Technical Report

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Abstract

The commercial potential of the autonomous underwater vehicle (AUV) is now just beginning to be realized in the fields of environmental monitoring, oceanographic sampling, and undersea search and survey. The AUV was initially conceived as a naval ordnance delivery technology (torpedo), but its possible uses have expanded with revolutions in microelectronics, computing, sensing, battery technologies, acoustics, and miniaturization. MIT's Odyssey II vehicle exemplifies progress in this area. Even with these advances, however, we regard the AUV technology as still in the infancy of its commercial potential. In this report, we examine the potential opportunities—both public and private—for the application of AUV technologies in Massachusetts Bay. Our examination involves interviews with a number of experts in the AUV field as well as a survey of natural resource managers and ocean users in Massachusetts Bay. The common opinion we have encountered in the course of this study is that, *at present*, few if any existing research questions or monitoring tasks specifically concerning Massachusetts Bay, including the Boston Harbor Outfall Project, can be better addressed using AUVs than with conventional technology. This conclusion results in part from the fact that traditional research questions and monitoring tasks are themselves posed in terms of conventional technology. Nevertheless, a prime opportunity offered by the Boston Harbor Outfall study is to frame new questions and paradigms to demonstrate the applications of AUVs. Given the backdrop of existing monitoring infrastructure associated with this project, MIT Sea Grant might issue a challenge to proponents of AUVs to demonstrate the suite of new capabilities, insights, economies, and needed technologies. With appropriate support, such a challenge could do much to advance the use of this class of vehicle.

1. Introduction

This report summarizes the potential opportunities for use of the MIT autonomous underwater vehicle (AUV) "Odyssey II" and other AUVs in Massachusetts Bay. Bay users now monitor the environment with a range of different technologies. Although still in the R&D phase, autonomous underwater vehicles (AUVs) represent alternative sampling platforms that may reduce the costs of environmental monitoring in some applications or open new possibilities for characterizing complex environments. As a result, there may exist a market for the services of AUVs in Massachusetts Bay.

In this report, we distinguish between the *need* and the *demand* for the environmental monitoring services of the Odyssey II system. In economic terms, the demand for environmental monitoring services is a need backed by both an ability and a willingness to pay for them. Several experts contacted by the authors have identified needs for the kind of data that might be generated by AUVs in Massachusetts Bay. If potential users are neither able nor willing to purchase AUV systems or services, however, then there is no market.

One way in which to measure potential demand is first to forecast the growth of industries or activities that either currently or might in the future possibly require the services of AUVs. These industries and activities include surveys of subsea telecommunication cables and energy pipelines; naval mine countermeasure tasks; underwater oil and natural gas exploration, development and production; underwater mining for hard minerals or gems; fisheries stock assessments; pollution monitoring, such as the tracking of gradients or plumes; marine search and salvage; scientific uses, such as surveys of hydrothermal vents or plankton blooms; and underwater archaeological exploration (Merrill 1999; Stone 1999; Irion 1998; Nadis 1997; Fricke 1994).

Forecasting the growth of ocean industries that might require the use of AUVs is beyond the scope of this study. Other analysts recently have published estimates of the growth of some industries that might employ AUVs. For example, John Westwood, a British marine industry analyst, predicts that the world offshore oil and gas survey field will grow from the 1998 level of $1.1 billion to $1.5 billion in 2003 (Westwood 1999).[1] Westwood believes that AUVs will garner a share of this market, but he has not published an estimate of the size of the share. Another prospective growth industry is transoceanic fiber optic cables. KMI Corporation and Pioneer Consulting expect the international fiber optic cable market to grow from about $12 billion in 1997 to $28 billion in 2003, representing a total of 890,000 km of undersea cable (ON&T 1999). This market may hold significant potential for AUVs serving in a survey mode, but this potential is as yet untapped. In contrast, even though oceanographers have argued for the development of worldwide "autonomous oceanographic sampling networks" involving potentially large numbers of AUVs (Webb, p.c., 1998; Kunzig

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[1] Westwood also estimates that the world subsea production market will grow from $5 billon in 1998 to $7 billion in 2003 and the total world nondefense ("civil") marine market may be as large as $30 billion in 2003 .

1996; Curtin *et al.* 1993), U.S. federal agency commitments to fund instrumentation may be waning (Irion 1998).[2]

Once industry growth projections are constructed, the costs of current technologies would need to be compared to the costs of AUVs. For example, the costs of existing technologies for environmental monitoring (ship time, labor, data processing) would need to be compared with the costs of deploying AUVs *per unit of sampled environmental data.* These costs include both capital costs and operating costs. At present, the capital costs of AUVs range from $50,000 to $500,000 per vehicle (Irion 1998). Some large-scale AUVs developed for military uses can cost more than $1 million (Curtin *et al.* 1993). Operating costs depend upon the method of deployment, the type of energy source, and the method of navigation. Operating costs may be as low as $1,000 per day for small AUVs that can be deployed from a small vessel (SPI 1999). If the expected unit costs of environmental monitoring using AUVs are less than or equal to those for alternative technologies, then a market for AUV services must exist.

AUV technology is still in a nascent stage, although it is developing rapidly. The AUV technology typically is described as having three potential economic advantages over current environmental monitoring and oceanographic sampling technologies (White 1999a; Fricke 1994). First, concerns about human safety that arise when humans scuba dive or descend in submersibles are removed through the use of remotely operated (ROVs) or autonomous vehicles.[3] Second, an AUV potentially can exhibit more freedom of movement because it is not fixed in one place, like a buoy, cumbersome to move, like a research vessel, or tethered to a surface vessel, like an ROV.[4] AUVs might be used to complement ROV or submersible surveys to enhance "lateral" coverage or to shuttle samples to the surface (Bellingham 1994). Third, AUVs are cheap to build, and they are potentially expendable.

At present, for coastal environmental monitoring tasks, the potential economic advantages of AUVs may not be fully realized. First, the cost advantage—in terms of reduced risk to human health and lives—is not as significant in shallow water coastal environments as it is in the deep sea. Second, the current state of technology for AUV navigation systems and the requirements for battery power may limit the extent to which AUVs are free to move around in the ocean (Travis 1993). Navigation systems are improving rapidly, but energy systems remain a constraint. One solution is to employ

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[2] This trend may change if recommendations made by the National Oceanographic Research Leadership Council (NORLC) are adopted (see Winokur 1999). A Gulf of Maine regional effort to promote an ocean observing system at different scales has been initiated (Incze *et al.* 1999), but the use of AUVs in that effort has not been a primary focus.

[3] ROVs are underwater vehicles that are connected to a surface vessel with a tether through which power can be supplied, commands can be issued, and data can be sent and received.

[4] MIT's Frank Van Mierlo estimates that the elimination of the tether may reduce costs from between 25 to 75 percent (Merrill 1999).

docking systems (described in the next section) that permit battery recharges. Another solution is to employ fuel cells. Third, AUVs are still fairly costly to build. Small, lower-cost AUVs under development by academic research institutes range from $50,000 to $100,000 (White 1999b), but, ideally, a vehicle for scientific purposes should cost from $10,000 to $50,000 (Curtin *et al.* 1993). Clearly, AUVs have not yet reached the stage at which they might be considered to be expendable.[5]

As depicted in Figure 1, temporal and spatial scale differences among monitoring technologies may render problematic estimates of the demand for AUV services through comparisons of unit costs. Many existing monitoring programs take place on a broad scale. Sampling often is conducted from a research vessel or at data buoy stations. Sample data also may be collected at infrequent, widely spaced intervals. AUV technology permits a different type of sampling that occurs potentially over shorter distances at more frequent intervals.[6] Data can then be uploaded through a docking station and telemetered in real time to shore.

Because of these differences, even though an AUV might collect data that is required for a specific activity, the spatial and temporal needs for data in that activity are not necessarily a close match to the AUV's capabilities for collecting data. Therefore, it may be difficult to measure demand for the AUV's services in this manner.

We have identified a wide range of human uses of Massachusetts Bay and its resources. Each of these uses is potentially associated with measurement of oceanographic or meteorological parameters in the course of doing business or because of regulatory requirements. In this report, we describe the range of human uses and associated environmental monitoring activities (*cf.* Lohse and Kildow 1996). For each activity, we characterize the existing environmental monitoring needs and, where feasible, present data on the costs of environmental monitoring. Based upon interviews with actual users and other experts, we provide a qualitative assessment of the potential of MIT's Odyssey II AUV technology to replace existing sampling technologies.

In the conclusion to this report, we present for each activity in Massachusetts Bay a qualitative appraisal of both the need and the demand for the environmental monitoring services of the Odyssey II system.

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[5] The extent to which AUVs can be considered to be expendable may depend upon the mission and the relative costs of alternative technologies. MIT's Jim Bellingham has suggested that AUVs costing around $16,000 might be considered expendable in the application of oceanographic exploration (Nadis 1997).

[6] Note that the ABE vehicle has been designed to extend the time scale constraint depicted in Figure 1 to between 10^2 and 10^3 days.

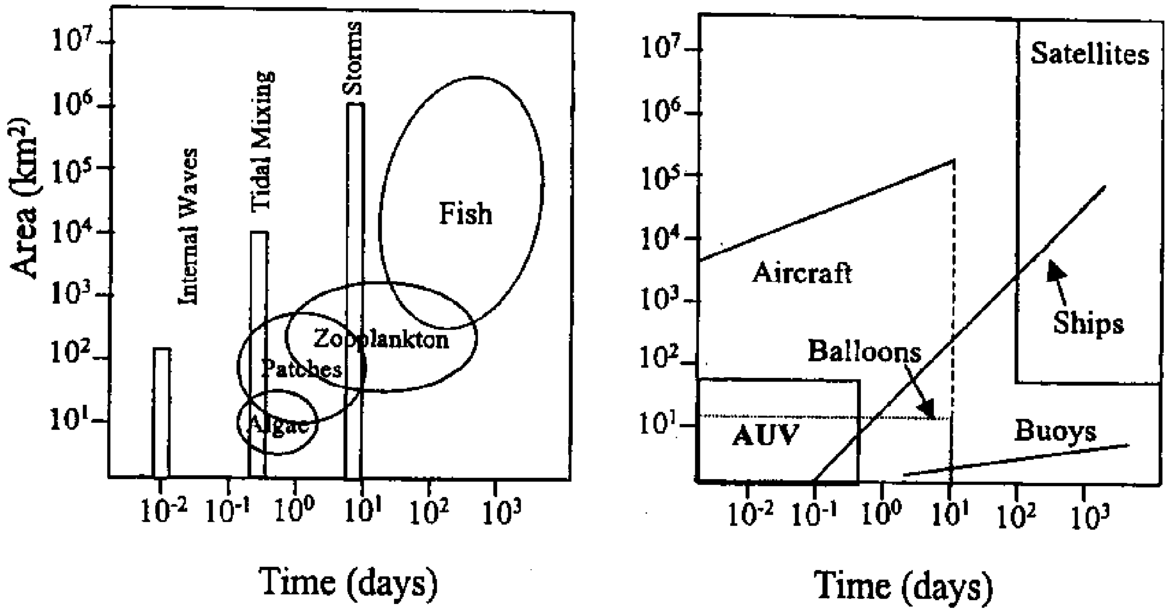

Figure 1. Spatial and temporal scales associated with selected environmental/ecological parameters and sampling/monitoring technologies

2. Basic Features and Modes of Deployment for AUVs in Coastal Monitoring

This section summarizes the principal operating features and deployment modes that distinguish AUVs from more conventional oceanographic research platforms and technologies. Additional detail on the specifications, applications, and foreign and domestic developers of more than sixty AUVs is provided in table 1.

Table 1 identifies the name of each AUV, its developer or owner, and the nationality of the developer or owner. Next, the following AUV characteristics are compared: capital cost; length (in meters); width (in meters); the energy source (type of battery or fuel cell); form of navigation (described below); weight (in kilograms); maximum speed (in nautical miles per hour); maximum depth (in meters); and range (in kilometers). For at least three reasons, table 1 has not been filled in completely. First, AUVs are developed for different purposes, and descriptive data that are useful for some AUVs may not be particularly relevant for others. Second, many of the AUVs listed are still in the development phase, and their capabilities and characteristics are under constant modification. Third, some of an AUV's characteristics or capabilities may be considered proprietary.

There are several forms of navigation (Fricke [1994] presents a useful overview of the types). The first form of navigation is known as "dead reckoning" (DR). An AUV can be preprogrammed to navigate a trackline, logging the desired data at a preprogrammed interval. The position of the vehicle is estimated based upon its initial location and its velocity. The vehicle is retrieved at a preprogrammed or acoustically marked destination for data retrieval, recharging, or recovery. A sophisticated form of dead reckoning, called an "inertial navigation system" (INS), involves the use of gyroscopes and sensitive accelerometers.

A second form of navigation is known as "acoustic navigation" (AN). Pingers planted on the seabed allow the location of the vehicle to be identified with precision. Ultra-short baseline (USBL) navigation uses one pinger for navigation over short distances; long baseline (LBL) navigation employs multiple pingers which are used to triangulate the vehicle's position over long distances. The vehicle's path can be preprogrammed or it can be steered with acoustic telemetry. In the latter mode, the path of the AUV could be modified, but the operator's knowledge of data being logged at any time by the vehicle may be limited by bandwidth of the acoustic telemetry. The vehicle could be retrieved at a preprogrammed or acoustically marked destination for data retrieval, servicing, or recovery. With a ship-based operations center, it is not clear that this application of AUVs would be significantly superior to ROV technology, and in some ways—such as duration of deployment, vehicle speed, telecommunications, and signal processing—it may be inferior.[7]

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[7] In the last two decades, significant advances have been made in the field of underwater acoustic telemetry (Kilfoyle and Baggeroer 1999). Research in this field is now very active, suggesting that improvements in underwater communications are quite likely.

Table 1: Autonomous Underwater Vehicles: Specifications and Applications

Vehicle	Developer/ Owner	Country	Applications	Cost	Length (m)	Width (m)	Energy Source	Navigation	Weight (kg)	Speed (max nmi)	Depth (m)	Range (nmi)
ABE	WHOI	US	Longterm (~1 year) monitoring of the seafloor				Gelled Pb-acid; alkaline; or Li	LBL; DR		2	5,000	27
Aqua Explorer 1000	Tokai University	JP	Inspection of underwater telecommunication cables								1,000	
Aqua Explorer 2	Tokai University	JP	Inspection of underwater telecommunication cables								1,000	
ALACE	Webb Research Corp.	US	Repeated vertical profiles of large-scale, low-frequency currents	$10k	1.0	0.2	Alkaline	none	23		2,000	
ALUV	Naval Postgraduate School	US	Mine countermeasures in shallow water and the surf zone									
APEX	Webb Research Corp.	US	Repeated vertical profiles of large-scale, low-frequency currents; active depth control	$10k	1.3	0.2	Alkaline	none	24		2,000	
ARCS	International Submarine Engineering Ltd.	CA	Under-ice hydrographic surveys		6.5	0.7	Al-O fuel cell; Pb-acid; Ni-Cd	INS	1,840	5	400	180
Aurora	International Submarine Engineering Ltd.	CA	Sidescan sonar		2.7	0.9	Li	INS; USBL	430	4	3,000	400
AUSS	SPAWAR San Diego	US	U.S. Navy deep ocean search; sonar-optical seabed imaging	>$1m	5.2	0.8	Ag-Zn	INS; ADL	1,270	5	3,658	50
Autosub-1a	Ocean Technology Division, Southampton Oceanography Centre	UK	Upper-ocean marine science		6.8	0.9	Mn-alkaline, Pb-acid	TBN; DR	1,700	4	500	142
CETUS	Lockheed/MIT	US	Mine reconnaissance and neutralization		1.8	0.8	Pb-acid		100	5	4,000	40
CR-01	Shenyang Institute of Automation	CH	Exploration of deep-sea mineral deposits; hydrography		4.4	0.8	Ag-Zn	LBL	1,300	3	6,000	46
Darpa UUV	Draper Labs	US	Marine reconnaissance and search	>$1m	10.7	1.1	Ag-Zn			10	1,500	240
Deepscan	Sias Patterson Inc. Newport News Shipbuilding	US	Oil, telecomm cable and marine surveying							4	4,000	120
DRIP	KISS Institute for Practical Robotics	US	Testbed; follows a light beam	$1k								
EAVE-III	MSEL/AUSI Univ. of New Hampshire	US	Testbed for environmental monitoring									
EMATT/ SUBMATT	Sippican	US	ASW training target									

Vehicle	Developer/ Owner	Country	Applications	Cost	Length (m)	Width (m)	Energy Source	Navigation	Weight (kg)	Speed (max nmi)	Depth (m)	Range (nmi)
Fetch	Sias Patterson Inc.	US	Marine science and surveying		1.7			DR	77	9	305	10
Flipper	Tokai university	JP	Testbed									
Free Swimmer II	SPAWAR San Diego (US Navy)	US	Offshore oil and gas pipeline and structures inspection									
FTAUV	Florida Institute of Technology	US	VHR laser imaging		3.7	0.3	Pb-acid	RF link	9	8	30	48
Hammerhead	Cranfield University	UK	Testbed; conversion of navy "deep mobile target"		3.0	0.3						
HIUV-2	Harbin Engineering University	CH	Survey hydrostatic damage of riverbanks		4.0	0.8		DR	900	4	50	
HUGIN I and II	Statoil, FFI, Norwegian Underwater Intervention A.S., Kongsberg Simrad A.S.	NO	Bathymetric surveys (pipeline routes); environmental monitoring; fishery research; mine countermeasures		4.8		Ni-Cd; Semi-fuel cells	LBL	700	4	600	144
JANUS	Johns Hopkins University	US	Testbed		1.3	0.5		DR	90			
Kambara	Australian National University	AU	Testbed									
LDUUV	Naval Underwater Warfare Center	US	Testbed for advanced sensors and payloads	>$1m	7.6	0.7	Ag-Zn	DR; LDL; INS	2,359	12	183	30
MADDOG	Florida Atlantic University	US	Oceanographic measurements	$5k		0.1		DR	20	4	300	
Manta-Ceresia	University of Tokyo	JP	Testbed		0.5	0.6	Ni-H cell	RF link	14	2	10	5
Martin 200	Maridan	DK	Bathymetry, Sub-bottom profiles, cable inspections, pipeline inspections		4.6	1.1	Pb-acid		998		200	48
Martin 1000	Maridan	DK	Bathymetry, Sub-bottom profiles, cable inspections, pipeline inspections		4.6	1.1	Ag-Zn		998		1,000	48
Microseeker	Hylands Underwater Vehicles	US	Testbed; micro-AUV		0.3	0.1	Alkaline AA	DR	1		50	
MRUV	Sippican	US	Mine reconnaissance underwater vehicle									
MUST Lab	Lockheed Martin	US	Testbed for AUV propulsion systems	>$1m	9.1	1.4	Pb-acid		8,845	8	610	120
NUI Explorer	Norwegian Underwater Intervention A.S.	NO	Subsea installation surveys; pipeline mapping, bathymetric surveys, search		4.8			Preprogrammed; Acoustic adjustments	700	4		144
Ocean Explorer	Florida Atlantic University	US	Environmental monitoring		3.2				408	3	305	30

Vehicle	Developer/ Owner	Country	Applications	Cost	Length (m)	Width (m)	Energy Source	Navigation	Weight (kg)	Speed (max nmi)	Depth (m)	Range (nmi)
Ocean Voyager II	University of South Florida; Florida Atlantic University	US	CHIRP sidescan and sub-bottom profiling; other sensors; groundtruth coastal satellite data					LBL				
ODIN	University of Hawaii	US	Testbed		0.6		Pb-gel	INS				
Odyssey I	MIT	US	Basic oceanographic research; environmental monitoring	$50k	2.1	0.6	Li	DR; LBL			6,000	540
Odyssey II	MIT	US	Basic oceanographic research; environmental monitoring	$70-100k	2.1	0.6	Ag-Zn	DR; LBL; USBL	163	3	6,000	30
Otter	MBARI	US	Seafloor imaging and video mosaicing									
Phoenix	Naval Postgraduate School	US	Experimental shallow water mine reconnaissance and neutralization		2.1	0.5	Pb-acid	INS	204	5	9	15
Pilotfish	Nekton Technologies	US	Operation in high-energy environments		1.0	0.5			105		100	
PTEROA150	Tokyo University	JP	Testbed		1.6	1.2	Ni-Cd	INS	220	3	2,000	22
PTEROA250	Tokyo University	JP	Testbed; underwater photography		2.6	2.0	Ni-Cd	INS	1,000	4	6,000	22
PURL	Simon Fraser University	CA	Ocean sensor testbed for ISER's Aurora		1.1	0.7	Pb-acid		70	1	100	2
PURL II	Simon Fraser University	CA	Small area lake search and survey		1.9	0.2	Gel Cells		70	1	70	
R1	Tokyo University; Mitsui Engineering and Shipbuilding	JP	Environmental monitoring		8.3	1.2	Closed-cycle diesel engine	INS; USBL	4,410	4	400	38
REDERMOR	Underwater Robotics Department, GESMA	FR	Remote mine hunting		6.0	1.0	Cd-Ni	LBL; DR	2,700-3,200	10	200	36
REMUS	Oceanographic Systems Laboratory WHOI	US	Environmental monitoring	$70k	1.3-2.3	0.2	Pb-acid; Li	USBL; LBL	45			11 32
RMS	U.S. Navy	US	Semi-autonomous; semi-submerged mine hunting									
SAUVIM	Autonomous Systems Laboratory, University of Hawaii	US	U.S. Navy intervention missions using a supervisory controller and mechanical manipulator arm		6.1	2.1	Pb-acid	TBM; controllable beam laser	6,000	3	6,000	20
Slocum Glider	Webb Research Corporation	US	Long-term upper-ocean temperature monitoring	$40-50k	1.8	1.0	Thermal propulsion engine		60	0.8	1,200	35,040
Seashuttle	APL, University of Washington											

Vehicle	Developer/ Owner	Country	Applications	Cost	Length (m)	Width (m)	Energy Source	Navigation	Weight (kg)	Speed (max nmi)	Depth (m)	Range (nmi)
Sea Squirt	MIT	US	Coastal environmental monitoring and testbed	$40k	1.0			LBL				
Sireno	IFREMER	FR	Environmental monitoring		1.7	0.01	Rechargeable D cells; LI		25	12		
STDV	Naval undersea Warfare Center	US	Technology testbed for the MANTA UUVs (sensors, weapons, countermeasures)		10.4	2.4	Pb-acid		7,256	10	244	25
Swimmer	Cybernetix	FR	Umbilical AUV system for use at subsea oil production facilities								400	
Theseus	International Submarine Engineering Ltd.	CA	Laying underwater fiber-optic cable	$2m*	10.8	1.3	Ni-Cd; Ag-Zn	DR; LBL	8,600	4	1,000	920
21UUV	Naval Underwater Warfare Center	US	Testbed for advanced sensors and payloads	>$1m	6.4		Ag-Zn	INS	1,270	18	457	8
TAIPAN	LIRMM	FR										
Twin Burger	Institute of Industrial Science, University of Tokyo; Toyota	JP	Testbed for software development		1.5	0.9			120		50	
XP-21	Applied Remote Technology (Raytheon)	US	Testbed for reconnaissance and mine countermeasures	$1m*	5.5-10.7	0.9	Pb-acid; Al-seawater fuel cell		816		610	

An alternative mode of navigation is "terrain based navigation" (TBN), in which sonar images of the seafloor are compared to a pre-existing map of the seafloor. This mode of navigation is limited to areas where the seafloor has been mapped in sufficient detail.

One of the more valuable applications of AUVs would require the vehicle to modify its track depending upon what it is sensing along the way. For example, if an AUV could sense chlorophyll (fluorescence) or turbidity, with proper sensing and control engineering, the vehicle could be used to contour the boundaries of an algal bloom or a sediment plume. Such contours at several depths would provide valuable information that could not be obtained readily by any other means.[8] The vehicle could be retrieved at a preprogrammed or acoustically marked destination.

Alternatively, an AUV may be deployed from a coastal site without use of a large vessel. The AUV would navigate a trackline and return to a designated location (predetermined or acoustically marked). A principal advantage of this approach would be the elimination of vessel-related costs and possible independence of related weather windows.

Engineers at WHOI and MIT have demonstrated the capability and practicality of using a remote docking station as a long-term base of operation for AUVs (von Alt, p.c., 1998). This has been demonstrated in the deep sea by the Autonomous Benthic Explorer (ABE) and in coastal waters using the Remote Environmental Measuring Units (REMUS) at LEO 15 off the coast of New Jersey and by MIT Sea Grant's Odyssey II in Massachusetts Bay. If the docking station is attached to the shore by fiber optic cable and power cable, as for LEO 15, the AUV can be recharged, data downloaded, and the mission reprogrammed for subsequent assignments. These features, employed at a docking station with its own immobile sensing array, such as at Leo 15, add a significant dimension to the overall sensing capabilities of the installation. Alternatively, docking stations could be used for only some of the above functionalities: battery recharge, data telemetry, or mission revision.

Given the feasibility of docking stations, there is no reason why a coastal area could not be equipped with several docking stations to extend the range or survey capabilities of one or more AUVs.

3. Relevant Activities and Demand for AUV Services in Massachusetts Bay

Table 2 matches the different types of marine activities that take place in Massachusetts Bay with the kinds of environmental parameters or measurements that are taken in support of that activity (check marks). The presence of the letter "R" next to a check mark indicates that government regulations may specifically require that the relevant parameters be sampled.

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[8] In-situ measurements of chemicals—some in low concentrations—is an important and active research field (see, for example, Byrne *et al.* 1999).

Table 2: General Ocean Uses in Massachusetts Bay and Relevant Environmental Parameters/Measurements

	Salinity	Temperature	Depth	Dissolved Oxygen	Surface Wind Speed	Surface Currents	Current Profile	Phloresconce	Toxic Algae	Zooplankton	Benthic Biota	Stock Assessments	Pollutants (Water)	Pollutants (Benthos)	Turbidity	Nutrients	Sonar Mapping	Subbottom Profile	Video/Still Imaging	Magnetometer	Geological Sampling
Basic & Applied Oceanography	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wastewater Disposal (Boston Outfall)	✓R	✓R	✓R	✓R	✓R	✓R	✓R	✓R		✓R	✓R		✓R	✓R	✓R	✓R					
Dredged Material Disposal	✓R	✓R	✓R	✓R		✓R	✓R	✓R	✓R	✓R	✓R		✓R	✓R	✓R	✓R	✓	✓	✓		✓
Commercial Fishing		✓	✓		✓	✓						✓					✓				
Recreational Fishing		✓	✓		✓	✓						✓					✓				
Stock Assessments	✓	✓	✓	✓								✓					✓		✓		
Ecological/Habitat Monitoring	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		
Cetacean Research	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓				✓		
Aquaculture	✓	✓	✓	✓			✓	✓	✓	✓	✓		✓R	✓R	✓	✓R			✓		
Whale Watching		✓	✓		✓	✓			✓	✓		✓							✓		
Sand & Gravel Mining	✓R	✓R	✓R	✓R			✓	✓R	✓R	✓R	✓R		✓R	✓R			✓	✓	✓		✓
Archaeology/Salvage			✓				✓								✓		✓	✓	✓	✓	
Commercial Shipping			✓		✓	✓							✓R	✓R							
Recreational Yachting					✓	✓															
[redacted]	✓	✓	✓				✓										✓	✓	✓		

✓ = Activity measures parameter as a course of doing business. R = Activity is required to measure parameter by regulation.

Bellingham (1998) identifies the following types of sensors that can be mounted on the Odyssey II:

- conductivity-temperature-depth (CTD)
- 150, 300, and 1200 kHz acoustic Doppler current profiler/Doppler velocity log (ADCP/DVL)
- 8 element acoustic acquisition array
- sub-bottom pinger
- ultra-short baseline (USBL) tracking system
- optical backscatter (OBS)
- video camera
- video frame-grab image capture system

A utility acoustic modem can also be included on the AUV for communication with docking buoys. As currently configured, the Odyssey II does not collect physical samples of the water (in bottles), although it may be possible to incorporate physical sampling in the future (Morris, p.c., 1998).

The bottom row of table 2 identifies the existing capabilities of the Odyssey II system, showing the extent to which Odyssey II is theoretically capable of meeting the environmental monitoring needs of the different activities in Massachusetts Bay.

3.1 Basic and Applied Oceanography

The U.S. Geological Survey (USGS) has been involved in oceanographic research to predict the long-term fate of sediments and contaminants in Massachusetts Bay (Butman and Bothner 1998). The work incorporates data from two stations in the bay: a subsurface one located near the site of the Boston Harbor wastewater outfall, and one near Scituate. The stations sample currents and CTD and take pictures of bottom sediments to develop a "regional picture" of the overall sediment environment of the bay. In cooperation with the Coast Guard, the stations are visited to collect the data for about 3 days every 4 months. Some bottom chemistry is also collected during these visits.

USGS is now building a telemetry system so that data can be collected in real time. The data may be displayed at the New England Aquarium. For the subsurface station, this will require an acoustic link between the sensor and a surface buoy. One advantage is that it will be possible to tell immediately when the instrument fails or to reprogram the sampling regime. It may still be necessary to visit the instruments every 4 months or so for antifouling and other maintenance.

An AUV may be useful in this broad-scale characterization of the sediment environment (Butman, p.c., 1998). For example, repeated transects by an AUV could be used to collect data on large-amplitude internal waves that flow over Stellwagen Bank. There is scientific interest in this phenomenon because of the possibility that the internal waves may mobilize contaminants from wastewater outflows that have settled in Stellwagen Basin. Such a mobilization could be detrimental to the fish and mammal stocks on the Bank.

In the realm of applied oceanography, the National Ocean Research Leadership Council has released a report to Congress (NORLC 1999) calling for an integrated ocean observing system that would expand, coordinate, and sustain the nation's existing "disparate observational systems and data sets to maximize their utility for many users and purposes" (NORLC 1999:exsumm.html). The report identifies seven important national needs to be met by such a system: forecasting climate variability; facilitating safe marine operations; ensuring national security; managing living resources for sustainable use; preserving healthy marine ecosystems and restoring degraded ones; mitigating natural hazards; and ensuring public health.

NORLC envisions a system in which AUVs deployed in coastal waters will contribute continuous measurements of temperature and salinity; daily or monthly measurements of phytoplankton biomass; and yearly measurements of benthic species biomass (NORLC 1999:chap3.html, Table 3.3-2). The infrastructure plan calls for the concentration of monitoring sites to be highest in coastal waters, particularly those off major population centers. Such a system, assuming it is funded, represents long-term demand for a modest but potentially expanding array of AUV services in Massachusetts Bay (and in other coastal locations around the country).

3.2 Wastewater Disposal - Boston Harbor Outfall

The Boston Harbor Outfall project is the result of a 1986 court order requiring the Massachusetts Water Resources Authority (MWRA) to bring wastewater treatment in the greater Boston area into compliance with the 1972 Clean Water Act. The main elements of the outfall project are new primary and secondary wastewater treatment plants; a 9.5-mile outfall pipe that will carry effluent beyond Boston Harbor for discharge in the much deeper waters of Massachusetts Bay;[9] and monitoring for environmental impacts. The entire system is slated to be fully operational in November 1999 (Hunt, p.c., 1999). It is expected to have "very limited" environmental effects in Massachusetts Bay and "virtually no effect on Cape Cod Bay" (MWRA 1997c:1).

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[9] The outfall pipe is equipped with 440 diffuser ports over the last 1.25 miles of its length. Discharge from the outfall pipe will be diluted in water depths of 100 feet in Massachusetts Bay, as opposed to the 30-foot depths of Boston Harbor.

MWRA's outfall monitoring program reflects a combination of EPA regulatory and court-ordered requirements. A wide range of environmental parameters are monitored for compliance with the National Pollutant Discharge Elimination System (NPDES) permit under which the completed system will operate, and for potential impacts beyond those predicted and deemed acceptable in the EPA's Supplemental Environmental Impact Statement. Monitoring will also support long-term management of the outfall itself (MWRA 1997a). Baseline environmental monitoring (Phase I) has been ongoing since 1992, and post-discharge monitoring (Phase II) will commence as soon as the outfall pipe is fully operational. Not including certain special studies, the monitoring program is designed to measure the same environmental parameters and to employ consistent data-collection methods across the two phases.

To date, baseline monitoring has provided greatly enhanced understanding of the natural seasonal variability of the Massachusetts Bay system, as well as evidence of substantial water-quality improvement in Boston Harbor as a result of system changes and upgrades that have already been completed.[10] Post-discharge monitoring will test whether change within the natural system exceeds certain levels identified in an MWRA Contingency Plan as "Caution" and "Warning" thresholds. The Contingency Plan is designed to set in motion a process for confirming parameter excedance, determining its causes and significance, and identifying appropriate responses if the changes are found to be attributable to the outfall (MWRA 1997c).

Table 3 provides a summary of the specific environmental parameters monitored by the MWRA (see also table 2), which fall into six categories of wastewater constituent: nutrients, organic material, toxic contaminants, pathogens, solids, and floatables. Monitoring is carried out in four general categories of sample location—effluent stream, water column, benthos, and fish and shellfish tissue—and involves a combination of physical sample collection and analysis, moored sensing, remote satellite sensing, plume tracking, and acoustic surveying. Sampling frequencies range from continuous sampling of basic oceanographic conditions (i.e., temperature, salinity, water clarity, chlorophyll) to annual surveys of hard bottom topography and contaminant concentrations in fish and shellfish.

Of the many requirements and activities that comprise the MWRA's outfall monitoring program, AUVs are most suited to perform certain components of water column monitoring that do not involve continuous sensing or physical sample collection. The main possibilities are periodic surveys of water quality and plankton abundance, and special plume-tracking studies. Even in these areas, however, it is not clear that AUVs, at least at their current state of development, would necessarily do the job better or more cost-effectively than the methods and technologies that MWRA currently employs for these tasks.

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[10] Improvements in water quality have been documented following upgrades in piping, pumping, and scum removal systems in the 1980s (MWRA 1993), the discontinuation of sludge disposal in Boston Harbor in 1991 (MWRA 1993), and the start-up of the new primary treatment plant in 1995 (MWRA 1997b).

Table 3: Trigger Parameters for MWRA Outfall Monitoring Program

Monitoring Area	**Trigger Parameter**
Effluent	Total suspended solids
	Biological oxygen demand
	Pathogenic indicator bacteria
	Nitrogen loading
	Toxic metals and organic chemicals
	Toxicity testing
	Floatables
	Oil and grease
	Plant compliance with permit limits
Water Column	Dissolved oxygen concentration
	Dissolve oxygen respiration rate
	Chlorophyll
	Nuisance and noxious algae
	Zooplankton
	Diffuser mixing
Benthos	Benthic community structure
	Sediment oxygen
	Sediment toxic metal and organic chemicals
Fish and shellfish	Mercury and PCBs in flounder, lobster, mussels
	Lead in mussels
	Lipophilic toxic contaminants
	Liver disease in flounder

Source: MWRA 1997a (Table 1-2, p. 1-4).

Regular surveys of the water column are conducted at 5 depths (surface, pycnocline, near-bottom, and two intermediate depths) at each of 47 sampling locations in Boston Harbor, Massachusetts Bay, and Cape Cod Bay (see Figure 2). The 21 nearfield locations (defined by MWRA [1997b] as being within a rectangle with sides 5 km from the outfall) are surveyed 17 times per year, and the 26 farfield locations (farther than 7 km from the outfall) are surveyed 6 times per year.[11] In addition to 10 water-quality measurements taken at all 47 locations (temperature, salinity, dissolved oxygen, plankton, nutrients, solids, chlorophyll, water clarity, photosynthesis, and respiration), the nearfield surveys include observations of marine mammals and sea turtles as well.

The regular surveys are performed from a research vessel of approximately 45 feet, which is staffed by a captain, a whalewatcher, a lead scientist, and 2 - 3 technicians. The entire program of regular water-column monitoring requires an average of 49 days at sea each year,[12] which suggests an estimated annual cost in excess of $100,000.

At their present stage of development, AUVs do not appear to offer significant advantages of cost, quality, or convenience over MWRA's regular water-column monitoring program as currently configured. Of the program's 10 regularly sampled parameters, AUVs can deploy sensors capable of detecting excedance of the Caution and Warning thresholds for only two: dissolved oxygen and chlorophyll. Given this limited range of sensing capability,[13] coupled with their unsuitability for collecting physical samples, AUVs do not appear to provide a means to avoid losing sampling days to bad weather[14] or to reduce ship-related sampling costs appreciably.

Special plume-tracking surveys within the Phase II monitoring program may provide some opportunity to exploit the special attributes of AUVs, but even here the opportunities seem quite limited. For each survey, two squares of towed sensor arrays will collect continuous data over the course of one day on salinity, temperature, nutrients, metals, suspended solids, and rhodamine dye tracer. The survey area, which is defined approximately by the horizontal dimensions of the tidal excursion, corresponds to the nearfield sampling area (Figure 2).

AUVs are excellent platforms for tracking dyes and collecting data on parameters that can be sensed electronically. Given the spatial scales involved in the nearfield plume-

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[11] No surveying is done from December through April (Hunt, p.c., 1999).

[12] The overall sampling approach and the selection of nearfield sites were designed to accommodate a one-day data "grab," and sampling of all 47 locations at 5 depths takes 3-4 days (Hunt, p.c., 1999).

[13] An important background consideration is the outfall project's history and continuing prospect of litigation, which is reflected in the monitoring program's exceptionally strong emphasis on high-quality data and thorough quality-control measures.

[14] About 15% to 25% of the planned 49 days of sampling per year are rescheduled because of weather. Although the delays add inconvenience and probably some cost to the sampling program, they do not seriously compromise the results (Hunt, p.c., 1999).

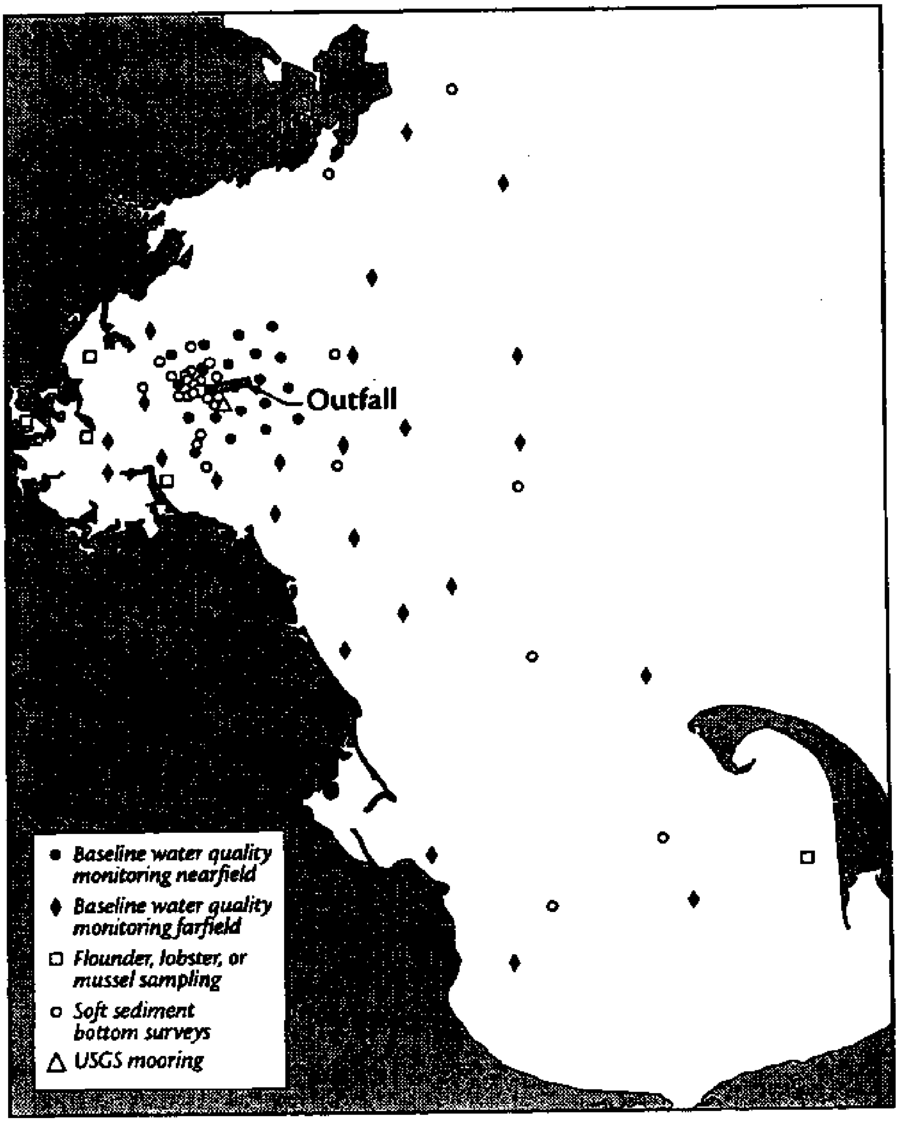

Figure 2. MWRA outfall monitoring locations.
Source: MWRA 1997 c (Fig. 24, pg. 22).

tracking surveys, however, it is unlikely that AUVs can provide a cost-effective alternative to current methods. The estimated costs of the plume-tracking surveys include capital costs of $100,000 to $200,000 for the full suite of sensors, cables, and computers, plus another $25,000 for back-up instrumentation to provide necessary redundancy. In addition, there are annual operating costs of approximately 1/5 person-year to maintain the system in working order and another $1500 for routine recalibration of sensors.

There is, however, one facet of MWRA's special plume-tracking studies for which AUVs are uniquely well suited and where demand may exist for their one-time use. A farfield rhodamine dye experiment is planned for late 1999, which will involve towing a full suite of sensors over a large area to verify the transport process model. This model serves as one basis for predictions of environmental effects within Massachusetts and Cape Cod Bays. Given that the plume is expected to be highly diffused before entering the farfield domain, it may be satisfactory and more cost-effective simply to deploy an AUV to transect the plume, or to use an AUV in conjunction with ships. In the modeling exercise, the boundary conditions are considered crucial, and AUV technology may be especially useful in defining these conditions.

3.3 Dredged Materials Disposal

Harbor and channel dredging and disposal of dredged materials is an activity that requires environmental monitoring, particularly whenever the dredged materials may be contaminated. Currently Massport is conducting a large-scale dredging project in Boston Harbor, where much of the dredged material is contaminated. Massport is employing the "confined aquatic disposal" (CAD) method to dispose of the dredged material. CAD involves the dredging of "cells" in the harbor bottom itself, at a depth of about 40 feet, into which contaminated dredged material is placed before capping with uncontaminated materials. The cells are capped with at least one meter of sand to prevent the migration of contaminated sediments from the cell. The original contents of each cell (primarily clean "blue clay") are taken to a disposal site adjacent to the Stellwagen Bank National Marine Sanctuary. Approximately 4-5 cells are planned in Boston Harbor, including a "supercell" northeast of the Tobin Bridge (Babb-Brott, p.c., 1998).

Regulations currently require monitoring during and immediately subsequent to the capping of each cell. In addition, geotechnical monitoring (multibeam and coring) will occur on an annual basis thereafter. Approximately one-third of the initial monitoring activities will involve geotechnical studies, including subbottom profiling, sidescan imaging, gravity coring, and vibracoring. In addition, video will be taken of recently capped cells for visual analysis of cap integrity. Two-thirds of the monitoring activity involves water column chemistry sampling using sample bottles cast from a research vessel. There will be no monitoring at the Massachusetts Bay site, because clean material is being disposed there.

The Army Corps of Engineers (ACoE) is experimenting with the deployment of tripod sonar reflectors in the cells. These reflectors are placed on top of the dredged material prior to the placement of the cap material. The tripods will not reflect a sonar signal unless the capping material has been eroded or displaced. Annual acoustic passes will permit an estimate of cap integrity based upon the absence of sonar returns from the buried reflectors.

It is possible that an Odyssey vehicle could be used to monitor cap integrity, to map the position and shape of the caps, and to sample some parameters at each of the capped sites. The original CAD plan for Boston Harbor involved the creation of about 50 disposal cells. In this situation, an AUV might provide a cost-effective technology for monitoring at a large number of locations on an annual basis. This argument is not as strong when the number of sites is small, as in the current configuration.

Massachusetts and ACoE are currently involved in developing a Dredged Material Management Plan (DMMP) for the state. In 1996, the Seaport Bond Bill authorized up to $100 million for dredging the ports of the state. Gloucester, Salem, New Bedford, and Fall River are the first four ports to be considered for dredging using these funds. Although all of the conceivable disposal alternatives, including land-based containment, are being considered, in reality CAD appears to be the most cost-effective and environmentally sound disposal technology. For example, a current federal dredging project in Hyannis Harbor involves the construction of a CAD cell. Although the DMMP is still in preparation, it is likely that municipalities will be responsible for management and monitoring of the disposal sites. At this juncture, it appears that these monitoring programs may not be at the scale at which the use of an AUV may be cost-effective.

3.4 Fish Stock Assessment and Management

Fisheries management might benefit from the use of AUVs to monitor fisheries closures, and through acoustic surveys. Stock assessments are still conducted using the time-tested methodology of sampling fish stocks by random tows of trawls. CTD casts are also done with each tow. The Northeast Fisheries Science Center (NEFSC) has just initiated an acoustic sampling program, which is in its third year. Acoustic surveys work well for pelagic stocks such as mackerel and squid. (Atlantic herring are difficult to spot because they have no swim bladders). Groundfish are problematic and difficult to survey with acoustic technologies. In general, it is necessary to verify the target species with either a tow or a video camera. The NEFSC stock assessment chief believes there is a need for broadscale acoustic surveys, but this may not be feasible with AUVs (Azarovitz, p.c., 1998).[15] What may be more feasible is the use of AUVs for fine-scale surveys in specific habitat areas, such as those for juvenile habitat or essential fish habitat. AUVs could also be used for video imaging of shellfish habitat (e.g., scallop beds).

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[15] The Norwegian "HUGIN" AUV has been tested as a fisheries stock assessment tool. One problem is that the AUV platform scares fish away, resuling in a sampling bias (Vestgård *et al.* 1999).

The Commonwealth of Massachusetts Division of Marine Fisheries (DMF) is involved in stock assessment, using a modified dragger, of the species assemblage in inshore waters, including Massachusetts Bay (Stevens, p.c., 1998). A one-quarter-inch net is used to sample juveniles. These data are integrated with the wider-scale NMFS assessments in one database. CTD casts and dissolved oxygen are sampled at each station. The Massachusetts assessments tend to focus on groundfish. A separate effort is used to sample quahog densities using hand tongs and hydraulic dredges, and divers are used to map juvenile burrows and habitat for lobsters. Tows are conducted at about 100 stations twice a year (May and September). DMF scientists feel that there may be some potential for using an AUV to survey the coastal river herring stocks (McKiernan, p.c., 1998).

3.5 Ecological Status and Habitat Monitoring

NOAA's National Undersea Research Program (NURP) has funded a "seafloor habitat monitoring program" in Stellwagen Bank National Marine Sanctuary for several years (Auster, p.c., 1998). The focus of the program is to assess and monitor biological diversity. This program involves the deployment of an ROV from a research vessel during about one week per year. A camera sled is towed from a smaller vessel (35-foot boat) for a total of about 30 days per year. Data collected include bottom camera images and CTD measurements.

NURP has proposed a "pelagic fish habitat project" which affords a possible role for AUVs but has not yet been funded. The purpose of the project is to map temporal changes in frontal boundary structures. Data would be collected from CTD and ADCP instruments. Stock assessments using net tows and vessel-mounted hydroacoustic surveys would be used to map changes in the short-term distribution of important species. If funded, the proposed work could include use of an AUV for sampling after storm events or for examining diurnal/nocturnal species behavior.

3.6 Cetacean Research

The Center for Coastal Studies (CCS) in Provincetown has for several years been conducting a program of research focusing on right whales and their environment (Mayo, p.c., 1998). In particular, CCS researchers have studied the behavior of right whales in relation to the spatial distribution of prey plankton species. CCS research focuses on plankton densities "close to the mouth" of the right whale, as opposed to general distribution patterns. CCS conducts about 20 to 25 cruises a year on a 40-foot research vessel. They sample zooplankton in nets close to surface-feeding right whales, and they do logging and vertical CTD casts. They will be using a flourimeter this year to measure phytoplankton and, with MWRA assistance, they will be analyzing nutrients in water samples. Charles Mayo, CCS Director, has an interest in the potential development of an AUV fitted with a particle counter or a video plankton recorder (VPR) that might be able to follow particle gradients. Such a technology, if it could be developed, would permit insight into the subsurface feeding behavior of the right whale. Application of this technology would complement the existing sampling and research programs at CCS.

The Cetacean Research Unit (CRU), a nonprofit environmental research center in Gloucester, has been studying the feeding behavior of humpback whales. CRU uses a 50 kHz echosounder on a 27-foot research vessel from one to four days a week from April through November. The echosounder is used to map the vertical density of prey species, especially the sand lance, and relate that density to the feeding behavior and decisionmaking of humpbacks. According to CRU, the Odyssey II vehicle would be useful for collecting data on the vertical distribution of humpback prey (Weinrich, p.c., 1998).

3.7 Activities Generating No Current Demand for AUV Services

Certain activities represent significant or potentially significant uses of Massachusetts Bay that so far have not generated demand for AUV services. These activities are briefly reviewed below, beginning with those where potentially important AUV applications have been identified but demand has not yet materialized—whether because relevant aspects of the activity itself are not yet sufficiently understood (e.g., fishing) or because the scale of the activity does not currently justify such an expenditure (aquaculture, whale watching, sand and gravel mining, archaeology/salvage). Other activities for which demand is likely to remain limited to infrequent events (oil spill monitoring resulting from commercial shipping accidents) or is essentially nonexistent (recreational yachting/boating and whalewatching) are not analyzed.

3.7.1 Commercial and Recreational Fishing. Use of AUVs by commercial fishing operations is presently at the conceptual level. Environmental data collected and utilized by commercial fishing include surface conditions, depth, and acoustic location of fish stocks. It has been suggested that AUVs could monitor corridors for fish movement, thereby enhancing the effectiveness of trawler operations (SPI 1999). Acoustic location of pelagic fish stocks might be feasible with an AUV, but at present this does not appear to be cost-effective. Identification of oceanographic temperature or density "fronts" may be useful if correlated with the location of target stocks (Auster, p.c., 1998). Understanding the association between fronts and stocks is an undeveloped area of research. Recreational fishing operations, where the need for environmental data is similar to that for commercial fishing, are also unlikely to be major users of AUV technologies in the foreseeable future.

3.7.2 Aquaculture. There are only a few offshore aquaculture operations in Massachusetts Bay. These involve small-scale scallop cage operations off Provincetown (Dutra Project) and at select locations in the Bay. Most aquaculture is nearshore, focusing on hard clam, mussel, or oyster grow-out operations. One expert on aquaculture technology at MIT Sea Grant believes that there is a need for the collection of real-time data for both coastal and offshore aquaculture (Goudey, p.c., 1998). Important parameters to be measured are temperature, chlorophyll, zooplankton densities, and harmful algal bloom events. Sensors at moored buoys and on AUVs would be useful in this regard. AUVs might have an advantage in monitoring suspended or dissolved effluents under large-scale net-pen operations, such as those for salmon grow-out along the coast of Maine. AUVs could also be used to detect and deter predators, to influence school behavior, or to take biomass measurements (substituting for scuba divers in this regard). Open ocean sites, such as the Seastead site south of Martha's Vineyard, could be monitored with an AUV, which could collect data on scallop health, mortality, movement, and interactions with other species.

3.7.3 Sand and Gravel Mining. Sand and gravel mining is prohibited in the Stellwagen Bank National Marine Sanctuary, and currently there are no such operations in the offshore waters of Massachusetts Bay. Some sand and gravel mining is undertaken closer to shore in connection with beach replenishment and shoreline protection projects. There may be a role for AUVs in learning more about the uncertain effects of such projects on shoreline processes and other coastal uses.

3.7.4 Archaeology/Salvage. There may be a limited need for the sidescan and sub-bottom profiling capabilities of the Odyssey II in a broadscale archaeological assessment or survey of areas in Massachusetts Bay. Historic shipwrecks and other underwater cultural resources are known to exist on Stellwagen Bank and along the Massachusetts coastline. There appears to be minimal need for AUV environmental monitoring in underwater salvage or archaeological study and recovery operations. Demand for these services is nonexistent at present and is not likely to be more than sporadic in the future.

4. Conclusion

This short review suggests that the era of the AUV is still largely ahead of us. The technology is very promising but has yet to demonstrate economic or technological superiority for general-purpose oceanographic research or ecological monitoring purposes. Consequently, the demand for AUV services remains moderate at best, even where the perceived need for such services is relatively high (see table 4).

In part this is because conventional ship-based survey methods, fixed instrument deployments, and ROV alternatives fulfill much of the present operational potential of AUVs. Also, approaches to planning, analyzing, and interpreting field surveys are conditioned by conventional sampling strategies (e.g., vertical profiles at discrete stations).

AUVs are most likely to find initial application as an integrated part of a coastal ocean observation system, such as LEO-15, which already incorporates an AUV, or the comprehensive national system recently proposed by the National Ocean Research Leadership Council.

Table 4: Ocean Use Activities in Massachusetts Bay and the Need/ Demand for AUV Environmental Monitoring Services

Activity	Need	Demand
Basic & Applied Oceanography	High	Moderate
Wastewater Disposal (Boston Outfall)	High	Moderate
Dredged Material Disposal	Moderate	Low
Stock Assessments	Low	Low
Ecological/Habitat Monitoring	Moderate	Low
Cetacean Research	Moderate	Low
Commercial Fishing	Low	None
Recreational Fishing	Low	None
Aquaculture	Low	None
Whale Watching	Low	None
Sand & Gravel Mining	None	None
Archaeology/Salvage	Low	None
Commercial Shipping	Low	None
Recreational Yachting	None	None

We strongly recommend demonstration projects as a way for proponents of AUV technology to test and showcase this class of vehicles. Such projects would be especially useful and productive in areas where conventional survey or research infrastructure is currently deployed, so that comparative assessments of technical and cost benefits can be made. The Boston Harbor Outfall Project provides such an opportunity, and MIT Sea Grant may wish to consider a program to support coordinated demonstration projects for AUVs in this very important, ongoing activity within Massachusetts Bay.

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