 min.)
Michael De Luca, Senior Associate Director, Institute of Marine and Coastal Sciences, Rutgers University & Manager, Jacques Cousteau National Estuarine Research Reserve, NJ
- QUESTIONS (10 min.)

9:30 AM Overview of Available Techniques for Shallow Water Mapping

- INTRODUCTION TO SHALLOW WATER MAPPING: COMPARING AVAILABLE TECHNOLOGIES
Walter Barnhardt, Geologist, Coastal and Marine Geology Program, U.S. Geological Survey, MA; & Megan Tyrrell, Chair, Gulf of Maine Mapping Initiative/Research & Monitoring Coordinator, Cape Cod National Seashore, National Park Service, MA

9:45 AM Technical Presentations on Shallow Water Mapping Techniques Exemplified Through Case-Studies

- AERIAL - OPTICAL REMOTE SENSING FOR SHALLOW-WATER HABITATS
Mark Finkbeiner, Physical Scientist, NOAA National Ocean Service, Coastal Services Center, SC

- 10:05 AM** APPLICATIONS OF LIDAR AND MULTI-SPECTRAL DATA AT CAPE COD NATIONAL SEASHORE
Mark Adams, GIS Specialist, Cape Cod National Seashore, National Park Service, MA
- 10:25 AM** ○ BATHYMETRIC SURVEY OF A SHALLOW WATER ESTUARINE SYSTEM, GREAT BAY, NEW HAMPSHIRE
Larry Ward, Research Associate Professor, University of New Hampshire Center for Coastal and Ocean Mapping, NH
- 10:50 AM** **Coffee Break**
- GEO-WALL DEMONSTRATION
Brian Calder, UNH University of New Hampshire Center for Coastal and Ocean Mapping, NH
- 11:10 AM** **Shallow Water Mapping Technologies (continued) & Examples of State/Federal/Academic Cooperative Mapping Mechanisms**
- NEARSHORE MAPPING OF THE SHOREFACE REGION: LINKING THE INNER SHELF AND BEACH SYSTEMS IN SOUTH CAROLINA AND NEW YORK
Paul Gayes, Director, Center for Marine and Wetland Studies, Coastal Carolina University, SC
- 11:35 AM** ○ HABITAT MAPPING FROM THE BEACH TO THE SHELF: LESSONS FROM RHODE ISLAND MAPPING PROJECTS
John King, Professor & Geological Oceanographer, University of Rhode Island, RI
- 12:05 PM** **Lunch**
- 1:05 PM** ○ DIVERSITY OF SHALLOW WATER APPLICATIONS BY AN AUV
Thomas Grothues, Assistant Research Professor, Institute of Marine and Coastal Sciences, Rutgers University, NJ
- 1:30 PM** ○ MAPPING THE FLOOR OF APALACHICOLA BAY, FLORIDA: SUMMARY OF ACOUSTIC MAPPING TECHNIQUES AND FINDINGS
David Twichell, Co-chief Scientist, U.S. Geological Survey, Woods Hole, MA
- 1:55 PM** ○ SHALLOW WATER MAPPING ON THE MASSACHUSETTS INNER CONTINENTAL SHELF
Walter Barnhardt, Geologist, Coastal and Marine Geology Program, U.S. Geological Survey, MA
- 2:20 PM** ○ APPLICATIONS FOR EDUCATION & OUTREACH
Melanie Reding, Education Coordinator, Jacques Cousteau NERR, NJ
- 2:35 PM** **Coffee Break & Tour of the Visualization Laboratory**
- 3:15 PM** **Focused Discussion**
- 5:00 PM** **Adjourn**

Appendix B: Speaker Abstracts

APPLICATIONS OF LIDAR AND MULTI-SPECTRAL DATA AT CAPE COD NATIONAL SEASHORE

Mark Adams^{1*}

¹ Cape Cod National Seashore, National Park Service, Wellfleet, MA 02667

Cape Cod National Seashore has studies in progress to survey coastal change, map coastal and intertidal habitats and detect landcover in formerly diked estuaries in various stages of restoration. Through the NPS North Coast and Barrier monitoring network NASA/USGS data has delivered ATM and EAARL LIDAR (green LIDAR with bathymetric capabilities) to the NPS since 1999. The Army Corps of Engineers also distributes topo-bathy LIDAR data through their CHARTS and SHOALS program website. These data sources will be compared and their value assessed for analyses of coastal features. High resolution estuarine cover type mapping using decision tree analysis is also being tested using Quickbird and other multi-spectral imagery.

Park-wide remotely sensed cover type mapping using stratified unsupervised ISODATA classification is in the planning stages for 2010 (via cooperators at URI). This project includes SAV mapping and will be augmented by underwater video.

SHALLOW WATER MAPPING ON THE MASSACHUSETTS INNER CONTINENTAL SHELF

Walter A. Barnhardt^{1*}

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The inner continental shelf of Massachusetts encompasses 6530 km² of diverse seafloor environments, including submerged rock ledges, mobile sand deposits, rugged boulder fields, and deep mud-floored basins. A cooperative program involving the U.S. Geological Survey and the Massachusetts Office of Coastal Zone Management has employed high-resolution sonars, bottom photography, and sediment sampling to characterize seafloor geology in water depths of approximately 5 to 90 m. Overlapping swaths of bathymetric and backscatter data, closely spaced subbottom profiles, sediment sampling, and bottom photography provide a comprehensive, three-dimensional view of the physical structure of the seafloor. Mapping began in 2003 and, to date, has covered 2200 km² of seafloor, approximately 34% of the total area under state jurisdiction. Research in the Boston Harbor region included data that were originally collected by the National Oceanic and Atmospheric Administration to update navigation charts. The maps from this project are available online as PDF files suitable for large-format printers, and all data are downloadable as GIS projects.

The primary objective of this program is to provide geologic information for management of coastal and marine resources as mandated by the Massachusetts Ocean Management Plan. Accurate maps of seafloor geology are important first steps toward protecting fish habitat, quantifying sediment resources for potential extraction, and assessing environmental changes due to natural or human impacts. This presentation gives examples of how geologic information can support management decisions and compares different approaches to creating seafloor maps. Choosing a particular mapping approach is based primarily on the objectives (habitat research, regional sediment management, etc.), time frame for results, and availability of funds. Water depths in the proposed survey area weigh heavily in determination of the appropriate technologies to use.

AERIAL - OPTICAL REMOTE SENSING FOR SHALLOW-WATER HABITATS

Mark A. Finkbeiner^{1*}

¹NOAA Coastal Services Center, 2234 South Hobson Ave., Charleston, SC 29405

Aerial optical imagery has been an established technology for identifying and assessing shallow-water resources for many years. Optical imagery has advantages that make it an appropriate tool for shallow-water mapping including comprehensive coverage over wide areas, ability to capture both submerged and terrestrial areas, a strong commercial base of data providers, and relative ease of use by many users. There are also important limitations on this technology and critical issues that need to be addressed to successfully use it for submerged resource mapping. Both the advantages and disadvantages of this technology will be presented in the context of case studies with representative data sets to illustrate capabilities and limitations.

The new emerging generation of digital sensors provides promise for improved data collection and analysis. An overview of these systems will be provided as well as new tools for deriving habitat information.

Finally, general information on costs and logistical issues will be provided to allow potential users to apply this technology effectively. This will also be presented in the context of case studies.

NEARSHORE MAPPING OF THE SHOREFACE REGION: LINKING THE INNER SHELF AND BEACH SYSTEMS IN SOUTH CAROLINA AND NEW YORK

Paul T. Gayes^{*1}, Clay McCoy¹, Cheryl Hapke², Neal Driscoll³, Bill Schwab², and Sara Brown⁴

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² U.S. Geological Survey/PWRC, 384 Woods Hole Rd., Woods Hole, MA 02543

³ Scripps Institution of Oceanography, La Jolla, CA 92093

⁴ US Army Corps of Engineers, 69 A Hagood Ave, Charleston SC 29403

Shallow coastal waters present a range of complexities and challenges to comprehensive mapping strategies commonly applied in adjacent shelf systems. The nation's immediate coastal zone is increasingly important and at risk from large-scale seawards migration of coastal populations and infrastructure towards a similarly persistent landwards migrating shoreline. As a result, there is growing need for more comprehensive and detailed characterization of these critical and challenging environments for improved management.

Several recent studies, by a partnering of federal, state agencies and academic institutions, focused on mapping of very shallow coastal areas for a range of applied and basic science objectives. These include: 1) a focus on linking the active beach and inner shelf across a range of temporal and spatial scales (beach erosion to development of transgressive reversion surface) as part of a USGS Cooperative Regional Coastal Erosion Study, 2) increased spatial resolution of nearshore bathymetric baselines and change within long large tidal inlet areas as part of US Army Corps of Engineers Regional Sediment Management program and 3) examining a potential connection between a field of large shoreface ridges and shoreline variability patterns along the Fire Island National Seashore associated with concern over potential effects of mining the nearshore ridge systems for beach renourishment.

Each of these projects enlisted a range of instruments and methods to improve characterization of very shallow and active systems. Collectively this includes: side scan sonar, chirp sub-bottom profiles, single and multibeam sonar bathymetric surveys, time-averaging video imagery, vibracores, surficial sediment samples and bottom video tows to characterize the sea floor, shallow subbottom and coastal behavior. In some areas electrical resistivity, continuous water quality sampling and hydrodynamic instrumentation (waves/currents) have also been incorporated.

Such shallow water mapping is challenged by: significant logistical and operational challenges, poor acoustic conditions, decreased efficiency of some instruments and associated increase in costs and time required to cover broad areas. For many applications, these difficulties may be prohibitive to support such comprehensive mapping as increasingly common in shelf and deeper settings.

Increasingly, however, the associated benefits of removing uncertainty associated with more limited data and improved resolution of these complex settings is sufficient to warrant sophisticated integrated mapping techniques at site-specific and more regional scales for specific applications. These have also served to support, and occasionally stimulate, additional interdisciplinary studies within these shallow settings focused on specific coastal management issues and needs.

DIVERSITY OF SHALLOW WATER APPLICATIONS BY AN AUV

Thomas M. Grothues^{1*}, Joseph Dobarro¹, Rose Petrecca¹, Michael P. De Luca¹

¹ Institute of Marine and Coastal Sciences, Rutgers University Marine Field Station, 800 c/o 132 Great Bay Blvd, Tuckerton, NJ 08087

Autonomous underwater vehicles (AUVs) were originally designed for continental shelf applications, but are proving highly capable at shallow water tasks. The Remote Ecosystem Measuring UnitS (REMUS) is a relatively small (1.6 m, 46 kg) AUV with a recommended operating depth range of 1.5-100 m operated by the Mid-Atlantic Bight National Undersea Research Center (MAB-NURC) at Rutgers University. The REMUS presents a diversity of operational modes and sensors useful to the challenges of mapping shallow water. These include the use of multiple navigation/guidance systems that may be used in complement or independently depending on mission constraints and objectives. It can be launched and recovered from a ship, small boat, or from a beach or dock. Mapping is accomplished with a 600 kHz sidescan sonar. The unit presents exceptionally clear sonograph imagery because the transducer is decoupled from surface chop, swell or a tow cable, and because the vehicle maintains a near-constant altitude above-bottom. Mapping is enhanced by simultaneous operation of additional sensors including: upward and downward-looking Acoustic Doppler Current Profilers (ADCPs) that provide bathymetry, flow, and particulate backscatter concentration data, conductivity, temperature and depth sensors (CTD), chromatic dissolved organic material (CDOM), chlorophyll A, and dissolved oxygen concentration/saturation (via three independent optical sensors). A telemetry hydrophone or plankton collector is optionally supported. Data streams are merged and processed into HTML or native software reports in ASCII, MATLAB, or MS Excel within minutes of AUV recovery. The ease of use and ready shoreside accessibility of the AUV also provides a segue between engineering and ecosystem interests and has therefore been central to engaging students of diverse backgrounds in outreach efforts. These couple real-time data collection missions with exercises in simple underwater vehicle construction and sonography. We present results from recent shallow water missions to demonstrate the flexibility and data quality as well as the challenges presented by AUV use. Demonstrated results include missions mapping benthic sediment structure, reef, anthropogenic artifacts, and benthic and nektonic biota in the Hudson River (NY), Navesink River estuary (NJ), Delaware Bay (NJ), Chesapeake Bay (MD), Lake Erie (OH), and coastal ocean from the surfzone to offshore (CT, NY, NJ, NC, SC, and FL).

HABITAT MAPPING FROM THE BEACH TO THE SHELF: LESSONS FROM RHODE ISLAND MAPPING PROJECTS

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There currently are three major mapping projects underway in Rhode Island waters. "MapCoast" is a subaqueous soil mapping project focused on 0 - 5 m depths in coastal waters. "BayMap" is a biological, geological, and "cultural" habitat mapping project focused within Narragansett Bay and Rhode Island coastal ponds. The "Rhode Island Special Area Management Plan (SAMP)" is mapping offshore water in Rhode Island and Block Island Sound to approximately 50 meters in depth, and is essentially an offshore zoning project. We have developed a mapping protocol and habitat mapping approach across the three projects. The approach utilizes simultaneously acquired interferometric sonar and CHIRP subbottom sonar data to produce bathymetry, sidescan sonar, and subbottom stratigraphy data layers. Initial habitat polygons are identified primarily from a combination of visual inspection of sidescan mosaic, and analysis of the sidescan data with acoustic bottom classification software. Groundtruth studies are done using a sediment profile imagery (SPI) camera system, underwater video and plan-view photography, and sediment grabs and cores. Grabs are analyzed for both benthic biology and geology/geochemistry. Cores are used in conjunction with seismic profiles to reconstruct paleoenvironmental changes and paleolandscapes.

The production of habitat maps that will conform to the new NOAA Coastal and Marine Ecological Classification Standard Version III (Madden, *et al.*, 2009) is a major challenge. The approach we are taking in the Rhode Island projects will be discussed. Cost estimates for mapping in very shallow waters (0 - 5 m) intermediate depths (5 - 30 m), and deeper waters (30 - 60 m) will also be discussed.

EDUCATION AND OUTREACH APPLICATIONS OF SHALLOW MAPPING TECHNIQUES

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The multidisciplinary nature of shallow water habitat mapping makes this technology a useful tool for teaching about the major challenges facing coastal areas. Habitat mapping within public and governmental land holdings can provide data products which easily allow for formal and non-formal study and comparison of benthic habitat characteristics. Lesson plans and outreach presentations focused on current research and state of the art mapping technologies are well-suited for addressing national and local science education standards as well as Ocean Literacy Principles. Shallow water mapping "missions" provide a platform for researchers and educators to collaborate in the creation of education resources that can reach far beyond the classroom and out into the community. Shallow water mapping provides integrated datasets relevant to current coastal policy issues such as hypoxia, shifts in resource abundance and distribution, defining migratory pathways, habitat use and behavior of fauna.

MAPPING THE FLOOR OF APALACHICOLA BAY, FLORIDA: SUMMARY OF ACOUSTIC MAPPING TECHNIQUES AND FINDINGS

David Twichell^{1*}, Lee Edmiston², William Stevenson³, Brian Andrews¹, Emile Bergeron¹, William Danforth¹, Jane Denny¹, Thomas O'Brien¹, Elizabeth Pendleton¹, and Charles Worley¹

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Apalachicola Bay is the largest oyster fishery in Florida, and an updated map of oyster bed distribution was needed as baseline information for management of this resource in light of proposed water diversions from the Apalachicola drainage basin. Shallow-water depths (average depth of 3 m), the large size of the study area (35 km long by 8 km wide), and high turbidity combined to make this a challenging area for data collection. During 2005 and 2006, the U.S. Geological Survey, in cooperation with the Apalachicola Bay National Estuarine Research Reserve and the NOAA Coastal Services Center, collected seafloor acoustic data from a 232 km² section of the bay. Two survey systems were used: an 8-m vessel equipped with sidescan sonar, interferometric bathymetry, and chirp subbottom profiler systems was used in depths exceeding 2 m; and an Autonomous Surface Vehicle (ASV) was used in water depths of 0.5-2 m. The ASV is a 3.2-m-long remotely operated catamaran, equipped with sidescan sonar, single-beam bathymetry, and chirp subbottom profiler systems. In addition to the geophysical data, video observations and grab samples were used to verify the interpretation of the seafloor geology, and vibracores were collected and analyzed to define the shallow stratigraphy and chronology of the bay's evolution. The geophysical data have been archived and are online in GIS-ready format (<http://woodshole.er.usgs.gov/pubs/of2006-1381/>). The suite of acoustic used tools allowed mapping the extent of oyster beds as well as the relationship of the oyster beds to seafloor morphology and underlying geologic features. Integration of the sidescan imagery with the bathymetry showed that all oyster beds occur on bathymetric shoals, but that not all shoals have oyster beds. Examination of subbottom seismic data showed that oyster beds are associated with high-amplitude reflections whose seafloor exposure has been diminished due to burial by mud, which continues to be supplied to the bay by the Apalachicola River. Analysis of vibracores showed that the sandy parts of deltas that formed in the bay between 6,400 and 4,400 B.P. underlie the oyster beds. While a variety of conditions influence oyster distribution in the bay, this study demonstrates that the underlying geology has significant control on oyster distribution by providing appropriate substrate for their growth.

BATHYMETRIC SURVEY OF A SHALLOW WATER ESTUARINE SYSTEM, GREAT BAY, NEW HAMPSHIRE

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Great Bay is a moderately sized (~25 km²), shallow (average depth ~2.5 to 3.0 m) embayment located in the upper reaches of Great Bay Estuary (GBE), New Hampshire. Great Bay, which is designated a National Estuarine Research Reserve, contains numerous valuable habitats and is a major sedimentary system in GBE. In addition, Great Bay is extensively used for recreational purposes. Despite the recognition of the need for accurate bathymetry, only limited areas of Great Bay have been surveyed in recent times. To begin to address this gap, a single beam echosounder survey was conducted in Great Bay during summer 2009. Challenges for the survey resulted from multiple sources including shallow water depths, relatively extensive eelgrass beds, a wide range in salinity conditions over relatively short distances, and complex and rapidly changing tidal conditions (mean range ~2.1 m). For instance, Great Bay contains extensive fine-grained intertidal and subtidal flats. As a result of the shallow depths in Great Bay much of the bottom is exposed during maximum spring low tides. Finally, the water column is frequently very turbid. Due to the very shallow nature of the bay, the primary survey was conducted with two small boats (16' and 19'). Acoustic systems used in this survey included an Odom Echotrac CV200 operating at 24 kHz/100kHz and a Knudsen 320B/P operating at 50 kHz/200kHz. Positioning was achieved through RTK GPS with a base station located at Jackson Estuarine Laboratory (located ~ 0.5 km north of the survey area). Data acquisition was done using software associated with the acoustic systems as well as Hypack hydrographic survey software. Hypack was also used for survey planning and execution. Survey lines were run from as close to shore as possible at a maximum of 100 m spacing across the entire embayment. Cross-lines were run at 300 m line spacing. All depths are referenced to the WGS84 ellipsoid using the GPS data collected on the survey platforms. In addition, water levels were monitored at three fixed tide stations with pressure sensors and at a mid-bay location with a RTK GPS buoy. Salinity and temperature were measured at the tide stations as well. The additional water level observations will allow the determination of the relationship between WGS84 vertical datum and the tidal datum in various locations. During the presentation an overview of the study and preliminary results will be discussed.

Appendix C: PARTICIPANT LIST

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Appendix D: References and Web-links for Shallow Water Mapping Technologies & Case-studies

This document includes a sampling of references and web-links that focus on shallow mapping technologies and examples of their applications. Many of these references have been supplied by the steering committee members and speakers associated with this workshop. This document is not intended to comprise a comprehensive or exhaustive review of available resources on this topic.

Shallow Water Benthic Mapping Techniques

I. Seafloor & Benthic Habitat Mapping (General Resources)

- 1) Benthic Habitat Mapping [Internet]. Charleston (SC): NOAA Coastal Services Center; [cited 2009 September 1]. Available from: <http://www.csc.noaa.gov/benthic/>
- 2) The Scoping Tool [Internet]. Mapping European Seabed Habitats (MESH); [cited 2009 September 22]. Available from: <http://www.searchmesh.net/default.aspx?page=1931>
 - This scoping tool guides the user through a series of prompts to consider the purpose of the survey, factors that will affect the amount of survey effort required and how different survey and environmental conditions will affect the suitability of various survey tools that may be available.
- 3) Remote Sensing in Shallow Water. [Internet]. Mapping European Seabed Habitats (MESH); [cited 2009 September 22]. Available from: <http://www.searchmesh.net/default.aspx?page=1832>
- 4) Coggan, R., J. Populus, J. White, K. Sheehan, F. Fitzpatrick, and S. Piel. (eds.) 2007. Review of Standards and Protocols for Seabed Habitat Mapping. Mapping European Seabed Habitats [Internet]. [cited 2009 September 22]. Available from: <http://www.searchmesh.net/default.aspx?page=1442>

The reviews cover:

 - Remote sensing techniques for shoreline & shallow water surveys, e.g., LiDAR, CASI, aerial and satellite imaging, shoreline surveys, and ground-truth sampling.
 - Remote sensing techniques for deeper water surveys, e.g., acoustic systems, AGDS and 3D seismic systems, & optical techniques including camera sledges, ROVs, drop cameras and sediment profile imagery.
- 5) Kvitek, R., P. Iampietro, E. Sandoval, M. Castleton, C. Bretz, T. Manouki, and A. Green. 1999. Final Report: Early Implementation Of Nearshore Ecosystem Database Project [Internet]. Seaside (CA): SIVA Resource Center; [cited 2000 September 20]. Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>.
- 6) Shallow Survey 2008: 5th International Conference on High-resolution Surveys in Shallow Water; October 21-24, 2008; Portsmouth, NH [Internet]. Durham (NH): University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center. [Cited 2009 September 22]. Available from: http://www.shallowsurvey2008.org/index.php?option=com_content&task=blogcategory&id=35&Itemid=68

- 7) Denny, J.F., W.C. Schwab, D.C. Twichell, T.F. O'Brien, W.W. Danforth, D.S. Foster, E. Bergeron, C.W. Worley, B.J. Irwin, B. Butman, P.C. Valentine, W.E. Baldwin, R.A. Morton, E.R. Thieler, D.R. Nichols, and B.C. Andrews. 2007. USGS Advances in Integrated, High-Resolution Sea-Floor Mapping: Inner Continental Shelf to Estuaries [Internet]. In: Proceedings of the Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Process; 2007 May 13-17; New Orleans, LA. American Society of Civil Engineers (US): p. 2487-2500. Report No. doi 10.1061/40926(239)195. [cited 2009 September 15] Available from: <http://cedb.asce.org/cgi/WWWdisplay.cgi?0701595>
- 8) WHSC Sea-floor Mapping Technology [Internet]. [updated 2007 Dec 19]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center; cited 2009 August 30] Available from: <http://woodshole.er.usgs.gov/operations/sfmapping/>
- 9) Gulf of Maine Mapping Initiative: Mapping Techniques [Internet]. [updated 2009]. Gulf of Maine Council on the Marine Environment; [cited 2009 September 17]. Available from: <http://www.gulfofmaine.org/gommi/mappingtechniques.php>
- 10) Benthic Habitat Mapping: Data Portal [Internet]. Charleston (SC): NOAA Coastal Services Center; [cited 2009 September 22]. Available from: <http://www.csc.noaa.gov/benthic/data/dataportal.htm>
- 11) Sea-floor Mapping [Internet]. [updated 2008 March 25]. Silver Spring (MD): NOAA Ocean Service Education; [cited 2009 September 22]. Available from: <http://oceanservice.noaa.gov/education/seafloor-mapping/welcome.html>

II. *Satellite and Aerial Technologies:*

A) Summary of Satellite and Aerial Technologies (satellite imaging, airborne hyperspectral imaging (HSI), aerial imaging, and light detection and ranging (LIDAR))

- 1) See Reference I1: <http://www.csc.noaa.gov/benthic/mapping/techniques/satair.htm>
- 2) See Reference I5. Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>.
 - Airborne techniques including lasers and multispectral sensors may be the ideal tools for rapidly collecting elevation, depth, substrate and time series data in the 0-10 m zone.

B) Satellite Imaging

- 1) See Reference I1: <http://www.csc.noaa.gov/benthic/mapping/techniques/sensors/satellites.htm>
 - Advantages: satellite imaging can cover large areas (spanning several kilometers) at relatively low cost. New high-resolution satellites are equipped with cameras that can distinguish objects as small as one square meter, but such data are not yet widely available due to security and licensing concerns.
 - Disadvantages: It is seldom possible to acquire satellite imagery under the appropriate conditions for effective benthic mapping. Shorelines are often difficult to

detect because reflection through the water produces signatures similar to those received from adjacent land. Cloud cover, turbidity, and sun glare can cause interference.

C) Airborne Hyperspectral Imaging (HSI)

- 1) Tyrrell, M.C. 2004. Strategic plan for mapping Massachusetts' benthic marine habitats. Massachusetts Office of Coastal Zone Management, Boston, MA.
 - Advantages: Hyperspectral imaging instruments can collect very high resolution data in shallow water. The information gathered by certain systems (e.g., CASI) can be used for mapping bathymetry, substrate and vegetation in shallow water. CASI systems are capable of obtaining meter resolution data, making this technology ideal for nearshore subtidal habitat mapping in areas with high water clarity. Surveys are more cost effective than swath acoustic techniques, especially in shallow water (approximately \$3100-\$3900/ km² for CASI data acquisition and processing (Kvitek et al. 1999)).
 - Disadvantages: Data requires special image-processing software before they can be imported into GIS. Clear, calm, shallow water is required to obtain high quality data and the systems are generally only effective within secchi disk depths. Variable water chemistry, tidal, or solar conditions can alter the spectral signal of particular bottom features, and therefore a highly trained observer is required to interpret the data.
- 2) See Reference I1. Available from:
<http://www.csc.noaa.gov/benthic/mapping/techniques/sensors/hyperspec.htm>
 - Advantages: Airborne hyperspectral imaging is an emerging technology for classifying benthic habitats in coastal zones, such as live coral, sand, and algae. This technology can achieve far better resolution than multispectral instruments.
 - Disadvantages: The limitations associated with hyperspectral imaging include its relatively high cost and overall lack of availability to average users. This technique is still primarily useful only in shallow, non-turbid water.
 - Uses: Mapping habitat features of intertidal marshes, shallow estuarine systems, and marine systems. Monitoring for oil spills, pulp mill effluent, schools of fish and coastal zone water flow. It has been particularly successful in classifying tropical benthic habitats.
- 3) See Reference I5. Available from:
<http://seafloor.csUMB.edu/taskforce/html%20%20web/finalreport.htm>
 - CASI uses: to map vegetation, substrate, phytoplankton abundance, thermal and pollution plumes, and other features. Vegetation can be distinguished taxonomically, to species in some cases. CASI has been used to map benthic algae and substrate type in one of the largest airborne mapping projects to date.

D) Aerial Imagery

- 1) Bradley, M., K. Raposa, and S. Tuxbury. 2007. Report on the Analysis of True Color Aerial Photography to Map and Inventory *Zostera marina* L. in Narragansett Bay and Block Island, Rhode Island. Kingston [Internet]. Kingston (RI): Rhode Island Natural History Survey; [cited 2009 September 1]. p. 1-16 and 9 (Mapsheets). Available from:
http://www.ci.uri.edu/projects/mapcoast/docs/Eelgrass_Report_2007.pdf

- Advantages: Surveys can cover large areas of shallow, estuarine habitats. This study showed that true-color aerial photographs are an effective tool for mapping eelgrass beds when accompanied by comprehensive groundtruthing efforts to identify deep water edges of eelgrass beds.
 - Disadvantages: Photo-signatures from true-color aerial photographs are highly variable and can be flight specific. Ground-truthing is required. Limitations include issues with water clarity, photographic quality, and challenges in interpretation of eelgrass photo-signatures.
- 2) King, J., E. Shumchenia, M. Bradley, and C. Hapke. 2007. The Sky Above, The Mud Below. 41'N: A Publication of Rhode Island Sea Grant & The University of Rhode Island Coastal Institute [Internet]. [cited 2009 Aug 20]; 4(1): 10. Available from: http://seagrant.gso.uri.edu/41N/vol4no1/8_king_et al.html
 - 3) See Reference I1: <http://www.csc.noaa.gov/benthic/mapping/techniques/sensors/aerial.htm>
 - Advantages: The advantages include a wide area of data coverage, readily obtainable photographs that provide sufficient resolution for detecting subtle submerged features and resolving features smaller than 1 meter, and results that are easily integrated into the coastal management process.
 - Disadvantages: Like satellite imagery, aerial photography is limited by environmental conditions, including water turbidity, sun angle, cloud cover, haze, and surface waves. However, by careful mission planning, the effects of these conditions can be minimized. It is usually not suitable for identifying individual species.
 - Uses: In nearshore estuarine and marine environments, aerial photography is used primarily for identifying and delineating habitats within the photic zone.

E) Light Detection and Ranging (LIDAR)

- 1) Lidar [Internet]. [updated 2009 April 30]. Durham (NH): University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center; [cited 2009 September 22]. Available from: <http://www.ccom-jhc.unh.edu/index.php?page=research/lidar.php&p=51%7C69%7C70>
- 2) Pe'eri, S., J.V. Gardner, L.G. Ward, J.R. Morrison, and J. Lillycrop. 2007. Identifying subtidal coastal environments using airborne lidar bathymetry (ALB) [abstract]. In: Fall Meeting of the American Geophysical Union; 2007 Dec 10-14; San Francisco (CA): American Geophysical Union.
- 3) Pe'eri, S., J.V. Gardner, L.G. Ward, J.R. Morrison, and J. Lillycrop. 2007. The seafloor as key component for the success of lidar in bottom detection. In: Conference Proceedings of the 8th Annual Joint Airborne LIDAR Bathymetry Technical Center of Expertise Coastal Mapping and Charting Workshop; 2007 May 23-24; Seattle (WA).
- 4) Costa, B.M., T.A. Battista, and S.J. Pittman. 2009. Comparative evaluation of airborne LiDAR and ship-based multibeam SoNAR bathymetry and intensity for mapping coral reef ecosystems. Remote Sensing of the Marine Environment 113: 1082-1100.
- 5) See Reference I5: Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>.

- Data resolutions nearing those of multibeam are now possible with some of the new LIDAR laser topographic mapping systems, although water clarity generally limits their application to the very nearshore environment (< 20m).
- 6) See Reference I1: <http://www.csc.noaa.gov/benthic/mapping/techniques/sensors/lidar.htm>
- Advantages: Hydrographic LIDAR can provide uniform and dense data in extremely shallow water. It is a good complement to acoustical surveys, which are less effective in depths less than about 5 meters. LIDAR is cost effective for surveying large, shallow areas with generally good water clarity.
 - Disadvantages: The biggest limitation of LIDAR, as with other airborne techniques, is its dependency on water clarity. In clear waters it can be used to depths of over 50 meters (over 150 feet), but in turbid water it is only successful to depths of two to three times the visible depth.

III. Acoustic Technologies

A) General Resources on Acoustic Technologies

- 1) Erhold, A., D. Hamon, and B. Guillaumont. 2006. The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore macrobenthic habitats: application to the Bay of Concameau (South Brittany, France). ICES Journal of Marine Science, 63: 1604-1615 / Erhold, A. 2004. Mapping Shallow Coastal Habitats Using Acoustic Methods [Internet]. [cited 2009 September 22]. Available from: http://www.searchmesh.net/PDF/GMHM2_Mapping_shallow_coastal_habitats.pdf
- 2) RESON: Underwater Acoustic Solutions [Internet]. [updated 2009 June 08]. Slangerup, Denmark: RESON Group; [cited 2009 September 15]. Available from: <http://www.reson.com/>
- 3) See reference I5. Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>.
 - Disadvantages: Wave height, submerged rocks, kelp canopy and irregular coastlines all make boat based acoustic survey operations difficult in the 0-10 m. depth zone.
 - The relatively slow survey speeds (4-10 knots) required for acoustic surveys can make mapping large areas at high resolution a long and costly enterprise. This situation is especially true in shallow water habitats due to the limitations imposed on swath width by water depth. For sidescan and multibeam systems, the closer the sensor is to the seafloor, the narrower the swath coverage. Survey track line spacing for shallow water surveys must therefore be closer than for deeper water work, where wider swath ranges can be successfully used. Even where wider swaths can be used, however, there is a trade off with resolution, which is directly and inversely proportional to swath width. (For example, a sidescan resolution of 20 cm. at the 50 m. range, drops to 40 cm. at the 100 m. range.)

B) Single Beam

- 1) Sea-floor Mapping: Bathymetry Systems [Internet]. [updated: 2007 Dec 19]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center; [cited 2009 August 30]. Available from: <http://woodshole.er.usgs.gov/operations/sfmapping/bathy.htm>

- 2) Remote Sensing for Coastal Management: Single Beam Sonar [Internet]. Charleston (SC): NOAA Coastal Services Center; [cited 2009 September 17]. Available from: http://www.csc.noaa.gov/crs/rs_apps/sensors/single_beam.htm
- 3) Single Beam Sonar and Mapping and Characterization [Internet]. [updated 2009 April 30]. Durham, NH: University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center; [cited 2009 September 22]. Available from: http://www.ccom-jhc.unh.edu/index.php?p=51|69|70|69&page=research/seafloor_characterization.php

C) Multibeam Swath Systems

- 1) See reference I5. Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>.
 - Advantages: The ability to acquire denser sounding data while surveying fewer tracklines (with greater spacing between lines), and simultaneously acquiring backscatter imagery using the same sensor.
 - Advantages: The introduction of swath mapping and multibeam bathymetry systems has dramatically improved our ability to acquire continuous high-resolution depth data. Bathymetric data with horizontal postings of less than 1 m. are now routinely collected over wide areas using multibeam techniques.
 - Trade-off: While multibeam backscatter images generally lack the resolutions and detail found in conventional sidescan images, they can be corrected for distortion resulting from unintended sensor motion (e.g., roll, pitch, and heave due to waves). This type of correction has not yet been developed for sidescan sonar systems.
 - Disadvantage: rigorous groundtruthing to verify that the resulting classifications are accurate is essential, because the results from this "automated" approach to seafloor substrate classification can vary widely between sites and under varying environmental conditions.
- 2) Multibeam and Interferometric Sonars [Internet]. [updated 2009 April 30]. Durham, NH: University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center; [cited 2009 September 22]. Available from: http://www.ccom-jhc.unh.edu/index.php?p=51|69|70|69&page=research/seafloor_characterization.php
- 3) Hughes Clarke, John E., L.A. Mayer, and D.E. Wells. 2006. Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf. *Marine Geophysical Researches* 18 (6): 607-629. Available from: <http://www.springerlink.com/content/h1p26860q8171747/>
- 4) Malik, M. A., L.A. Mayer, L. Fonseca, L.G. Ward., L.C. Huff, and B.R. Calder. Approaches and requirements of quantitative comparison of the multibeam sonar benthic acoustic backscatter [abstract]. In: 5th International Shallow Water Survey Conference; 2008 October 21-24; Durham, NH, USA.
- 5) Felzenberg, J., L.G. Ward, Y. Rzhanov, and L.A. Mayer. Detecting bedform migration in Portsmouth Harbor on relatively short time-scales from high-resolution multibeam bathymetry [abstract]. In: 5th International Shallow Water Survey Conference; 2008 October 21 – 24; Durham, NH, USA.

- 6) Hughes Clarke, J. E., L.A. Mayer, and D. E. Wells. 1996. Shallow-water imaging multibeam sonars: a new tool for investigating seafloor processes in the coastal zone and on the continental shelf. *Marine Geophysical Research* 18:607-629.

7)

D) Side-scan Sonar

- 1) See Reference I5: Available from:

<http://seafloor.csUMB.edu/taskforce/html%20%20web/finalreport.htm>.

- Challenges specific to shallow water nearshore marine habitats make sidescan sonar surveys in these areas more difficult, and costly than for deep water offshore surveys. Close to shore, waves are often higher and small vessels must be used. These factors combined with the shorter cable lengths required for shallow water surveys mean that, under certain conditions, there will be more wave induced vessel motion transferred to the towfish during a shallow water vs. a deep water survey. Any towfish motion other than along track movement (e.g., pitch, yaw and heave) will create distortion in the sonograph. While motion sensors are available for single beam and multibeam systems, they have not yet been developed to remove motion induced distortion from sidescan sonar data.
- For most sidescan systems, swath width is limited to no more than 80% of the transducer altitude above the seafloor.

- 2) King, J., J. Boothroyd, and B. Oakley. Finding More Than Fish. 2007. 41°N: A Publication of Rhode Island Sea Grant & The University of Rhode Island Coastal Institute [Internet]. [cited 2009 Aug 20]; 4(1): 10. Available from:

http://seagrant.gso.uri.edu/41N/vol4no1/9_king_et al.html

- Advantages: Because of the excellent spatial coverage generated by side-scan sonar, the acoustic data act as a guide for ground-truthing surveys aimed at maximizing our understanding of different habitat types.
- Disadvantages: In order to determine if the acoustically distinct areas really are different habitats, it is important to ground-truth the acoustic map. Ground-truthing is an essential step in creating benthic habitat maps using remotely sensed data. Factors like water depth, bottom slope, and vegetation can change the acoustic signature from place to place.
- Uses: The [side-scan] imagery collected by the MapCoast research team is the basis for geological mapping of the seafloor, benthic habitat mapping, and subaqueous soil delineation.

- 3) Sea-floor Mapping: Sonar Systems [Internet]. [updated: 2007 Dec 19]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center; [cited 2009 August 30]. Available from:

<http://woodshole.er.usgs.gov/operations/sfmapping/sonar.htm>

- 4) Able, K.W., et. al. 1987. Sidescan-Sonar as a tool for detection of demersal fish habitats. *Fishing Bulletin* 85: 4.
- 5) Fish, J.P. and H.A. Carr. 1991. Sound underwater images, a guide to the generation and interpretation of sidescan sonar data, second edition. Orleans (MA): Lower cape Publishing.
- 6) Lurton, X. 2002. An introduction to underwater acoustics, principles and applications. New York, NY: Springer (in association with Praxis Publishing), p.3.

- 7) Urick, R.J. 1983. Principles of underwater sound. Newport Beach (CA): Peninsula Pub., 423 pp.

E) Interferometric Sonar

- 1) Sea-floor Mapping: Bathymetry Systems. [Internet]. [updated: 2007 Dec 19]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center; [cited 2009 August 30]. Available from: <http://woodshole.er.usgs.gov/operations/sfmapping/bathy.htm>
- 2) Gostnell, C. Efficacy of an interferometric sonar for hydrographic surveying: Do interferometers warrant an in depth examination? NOAA National Ocean Service Office of Coast Survey, Hydrographic Surveys Division, [cited 2009 December 10]. Available from: http://www.nauticalcharts.noaa.gov/hsd/docs/SW_techpaper_gostnell.pdf

F) Sub-bottom Profiling/Seismic

- 1) WHSC Seismic Profiling systems. [Internet]. [updated: 2007 Dec 19]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center; [cited 2009 August 30]. Available from: <http://woodshole.er.usgs.gov/operations/sfmapping/seismic.htm>
 - Trade-offs: The higher frequencies of operation provide the highest resolution, but are limited in amount of penetration below the sea floor. The lower frequencies yield more penetration, but less resolution. In the marine, lacustrine, or estuarine environments, the decision is determined primarily by the water depth and the type of sediments/rocks in the substrate. Additionally, logistical parameters (e.g., cost, boat size, noise, time available, number of crew available, weather, environmental factors (ambient noise, ship traffic, etc.) enter into the decision as to which system(s) will be utilized for a given survey.

IV. *Light and Photographic Imaging:*

A) Summary of Light and Imaging (including Laser Line Scan, Sediment Profile Imaging, Plan-view Photography, and Underwater Video)

- 1) Benthic Habitat Mapping: Mapping Techniques: Satellites and Aerial Photos: Light and Imaging [Internet]. Charleston (SC): NOAA Coastal Services Center. [cited 2009 September 1]. Available from: <http://www.csc.noaa.gov/benthic/mapping/techniques/imaging.htm>

B) Laser Line Scan (LLS)

- 1) See Reference I5. Available from: <http://seafloor.csumb.edu/taskforce/html%20%20web/finalreport.htm>
 - Optical techniques are being developed for seafloor substrate mapping, including laser line scanner and multispectral imaging. Few of these instruments are in service at this time, in part due to their high cost and the still experimental nature of the technology. For this reason there is a scarcity of examples for comparison in terms of cost, quality, resolution, scale, etc. Nevertheless, these instruments show great promise; laser linescanners for their potential to dramatically increase image resolution over broad survey areas; and airborne multispectral systems for their ability to rapidly map habitat and vegetation types at meter resolution over vast areas in

depths too shallow for survey vessel operations. As with all optical sensors, however, both of these technologies are limited in their depth range by water clarity.

C) Sediment Profile Imaging (SPI)

- 1) J. King and E. Shumchenia. Spying on the Ecosystem (SPI Technology). 2007. 41stN: A Publication of Rhode Island Sea Grant & The University of Rhode Island Coastal Institute [Internet]. [cited 2009 Aug 20]; 4(1): 10. Available from: http://seagrant.gso.uri.edu/41N/vol4no1/4_king_shumchenia.html

D) Underwater Still & Video Photography

- 1) See Reference IIC1: http://seagrant.gso.uri.edu/41N/vol4no1/9_king_et.al.html

V. Other

A) Automated Underwater Vehicles (AUV) & Automated Surface Vehicles (ASV)

- 1) Mid-Atlantic Bight (MAB) Center of NOAA's Undersea Research Program [Internet]. [updated 2009 April 9]. New Brunswick (NJ): Institute of Marine and Coastal Sciences, Rutgers University; [cited 2009 Sep 1]. Available from: http://marine.rutgers.edu/nurp/REMUS_missions.html
- 2) Stokey, R., T. Austin, C. Von Alt, M. Purrell, R. Goldsborough, N. Forrester, and B. Allen. 1999. AUV bloopers or why Murphy must have been an optimist: A practical look at achieving mission level reliability in an AUV [Internet]. In: Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology, 1999; Durham, New Hampshire. pp. 32-40. [cited: 2009 September 22]. Available from: http://auvac.org/research/publications/detail.php?publication_id=2
- 3) AUV Platform Fact Sheet [Internet]. Lee (NH): Autonomous Undersea Vehicle Applications Center; [Cited 2009 Sep 1]. Available from: http://auvac.org/resources/browse/platform/detail.php?platform_id=10
- 4) Bergeron, E., C. Worley, and T. O'Brien. 2007. Progress in the development of shallow-water mapping systems using an Autonomous Surface Vehicle for shallow-water geophysical studies: Sea Technology 48 (6): 10-15.
- 5) Danforth, W.W., J.F. Denny, T.F. O'Brien, E. Bergeron, D.C. Twichell, C.R. Worley, B.D. Andrews, and B. Irwin. USGS Shallow Water Geophysical Mapping Operations Using a New Autonomous Surface Vehicle, Apalachicola Bay [Internet]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center, pp. 1-10. [cited 2009 September 20]. Available from: http://www.thsoa.org/hy07/12_02.pdf
- 6) ROVs in a bucket [Internet]. [cited 2009 September 22]. Available from: http://monitor.noaa.gov/publications/education/rov_manual.pdf

B) Surf zone bathymetry survey techniques (e.g., CBASS)

- 1) Cote, J. M., 1999, The measurement of nearshore bathymetry on intermediate and dissipative beaches, MS Thesis, Oregon State University, Corvallis, OR.

- 2) Dugan, J. P., K. C. Vierra, W. D. Morris, G. J. Farruggia, D. C. Campion, and H. C. Miller, 1999, Unique vehicles used for bathymetry surveys in exposed coastal regions, Proc. US Hydrographic Conf. Soc. National Meeting.
- 3) Lippmann, T. C., and G. M. Smith, 2009, Shallow surveying in hazardous waters, Proc. U. S. Hydro '09., <http://www.ushydro2009.com>, 1-11.
- 4) MacMahan, J., 2001, Hydrographic surveying from personal watercraft, J. Surveying Engineering, 127(1), 12-24.

C) Vibracoring

- 1) Stolt, M., M. Bradley, J. Turenne, M. Payne, and J. King. Cutting to the Core. 2007. 41*N: A Publication of Rhode Island Sea Grant & The University of Rhode Island Coastal Institute [Internet]. [cited 2009 Aug 20]; 4(1): 10. Available from: http://seagrant.gso.uri.edu/41N/vol4no1/5_stolt_etal.html

D) Classification Systems

- 1) Coastal and Marine Ecological Classification Standard: A National Standard to Support Ecosystem-Based Resource Management [Internet]. Charleston (SC): NOAA Coastal Services Center; [cited 2009 September 1]. Available from: <http://www.csc.noaa.gov/benthic/cmecs/index.html>
- 2) Madden, C. J., K. Goodin, R. J. Allee, G. Cicchetti, C. Moses, M. Finkbeiner, and D. Bamford, 2009. Coastal and Marine Ecological Classification Standard. NOAA and NatureServe. 109 p.

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A) Apalachicola Bay, SC

- 1) Osterman, L.E., D.C. Twichell, and R.Z. Poore (in press). Holocene evolution of Apalachicola Bay, Florida: Geo-Marine Letters.
- 2) Twichell, D., B. Andrews, L. Edmiston, and B. Stevenson. 2007. Geophysical mapping of oyster habitats in a shallow estuary: Apalachicola Bay, Florida [Internet]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center. USGS Open-File Report 2006-1381. [cited 2009 September 1]. Available at: <http://woodshole.er.usgs.gov/pubs/of2006-1381/>
- 3) Twichell, D.C., E.A. Pendleton, R.Z. Poore, L.E. Osterman, and K. Kelso. 2009. Vibracore, radiocarbon, microfossil, and grain-size data from Apalachicola Bay, Florida. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center: USGS Open-File Report 2009-1031 (in review).
- 4) Danforth, W.W., J.F. Denny, T.F. O'Brien, E. Bergeron, D.C. Twichell, C.R. Worley, B.D. Andrews, and B. Irwin. USGS Shallow Water Geophysical Mapping Operations Using a New Autonomous Surface Vehicle, Apalachicola Bay [Internet]. Woods Hole (MA): U.S. Geological Survey Woods Hole Science Center. [cited 2009 September 20]. Available from: http://www.thsoa.org/hy07/12_02.pdf

- 5) Twichell, D.C., B.D. Andrews, H.L. Edmiston, and W.R. Stevenson. 2007. Geophysical Mapping of Oyster Habitats in a Shallow Estuary; Apalachicola Bay, Florida [Internet]. Woods Hole (MA): U.S. Geological Survey. USGS Open-File Report 2006-1381. [cited 2009 August 15]. Available from: <http://woodshole.er.usgs.gov/pubs/of2006-1381/index.html>

B) Great Bay, NH

- 1) Great Bay Estuary [Internet]. [updated 2007 Mar 12]. Durham (NH): University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center; [cited 2009 Aug 25]. Available from: http://ccom.unh.edu/index.php?p=39%7C40&page=great_bay.php
- 2) Coastal Geology Research [Internet]. [updated 2007 May 31]. Durham (NH): University of New Hampshire Marine Program Jackson Estuarine Laboratory; [cited 2009 Aug 28]. Available from: http://marine.unh.edu/jel/coastal_geology/research.htm

C) South Carolina Coast

- 1) Center for Marine and Wetland Studies: Beach Erosion Research and Monitoring [Internet]. [Updated 2009]. Conway (SC): Coastal Carolina University; [cited 2009 Sep 11]. Available from: <http://www.coastal.edu/cmws/projects/berm/index.html>

E) Rhode Island

- 1) The Partnership for Mapping Coastal Soils and Sediments [Internet]. [updated 2008]. (RI): MapCoast Partnership; [cited 2009 Sep 1]. Available from: <http://www.ci.uri.edu/projects/mapcoast/default.html>

Appendix E: Comparative Matrix

The matrix is being reviewed and will be submitted for publication approval by the Gulf of Maine Council on the Marine Environment. If approved, the matrix will be posted on the [Gulf of Maine Mapping Initiative](#) website. If you are seeking a draft of this document immediately, please email [Megan Tyrrell](#) or access Northeast Coastal and Barrier Network at <http://science.nature.nps.gov/im/units/ncbn/index.aspx>.

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