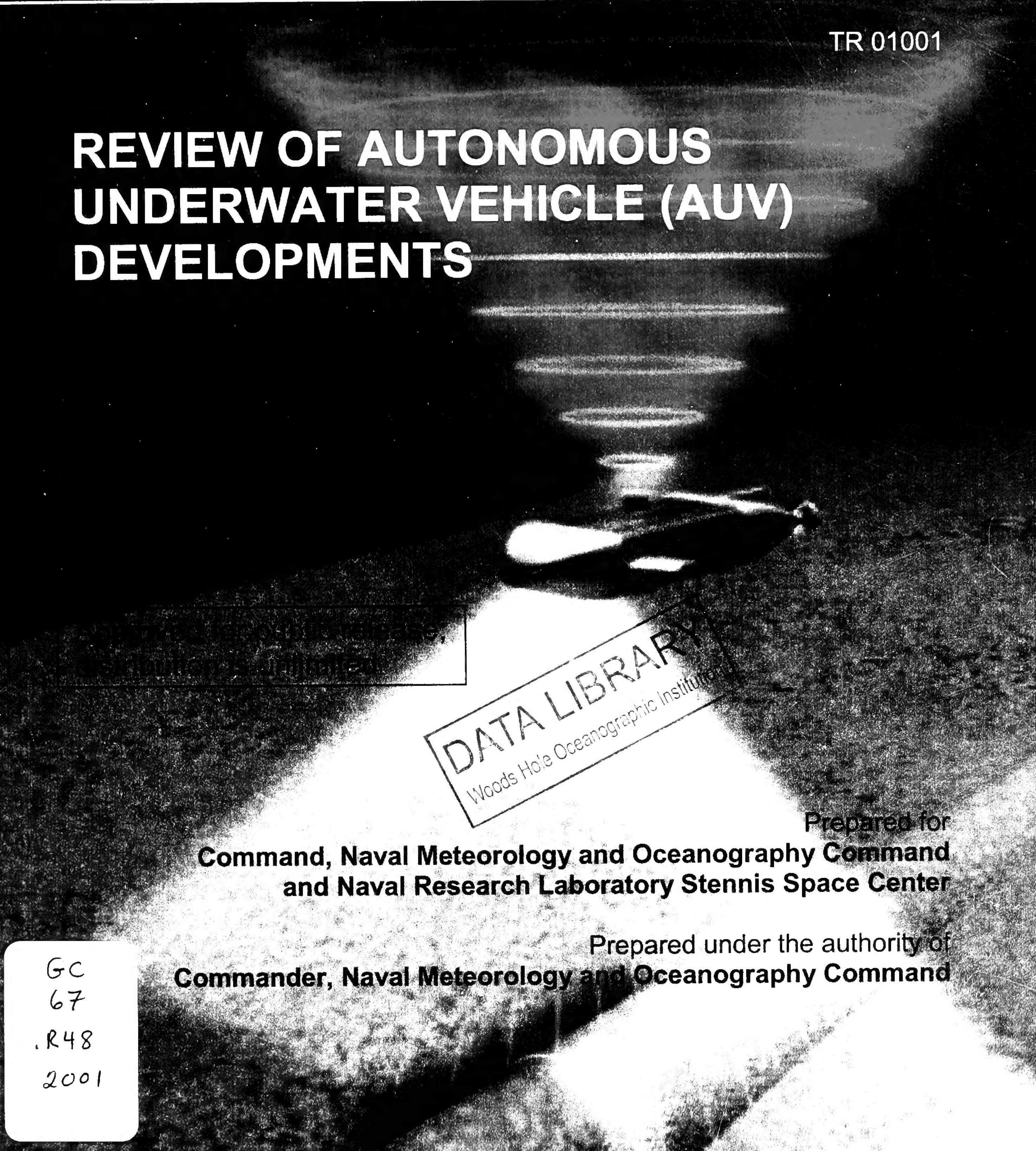
Commander, Naval Meteorology and
Oceanography Command
Stennis Space Center, MS 39522-5001
Technical Report (TR 01001) February 2001

TR 01001

REVIEW OF AUTONOMOUS UNDERWATER VEHICLE (AUV) DEVELOPMENTS



Approved for public release, distribution is unlimited

Prepared for
Command, Naval Meteorology and Oceanography Command
and Naval Research Laboratory Stennis Space Center

Prepared under the authority of
Commander, Naval Meteorology and Oceanography Command

FOREWORD

A maturing Autonomous Underwater Vehicle (AUV) technology currently offers a wide range of applications, for both commercial and military sectors. The Naval Meteorology and Oceanography Command (NAVMETOCCOM), in coordination with the US Navy AUV program, has specific plans for the use of AUVs to augment the NAVMETOCCOM fleet of ocean survey ships. In support of those plans NAVMETOCCOM, the Office of Naval Research and the Naval Research Laboratory have partnered with commercial and academic developers and have provided a test range with exercise opportunities to facilitate AUV technology developments. As a result of those efforts, NAVMETOCCOM is in the process of fielding its first AUV for operational ocean survey.

This report was commissioned to provide a snapshot of the current state of AUV technology, with emphasis on the area we consider is the greatest limiting factor – power sources. We owe a special acknowledgement for the contributions of RADM J. Brad Mooney, USN (Ret), who continues a career dedicated to advancing research and development for naval submersibles.

T. Q. Donaldson V
RDML, U. S. Navy
Commander,
Naval Meteorology and Oceanography Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 2001

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
Review of Autonomous Underwater Vehicle (AUV) Developments

5. FUNDING NUMBERS

6. AUTHOR(S)
RADM Brad Mooney USN (Ret.), Anteon Corp.
Donald Collins, Anteon Corp.
Jerry Boatman, Naval Meteorology and Oceanography Command

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Commanding Officer
Naval Oceanographic Office
1002 Balch Blvd.
Stennis Space Center, MS 39522

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 318

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander
Naval Meteorology and Oceanography Command
1100 Balch Blvd.
Stennis Space Center, MS 39522

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
This report was produced by Anteon Corporation for the Commander, Naval Meteorology and Oceanography Command (COMNAVMETOCCOM). The Naval Oceanographic Office, a subordinate command of COMNAVMETOCCOM, finalized the report and is the distribution point of contact for the report. The inclusion of names of any specific commercial product, commodity, or service in this publication is for information purpose only and does not imply endorsement by the Navy.

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approval for public release, distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report provides information on developments in Autonomous Underwater Vehicles (AUVs) for use in considering and developing plans to improve the mission capability of Commander, Naval Meteorology and Oceanography Command through the applications of AUVs. That mission is to collect, interpret, and apply global data and information for safety at sea, for strategic and tactical warfare, and for weapons systems design, development, and deployments.

14. SUBJECT TERMS
Autonomous Underwater Vehicle (AUV), Unmanned Underwater Vehicle (UUV)

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL

Standard Form 298 (Rev. 2-89) (EG)

Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

In 1991, the Office of Naval Research, the Deep Submergence Office of the U.S. Navy (OP23), the National Science Foundation, the National Undersea Research Program of the National Oceanic and Atmospheric Administration, and the Advanced Research Programs Agency of the U.S. Department of Defense provided funds for the Marine Board of the National Research Council to conduct a study, "Undersea Vehicles and National Needs" [1]. The study was completed and published in 1996. One conclusion of this study stated that undersea vehicle technologies are generally mature enough to permit autonomous underwater vehicles (AUVs) to be built ... designed to work in parallel with survey vessels increasing the efficiency of oceanographic sections and hydrographic surveys. In addition, AUVs are able to operate independently on data-gathering missions to provide detailed information about ocean dynamics, including physical, biological, and chemical processes.

This report provides information on developments in AUVs for use in considering and developing plans to improve the mission capability of COMNAVMETOCCOM through the application of AUVs. That mission is to collect, interpret, and apply global data and information for safety at sea for strategic and tactical warfare and for weapons system design, development, and deployment.

AUVs hold great promise for enhancing Naval tactical oceanography knowledge. The need for real-time littoral zone oceanographic capabilities is described by the National Research Council Naval Studies Board [2].

On November 28, 1995, the Chief of Naval Operations requested that the National Research Council initiate (through its Naval Studies Board) a thorough examination of the impact of advancing technology on the form and capability of the naval forces to the year 2035. One panel focused on future naval forces and the operating environment. In their 1997 report [2], the Panel emphasized the importance of highly accurate and timely knowledge of the operating environment.

To partially satisfy the recommendations, the Study Board described technologies that need to be developed by the Department of the Navy in Unmanned Underwater Vehicles (UUVs) [2].

> "The most significant UUV technology needed for long-duration (30 days or longer) autonomous operation is safe, reliable, high-energy-density and high-power-density batteries and fuel cells operating from seawater or equivalent sources of energy. Of almost equal importance is the need for compact, cost-effective, reliable UUV hardware and software systems.
>
> On-board intelligent navigation and control and decision planning and re-planning are essential technologies for reliable, long-term unattended operations. Other important technologies include low-power, high-performance acoustic and non-acoustic sensors; high-bandwidth, continuous, covert communications between cooperating UUVs, between UUVs and hosts, and between UUVs and global-reaching operators; and automated re-supply, launch, and recovery from unmanned hosts.
>
> Low observability to avoid acoustic and non-acoustic detection is essential to the survivability of autonomous UUVs. This requires vehicle shaping, acoustic and optically absorbing material coatings, equipment quieting, and low-noise propulsion, such as direct electric drive.
>
> Technologies for long-duration, highly reliable autonomous surveillance and tactical missions will need to be developed by the Department of the Navy."

Since these two major reports were published, much has been accomplished in the UUV technologies. Much remains to be done. UUV systems have advanced relatively slowly. The U.S. Navy is now developing UUVs for various tasks. The offshore oil, gas, and communication industries are recognizing AUVs as an extremely reliable and cost-effective tool. Most recently UUVs have been used to search for diamonds!

This report covers the current state of UUV development, advances, and acceptance.

INTRODUCTION

The U.S. Navy Unmanned Undersea Vehicle (UUV) Master Plan [3] establishes Tactical Oceanography, as well as Intelligence Collection and Surveillance as the third priority of a four-priority program. The first two priorities are (1) Near-Term Clandestine Mine Reconnaissance and (2) Longer-Term, Improved Clandestine Mine Reconnaissance. These top two priorities are currently funded. The fourth and last priority is Exploring Advanced UUV Designs for the Future. The Navy UUV Master Plan identifies the importance of meteorology and oceanography for strategic and tactical operations and the ability of UUVs to gather data more cost-effectively.

> "Collection of oceanographic data is key in importance both for strategic and tactical operations. A complete and up to the moment knowledge of the ocean bottom, its characteristics and environmental conditions is a vital asset for mission planning. Long-term observation of water column characteristics will provide for improved communication and operational capabilities. UUVs are well suited for many oceanographic tasks as they can independently collect information for later delivery or transmission. Conventional oceanographic data collection is largely dependent on hull-mounted or towed systems that require extensive surface ship support and suffer speed limitations imposed by the tow cable. UUVs will permit collection of significantly greater quantities of data at less cost by multiplying the effectiveness of existing platforms. UUV technology provides the opportunity to acquire affordable, near real time data at required temporal and spatial sampling densities. Analysts will integrate these UUV gathered data with remotely sensed and conventional survey data and models to provide maritime war- fighters with critical knowledge of areas such as bathymetry, tides, waves, currents, winds, mines, wrecks and obstructions, and acoustic and EM/EO propagation. Envisioned missions of this type include:
>
> Bottom Structure and Composition
> Bathymetry
> Sampling
> Chemical and Physical Sampling and Tracking
> Meteorological Data
> Long Term Observation Stations
> Thermal and Salinity Profiling"

This report provides information on developments in autonomous undersea vehicles (AUVs) and highlights findings targeted for the following:

- Provide and collect current technical ocean engineering initiatives in underwater systems, with emphasis on AUVs
- Identify opportunities to integrate these systems into operational use for Meteorological and Oceanographic (METOC) surveys
- Keep current on the information available from the following activities:
    - The Commission for Geosciences, Environment, and Resources of the National Research Council
    - The Consortium for Ocean Research and Education
    - The Marine Technology Society
    - Autonomous Unmanned Vehicle Systems International
    - The National Undersea Research Program of NOAA
    - The Deep Submergence Science Committee of UNOLS
    - The Scientific Environmental Research Foundation

The information presented herein is not intended to be all inclusive on the developments of AUVs and UUVs. Rather, this report includes developments uncovered in assessing the state of technology versus COMNAVMETOCCOM needs. The information is intended to be useful in considering and developing plans to improve the mission capability of COMNAVMETOCCOM through the application of AUVs. That mission is to collect, interpret, and apply global data and information for safety at sea, for strategic and tactical warfare, and for weapons system design, development, and deployment. The reader should be aware that the terms "unmanned underwater vehicle" (UUV) and "autonomous underwater vehicle" (AUV) are used interchangeably in this report. Also, no information is provided on the Scientific Environmental Research Foundation since it was unable to obtain sufficient funding to continue operations and is no longer in existence.

ENVIRONMENTAL AWARENESS

On November 28, 1995, the Chief of Naval Operations requested that the National Research Council initiate, through its Naval Studies Board (NSB), a thorough examination of the impact of advancing technology on the form and capability of naval forces to the year 2035. One panel focused on future naval forces and the operating environment. In their 1997 report [2], the Panel emphasized the importance of highly accurate and timely knowledge of the operating environment.

> "Effective Navy and Marine Corps operations of all types require a comprehensive knowledge of the operating environment and, in-turn, an understanding of the impact of those operations on the environment. The tools for characterizing the operating environment include long- and short-term weather forecasting and mapping and modeling of ocean and littoral waters, including positions of submarines, ships, and mines.
>
> Readily available supercomputing-scale computational power, combined with high-resolution, pervasive sensor information, increasingly sophisticated sensor fusion and filtering of data, and improved data display and assimilation tools, will provide Navy and Marine Corps decision makers with access to accurate and predictive battle-space environment information.
>
> Recent advances in remotely acquired data, mainly from satellites, are providing a wealth of information about the ocean and atmospheric environment not previously available. The Navy complements such remote sensing with ship-based measurements of ocean depths, temperatures, salinities, and other parameters and has good historical data sets derived from more than 100 ship-years of dedicated time. New distributed sensors will provide real-time data at high resolution representing large areas, with deployment possible in remote or otherwise inaccessible regions as needed.
>
> A major thrust for the future will be the enhancement of environmental data through the use of increasingly sophisticated models of the ocean/atmosphere system. Assimilation of these data into the Coupled Ocean-Atmosphere Dynamic System (COADS) model will be enabled by the rapid advances in computational power and modeling and simulation technology. The real-time weather prediction made possible by this combination of massive database modeling and computational power will allow tactical users to anticipate events in real time and strategic planners to more accurately predict seasonal weather.
>
> NRL is a world leader in modeling the world oceans for aspects critical to naval operations. It routinely calculates ocean currents, fronts, and eddy locations (in hindcast mode) using daily surface weather fields including those obtained from the European Forecasting Center. Despite this excellent capability, naval forces in the future must have real-time access to the output of a global model driven by current input data on (1) surface wind fields, (2) surface sea level, and (3) the internal variability of thermal fields.
>
> Wind data may be obtained from scatterometers on polar-orbiting satellites, such as NSCAT. Two satellites are required to give the Navy the coverage needed to monitor all remote areas. Altimeters mounted on the Navy GEOSAT and NASA TOPEX-POSIEDON satellite have demonstrated the ability to measure the shape of the ocean surface. Given an accurate geoid and tidal model, such data can be assimilated into ocean models to provide an estimate of ocean currents, front location, and eddy location.
>
> Measuring the internal variability of thermal fields is more difficult because the information comes from the mid-water (on the order of 500- to 2,000-m) ocean thermal structure. The two technical systems that are candidates for future development are acoustic tomography and drifting smart floats that measure current and temperature and maintain position in a constant water density. Both systems have been tested by the academic community, and both show promise. The global acoustic monitoring of ocean thermometry (GAMOT) project, for example, has demonstrated that the feasibility of deploying very inexpensive drifting passive sonar buoys capable of measuring deep-water travel time using fixed-sound-source acoustic transmission and data up-link to satellites. Such measurements allow the development of models of the upper 1,000 m of a 4- to 5-km-deep ocean. The other 80 percent is below the level of most conceivable naval operations. Because the ocean is stratified, slow moving, and, consequently, hydrostatic, almost all of the fundamental environmental information that is time dependent is transferred to the deep ocean through conservation of mass and momentum.

> The ocean's response to the atmosphere, radiant energy, and tides may be characterized according to its local depth. The domains are the deep ocean (depths greater than 1,000 m), the continental slopes (depths from 2,000 m to 200 m), the continental shelf (depths from 200 m to 20 m), and the near-shore littoral zone (depths shallower than 50 m). A thorough understanding and modeling of near-shore littoral waters is critically important for future naval forces. A physical understanding is reasonably well established, but this zone also encompasses much greater variability in current, sediment transport, visibility, salinity, and so on, than the deeper regions of the ocean. The physical variability, the acoustic environment, and the visibility of the littoral zones are not well modeled. Each region on Earth is affected differently primarily because of variations in bottom topography, water runoff, climate, and bottom composition. There are, however, well-understood (except for turbulence) physical principles to assist in characterizing each regime. If appropriate data are acquired and retrospective studies performed, it is possible to anticipate the physical state of the littoral zone that might be encountered in naval operations. Multimodality sensor systems that provide real-time data are being developed for this highly variable environment.
>
> Model scenarios for each potential area could be developed and validated. Codes, climatologies, topographic configurations, and the like, can be stored in a modern high-speed, large-memory workstation. Modern data assimilation protocols (either variational adjoint or Kalman-Bucy filtering) can be overlaid on the basic model database. Either in anticipation of actions or during an event, all data gathered in the region can be assimilated to produce the most probable physical environment needed for surface, underwater, acoustic, and countermeasure operations.
>
> The data output from these physical models is time dependent and three-dimensional. Shipboard personnel generally do not have the technical background to interpret the complex environmental fields. A solution is to develop four-dimensional graphical visualization systems to be used to identify patterns of such phenomena as currents, temperature fronts, and low-visibility regions. Such software is not currently available except in primitive form but is under development.
>
> Mapping the shape of the bottom is currently straightforward, but visualization of the flow in the water volume is difficult because of the enormous databases involved and the inherent problem of mapping a four-dimensional picture onto a two-dimensional computer screen. Workstations of the future will have enough cycle power, memory, and storage to handle the computations, but new visualization techniques have to be developed, such as four-dimensional virtual reality systems. Within 10 years, it should be possible to provide on shipboard modest-sized virtual-reality sites for naval personnel to see the present and evolving underwater physical environment.
>
> The physics of acoustic phenomena in the open ocean is well understood. Given a source location, a receiver, and information on such things as water density and the shape of the bottom, the behavior of sound can be calculated. But in most littoral zones, this is almost impossible because the temperature and salinity of the water change with season and weather conditions. Moreover, surface sea waves change quickly and frequently and the behavior of the bottom reflectivity and absorption changes within waters. Thus, reliable interpretation of acoustic transmission in near-shore waters is technologically challenging.
>
> Unfortunately, foreign navies are investing in electric submarines that are relatively small and quiet. These, along with inexpensive and plentiful mines, pose serious threats to naval forces in shallow water. Special attention needs to be directed toward pattern recognition and signal recognition of moving and stationary objects in shallow water. Extensive simulation of acoustic systems must be carried out with the various scenarios predicted by the physical modeling system. For example, high-frequency active sonar may be effective for mine detection in shallow water but not have enough range for ASW in deeper water. Modeling will provide the information necessary to make informed choices of sensor-system deployment and enable the development of protocols to identify interdicted structures not encountered in tests of the anticipated acoustic environments."

This panel made the following recommendations:

> "Battle-space awareness, communications, target identification, navigation, weapon guidance, and tactical planning all require real-time understanding and forecasting of the atmospheric, space, and sea environments of operation. Global weather models with improved satellite data on winds, temperature, solar inputs, and so on will permit the generation of accurate weather forecasts. Space weather

forecasting of solar disturbances, scintillation phenomena, and other disturbances will be modeled based on real-time satellite data. The Department of the Navy must support the development of this modeling capability.

With respect to terrestrial weather and climate prediction, the panel presents the following recommendations:

- To take advantage of the vast quantities of new environmental data from an increasing array of remote-sensing devices—in space, in the upper atmosphere, on land, and on and under the sea—the Department of the Navy should pursue the development of shipboard computational and data communication systems coupled to land-based high-performance computers.
- Emphasis should be placed on developing the higher-resolution climate prediction models that are necessary for tactical warfare operations.
- R&D emphasis should be placed on the high-performance hardware, algorithms, and memory storage required to enable real-time applications under realistic battle-space conditions.

With respect to littoral-water modeling, the panel presents the following recommendations:

- Greater attention should be paid to the dynamics of near-shore environments, including such phenomena as shallow-water acoustics, variable visibility, and strong, near-shore currents, which at present are not well understood.
- Databases should be developed that sufficiently describe near-shore phenomena, including beach characteristics that can lead to accurate forecasting of littoral conditions.
- To enable naval personnel to use such databases, graphical interface technologies need to be developed, including on-board, multidimensional, multisensorial virtual-reality systems capable of representing real-time and evolving underwater physical environments near shore."

AUVs represent one tool to deploy data gathering capabilities to address these recommendations.

TACTICAL OCEANOGRAPHY

Developments in autonomous underwater vehicles over the past decade have reached a level of practical technological maturity. Some testing will be required of AUV technology to oceanography application. These developments will enable the Navy Meteorology and Oceanography Command to more cost-effectively accomplish its mission--to collect, interpret, and apply global data and information for safety at sea, for strategic and tactical warfare, and for weapons system design, development, and deployment. Figure 1 depicts developments that improve how the Naval Meteorology and Oceanography Command performs surveys to:

- measure water depths
- measure variations in the Earth's magnetic field
- determine gravity anomalies
- define the shape and texture of the ocean floor
- measure and describe the physical features of the ocean

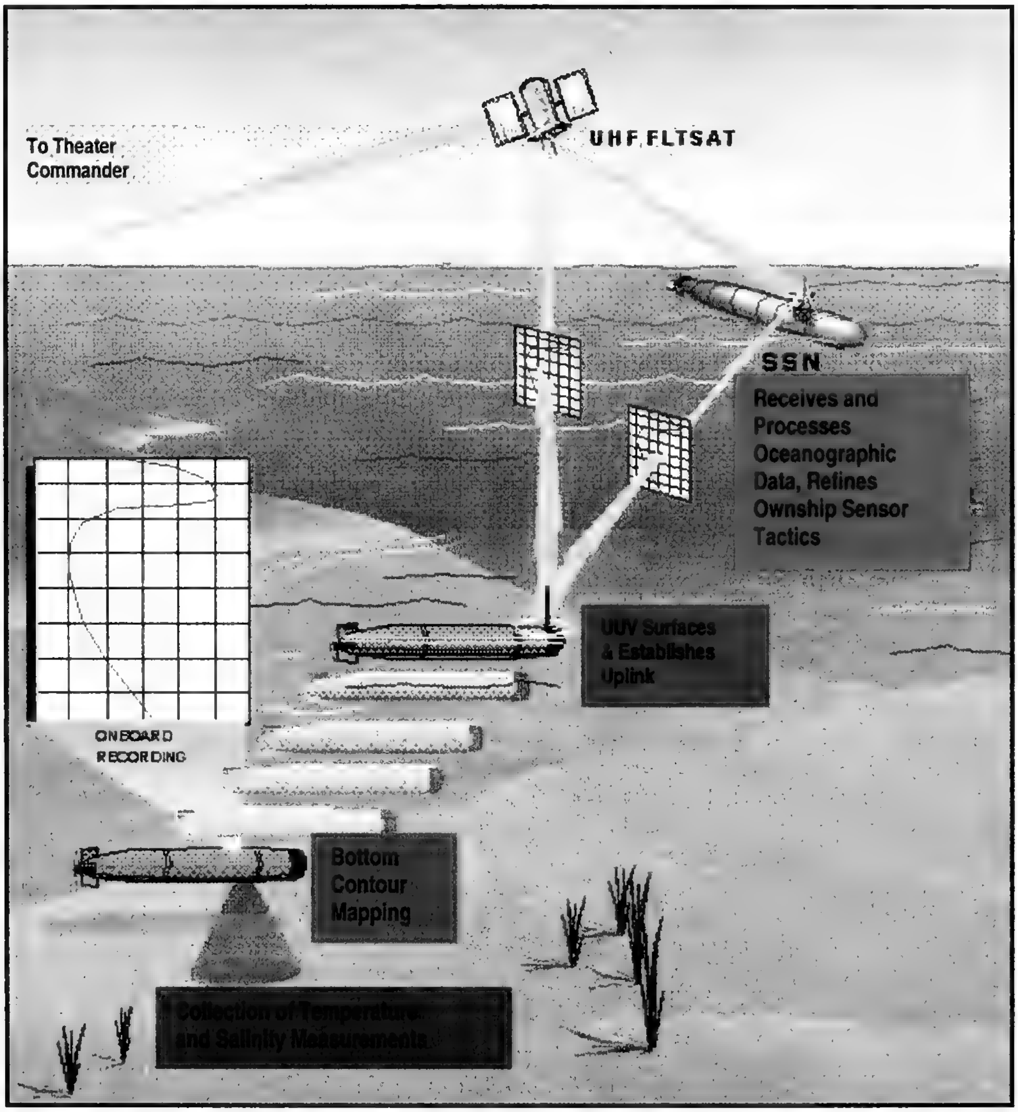


FIGURE 1. Tactical Oceanography Links

Concerning anti-submarine warfare (ASW) application of oceanography, the NSB provided the following [2]:

> "The real-time acquisition of environmental data is an imperative, but challenging, task for a mobile system that must be capable of operating anywhere in the world. The research community has gone to great lengths to acquire such data, but the requisite oceanographic data are both site and time specific, with many scales of variability, and tend to be undersampled in both space and time. The important issue is that up-to-date site-specific environmental data must be incorporated in the deployment of mobile sonar if high detection gains are to be realized.
>
> One development currently in its infancy is the use of networked unmanned underwater vehicles for synoptic (fully three-dimensional) environmental sensing. Such environmental information, obtained through local sampling or tomography, could be of significant operational usefulness in improving sonar capabilities. In addition, the imagination is stimulated by the vision that many small, dispersed platforms could be connected with a few manned platforms for networked warfighting. Such a vision is currently premature but might become practical over the time horizon of this study. The panel believes that the environmental sensing applications of UUV networks should be pursued first. In this way, the Navy will develop the enabling technologies for such networks, as well as operational experience in their deployment.
>
> The two key enabling technologies for UUV networks are their power sources and reliable underwater communications. There has been much activity in the area of air-independent long-duration power sources, but there does not seem to be any consensus regarding which of many possible avenues--batteries, fuel cells, and air-independent combustion--should be pursued. This is an area in which considerable interest also exists in the commercial sector, and new long-duration power sources may arise from activities such as the Partnership for Next-Generation Vehicles. Thus, a top-down research approach may be effective in guiding R&D in this area into the most promising paths.
>
> Currently, the leading candidate for underwater communication is acoustic communications. Data rates of 2 to 20 kilobits per second (kbps) are currently achievable, although distances are limited to a few kilometers in shallow water. It is even possible to give UUVs Internet addresses and to communicate with them using standard Transmission Control Protocol/Internet Protocol (TCP/IP) protocols. An improved understanding of ocean acoustic coherence could also improve our ability to communicate underwater. Little work, however, has been done on the vulnerability of acoustic communications networks to acoustic jamming or on covert underwater communication.
>
> Several science and technology issues must be addressed to ensure the continuous evolution of improved performance for both mobile and fixed sonar systems. Although signal processing algorithms and computational capabilities are necessary for a high-performance sonar, the acoustic-oceanographic coherence is what ultimately sets the limits. The science and technology issues for coherence have several environmental contexts.
>
> Littoral waters, where these sonars must operate, can be quite shallow (10 to 200 m) or deep (kilometers) and include a range-dependent shelf break. In shallow water and on the shelf, strong horizontally anisotropic internal waves driven by tidal and topographic forcing, usually with a diurnal period, can modulate sound speed profiles dramatically. In upslope-downslope geometries these can precipitously interrupt surface duct propagation and impact coherences through mode coupling and/or ray path fluctuations. When bottom refraction sound speed profiles are present, bottom interaction can significantly impact coherence. Even well-lineated, constant-depth shallow water introduces problems because of differential absorption; the complexities of rapidly range-dependent slope with high geologic roughness are even more challenging.
>
> Coherence in deep water is greater than in the littoral, especially when the signals are not bottom interacting. This presents an opportunity to significantly increase detection ranges by pushing coherence to the limits. VLF deep-water experiments have demonstrated significant frequency dependence on coherences, with those in the lower edge of the band demonstrating remarkable ray-mode coherence, whereas those in the upper section have different coherences for the high-angle paths and the ducted paths. The cumulative effects of internal waves appear to be the problem, but there is a great deal of controversy about this issue. Bottom interaction has received less consideration; but it is an unavoidable issue, especially for active systems.

The development imperative is to improve the gains of sonar devices to enable the detection of potentially hostile submarines that will be characterized by low source levels and target strengths. Sonars have evolved continuously from a few bulky sensors with analog signal processing to arrays with hundreds of miniaturized sensors and high-speed digital signal processing. The understanding of oceanography has grown from the discovery of propagation channels in the ocean to the development of accurate, range-dependent propagation codes and environmental models for noise and reverberation. Similarly, reliable and smart sensing systems can now be deployed using advances in ocean engineering, a lot of hard-won field experience, and rugged very-large-scale integration (VLSI) electronics. This evolution has been scientifically and technologically intensive; at this point, the easily attainable performance gains have been achieved, and even greater exploitation of the science and technology will be required in order to develop future systems that incorporate significant performance gains.

The necessary components of an effective ASW technology development program are as follows:

- Well-posed science and technology;
- At-sea experiments with sensors that are both well calibrated and accurately navigated to provide real-time environmental data;
- Fundamental exploitation of the advances in ocean acoustics, oceanography, and signal processing;
- Robust ocean engineering for their deployment;
- Integration of communications, navigation, and high-speed computation; and
- Highly trained operators. "

ELECTRIC POWER SYSTEMS

The NSB also assigned one panel to focus on those electric power generation, storage, and propulsion technologies that, when applied as a system, will support the electrification of ships, submarines, and land-based vehicles [2]. It surveyed the status of key elements of power systems such as energy storage devices, electric power recovery subsystems, and battery technologies. Industrial development is ongoing in most of these areas, and current trends suggest steady improvement in capacity, density, modularity, and reliability. The Naval forces can take advantage of commercial developments by actively monitoring the commercial marine power and propulsion sector and by applying a top-down systems engineering process to fleet capability upgrades. Of the technology areas covered by the panel, fuel cells and batteries are covered in this report since they hold the most promise for AUV applications.

Fuel Cell Power Systems

The panel had the following comments regarding fuel cell power generation technology [2]. (Table 1 lists the available fuel cell systems.)

> "Fuel cells hold promise for zonal power generation. They are a particularly efficient and clean method of utilizing hydrocarbon fuels and are appropriate for medium-sized power generation units (1 to 4 kW). Hydrogen-based fuel cells electrochemically oxidize hydrogen with oxygen (or air) and directly convert chemical energy to electric energy. The product of this combustion is water, and this combined with the extremely low signature of the cell make it a very attractive power alternative for Navy and Marine operations. Because they are essentially isothermal devices and therefore not limited by heat engine thermodynamics, they can in principle have very high energy densities (watthours per kilogram), limited only by the specific free energy change in converting hydrogen and oxygen to water. The great obstacle to hydrogen-based fuel cells for mobile, battle-zone applications is the volumetric problem of storing hydrogen. Although hydrogen produces a great deal of energy on a weight basis, it produces very little energy on a volume basis, even when stored at high pressure.
>
> Today hydrogen is the only fuel that can be electrochemically oxidized in a fuel cell system at practical rates. The ideal system would directly convert the free energy of combustion of other fuels, such as hydrocarbons, into electric energy. Other fuels are used in prototype fuel cell systems by either externally or internally reforming them to a mixture of hydrogen and carbon dioxide, then using the hydrogen electrochemically in the fuel cell. A major breakthrough in electrocatalysis would be required before other fuels could be electrochemically oxidized at useful rates.
>
> Hydrogen fuel cells are impractical for at-sea applications because of the space required to store hydrogen, but hydrocarbon fuel conversion designs would be directly applicable to Navy use. Most units under development (primarily in the automotive industry) require higher-quality fuels than standard Navy distillates. Although there is no current evidence of an impending technical breakthrough in this area, the promise is such that near-term programs to develop converters for standard Navy fuels should be encouraged.
>
> Fuel cells convert chemical energy directly into electrical energy and as a power generation module can be viewed as a continuously fueled battery. They take in fuel and oxidant and produce electricity, water, and heat. In addition to the fuel cell stacks, the power generation module includes heat exchangers, regulators, controls, and fuel-processing and other auxiliary equipment. Besides enhanced energy density and efficiency, fuel cells have the potential for providing power with little or no emission of regulated pollutants. Other attributes include low-noise, reduced-exhaust IR signature, improved reliability and maintainability, and a high degree of modularity. Table 1 provides a summary of characteristics for the alternative fuel cell technologies being considered. It is anticipated that when fully matured, fuel cell costs could be as low as \$500/kW.
>
> Most of the fuel cell development to date has been focused on electric utility applications that use natural gas for fuel and for which compactness is not required. Recent developments include transportation

applications using methanol as fuel and where power density is an issue. For shipboard use, a diesel fuel reformer and desulfurizer would be required, and, although power density is an issue, it must be weighed against impact on acquisition cost--the further removed from commercial practice, the more expensive it will become. Existing Navy exploratory development efforts are focused on the fuel-processing issues of reforming and desulfurization with a 10-kW fuel cell demonstration planned. DARPA is supporting development of fuel cells that operate on logistic fuels (JP8 or DF2). "

Table 1. Available Fuel Cell Systems

Type	Electrolyte	Operating Temp (F)	Efficiency	lb/kW	ft3/kW
Phosphoric acid	Phosphoric acid (liquid)	350 to 450	38 to 40	30 to 46	0.93 to 1.5
Molten carbonate	Carbonate salts (liquid)	1,200 to 1,400	40 to 55	40 to 60	0.98 to 2.1
Solid oxide (tubular)	Zirconium oxide (solid)	1,700 to 1,900	45 to 60	20 to 30	0.6 to 1.2
Solid oxide (planar)	Zirconium oxide (solid)	1,700 to 1,900	45 to 60	8 to 13.5	0.3 to 0.81
Proton exchange membrane	Sulfonated polymer (solid)	180 to 250	39 to 42	6 to 11.9	0.19 to 0.3

SOURCE: Adapted from the Advanced Surface Machinery Programs Office, 1996, *A Strategy Paper on Power for U.S. Navy Surface Ships*, draft, Naval Sea Systems Command, Arlington, VA., Table A-1, p. A-7, April 8.

Included in this report NAVMETOCCOM commissioned a review of powering UUVs using Proton Exchange Membrane fuel cells. Several 5-kW systems were studied for integration. Direct-Feed Hydrogen systems were found to require excessive compressed pressure gas for extended missions. Reformed-Diesel systems expected to be available in the next two years are not feasible. Small modifications to the reformed-Diesel technology, when coupled with the A&T proprietary O_2-generator/CO_2/S-absorber, will perform at power densities approaching 500 w-hrs/kg. Two methanol-fueled systems were studied. The Reformed-Methanol technology is available today and will produce power at the 500 w-hr/kg standard. Direct-Methanol is mechanically much simpler and is the best solution for the UUV application. A 1-kW system is under development at the Jet Propulsion Laboratory. Five kW systems are expected in the next two to three years with appropriate development.

The key to using fuel cell technology in a UUV powered by a hydrocarbon fuel is the production of the oxidant and the management of carbon dioxide. A&T has developed a proprietary system that accomplishes these goals without using large parasitic electrical loads. This important technology can be used for fuel cells or any hydrocarbon fuel. The same need exists for turbines and small internal combustion engines.

Batteries

The NSB had the following comments regarding battery power systems [2].

> "The science of electrochemical energy storage is fundamentally mature. The pace of development is relatively slow, but the need for safe and reliable electric power is so pervasive that there is a constant high level of research and development. New commercial battery products find their way onto the market, as historical shortcomings in the safety and stability of materials and chemical reactions are resolved. This was the case, for instance, in the recent development of the nickel metal hydride (NiMH) battery as a replacement for the environmentally unsound nickel cadmium (NiCd) battery.
>
> Technology development promises evolutionary progress in the realization and utility of the physical potential within the basic chemistries. Several long-term efforts in commercial and government establishments focus on improvement in shelf life, safety, volumetric and gravimetric energy values, and, in the case of secondary batteries, smart controls for charging efficiency and cycle lifetimes.
>
> Where weight is a major concern or the application calls for both long shelf and operating lives, lithium-based chemistries are a clear leader. Primary lithium batteries with 20-year shelf lives are in current use in smart mines and kinetic kill weapons. The U.S. Army has been a leader in the development of high-density, high-power, 6- to 12-V battery power systems for vehicles, pulsed-power weapons, remote power backup, and missile systems. The utility of high-power systems that are capable of operating in severe environments is driving further research on lithium battery safety issues such as handling and mitigation of volatile chemistry systems.
>
> Nickel-hydrogen has long been the preferred spaceborne secondary battery technology. Capable of high discharge rates and nearly infinite charge-discharge cycling, nothing currently matches its reliability. Underwater applications have been dominated by silver zinc (AgZn) systems. Some silver aluminum units are in use for lower power applications such as small torpedoes and the smaller offboard vehicles, but AgZn batteries are widely used for high-power applications. These can provide up to 100 kW over 15 minutes and, together with advanced electric motors, can propel a torpedo at high speed."

Tables 2-5 provide additional details on power cells.

Table 2. Primary Battery Cell Types with Promise as Prospective Power Sources

Chemistry	Cell Volt	W-h/kg	Notes
Aluminum-Silver Dioxide Al-Ag2O2	1.57		Pumped electrolyte; heat exchanger required
Calcium-Thionyl Chloride Ca-SOCl2	3.0		Increased tolerance to abuse over Li
Calcium-Sulfuryl Chloride Ca-SO2Cl2	3.2		Increased tolerance to abuse over Li

SOURCE: Compilation of data from Bis, R.F., J.A. Barnes, W.V. Zajac, P.B. Davis, and R.M. Murphy, 1986, *Safety Characteristics of Lithium Primary and Secondary Battery Systems,* NSWC TR 86-296. Navy Surface Weapons Center, Silver Spring, Md., July; and Bis, R.F., and R.M. Murphy, 1986, *Safety Characteristics of Non-lithium Battery Systems,* NSWC TR 86-302 Rev. 1, Naval Surface Weapons Center, Silver Spring, Md., July.

Table 3. Primary Battery Cell Types Currently Available

Chemistry	Cell Volt	W-h/kg	Notes
Cadmium-Mercuric Oxide Cd-HgO	0.9		Long shelf life; sealable
Calcium-Calcium Chromate (thermal) Ca-CaCrO4	3		Long shelf life; high voltage; 1 s to 1 h operating life; tolerates extreme environments
Magnesium-Lead Chloride Mg-PbCl2	1.1		Seawater activated: torpedoes; emergency signaling; sonobuoys
Magnesium-Manganese Dioxide Mg-MnO2	1.8		Transceivers; sonobuoys; beacons; good temperature performance
Magnesium-Silver Chloride Mg-AgCl	1.7		Seawater activated
Zinc-Air Zn-O2	1.4	440	High capacity
Zinc-Manganese Dioxide (Leclanche) Zn-MnO2	1.5		
Zinc-Carbon Zn-C	3	105	Everyday flashlight cell
Alkaline Zn-MnO2	1.25	100	
Mercury Zn-HgO	1.3	105	
Zinc-Silver Chloride Zn-AgCl	1.0	2.1	Extremely long shelf storage; low rate supply
Zinc-Silver Oxide (Silver Zinc) Zn-Ag2O(2)	1.6/1.8	50 to 200	High energy/high rate: torpedo; space; submarine; ignition; rocket

SOURCE: Compilation of data from Bis, R.F., J.A. Barnes, W.V. Zajac, P.B. Davis, and R.M. Murphy, 1986, *Safety Characteristics of Lithium Primary and Secondary Battery Systems,* NSWC TR 86-296. Navy Surface Weapons Center, Silver Spring, Md., July; and Bis, R.F., and R.M. Murphy, 1986, *Safety Characteristics of Non-lithium Battery Systems,* NSWC TR 86-302 Rev. 1, Naval Surface Weapons Center, Silver Spring, Md., July.

Table 4. Secondary Battery Cell Types Currently Available

Chemistry	Cell Volt	W-hr/kg	Notes
Nickel-Cadmium (Nicad) Cd-NiOOH	1.2	25/35/210	Cyl/button/vented; long life; memory problems
Nickel-Metal Hydride Ni-MH	1.2	65	Replaces Cd in NiCd
Cadmium-Silver Oxide Cd-Ag2O(2)	1.4	75	Like NiCd but lower rate
Nickel-Hydrogen H2-NiOOH	2.5	50	Pressure vessel; extremely long life; satellites
Silver-Hydrogen H2-Ag2O(2)	1.4/1.1	80	Pressure vessel; extremely long life; deep discharge
Lithium-Thionyl Chloride Li-SOCl2	3.4	700	Primaries available as buttons; very wide temperature range; 20-year life
Lithium Ion Family:			
Lithium-Sulfur Dioxide Li-SO2	2.8	275	Wide temperature range; 20-year life
Lithium-Manganese Dioxide Li-MnO2	3.1	300	
Lithium-Titanium Sulfide Li-TiS2	3.6		
Lithium-Manganese Disulfide Li-MnS2	3.6		
Lithium-Sulfur Dioxide Li-SO2	2.8	275	Wide temperature range; 20-year life
Lithium Carbon Monofluoride Li-(CF)n	2.8	310	Long shelf life
Lithium-Iodine Li-I2	2.7	230	Long service life (<10 yrs)
Lithium-Copper Sufide Li-CuS			
Lead-Acid Pb-PbO2		100	Fuses; torpedoes; radio
(sulfuric acid)	2.0		
(fluoroboric)	1.8		
(perchloric)	1.9		
Zinc-Silver Oxide Zn-Ag2O(2)			
Zinc-Manganese Dioxide Zn-MnO2	1.2		"Renewal" brand; needs smart charger

SOURCE: Compilation of data from Bis, R.F., J.A. Barnes, W.V. Zajac, P.B. Davis, and R.M. Murphy, 1986, *Safety Characteristics of Lithium Primary and Secondary Battery Systems*, NSWC TR 86-296. Navy Surface Weapons Center, Silver Spring, Md., July; and Bis, R.F., and R.M. Murphy, 1986, *Safety Characteristics of Non-lithium Battery Systems*, NSWC TR 86-302 Rev. 1, Naval Surface Weapons Center, Silver Spring, Md., July.

Table 5. Secondary Battery Cell Types with Promise as Prospective Power Sources

Chemistry	Cell Volt	W-h/Kg	Safety
Aluminum-Air Al-O2	1.5 to 2.1	80	Seawater activated
Cadmium-Air Cd-O2	1.9	< 440	High cost
Hydrogen-Air LaNi5H6-O2	1.2	3650 theoretical 380 actual	Gas cross-leakage; short cycling life; low rate
Iron-Air Fe-O2	1.2	715 theoretical 90 actual	Electric vehicle (EV); H2, O2 production, poor thermal operation
Iron-Chromium (redox) Fe-Cr	1.2	120 theoretical 30 actual	Reactant cross-diffusion problems
Nickel-Iron Fe-NiOOH	1.3	263 theoretical	EV; long life; high H2
Iron - Silver Oxide Fe-Ag2O(2)	1.2/1.5	106	To improve Zn-Ag2O(2) life
Sodium-Sulfur (glass) Na-S	1.8	760 theoretical	High temperature (350 C)
Zinc-Bromine Zn-Br2	1.8	80	EV; electric load leveling; Br release danger
Zinc - Chlorine Zn-Cl2	2.1	826 theoretical 200+ actual	EV; electric load leveling; chilled recharge required
Zinc-Nickel Zn-NiOOH	1.5	345 theoretical 81 actual	EV; H2, O2 production
Zinc-Silver Oxide Zn-Ag2O(2)	1.8/1.6	130	Torpedoes, submarines, and so on
Zinc-Air Zn-O2	1.2	185	High-capacity replacement for Ni-MH

SOURCE: Compilation of data from Bis, R.F., J.A. Barnes, W.V. Zajac, P.B. Davis, and R.M. Murphy, 1986, *Safety Characteristics of Lithium Primary and Secondary Battery Systems,* NSWC TR 86-296. Navy Surface Weapons Center, Silver Spring, Md., July; and Bis, R.F., and R.M. Murphy, 1986, *Safety Characteristics of Non-lithium Battery Systems,* NSWC TR 86-302 Rev. 1, Naval Surface Weapons Center, Silver Spring, Md., July.

SENSORS

The NSB panel that focused on sensor technologies recommended the following [2]:

> Based on the technology trends and historical growth patterns, the panel anticipates that future sensor technology will be characterized by the following:
>
> - Ever-decreasing size and cost as microelectronics evolves into nanoelectronics within the limits and constraints implied by the physics of the interfaces.
> - Migration of the analog-to-digital conversion to the front end of the sensor, leaving only those analog elements absolutely necessary for interfacing with the physical phenomenon to be sensed--e.g., microwave LNA, filters and power amplifiers, fiber-optic transducers, MEMS transducers, and the like.
> - Ever-increasing application of computer processing as gigaflops grow to teraflops and then to petaflops.
> - Development of monolithic smart sensors, combining sensing transduction, ADC, digital signal processing, communication input and output, and perhaps power conditioning on a single chip. This offers interesting possibilities for very small, very smart weapons such as affordable smart bullets (figure 2).
>
>   Note that not all sensors can be small, even though the electronics can be. Size depends very much on the physics of the physical interface constraints. For example, propagation-based sensors such as RF radar and sonars typically require many wavelengths across the T/R aperture for good spatial resolution. Optical and millimeter-wave sensors, however, with their small wavelengths, and all MEMS-mediated sensors can and will become small and integrated.
> - As increasingly capable sensors evolve, it will be natural to deploy collections of autonomous, mobile, communicating sensors that can cooperate to function as a single, higher-level metasensor (figure 2).
>
> In a sense, the Navy's CEC already functions as a metasensor but is not yet viewed as such. In CEC, the radars are thought of as individual, independent sensors that are cooperating. The meta interpretation views the cooperating radars as a single sensor, which happens to have distributed and mobile components.
>
> In the future, as individual sensors grow smaller and more capable, and perhaps become autonomously mobile, they will be deployed in environments where each can see only a small part of the scene and can communicate only in a limited sense with other close-by minisensors. Under these conditions it becomes natural to think of the individual sensors as members of a distributed ant-like society that, through only local communications and simple local protocols, manages to behave as a single purposeful entity—that is, a metasensor. Investigations of the dynamics and potentially chaotic behavior of such distributed systems (e.g., flocks of birds or schools of fish) have recently begun to appear in the physics literature. This direction of research should be carefully nurtured.

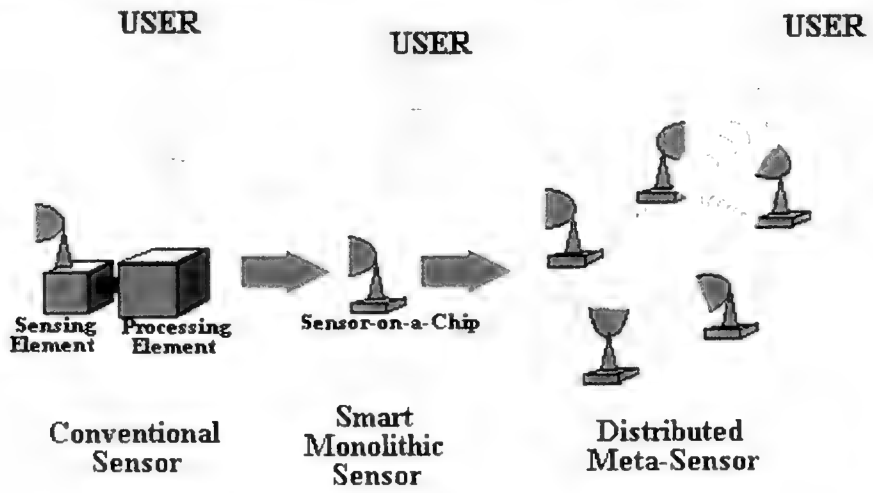


Figure 2. Sensor Technologies Development

RESEARCH AND DEVELOPMENT FOR UUV SYSTEMS

As the Navy shifts its focus from a global threat to a focus on regional challenges, it is developing the capabilities needed to execute successful operations in the complex "littoral environment." There is a need for cost-effective, unmanned, clandestine, undersea, off-board platforms with sensors that can serve in a wide variety of roles and missions, including mine warfare, surveillance, reconnaissance, intelligence collection, and tactical oceanography. To address these needs the Navy, led by Office of Naval Research (ONR) sponsorship, has coordinated research and development efforts. ONR has helped lay the foundation through active sponsorship of a wide range of academic initiatives. In partnership with the Naval Oceanographic Office, ONR hosts annual exercises of AUV/UUVs in their Gulf of Mexico UUV test range.

The UUV demonstrations, called "AUV Fest," provide opportunities for academic institutions and industry to showcase their UUVs. ONR also uses the event to evaluate technologies necessary to meet a concept of operations for schools of UUVs for ocean sampling and measurement. Participation has increased each year. The opportunity for "cross-pollination" among participating teams is significant. The Navy invites external observers aboard the mother ship to increase exposure to others interested in exploiting the technology.

Observed advances in UUV technology each year is remarkable. This event serves the UUV community immensely in advancing the state-of-the-art and generating enthusiasm. Operators of UUVs have gained confidence in their vehicles during these at-sea events. The UUV competitions sponsored by the Autonomous Unmanned Vehicle Systems International organization similarly stimulate the UUV community.

The Navy has initiated a strategic planning group to coordinate specific development and acquisition efforts begun by Navy Systems Laboratories.

NEAR-TERM MINE RECONNAISSANCE SYSTEM (NMRS) [4,5,6]

A significant portion of the Navy's regional challenges relate to mine warfare in the "littoral environment." One mine warfare tool the Navy is developing and fielding is a system designed to conduct clandestine, remote, unmanned minefield reconnaissance from a submarine. The system under development is the Near-Term Mine Reconnaissance System (NMRS) under a "special category" acquisition program for Fleet delivery and use. The NMRS entered operational use by the Type Commander (TYCOM) in early Calendar Year 1998 and participated in Demonstration II of the Joint Countermine Advanced Concept Technology Demonstration (JCM ACTD).

NMRS is being installed on various platforms, including the USS LOS ANGELES (SSN 688) Class attack submarines. The NMRS is a fiber-optic tethered vehicle that is equipped with side-scan sonar. The launch and recovery of the reconnaissance vehicle is via a torpedo tube.

Figure 3. Clandestine Minefield Reconnaissance

NMRS provides theater commanders with a near-term capability for conducting clandestine minefield reconnaissance from a submarine (figure 3). The UUV transits to an area to determine if littoral waters are seeded with mines, allowing theater commander to rapidly assess probability of mines in the area. A highly accurate NMRS survey precisely locates and classifies minelike objects, providing theater commander with detailed information used to estimate location of enemy-deployed mine defenses and unmined coastal areas. With this information the theater commanders can determine the need for further UUV sortie operations.

The NMRS incorporates SSN 688 torpedo tube technology hosted on a recoverable UUV with multibeam, active search sonar, and side-scan classification sonar. The NMRS consists of two reusable UUVs; launch and recovery equipment, including a winch and drogues; and shipboard control, processing, and monitoring equipment. Each UUV is slightly shorter than an Mk 48 torpedo and is launched and recovered via a standard SSN 688-Class torpedo tube. The UUVs contain highly accurate sonar systems that can pinpoint and classify minelike objects. Batteries provide the power needed to propel the vehicle during its sortie and operate the on-board electronic systems. Vehicle status, position, and sonar data are continuously relayed back to the host SSN via a fiber-optic cable, thereby allowing continuous monitoring of the vehicle during sortie operations and real-time analysis of data to the SSN from potentially mined waters.

The UUV is loaded backward into the SSN 688 torpedo tube. Once ship conditions are correct, the UUV backs out of the tube under its own power. Outside the SSN (but still coupled to it via a steel cable and drogue assembly), it is towed to its mission area. The UUV then releases from the drogue; fiber-optic cable begins to pay out from both the drogue and vehicle; and the UUV independently transits and conducts its mission. Should the fiber-optic cable break, the UUV is programmed to autonomously return to a pre-set rendezvous point for recovery by the SSN. When the mission is finished, the UUV will rendezvous and mate with the drogue. A winch located in the SSN torpedo room will then pull the complete combination back into the torpedo tube. A trained Navy cadre will be responsible for the operation and maintenance of the NMRS when deployed. Cadre members are responsible to prepare and conduct UUV sorties; monitor vehicle status during transit and operation; replenish the UUVs post-sortie; and compile analysis of mission data.

The NMRS Prototype (figure 4) commenced its at-sea test period in March 1998 at the Dabob Bay Test Range in Keyport, Washington. A detailed series of tests assessing vehicle and drogue stability, hydrodynamic control, navigation, and sensor performance was performed. In June 1998, the Navy successfully demonstrated its NMRS during the JCM ACTD held under NATO auspices off Stephenville, Newfoundland. NMRS was part of a large-scale amphibious warfare exercise designed to showcase emerging shallow-water mine warfare technologies.

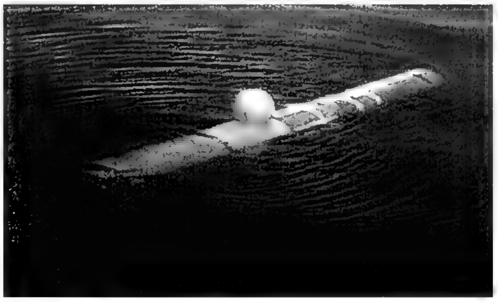


Figure 4. NMRS Prototype

During the ACTD demonstration, the NMRS conducted five mine reconnaissance and survey sorties both in deep-water areas, with depths greater than 200 feet, and in shallow water (less than 200 feet) with varying bottom types. Since NMRS is designed to operate from a submarine torpedo tube, new procedures were developed to support surface launch and recovery from the research vessel. Navy Cadre members constructed all sortie plans using available information provided about the area and anticipated threat. Ultimately, all tasks were successfully completed, and the NMRS logged more than ten hours of operational search time. Suspected minelike objects were reported using standard mine warfare messages after detailed reconstruction and review of sonar data from the sorties.

LONG-TERM MINE RECONNAISSANCE SYSTEM (LMRS) [4,7,8]

The Long-Term Mine Reconnaissance System (LMRS) is a clandestine mine reconnaissance system that employs UUVs that are capable of launch and recovery from LOS ANGELES (SSN 688) and VIRGINIA (SSN 774) class submarines. The LMRS will provide an early, rapid, accurate means of surveying potential mine fields in support of proposed amphibious operations, other battle group operations, and for safe ship transit around mined waters.

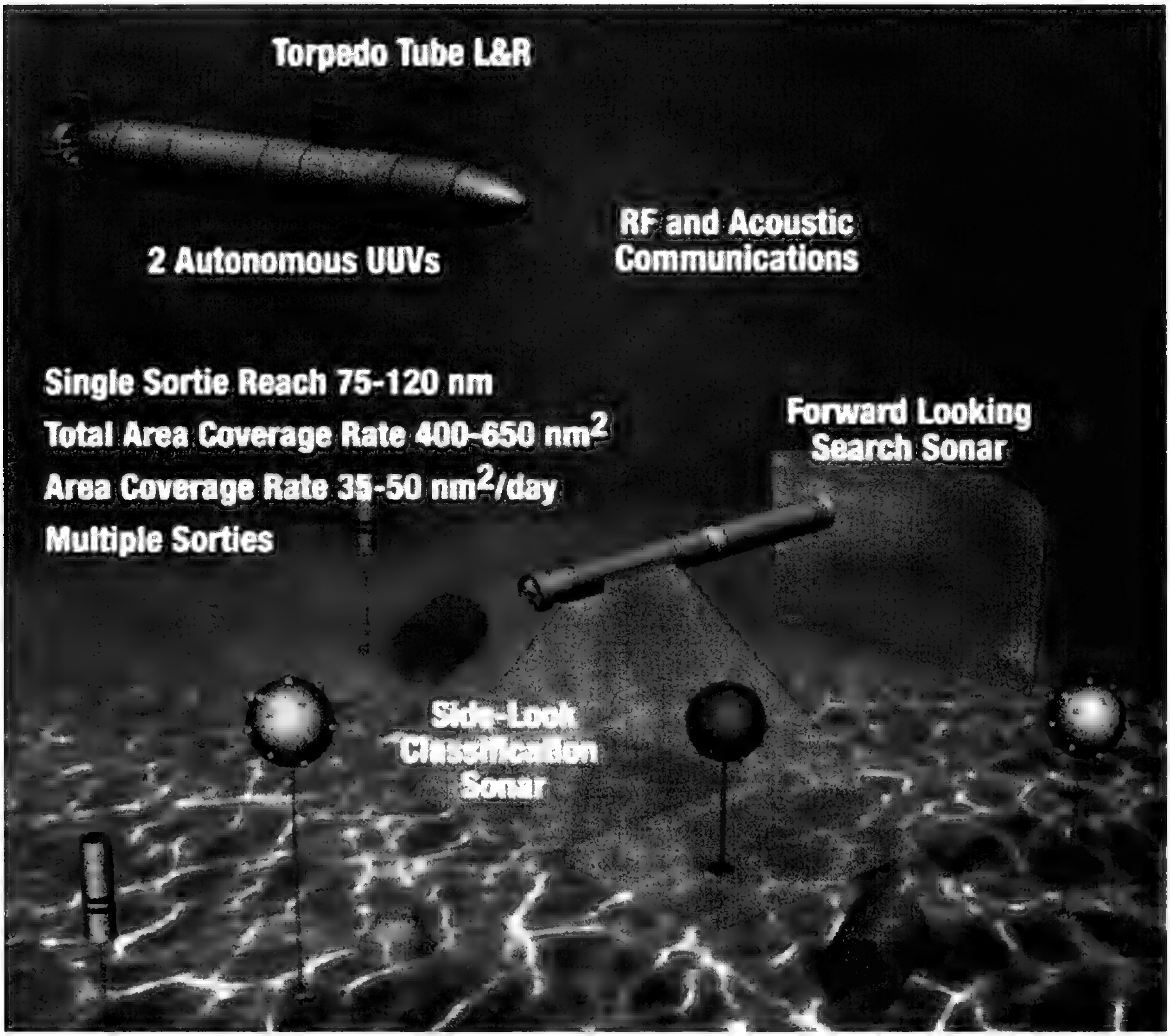


Figure 5. LMRS Concept

The U.S. Navy's UUV program office recently announced the selection of a team headed by Boeing Inc. to proceed with detailed design of the Long-Term Mine Reconnaissance System (LMRS) (figure 5). Sonatech, Inc., of Santa Barbara, California, will be providing all of the acoustic subsystems for this portion of the LMRS program, which includes the advanced forward-looking and side-looking mine detection and classification sonars as well as the homing/docking and acoustic telemetry sonars. The LMRS is a sophisticated autonomous UUV system that will operate clandestinely from U.S. Navy nuclear submarines. It will be launched from a torpedo tube. The UUV will be recovered through the submarine's torpedo tubes via a mechanical arm that is housed in another tube. The LMRS consists of a self-propelled, 21-inch diameter autonomous UUV equipped with mine search and classification sonars for locating mine-like objects in a naval operational area of interest. The LMRS will provide an early, rapid, accurate means of surveying potential mine fields in support of proposed amphibious operations, other battle group operations, and safe ship transit around mined waters.

MISSION RECONFIGURABLE UUV [3,4]

In 1995, under the sponsorship of several federal agencies, the World Technology Evaluation Center (WTEC) of Loyola College in Baltimore, Maryland sent a group of experts to Russia to benchmark the non-military undersea technology of the Former Soviet Union. In Valdivostok, the group visited the Institute of Marine Technology Problems and observed a very large number of AUVs. Most of the AUVs had conducted operational missions to depths exceeding 20,000 feet. Funding and emphasis for this institute was due in large part to the U.S. operation to recover a sunken Soviet submarine in the Pacific (Operation Jennifer). Russia desired to know what the United States did and did not recover. These vehicles were for the most part reconfigurable and modular. The WTEC report resulting from this visit to the Institute influenced AUV construction in the United States. The value of modular, reconfigurable AUVs was recognized.

The core of the Navy's UUV Master Plan is the development of modular UUV systems that can be readily configured to perform a variety of missions. With common functional modules and standardized internal interfaces, great flexibility and transition between systems can be achieved. This plan recommends standardizing on two module sizes: a small 6 to 12-inch-diameter module and a larger, nominally 21-inch-diameter module. The UUV Master Plan describes these two module standards as follows.

The Mini-Modular UUV (M^2UUV) will be fielded in various sizes based on the small undersea modules. These modules would provide the Comm/Nav Aid capability and augment the current SSN capability (figure 6). The first step in developing the M^2UUV would be standardization of the module size and contents, with special attention paid to those capabilities needed by the vehicle system as a whole. As these standard modules are developed, payload modules will be developed on a parallel path, thus ensuring system compatibility. These payload modules will include specific packages such as oceanographic sensors, communications links, and navigation systems. In turn, they can provide building blocks for larger systems. Following the initial module development, UUVs that meet the requirements of the Comm/NAV aid mission can be fielded, possibly as early as FY2005. Later M^2UUVs will form the core of the SWARM concept, providing a rapid mine reconnaissance capability by FY08 with a clearance capability to follow. As required, oceanographic and other missions enabled by the M^2UUVs would follow.

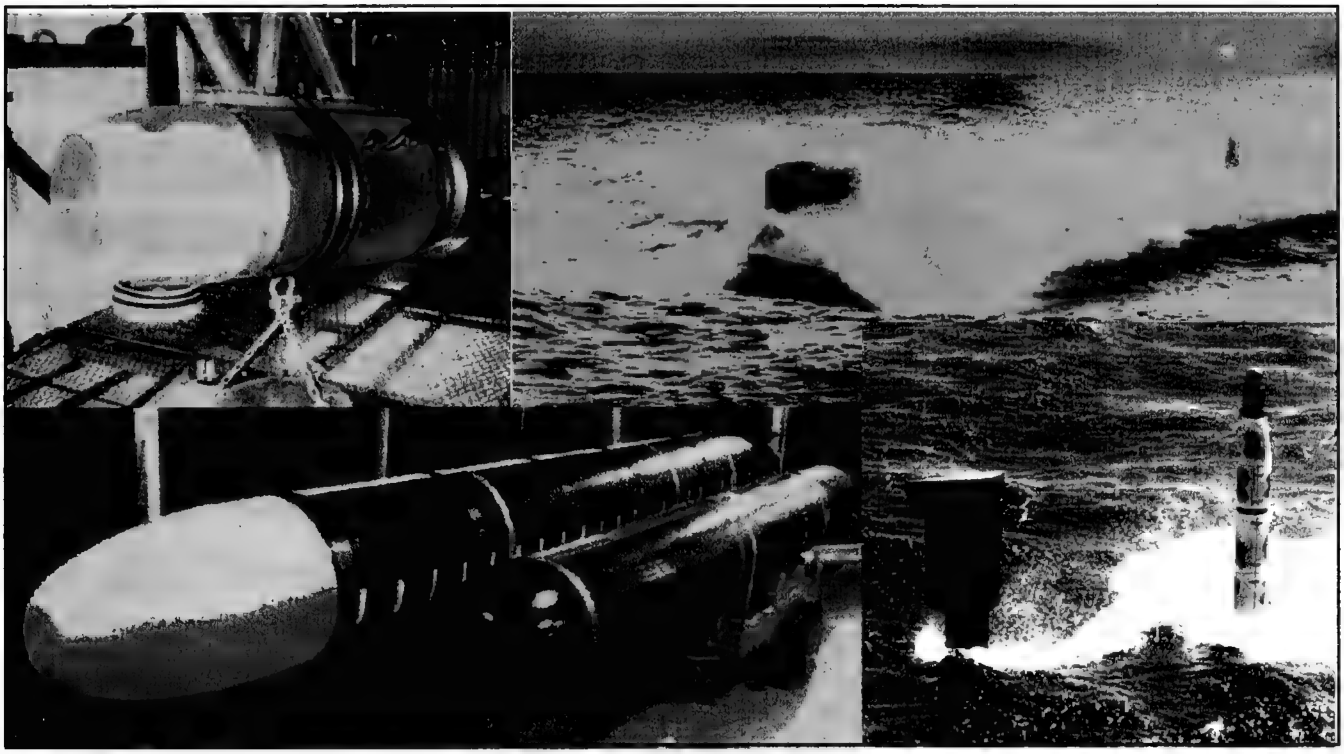


Figure 6. Submarine-Launched UUVs

The Tactical Modular UUV (figure 6) would address the needs of the Maritime Reconnaissance and Submarine Track and Trail capabilities. As with the M^2UUVs, the first step is the standardization of module size contents, with special attention paid to those capabilities needed by the vehicle system as a whole. As these modules are developed, the payload modules will be developed on a parallel path, ensuring system compatibility. Modules developed under the M^2UUV program will also be considered for incorporation in the system. This approach can lead to an initial Maritime Reconnaissance Capability by FY07. The Submarine Track and Trail capability is obviously more difficult to achieve; however, if the technology is pushed, an effective UUV capability can be fielded. Initial variants of the Submarine Track and Trail capability may be less autonomous, require closer coordination to U.S. Forces (both surface ship and submarine), and may be smaller than the systems of the Vision. As dedicated modules become established and UUV mission capabilities grow, more complex mission can be pursued. Eventually, the full Maritime Reconnaissance and Submarine Track and Trail Capability can be achieved, and perhaps, tactical engagement with missiles and/or weapons launched from UUVs can be explored.

PHOENIX AUV [9,10]

The Naval Postgraduate School (NAVPGSCOL) has designed and built two underwater vehicles, NAVPGSCOL AUV I and the Phoenix AUV. The Phoenix AUV is in the 2-meter vehicle class weighing approximately 400 pounds (wet) but operated neutrally buoyant. It has been used for many studies relating to the design of control system architectures. The Phoenix has been the experimental test-bed for development and evaluation of nonlinear and adaptive control of vehicle motion. It has supported experimental work in system identification and the development of physical modeling and visualization. Figures 7 and 8 are schematics for the Phoenix AUV, and table 6 lists its specifications.

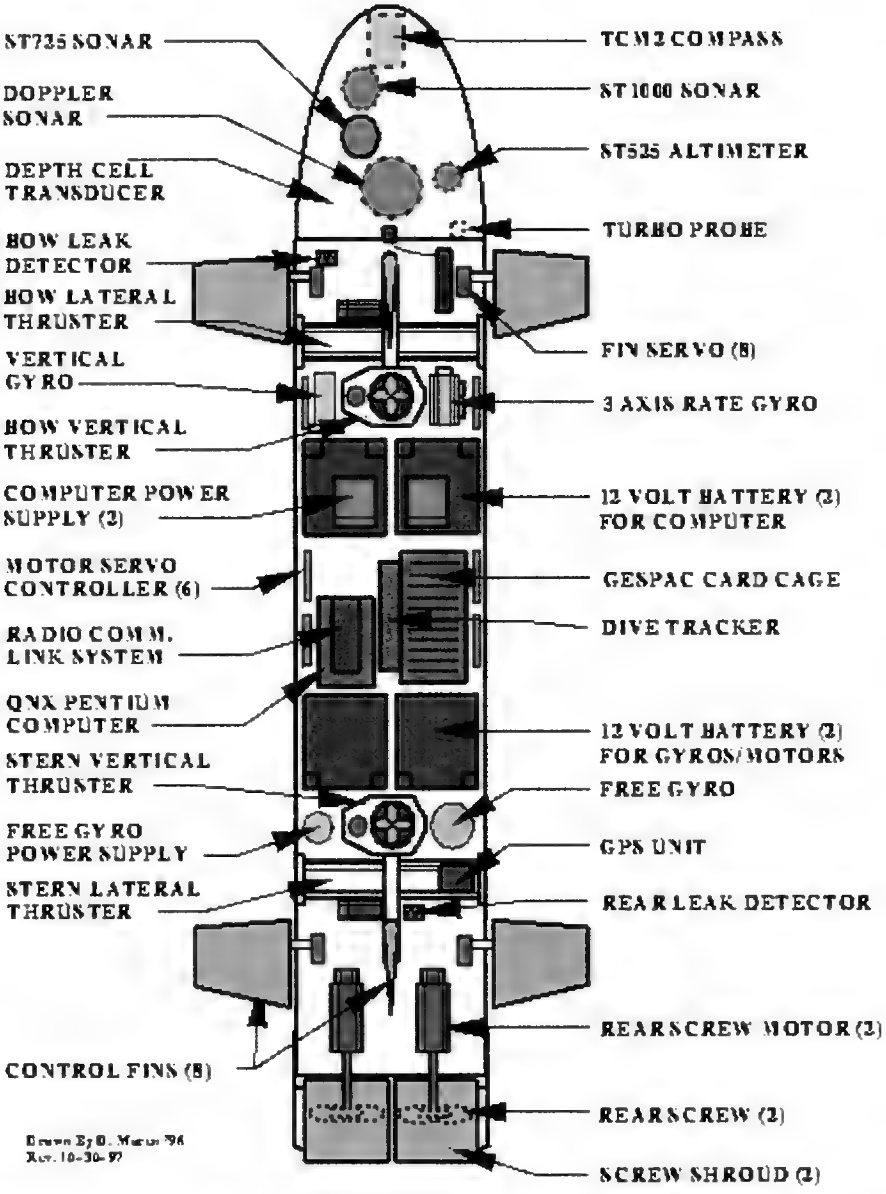


Figure 7. Phoenix AUV for Mine Reconnaissance/Neutralization in Very Shallow Water

Table 6. Phoenix Specifications

Length	7 feet
Breadth	1.5 feet
Displacement	approximately 450 lbs
Top Speed	knots
Maneuvering	0 - 3 knots, Phoenix has vertical and horizontal cross-body thrusters, enabling it to hover.
Depth	Used for shallow-water application in depths less than 30 feet
Mission Duration	3 hrs using lead-acid batteries
Propulsion	twin screw, one 1/4 hp brushless DC motor on each shaft
System Control	PC-104 board with a pentium node running QNX. There is an ethernet module for network communications between internal vehicle processors and external computers. This is accomplished by either an Ethernet & Starlan Data Link or by a 900-MHz radio modem.
Vehicle Control	GESPAC Computer System running OS-9 real-time operating system
Navigation	- magnetic compass - Precision Nav - INS
Sensors	- Sistron and Donner motion package - Depth Cell, Psi-Tronix Inc., model S11-131 - DiveTracker, a short baseline acoustic positioning system by Desert Star Systems. - Scanning Sonar - Profiling Sonar - Doppler - Altimeter - ADCP
Employment	Phoenix is an experimental vehicle used for proof of concept.
Deployment	Vehicle may be deployed at any boat landing via trailer and is also capable of being lifted and launched from a pier or boat.

The AUV Center at NAVPGSCOL began in 1987 with the joining of interested faculty from the Departments of Mechanical Engineering, Computer Science, and Electrical and Computer Engineering. Instrumental in its formation was the Navy's interest in such vehicles for clandestine mine countermeasures work. While that is still of great interest to the Navy, other applications to Ocean Science and commercial usage for monitoring and surveillance have grown. The Center is focused on the development of advanced control methodologies for using this type of vehicle in very shallow waters, where persistent wave and current action from the seaway make operations difficult.

The AUV Center has been funded for several projects by the National Science Foundation and ONR, and works collaboratively with the Florida Atlantic University. Other related work using multiple small robotic land vehicles for minefield clearance and missions clearing unexploded ordnance (UXO) has been funded by the Naval Explosive Ordinance Disposal (EOD) Technical Division (Indian Head).

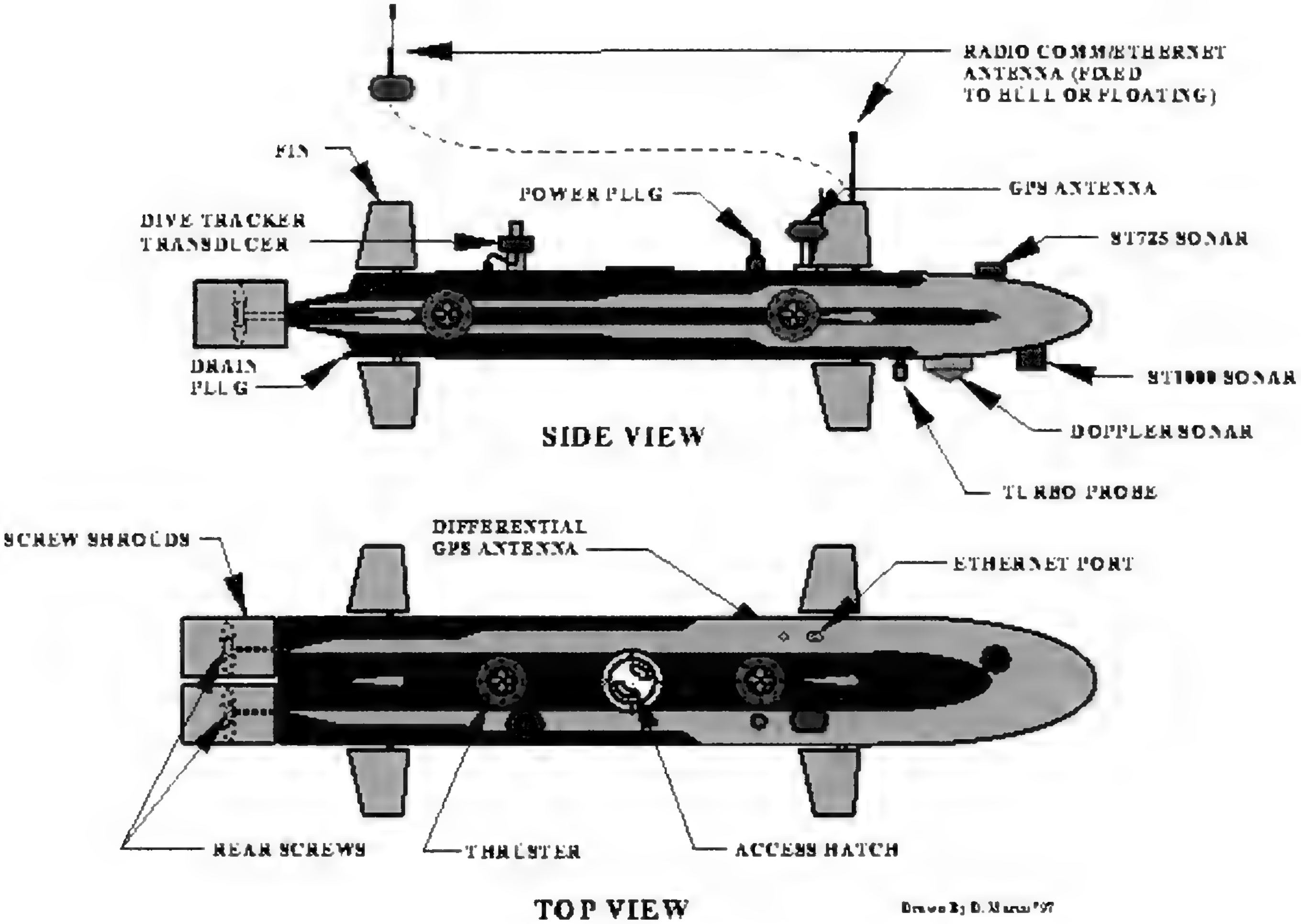


Figure 8. Phoenix AUV – External View

ADVANCED UNMANNED SEARCH SYSTEM (AUSS) [1,11,12,13,14]

The Ocean Engineering Division at the Naval Command Control and Ocean Surveillance Center Research, Development, Test and Evaluation Division (Naval Research and Development (NraD)) has developed and fielded two successive un-tethered, supervisory-controlled UUV systems: a prototype and an improved model. These robotic vehicle systems were part of the Advanced Unmanned Search System (AUSS) program that had its genesis in the early 1970s. This program, and the verity of these two vehicles showed that supervisory-controlled systems can be employed effectively. AUSS program evolutions encompassed a search database, computer modeling of search, subsystems evaluation, the test-bed prototype search system, and finally the improved delivery system. Throughout this program, from 1973 until 1993, engineers at Naval Oceans Systems Center continued the AUSS program, acquiring experience and applying their knowledge to improve both search technology and vehicle technology.

System feasibility was fully demonstrated after the prototype was fielded, many lessons were learned, and the prototype experienced major evolutionary changes. The second system was a complete redesign, using state-of-the-art subsystems and technologies. The resulting product was capable and reliable, yet flexible, creating a plethora of system evolutionary possibilities. Sea tests, improved tactics, and systems engineering became synergistic and interactive. Increases in vehicle autonomy enhanced the human operator's capability to supervise by decreasing piloting and navigating burdens. The resulting system significantly exceeded expectations and was delivered to the fleet. The AUSS is shown in figure 9.

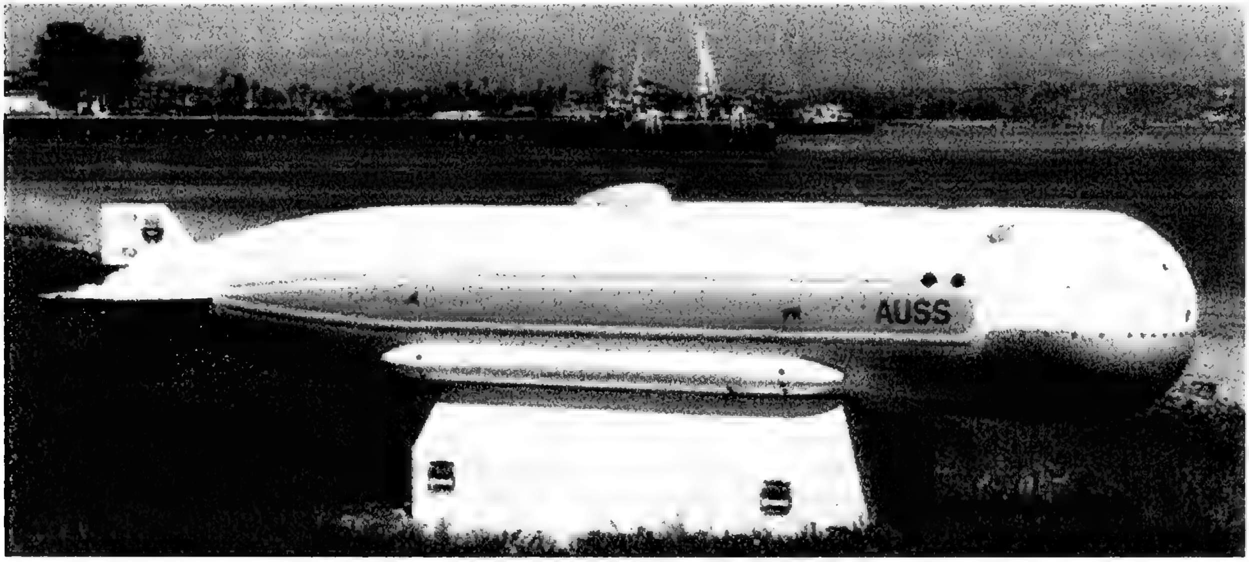


Figure 9. AUSS

AUSS involved pioneering research in underwater search and in UUV systems. Important knowledge was also gained in systems analysis, system engineering, and program evolution. Two systems have been built and fielded which in combination have experienced 114 untethered launches (and 114 successful recoveries) to depths between 2500 and 12,000 feet. AUSS proved it did not require a long, clumsy, and potentially dangerous leash.

System tradeoff studies and analysis showed that an untethered search vehicle with supervisory control outperformed all other tethered, towed, and untethered options. Concurrently development of an underwater acoustic communications capability allowed supervised control without a tethered cable.

Potential strengths of properly designed untethered systems are agility, stability, ability to hover in three dimensions, high forward speeds, rapid turns, combined with low risk of loss. Untethered systems, however, will not have enough self-intelligence in the foreseeable future to replace the human decision making capability afforded by vehicle/operator communications.

The human operator, when allowed to supervise the operation of an untethered system, fills in where the untethered system is deficient: complex decision making. The human plans the mission and decides how to alter the mission based upon information obtained from both the support ship systems and the vehicle itself. The human analyzes vehicle sensor data and decides which anomalies in the data are of interest to the mission and therefore deserve further investigation, and which are not. The human operator can also alter the tactics pursued by the vehicle based upon environmental changes indicated in sensor data. Finally, the human operator is uniquely qualified to declare when the mission is completed.

Autonomous systems can profit by the inclusion of a real-time (cable or fiber optic) or near-real-time (acoustic) communications capability during development testing. With this approach, the developers/operators have an opportunity to interact with the system and monitor system performance in real time while they work out system bugs.

The evolution toward more autonomy with an untethered system can be carried to completion if the mission permits. Increases in AUSS vehicle autonomy have enhanced the human operator's capability to supervise by eliminating pilot and navigation burdens, and even allowed the matured AUSS vehicle to be used for certain complex, fully autonomous functions. These included performing sonar search patterns covering several square nautical miles and transiting long distances without operator commands being sent for hours.

The prototype was a product more of evolution than of its original system engineering. Post-design breadboard-level implementations existed throughout, resulting in an unaccountable signal-to-noise ratio in the acoustic link system. Transmissions of high-quality images through the acoustic link required so much time that the rate at which the system could search was below optimal. The vehicle buoyancy system consisted of a pressure vessel providing less than adequate displacement supplemented by ad hoc, oddly shaped pieces of syntactic foam. The vehicle fiberglass fairings suffered from extensive modifications including holing, sawing, and gluing.

The improved system's ground-up design was based upon the prototype lessons. The electrical and acoustic signal-to-noise ratios were excellent. The vehicle computer systems were expanded and upgraded to the best available technology. Contractor-supplied surface console software was rewritten and ported to a network of off-the-shelf industrial computers. Original image compression algorithms were developed so the optical and sonar images were seen by the operator within seconds of acquisition, and the advance speed of the vehicle was optimized during sonar imaging for the travel time of the sonar pings.

An important AUSS goal was to produce a small, lightweight system that could be transported easily and placed upon a large cross section of ships of opportunity. As with any overall vehicle system, the size of AUSS depends heavily upon the weight and size of the undersea vehicle. If the vehicle is allowed to increase in size, the launch and recovery gear, the handling gear, and the maintenance areas grow in kind. There is also a vicious cycle of growth associated within the self-powered vehicle design. A larger vehicle requires more propulsion power, requiring more energy for the same speed and endurance. More energy leads to more weight and volume in the energy source, which leads to a larger vehicle.

Deep service syntactic foam is a much less efficient form of buoyancy than properly designed pressure vessels. Syntactic foam was used extensively on the AUSS prototype vehicle, as has been the case for many undersea vehicles. Thus a commitment was made to avoid its use on the improved vehicle. To meet this objective, several measures were taken.

Extremely efficient graphite-pressure hull technology was developed with the prototype and applied to the improved system. A 30-inch-diameter graphite cylinder was manufactured to provide all of the buoyancy required for the improved vehicle. Other measures taken were the use of SpectraTM (which has a specific gravity very close to that of sea water) for the free-flooded fairings, magnesium for the chassis inside the vehicle, titanium for the wet connectors, and titanium and aluminum for redesigns of various sensor housings. The only syntactic foam in the system was the deployable nose float used for recovery.

The time required for signals to travel between the surface and vehicle is dependent on speed of sound in water and the distance to the surface. Range of operation therefore affects the response time of the vehicle to supervisory commands, and it also affects the delay time taken for sensor information to reach the supervisor. These delays will increase with operational range, amounting to a round-trip delay of ten seconds or more at 20,000-foot depth with moderate standoff. The only way to prevent degradation of performance with range in an acoustically supervised system is to develop strategies that utilize vehicle autonomy.

An example of more autonomy yielding better range independence is with an approach developed during the AUSS interactive sea test/development process for viewing objects on the bottom of the ocean. Neither the prototype nor the improved vehicles had side thrusters, and hovering over an object in a current proved impossible. With the prototype, pictures of the object were taken while the vehicle glided above the object at some forward velocity. The operator had to guess when to command the vehicle to take a picture. The combined acoustic link/supervisor reaction time increased with range to the vehicle. This process was marginally possible for ranges of 2500 feet, and would have been nearly impossible at the maximum range of 20,000 feet.

During the improved vehicle evolution, an autonomous "hover at a radius" algorithm was implemented. This simple algorithm is analogous to a boat standing off from a buoy; the vehicle points at a position and maintains a given standoff from that position. The vehicle "weathervanes" into the current but remains aimed toward the target object. If the standoff distance is selected to be equal to the distance between the imaging camera (at the front of the vehicle) and the Doppler sonar (which is aft of the camera and is used to determine the position of the vehicle), the camera stays over the target. This is a completely autonomous routine that is range insensitive and requires only one supervisory command to send the vehicle to a target.

As the AUSS system became operational and more dependable, a number of other innovative supervisory control system advances were invented to simplify the supervision of the undersea vehicle operations. Among these was target marking, wherein the location of a target object in the vehicle's onboard navigation coordinate system is automatically calculated when a cursor is placed over its image. Target marking was applied to Side Looking Sonar (SLS), Forward Looking Sonar (FLS), and Cooled Charged Coupled Device (CCCD) imaging portions of the AUSS mission.

The synergy of hover at a radius and target marking made a significant contribution to the efficiency with which the system could view objects (targets) on the bottom. Each step in the target marking/hover at a radius sequence brings the AUSS closer to the objective target using successively shorter range, higher resolution sensing. An SLS target mark is used to determine a position for the vehicle to go to, hover at, and obtain an updated target mark with the FLS. FLS target mark is used to determine a position for the vehicle to go to, hover at, and obtain the first CCCD image. Finally, the cursor is moved about on the CCCD screen to mark positions for the vehicle to go to and obtain CD image coverage of the target area.

Sixty-five hours of bottom time were logged during eight dives between 5 April and 24 June 1992. These eight dives produced some compelling results. During the showcase, SLS search rates were as high as 1.5 sq-nmi/hr. Contact evaluations (the process by which targets are found and imaged with CCD) typically took between 10 and 15 minutes. This process includes the time between the operator's identification of a potential target on SLS and the time when the vehicle was once again searching with SLS. The AUSS demonstrated fully operational dives between 2500 and 12,000 feet, depth-independent supervisory controlled search tactics, and excellent compression-enhanced acoustic link performance to 12,000 feet.

During a single dive at 4000 feet, consistent SLS search was conducted at speeds between 4.5 and 5 knots with a swath of 2000 feet. The area searched during the dive was 7.5 sq-nmi, and the time to conduct SLS search and contact evaluations was 8.5 hours. This demonstrated an SLS search rate better than 1.5 sq-nmi/hr and an overall search rate (including contact evaluations) of 0.9 sq-nmi/hr.

In another 4000-foot dive, over 2.5 sq-nmi were searched, including several lengthy contact evaluations and three photomosaics (series of overlapped CCD images taken while the vehicle performed a small search pattern over a target area). The contact evaluations included a 55-foot yacht and a Korean War vintage Skyraider night fighter aircraft that were both discovered and position pinpointed during the dive. An autonomous 5-nmi transit was also performed during the 14 hours the AUSS vehicle was submerged.

During a 12,000-foot dive, the vehicle operated for 11 hours. The images were compressed and transmitted through the acoustic link at 2400 bps. Communications during the 12,000-foot dive were excellent, and search and contact evaluation tactics were proven to be depth insensitive.

ROVER, AUTONOMOUS BOTTOM-TRANSECTING VEHICLE [15,16]

The Scripps Institution of Oceanography (SIO) developed an autonomous underwater device available for performing long-term sequential measurements of benthic community activity. Sediment community oxygen consumption (SCOC) is one measurement of benthic community activity that has only been measured over short time periods of one month or less. SIO has developed and successfully collected data with a unique, autonomous, bottom-transecting vehicle (ROVER) that permits the first long-time-series measurements of SCOC (figure 10). This instrument was developed with the following capabilities:

- The instrument autonomously operates as a free vehicle on the sea floor to 6000-meter depth for periods up to six months.
- The instrument crawls across the sea floor, minimizing the impact that a long-term, free vehicle would have on measurement sites.
- SCOC is measured using two benthic chambers at up to 30 different sites over a single deployment.
- Sediment pore water oxygen concentration is measured using a microprofiler at up to 30 different sites over a single deployment period.
- Incubation period is programmable for each SCOC measurement.
- Operation of instruments and the surrounding area is monitored with time-lapse still and video cameras.
- ROVER can be used as an autonomous programmable platform for a wide variety of benthic boundary layer measurements.
- A water sample for oxygen or other analyses is collected at the end of deployment.

ROVER Description

The ROVER resembles a small forklift with a forward-mounted instrument rack, a savonious rotor and vane for measuring water currents, double-tread propulsion system, central battery packs and controller electronics, flotation, acoustic releases, and disposable ballast. The structural frame is constructed of titanium and fiberglass angle and tubing on which all the components are mounted. A polypropylene bumper extends ~30 cm beyond the vehicle frame to provide protection while handling the instrument during deployment and recovery. All materials and fabrication procedures used in the construction of each component of the ROVER were selected to minimize corrosion for long-term deployments to full-ocean depths (6000 meters). The overall dimensions of the ROVER are 2.74 meters long, 2.03 meters wide, and 2.19 meters high from the base of the propulsion treads to the top of the lifting bail.

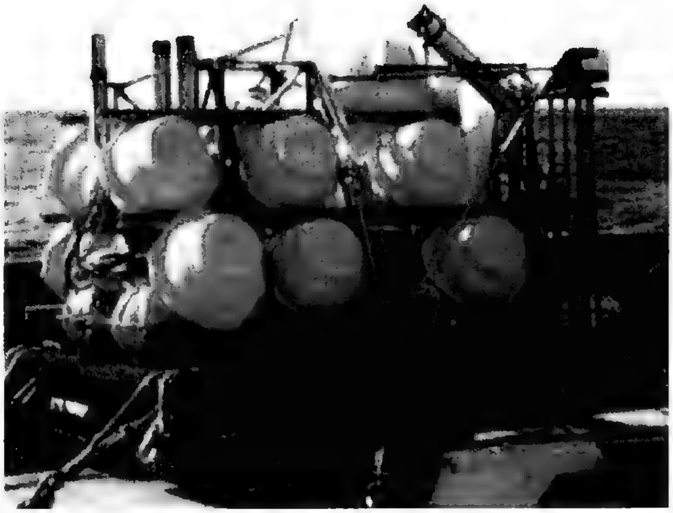


Figure 10. ROVER

Instrument rack - The instrument rack consists of two cylindrical benthic chambers and an oxygen microprofiler mounted to a titanium vertically-moveable rack on the front of the ROVER frame. This assembly can be slowly lowered and raised with two titanium lead screws mounted vertically on both sides.

Two acrylic transparent benthic chambers are mounted on either end of the instrument assembly. A bottom leading edge of thin, teflon-coated titanium reduces the force required to push the chambers into the sediment and eliminates adhesion of sediment to the chamber wall. A stirring bar, centrally mounted in each chamber, is driven by a pressure-compensated stepper motor via a magnetic coupling. This stirring assembly moves vertically on three titanium guide rods powered by a drive motor and a fine-scale lead screw. In the "up" position, the stirring assembly leaves a large hole in the chamber top, allowing the chamber to purge during insertion into the sediment. In the "down" position, the stirring assembly seals against an O-ring on the top plate of the benthic chamber.

The oxygen-sensing system for each benthic chamber consists of a polarographic oxygen sensor and a flow cell. The oxygen sensor for each chamber on the ROVER is mounted in an external flow cell and is alternately exposed to chamber and ambient water using a pump and valve system. The ambient reference measurement is necessary to correct for long-term drift in the oxygen sensors and provides a direct comparison between chamber-water oxygen concentration during the incubation and stable oxygen concentration in the ambient bottom water. The flow-cell sample water is transferred by a DC motor-driven pump to the flow cell through plastic capillary tubing. A 3-position slider valve is used to switch the water supply to the flow cell from chamber to ambient, and this valve is under the control of the benthic chamber controller. A 1-liter Niskin bottle is mounted vertically on the instrument rack near one of the benthic chambers to take a water sample for dissolved oxygen analysis at the end of the last incubation. Closure of this bottle is triggered by a burn-wire release via the central controller.

At each new measurement site, the instrument rack is lowered to place the oxygen microprofiler sensors just above the sediment and the benthic chambers ~6 cm into the sediment. The oxygen microprofiler is mounted on the instrument rack between the two benthic chambers. This microprofiler can accept up to 12 oxygen (or other) microsensors and four resistivity sensors that are arranged in a circular pattern on a plate that is mounted beneath the microprofiler-controller electronics cylinder. The titanium controller housing and electrodes are lowered stepwise toward the sediment surface by a fine-scale, DC-motor-driven lead screw (1 mm pitch). The resistivity sensors detect the sediment-water interface as a change in resistivity and allow the microprofiler controller to determine the sensor penetration depth into the sediment. Feedback from the resistivity sensors sets the system to profile an additional programmable distance into the sediment, and readings from each oxygen sensor are recorded at 0.5-mm increments. When the microprofiler completes the oxygen measurements to the programmed depth, the unit is retracted from the sediment. Oxygen sensor outputs from the benthic chambers and microprofiler are digitized and then transferred to the central controller for storage on a disk drive.

Video and time-lapse still cameras - Two video cameras and flood lights are mounted on the ROVER frame to monitor the operation of the benthic chambers and microprofiler. The cameras and flood lights are operated by the central controller, and the cameras' video output is recorded on two Sony camcorders housed in the central-controller pressure case. The recordings provide information on the penetration of the benthic chambers and microprofiler into the sediment and the operation of the stir bars. The topography of the sediment surface and the activity of animals within the transparent chambers and around the microprofiler are also monitored by the video system. A time-lapse still camera mounted on the ROVER frame and a remote strobe light mounted on the instrument rack are used to photograph the area in front of the ROVER during transits between measurement sites.

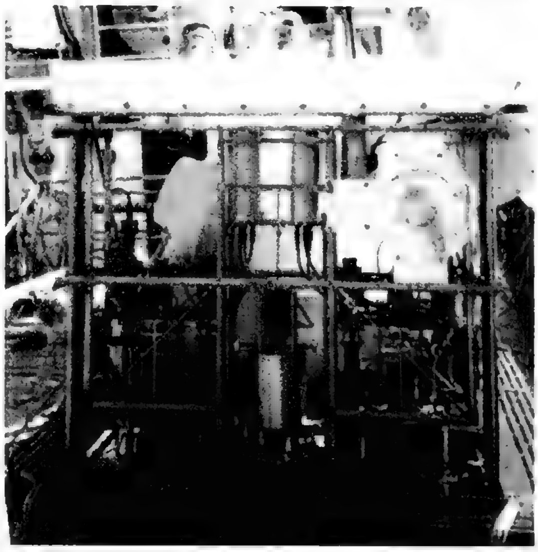


Figure 11. ROVER-Current Monitors

Current rotor and vane - Near-bottom current speed and direction are monitored using a Savonius rotor. The turning speed of the rotor is detected by an optical sensor. Current direction is determined by a vane, magnetically coupled to a servo-potentiometer. Outputs from the current rotor and vane are recorded by the central controller during the entire deployment. The current rotor and vane are mounted on a small arm, which is raised and lowered by a lead screw (figure 11).

Propulsion system - The ROVER is propelled across the sea floor by two, flexible, fiber-reinforced PVC tractor treads (50 cm wide by 3.6 m long). Each tread is independently driven to allow directional movement, which is determined by the central controller. Treads have molded external cleats in order to ensure traction in soft sediment. Each tread is driven by a 1/8-HP DC motor and a reduction gear train, housed in oil-compensated PVC housings. A load-bearing, low-friction, polyethylene pressure plate supports each tread.

Central controller with data storage and central battery - The propulsion system, instrument assembly, cameras, current rotor and vane are all controlled by a central controller which consists of a microcontroller, interface electronics, electronic compass, tilt sensor, and video camcorders. The microcontroller (Onset, Model 7) has a real-time clock, a 64-MB hard drive and a 12-bit A/D converter to digitize sensor outputs. It is located in a titanium pressure cylinder, mounted on the mainframe of the ROVER. The electronic compass (KVH Industries, Model C100) allows the ROVER to maintain course during transits and turns. A tilt sensor (Lucas, Model Accustar II) provides tilt information to the controller to determine if the Rover is approaching a mound or slope. The distance traveled by the ROVER over the bottom is estimated by a Hall-effect sensor that detects the revolution of magnets embedded in the forward drive roller. Power for the ROVER and its instrumentation is provided by two alkaline battery packs (180 D-cells each), located in independent titanium pressure housings mounted on the ROVER frame beneath the central controller. These batteries have a total capacity of 5000 watt-hours and are sufficient to power the ROVER in a typical deployment for up to 6 months.

The operational status of the ROVER can be obtained by interrogating an acoustic transponder from a surface ship. The number of pings returned is increased as the ROVER progresses successfully through its program. Serious faults are indicated by a return to a single ping.

Acoustic release and disposable ballast -Two acoustic releases in titanium pressure housings are mounted on the after end of the structural frame. Each release activates a remote burnwire trigger mechanism that can drop a disposable ballast rod of cold-rolled steel. With the release of either burnwire mechanism, the ballast falls between the treads, causing the instrument to become positively buoyant and rise off the sea floor. A submersible VHF transmitter, submersible flasher and flag mounted on the aft end of the ROVER and a second set on the mast assembly facilitate location by a ship in the vicinity. In the event of a premature release of the ballast there is also an ARGOS satellite transmitter mounted on the top of the ROVER for detection and tracking.

Flotation – The ROVER's flotation consists of 18 evacuated glass spheres (Benthos, 10 and 17 inch; Billings, 12 inch) mounted on the structural frame. The floats provide positive buoyancy of 385 kg, and an additional 41-kg buoyancy is provided by the floats on the recovery mast assembly. Syntactic foam was considered as flotation for the ROVER, but the added cost and air weight of foam proved excessive for the initial design. The spheres are inspected before each deployment for excessive spalling to reduce the chance of implosion.

Weight and balance - In designing the ROVER it was critical that the instrument not sink too deeply into soft sediment, yet still be heavy enough to gain traction for maneuvering. The entire instrument weighs 40 kg on the sea floor, which permits optimum mobility with the double-track propulsion system.

ROVER Operation

The ROVER is deployed from a research ship using the ship's crane to lower the instrument into the water. (figure 12) A "quick-release" system is used to detach the ROVER from the crane's hook. Once released, it takes about two hours for the ROVER to sink to the bottom in 4000 meters of water. After landing, the current rotor and vane-assembly are raised vertical by a lead screw in order to provide measurements of current speed and direction while the ROVER is on the sea floor. The central controller will monitor the current flow for a programmable period (about 24 hours) to determine predominant current flow direction. After the initial current monitoring period, the ROVER will wait for the right current flow conditions and then travel upstream in the direction of predominant current flow. This way, any sediment the instrument's tracks stir up will move downstream from the next measurement site. The ROVER will typically be programmed to move 5-10 meters from site to site.

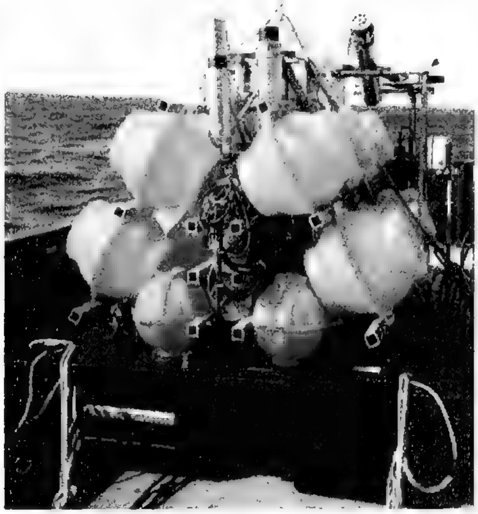


Figure 12. ROVER – Ready for Deployment

At each measurement site, the instrument assembly with benthic chambers and oxygen microprofiler is slowly lowered into the sediment while being monitored by the two video cameras. Once implanted in the sediment, the central controller commands the benthic chamber controllers to begin their measurement cycles. The cycle begins by lowering the stir motor assemblies to seal the top of the chamber and starting the slow rotation (~9 rpm) of the stir bars. The oxygen level in the benthic chambers is measured for a period of 1-7 days, which is determined by the central controller. After the completion of an incubation period, the stir bars are stopped and retracted, and the instrument rack is raised above the surrounding bumper.

After sequential sampling for periods up to six months (~30 sites), the instrument and current rotor and vane assemblies are retracted into their protected positions, and the ROVER is commanded to release its ballast and return to the surface. At the surface, the ROVER is located using the directional VHF transmitter and strobe.

Four-Month Deployment

The ROVER was deployed for a 4-month period beginning January 28, 1996 at Sta. M (34° 50'N, 123° 00' W; 4,100-m depth) 220 km west of the central California coast from the R/V Wecoma. The microprofiler was not used during this deployment, but SCOC was measured within the two benthic chambers. The ROVER was programmed to occupy 17 sites during the deployment with incubation periods of the benthic chambers at each site set for ~6 days.

At the end of the 4-month deployment, the ROVER was recovered on June 1, 1997 using the *R/V New Horizon*. Analysis of the central controller data showed that the ROVER had completed its mission of crawling to the 17 measurement sites. Benthic chamber data and video recordings showed the chamber design largely performed its mission and useful data was recovered from most sites. The time-lapse camera operated correctly and returned many photos taken of the sea floor while traveling between measurement sites.

This ROVER is particularly suitable in remote areas, such as polar regions or mid-basin portions of the Pacific and Indian Oceans that are difficult to occupy routinely due to logistical or weather constraints. It also can be operated at a fraction of the cost of using manned submersibles or tethered ROVs, especially in these remote or weather-limited areas.

The ROVER can be used as a programmable platform from which to conduct a wide variety of research, including photographic transects, fine-scale bottom-water profiling for nutrients, fine-scale mapping of sea floor relief, and fine-scale mapping of sediment properties using sequential sediment cores and shear vanes. The increase in sampling resolution provided by the ROVER over conventional techniques should provide valuable insights into the dynamics of carbon cycling in the deep-sea benthic boundary layer.

HUGIN 3000 [17,18,19,20,21]

The HUGIN 3000 is the new and third generation of the HUGIN vehicles that were developed and operated in partnership with the Norwegian oil company, Statoil, the Norwegian Defense Research Establishment (FFI), and Norwegian Underwater Intervention (NUI). The HUGIN (figures 13, 14) project started in 1995, and the HUGIN vehicles have now performed more than 100 missions, including several commercial pipeline route surveys for Statoil in Norwegian waters. The HUGIN vehicles have so far proven very cost effective and will enhance quality of survey data compared to existing methods.

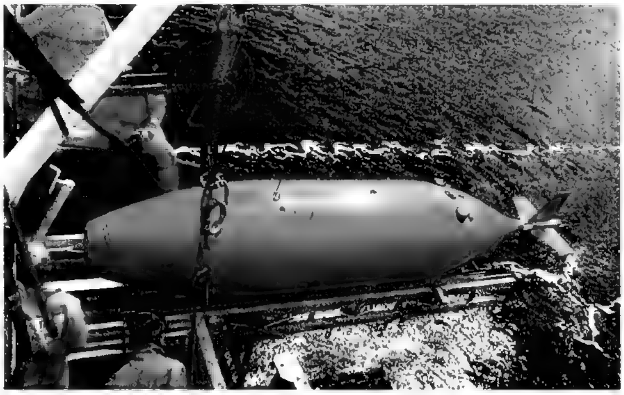


Figure 13. HUGIN 3000 Recovery

The Hugin 3000, rated to 3000 meters, is 5 meters long and powered by a state-of-the-art aluminum oxygen fuel cell, providing a mission capacity of up to 48 hours before resurfacing. The AUV will carry a variety of sensors, including the EM 2000 multibeam echo sounder for bathymetry and imagery. Underwater positioning will be performed using a HiPAP® Super Short Base Line (SSBL) system integrated with Doppler speed log, Inertial Navigation System, and for surface reference, Differential Global Positioning System (DGPS). Acoustic links for control of the AUV, reading of sensor data, and emergency control are part of the delivery.

C&C Technologies, an international hydrographic surveying company, has acquired and plans to use the HUGIN AUV as a deep-water survey tool for Minerals Management Service (MMS) Pipeline Hazard Surveys and Block Surveys. The HUGIN will provide the customer with engineering quality bathymetry data for the design of pipelines, pipeline risers, templates, and other sea floor equipment.

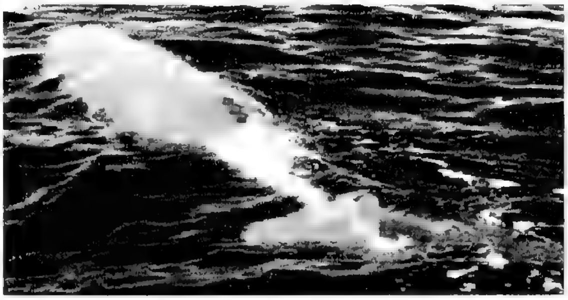


Figure 14. HUGIN 3000 in Operation

Kongsberg Simrad's new deep-water dynamic positioning (DP) and vessel-control functions and systems for the company's SDP/SVC/STC systems are designed to improve the safety and reliability of DP operations in deep water. These functions are enabling AUVs to be used for drilling, production, testing, and intervention operations that are traditionally accomplished with moored systems. Included in these systems is a riser management system (RMS)--a result of cooperation with Seaflex and designed to improve drilling, workover, and completion of operations in deep water.

These developments by Kongsberg Simrad are demonstrating that AUVs not only have significant cost advantages over current methods, but can also reliably undertake commercial survey work. Due to inherent low noise and high stability, HUGIN 3000-acquired survey data are typically of higher quality than data gathered with conventional techniques, such as surface tow and ROV-mount survey spreads. One major oil and gas company has already committed to C&C Technologies for HUGIN AUV survey work, and C&C is currently offering discounts for additional early commitments.

ODYSSEY [1,22,23,24,25,26,27,28,29]

During 1991 and 1992 a revolutionary new AUV was developed at the Massachusetts Institute of Technology (MIT) Sea Grant College Program AUV Laboratory. This vehicle, called Odyssey, was designed to provide marine scientists with economical access to the ocean. This first Odyssey AUV underwent field trials off New England in 1992 and was deployed from the National Science Foundation (NSF) icebreaker, the *Nathaniel B. Palmer*, off Antarctica in early 1993. Work on Odyssey was supported by the Sea Grant College Program, MIT, the National Science Foundation, and the National Underwater Research Program.

The results of these deployments led to the creation of a second-generation vehicle, Odyssey II, work that was supported by the ONR. In spring 1994, Odyssey II was deployed from an ice-camp in the Beaufort Sea in support of a program to understand Arctic sea-ice mechanics. All operations were carried out in a 15' x 15' tent, enclosing a hydrohole through five feet of ice. While at the ice camp, Odyssey II performed a series of "out-and-back" missions, demonstrating its ability to home into the recovery net. These tests set the groundwork for providing a unique capability for responding to transient events in the ice.

Odyssey is propelled by a motor running on batteries that can last six hours on a typical mission. Mounted in its nose for this pilot experiment is Crittercam, a computer-controlled video camera. Odyssey's antenna communicates with a radio beacon for locating the robot sub; the strobe has the same function. The acoustic transponder enables operators on *Tanekaha* to track Odyssey (figures 15 and 16). See table 7 for specifications.

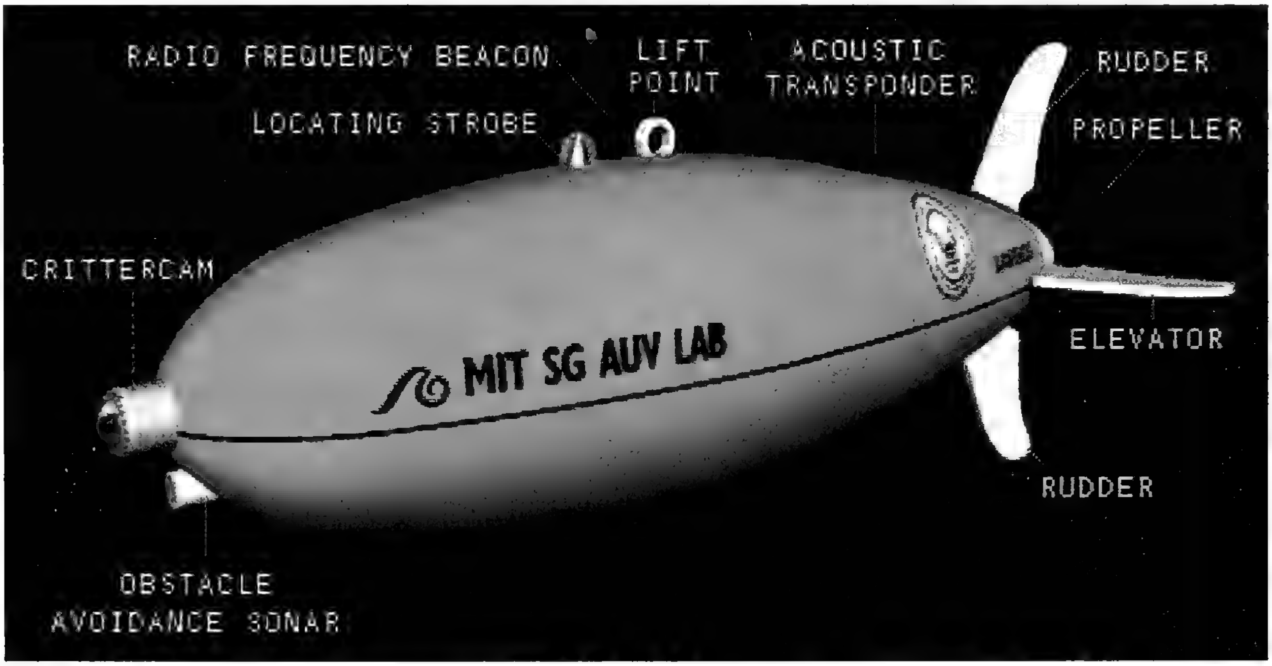


Figure 15. Odyssey

Under Sea Grant support, Odyssey II was operated from the National Oceanic and Atmospheric Administration (NOAA) ship *Discoverer* as part of the 1994 and 1995 VENTS programs (in a collaboration with the NOAA Pacific Marine Environmental Laboratory). A combination of tethered and free-swimming dives demonstrated navigation and tracking of the AUV over the Juan de Fuca Ridge, and fully-autonomous, untethered operation, as deep as 1400 meters.

In 1995, four new vehicles were built under ONR sponsorship. As some elements of the design were improved, these vehicles are denoted Odyssey IIb. The original Odyssey II was upgraded to be the same as the Odyssey IIb vehicles. Some of the vehicles have been loaned to collaborators at Woods Hole, the Navy NRaD center in San Diego, and to industry (Electronic Design Consultants in Chapel Hill, North Carolina). These vehicles have proved to be relatively simple to use and robust when operated by non-MIT personnel. For example, in June 1996 two of the Odyssey IIb AUVs were used in a month-long experiment that studied the dynamics of frontal mixing in the Haro Strait, off Vancouver Island. The vehicles carried water quality sensors, a side-scan sonar, and a water-current profiler. Over a 21-day period, the two vehicles performed 67 dives with no failures of the base vehicles and only one day lost to weather. The 430-pound (195-kilogram) robot sub is hoisted in and out of water via its lift point.

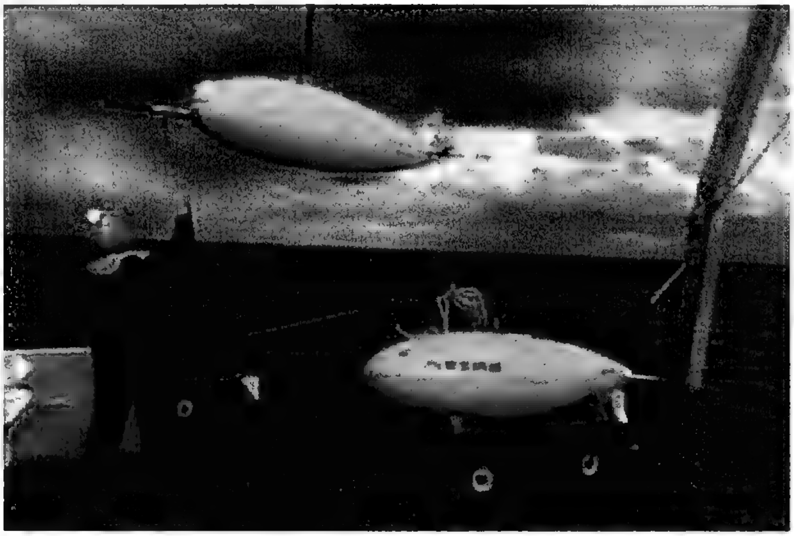


Figure 16. Odyssey Launch/Recovery

Table 7. Odyssey Specifications

Displacement	165 kg
Thruster	1 electric (brushless), 20 lbs max. thrust
Depth rating	6000 m
Power	Silver-Zinc Cells, 3.2 kW-hr
Endurance/Range	12 hours @ 5 km/hr
Onboard Computer	68040 based
Statu	5 Operational AUVs
Reliability	Over 400 dives with no vehicle losses
Payloads	CTD, ADCP, Camera, Side-scan Sonar

LITTORAL OCEAN OBSERVING AND PREDICTIVE SYSTEM (LOOPS) [30]

This project includes twelve partners from academia, government laboratories, and industry for the development of the scientific and technical conceptual basis of a generally applicable interdisciplinary littoral ocean and observing system, the Littoral Ocean Observing and Predictive System (LOOPS). A modular structural concept for linking, with feedbacks, dynamical models, and measurements via data assimilation will be developed, with an emphasis upon adaptive sampling, flexibility, and portability. The integrated system software architecture and infrastructure will stress versatility and efficiency via central databases for the measured ocean and the estimated ocean. Research to be carried out includes Observational System Simulation Experiments (OSSEs) for generic coastal processes and a range of civilian and naval application areas and sea trials to explore issues in the real-time implementation of LOOPS. The partners bring to the program diverse and relevant expertise and experience in interdisciplinary ocean science; systems and ocean engineering; data assimilation and ocean prediction methodologies; and synthesis and collaboration, as well as a suite of existing robust and tested measurement and model components for integration into the overall system.

ATLANTIC LAYER TRACKING EXPERIMENT (ALTEX) [31,32]

The project goal is to develop AUVs capable of observing basin-scale evolution in the Arctic (figures 17, 18). This requires the development of energy, navigation, and communication systems specifically tailored for extended autonomous operations under ice. One program objective is to provide a means of monitoring changes taking place in the Arctic Ocean and investigate its impact on global warming. Such a capability is of national and global interest and

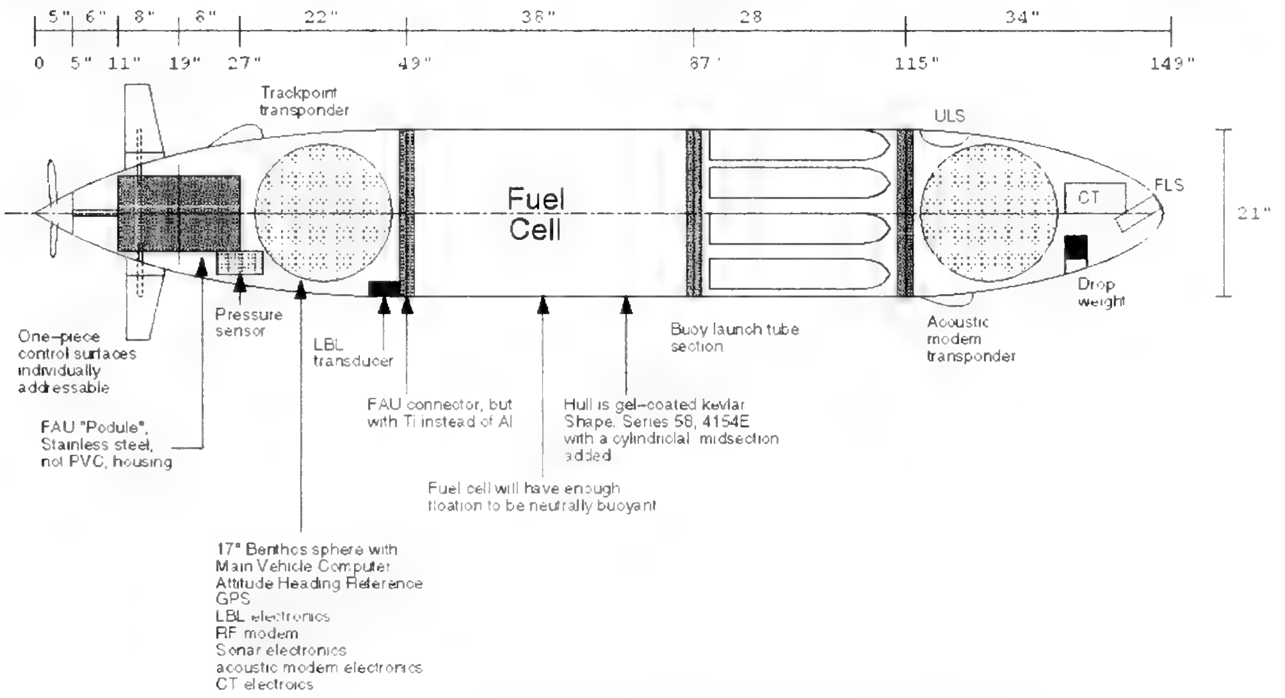


Figure 17. ALTEX-Reference Vehicle Mechanical Layout

importance. A modular AUV with parallel mid-body sections is being developed. The general AUV design called the Atlantic Layer Tracking Experiment (ALTEX) minimizes the use of pressure housings, putting as many systems as possible in smaller, lighter oil-filled (pressure-compensated) enclosures resulting in a small, deep-rated system. To achieve the desired range capability, the ALTEX program will employ a fuel cell energy system constructed by a team composed of Yardney Technical Products and Fuel Cell Technologies (FCT), Ltd. The system being developed is unique in that it will be pressure compensated and therefore deep-ocean rated. Communication will be provided by buoys designed to melt through the ice and telemeter mission data via Argos. The buoys will also be equipped with GPS, so that a position fix can be obtained. Other components of the vehicle will be a mix of systems developed for earlier generations of AUVs by the partner organizations. While some new systems are being developed, the objective is to leverage existing technology to the highest degree possible. The AUV capability goals are to deliver a suite of oceanographic and mapping sensors up to 1000 kilometers and down to least 1500 meters. Research will also be directed toward the development of communication systems using self-locating transponders that are remotely installed in the ice.

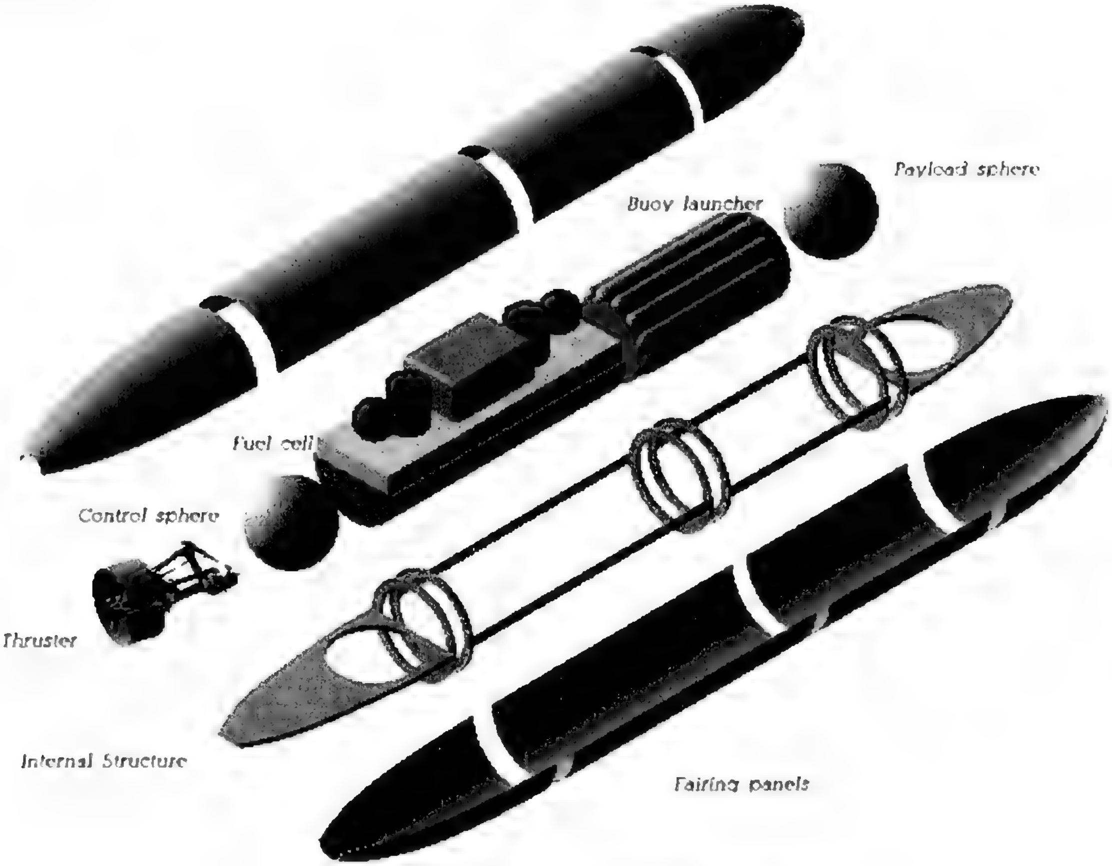


Figure 18. ALTEX – Exploded View

AUTONOMOUS OCEAN SAMPLING NETWORK (AOSN) [32,33,34,35]

The long-term goals of this project are to create and demonstrate a reactive ocean survey system, capable of long-term unattended deployments in remote environments. Such a system is referred to as an Autonomous Ocean Sampling Network (AOSN). The work described Institute of below is the product of a collaboration of research groups at MIT, Woods Hole Oceanographic Institution, SIO, University of Washington, and Northeastern University. The objective of this project is to create and demonstrate the next-generation robotic oceanographic survey system. This is being accomplished by:

1) Creating small, high-performance mobile platforms capable of several month deployments. Both propeller-driven, fast survey vehicles and buoyancy-driven glider vehicles have been developed.
2) Creating an infrastructure that supports controlling, recovering data from, and managing the energy of, remotely deployed mobile platforms. Elements include moorings, docking stations, acoustic communications, two-way satellite communications, and the Internet.
3) Demonstrating these capabilities in science-driven field experiments.
4) Developing operational techniques that make most effective use of these new assets, including adaptive sampling strategies.

CETUS [36]

In response to a request by Lockheed Corporation for the development of a flatfish-type AUV for mine countermeasures, the CETUS vehicle (figure 19) was designed and built at MIT Sea Grant's AUV Lab. The vehicle is designed to be passively stable, easily controlled, and capable of hovering. The project objective was to produce a vehicle that was not only inexpensive to manufacture but also durable and easy to service.

The final design has a single-piece High-Density Polyethylene (HDPE) hull, formed using a rotational molding process. It employs two propulsive thrusters and three hovering thrusters, with no active control surfaces. The fabrication, from concept to delivery, was achieved in nine months. Specifications are listed in table 8.

Figure 19. CETUS

Table 8. CETUS Specifications

Hull Size	Length 1.8m, Width .8m, Height .5m
Hull Composition	Rotary-Molded High-Impact Plastic
Weight	100 kg stand-alone, 150 kg with ALS and additional sensors
Depth Rating	Al Pressure Vessels 200m, Titanium PV >4000m
Control	Differential Thrust
Propulsion	Brushless DC Thrusters
Power	Battery (lead acid)
Speed	Cruising 1.5 - 2.5 knots, Maximum 5 knots
Range	20-40km (speed/sensor dependent)

COMMANDER, NAVAL METEOROLOGY AND OCEANOGRAPHY COMMAND

Requirements for oceanographic environmental support are identical to optimizing effectiveness of Navy high-technology warfare systems. With the Navy's shift to littoral operations, these requirements have increased significantly. Commander, Naval Meteorology and Oceanography Command (COMNAVMETOCCOM) is emphasizing integration of UUVs into the survey fleet as force multipliers to meet this increased demand for environmental support of several Integrated Warfare Architecture (IWAR) sub-domains. Naval Research Laboratory, South (NRLS) worked with an ISE developed "Dolphin" UUV, changed its name to "ORCA," and developed it as a force multiplier for survey work. This air-breathing internal-combustion engine-powered UUV was the prototype for the Remote Mine-hunting System (RMS) currently being developed.

SEAHORSE

COMNAVMETOCCOM's entry into the large UUV realm was initiated with the transfer of vehicles (1997/98) developed and tested at Draper Labs under the Defense Advanced Research Projects Agency (DARPA) project. The Naval Oceanographic Office (NAVOCEANO) teamed with Penn State University Applied Research Laboratory (ARL) to integrate commercial off-the-shelf (COTS) systems to build the SEAHORSE-class UUV, a low-cost, long-mission-endurance vehicle for standard shipboard deployment (figure 20). The design emphasizes:

- Modularity for quick turnaround shipboard maintainability in forward-deployed modes--rapid energy refurbishment and sensor payload change out
- Use of commercial oceanographic sensors that have been integrated and proven in the small UUV realm, and low-cost D-cell power pack technology
- Propulsor and autonomous control designed for shallow-water, energetic environments

The benefits to oceanographic surveys to be realized with SEAHORSE include:

- Force multiplier for T-AGS 60 oceanographic survey vessels
- Progress on UUV Priority III to provide large-area oceanography and tactical oceanography support
- Compatibility with standard NAVOCEANO oceanographic sensors
- Autonomous operating range of 300 nmi or 72 hours with existing battery system
- Deploy and leave ability increases survey effectiveness by allowing T-AGS 60 to depart SEAHORSE survey area and conduct surveys in other ocean areas
- Autonomous operating range of 1000 nmi, or more than one-week deployment time with future battery system

Figure 20. SEAHORSE Launch

SEMI-AUTONOMOUS MAPPING SYSTEM (SAMS)

NAVOCEANO is also pursuing small UUV technologies in the form of a modified Woods Hole Oceanographic Institution REMUS vehicle, identified as Semi-Autonomous Mapping System (SAMS). SAMS leverages existing Towed Oceanographic Survey System (TOSS) Relative Acoustic Tracking System (RATS) to achieve precise acoustic positioning. To simplify installation of upgrades, SAMS design focuses heavily on the application of COTS sensors. Drop weights are utilized to reduce time and energy consumption during pre-mission descent and post-mission ascent. Power is provided via commercially available lithium-ion batteries. The capability improvements and benefits to be realized with SAMS include:

- Extended capability of existing TOSS full-ocean depth camera and side-scan sled
- Increased rate of survey coverage, reduced ship time, and/or significantly increased survey coverage and data collection
- Progress on UUV Priority III to provide large-area oceanography and tactical oceanography support
- Greater positioning accuracy via internal navigation system
- Compatibility with existing ship stowage, deployment, and retrieval systems
- 14-hour autonomous survey time
- Uninterrupted survey with continuous two AUV rotation operational plan

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole Oceanographic Institution is dedicated to research and higher education at the frontiers of ocean science. Its primary mission is to develop and effectively communicate a fundamental understanding of the processes and characteristics governing how the oceans function and how they interact with Earth as a whole. Two key AUV developments at Woods Hole Oceanographic Institution are the Remote Environmental Monitoring Units (REMUS) and the Autonomous Benthic Explorer (ABE).

REMOTE ENVIRONMENTAL MONITORING UNITS (REMUS) [37]

REMUS, or Remote Environmental Monitoring Units, is a low-cost AUV developed by the Oceanographic Systems Laboratory for coastal monitoring and multiple vehicle survey operations.

As described in table 9, the current vehicle is 53 inches long with a body diameter of 7.5 inches, although the length may be increased to support any reasonable payload. Weighing only 68 pounds in air, REMUS (figure 21) is neutrally buoyant in water and is powered by sealed lead acid batteries. The vehicle can be operated in fresh or salt water. Because REMUS is so small, it can be easily transported by compact car, is air shippable as baggage, and may be launched and recovered from a small vessel; special handling equipment is not required.

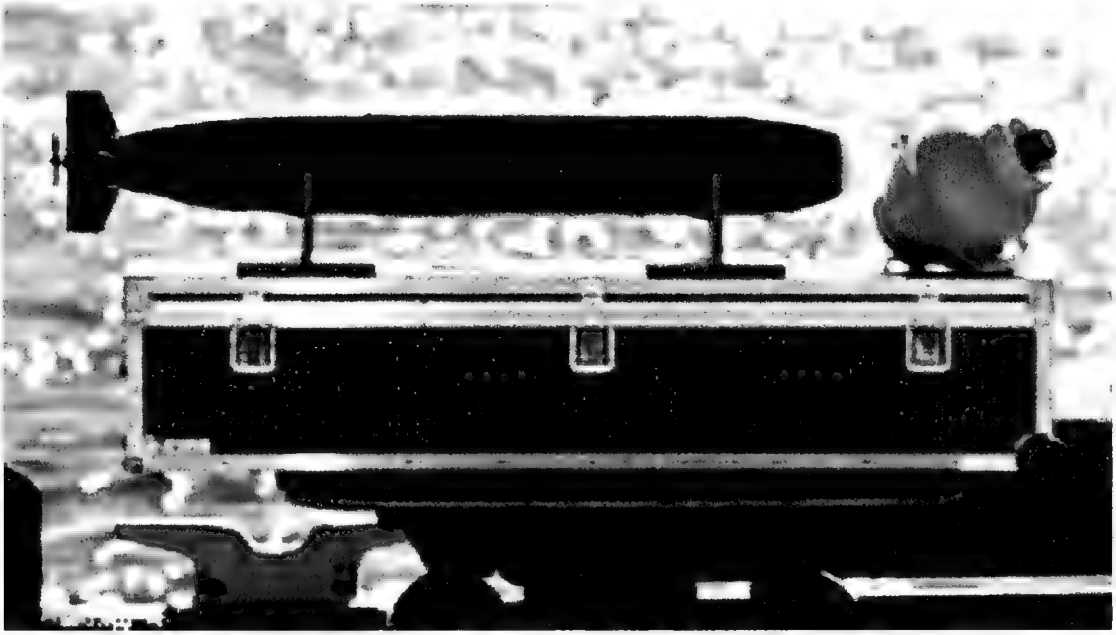


Figure 21. REMUS

Although small in size, the REMUS vehicle is configured to support a variety of sensor packages. The vehicle has a CTD (conductivity/temperature/depth) sensor and an optical backscatter sensor on board. Telemetry data provides time of day, depth, heading, and a geographic fix for the data. A longer version of REMUS with an acoustic doppler current profiler and GPS system is undergoing tests. Additional PC-104 slots and RS-232 ports are available for user-designed payloads.

REMUS has three motors forward of the propeller. The REMUS propulsion assembly is optimized to provide 1.5 pounds of thrust at a forward speed of 4 knots. At this speed a 40-nautical-mile track can be completed in 10 hours. REMUS runs from a 24-volt power supply and draws approximately 32 watts while maneuvering through the ocean, enabling the vehicle to operate at 4 knots for 14 hours.

The REMUS control computer is based on PC-104 technology, a small-scale computerized version of the common IBM-PC hardware. The CPU sits in a custom motherboard, on which are eight 12-bit analog to digital channels, input/output ports, power supplies, and other interface circuitry. Internally, REMUS runs a DOS program written in C++ that executes out of an autoexec.bat file. The vehicle user interface is designed to run on a laptop computer.

REMUS possesses a sophisticated acoustical system with a digital signal processor. A receiving array of four hydrophones is located in the nose, and on the bottom is a hydrophone that can both transmit and receive. To determine its position, REMUS transmits a coded ping to a transponder and listens for a reply. The range and bearing of the reply allows REMUS to determine its location. REMUS can be programmed to interrogate a trail of transponders, approaching each transponder by minimizing range. When the range to a transponder is below a predetermined threshold, the vehicle then listens on a different channel for the next transponder and approaches it using the same technique. By setting the transponders once using GPS, a known trackline may be followed on mission after mission. This system has been used to autonomously dock the vehicle.

Table 9. REMUS Specifications

Length: 53 inches (1.3 meters)
Beam: Approx. 5.5 feet
Diameter: 7.5 inches (19.1 cm)
Maximum Operating Depth: 492 feet (150 meters)
Gross Weight: 68 lbs. in the air, neutrally buoyant in water
Dive Duration: 14 hours at 4 knots
Propulsion: Three motors; one direct drive thruster and sprocket-driven rudder, two pitch motors, and one stem propeller
Power requirements: 24-volt supply, 32 watts while maneuvering at 4 knots
Power Source: Rechargeable lead acid batteries

AUTONOMOUS BENTHIC EXPLORER (ABE) [1,38]

The Autonomous Benthic Explorer (ABE) (figures 22 and 23) was designed to address the need for long-term monitoring of the sea floor which is very expensive using a surface ship for repeated visits with *ALVIN* or *Jason.* While manned submersibles and ROVs allow intensive study of an area, they can remain on station for only hours, days, or weeks. Consequently, a system that can remain in an area gathering data to fill the time voids between submersible and ROV visits would provide another level of more detailed information on temporal variations. Cameras and other fixed instruments may not always be the best solution to this problem because they have limited spatial coverage and are vulnerable to fouling from bacterial growth or mineral deposits.

After discussions with many scientists studying hydrothermal systems, the concept of a roving robot that could remain working on station for up to a year was developed. The robot would spend most of its time "sleeping" in a safe location, then, at pre-programmed intervals, undock, perform a survey with video cameras and other sensors, then redock and go back to "sleep." From these ideas, the ABE was created and built at Woods Hole.

ABE is a true robot, able to move on its own with no pilot or tether to a ship, and designed to perform a predetermined set of maneuvers to take photographs and collect data and samples within an area about the size of a city block. During long deployments, ABE will “sleep” at a docking station between data excursions, conserving power for months of extended operation.

ABE was developed by a team of engineers, who assembled what might be called the robot's body, muscles (thrusters), nerves (cabling and power to operate the motors, cameras, and sensors), and brain (computer systems for powering up and down and for determining where to go and when to make measurements). Each of these components presented a complex design challenge.

Currently, ABE follows a set of instructions placed in its memory before deployment and is recovered for data download following an excursion. However, its developers envision the not-too-distant day when underwater acoustic transmission systems now being developed will allow scientists anywhere in the world to receive video and data from ABE and to control its movement and measurements from their home laboratories.

To minimize cost, ABE is a three-body, open-frame vehicle. This allows glass balls to be used for flotation (there are three in each of the two free-flooded, upper pods), and all the batteries and electronics to be placed in a single, lower housing. This separation of buoyancy and payload gives a large righting moment that simplifies control and allows the propellers to be located inside the protected space between the three faired bodies. ABE has seven thrusters and can move in any direction. It can travel forward at 1m/sec on about 50 watts to its motors. Navigation and control take only about 12 additional watts.

Figure 22. ABE

As presently configured, ABE's principal data are CTD, magnetometer, bathymetry, and monochrome stereo image pairs of the bottom at selected locations. The image recording system has been designed and built in collaboration with Electronic Imaging Systems, Ltd. of Oxford, England. The imaging system is capable of supporting as many CCD cameras as desired with resolutions up to 1Kx1K. Cameras may be of different types and resolutions. They may be in separate housings and may be aimed in different directions for different missions. The system captures all images simultaneously from a single photoflash. Currently, two downward-pointing monochrome cameras are installed for stereo imaging. Each provides an image resolution of 576x768 pixels with a dynamic range of 8 bits. The images are stored digitally on two hard disks. The current disks can store approximately 4500 image planes (one color image has three planes while each monochrome has only one). They can be upgraded to provide more images than any researcher would want, limited mainly by system power consumption from the vehicle's batteries.

ABE is powered by rechargeable, gelled lead-acid batteries to facilitate testing and reduce cost. Even with these batteries, ABE could travel over 50 kilometers in a straight line. In any real mission, however, the energy required to maneuver, operate sensors, and power the flash will limit the range to a fraction of this value. For a long mission, alkaline batteries could be used for a four-fold improvement in energy available. Ultimately, lithium batteries will be installed for an improvement of more than twelve-fold in energy, compared to the present lead-acid cells.

In order to accomplish its scientific objectives and ensure vehicle safety, ABE must have reliable and precise navigation and control. Two complementary navigation systems that are already proven in previous deep-ocean operations have been selected. Medium-frequency (10- to 14-kHz) transponders, identical to those used for ALVIN, guide ABE during descent to its worksite and are used to navigate for surveys over long distances. With this navigation system, ABE has the ability to follow tracklines with repeatability of several meters.

At the worksite, ABE switches to broadband 300-kHz transponders to navigate precisely over ranges of about 100 meters with a repeatability of several centimeters. This system (EXACT) has been demonstrated on the ROV Jason at Endeavour and Guaymas Basin vent sites. With two navigation hosts on the vehicle and two transponders, ABE can obtain a range and bearing from either transponder, or it can obtain a long baseline fix when ranges to both transponders are available. In on-going dockside tests, ABE demonstrated the capability to hover and follow tracklines within several tens of centimeters, and most importantly, to return to its docking mooring. In addition, ABE's power consumption during closed-loop maneuvers falls well within previous estimates.

In spring 1993, as soon as it was mechanically complete but before the navigation system was installed, ABE was taken out on the ATLANTIS II during a series of ALVIN engineering dives. An anchor was rigged on 60 meters of line below ABE, and the combination was allowed to free-fall to the seafloor at a depth of 1600 meters. After reaching the bottom, ABE exercised its seven thrusters one at a time, recording the rpm resulting from the varying torque commands. This tested the control system, internal communication bus, power system, and all the thrusters. At the end of the test, ABE released its anchor and freely ascended to the surface. ABE's progress was monitored by measuring the range to one of its two built-in transponders. It was quickly located on the surface.

Since then, ABE's capabilities have grown and it was taught to perform increasingly involved tasks. In summer 1993 it performed brief autonomous missions using dead-reckoning navigation. The video system and the EXACT navigation system were added in fall 1993. The navigation system is currently performing well and allows ABE to hover (holding x,y,z and heading) in strong tidal currents with only a few centimeters of wander. Forward or sideways movements can be commanded, and ABE executes them smoothly. In addition, ABE can find the beacon that marks its docking mooring, turn toward it, and dock.

In June 1994, ABE was shipped to join the ATLANTIS II in San Diego, again in conjunction with a series of ALVIN engineering dives. ABE's capabilities to conduct repeated dockings, follow tracklines within the ALVIN transponder net, and capture images at specified locations were demonstrated.

The first real science mission occurred in mid-1995, when ABE was used to conduct a complete magnetometer survey over a lava flow, known to have erupted in July 1993 along the Coaxial Segment of the Juan de Fuca Ridge. A previous survey conducted from ALVIN indicated the presence of a notchlike magnetic low at the center of the new flow, which has been interpreted to be related to the thermal demagnetization of the underlying feeder dike.

Figure 23. ABE Launch

The survey with ABE flew at an altitude of 20 meters above the bottom and covered an area of 1 kilometer by 300 meters with about 20-meter spacing between tracklines. ABE was designed to investigate how this anomaly changes with time, thereby providing constraints on the cooling and structure of the lava flow.

In 1996 ABE was back on the Juan de Fuca Ridge, this time in conjunction with the ROV Jason. ABE mapped the magnetic field above a feature called New Flow, flew over Cage Seamount, and explored the Gorda New Eruption site. Long-baseline navigation significantly improved, and ABE flew closed-loop tracklines using its in-hull navigation in real time. This made the surveys much more efficient and gave more direct control to the science party.

ABE's standard data products include the following items:

- Vehicle position determined at the long-baseline (LBL) transponder cycle interval, typically every 10 seconds (water depth dependent). These data are obtained by ABE directly, so errors caused by uncertainties in the sound velocity profile of the water column are minimal.

- Vehicle science sensors, sampled at the LBL interval. These include three axis magnetometer (Develco 9200C-01), Seabird conductivity and temperature sensors, and an optical backscatter sensor (Seapoint Turbidity Meter).
- Vehicle attitude (pitch, roll, heading), depth, and altitude at the LBL cycle interval or at higher rates up to two samples/second. Pitch and roll are measured with inclinometers; heading is a composite estimate obtained from a flux gate compass and a rate gyro. Depth is measured with a Paroscientific pressure sensor. Altitude is obtained from the acoustic altimeter, which points forward 30 degrees and has a beamwidth of approximately 15 degrees.
- Video snapshots: ABE can take simultaneous monochrome stereo pairs at intervals of 10 seconds (currently this rate is limited by strobe recharge time). Each camera provides an image resolution of 576 x 768 pixels with a dynamic range of 8 bits. ABE can provide about 2500 image pairs on a single dive. These cameras can be oriented to optimize stereo or panoramic imaging. The images can be viewed and processed with a variety of commercial imaging software packages (i.e., PhotoShop or PhotoPaint) for PCs, Macintosh and Sun computers.
- Engineering data from the vehicle are also available if desired. These data include commanded thrust levels, measured propeller speeds, battery voltage and power consumption.
- Imagenix 675-kHz scanning sonar for cross-track bathymetry out to ranges of approximately 40 meters.

Sensors in development include:

- Doppler navigation and current profiling: A 1.2-MHz RD Instruments doppler was ordered to operate both as a bottom lock navigator and to determine the 3-D current profile beneath or above the vehicle.
- Improved strobe: This will provide an option for image rates of 5 seconds and improved beam pattern.
- Higher image capacity: The hard drives for the image data could be swapped out for higher capacity if needed.
- New cameras: ABE's video system can be configured for a variety of commercially available cameras, both monochrome and color.

ABE specifications are detailed in table 10.

Table 10. ABE Specifications

Length: 10.5 feet (3 m)
Beam: Approx. 5.5 feet
Height: 5 feet
Gross Weight: 1,500 lbs.
Maximum Operating Depth: 20,000 feet (6,000 meters)
Dive Duration: 6 hours to 1 year, 4-100 active hours
Propulsion: 7 thrusters
Navigation: Medium frequency (7-14 kHz) transponders guide ABE during descent to the worksite and are used to navigate for surveys.
Power requirements:
  Sleep: 50 milliwatts
  Maximum Propulsion Power: 200 watts
  Science Power: 10-100 watts
Vehicle Navigation and Control Power: 17 watts
Power source:
    Option 1: Lead acid rechargeable cells - 1 kWh usable
    Option 2: 2-5 kWh usable (rate dependent)
    Option 3: Lithium primary cells - 17 kWh usable (expensive)

OCEAN VOYAGER II AND OCEAN EXPLORER [39]

The AUV program is an ever-expanding field of study in the Ocean Engineering Department of Florida Atlantic University (FAU). Small, low-cost, long-range vehicles have been developed as sensor platforms for educational, scientific, and military applications. Currently, two separate vehicles are under construction, development, and refinement: the Ocean Voyager II (OVII) and the Ocean Explorer series. Several projects directly related to the vehicles themselves are underway at the FAU Ocean Engineering Department and at the University of South Florida Marine Science Department. Some of these include CHIRP side-scan and sub-bottom sonar, passive imaging sonar, long baseline sonar, acoustic modems, exotic batteries, ocean small-scale turbulence sensors, and various suites of water quality packages.

Figure 24. Ocean Voyager II

The OVII (figures 24 and 25), was initiated as the child of 23 seniors of the Ocean Engineering Department in fall 1992. It was the senior design project of this class to design a practical AUV to carry a sensor package designed by the University of South Florida (USF) to measure the shallow-water coastal environment. These data are then used to ground truth data from satellites currently in orbit. OVII has been operational since January 1994 and is continually upgraded and modified by the staff and students here as tasks dictate. This vehicle has also been used to test CHIRP sidescan and sub-bottom sonars being developed here, as well as LBL navigation techniques. Following operations in the Dry Tortugas off the Florida Keys in August, the vehicle is slated to be turned over to USF for continued operations with their instrument packages.

The instruments aboard the OVII are the Bottom Classification Albedance Package (BCAP), an integrated suite which includes a Xybion multispectral downward-looking camera, upwelling and downwelling radiometers, fluorometer, transmissometer, and pencil lasers for sizing. The Bottom Classification and Albedo Package (BCAP) is an ensemble of optical sensors used to calibrate algorithms and validate satellite ocean color data in the coastal oceans. BCAP was prototyped aboard an ROV and has, since June 1995, been routinely deployed aboard OVII.

Figure 25. OVII Cut-Away

The Ocean Explorer is not just a single AUV but rather the name for the next generation of several vehicles currently being built. This is a new family of AUVs of modular construction, with hull, sensors, and software easily convertible for different payloads. The one pictured in figure 26 has been named COOK. It uses an extensive intelligent distributed control system called LonWorks (Neuron) for communications between numerous sensors and actuators. It is presently undergoing tests in the local waters around FAU. The docking system allows an Ocean Explorer AUV to rendezvous and dock with its base station using fuzzy logic control.

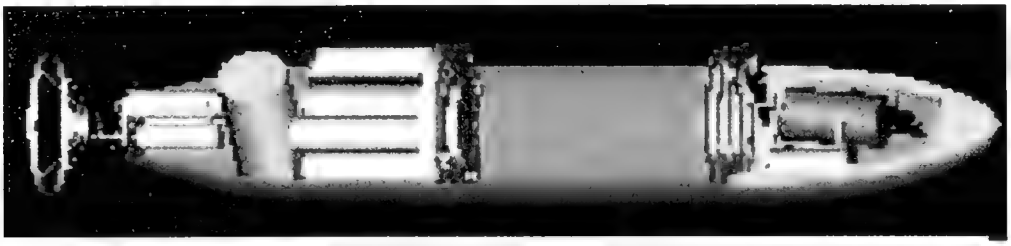


Figure 26. COOK

Note: The 3-foot parallel midbody version, containing approximately 7.5 cubic feet of payload volume. This version is about 10 1/2 feet long. The base vehicle is about 7 1/2 feet in length. Payload interfacing specifications are depicted in table 11.

Table 11. Ocean Explorer Payload Interface Specifications

Available Power:
- 48 Volts (42-56V)
- 5A max. current

Cables/Connectors:

Power/LonTalk Network
- SeaCon FAWM Series
  - Pin 1 BATTERY GND
  - Pin 2 BATTERY +48V
  - Pin 3 BATTERY GND
  - Pin 4 BATTERY +48V
  - Pin 5 BATTERY GND
  - Pin 6 BATTERY +48V
  - Pin 7 LonTalk Data A
  - Pin 8 LonTalk Data B
    - Note: LonTalk Data Lines A&B must be a twisted pair.

Ethernet/Serial
- SeaCon FAWM Series
  - Pin 1 TD+ 10Base-T Ethernet
  - Pin 2 TD- 10Base-T Ethernet
  - Pin 3 RD+ 10Base-T Ethernet
  - Pin 4 RD- 10Base-T Ethernet
  - Pin 5 EIA-232 Common
  - Pin 6 EIA-232 TX
  - Pin 7 EIA-232 Common
  - Pin 8 EIA-232 RX
    - Note: 10Base-T TD+/- and RD+/- are twisted pair.

Power

The Power/LonTalk network cable supplies 48-volt power. The maximum allowable current for a payload is 5A. The Ocean Explorer AUV total battery storage capacity is 40 Ampere-hours at a nominal voltage of 52V. This capacity is divided into eight 5-Ampere-hour battery packs. If the total capacity is insufficient, additional battery modules can be added to the payload compartment. BATTERY GND (pins 1, 3, and 5) should not be connected to the pressure vessel (i.e., seawater) which houses the payload electronics. If the payload circuit ground must be connected to seawater, then an isolated power supply should be used.

Communications

The preferred method of communication between the AUV and payload is through the LonTalk network (connections in the Power/LonTalk cable). The Lon/Talk network is used to communicate directly with any of the sensors or actuators that comprise the AUV's distributed control network. Typically a serial gateway module is provided to the payload manufacturer for incorporation into the payload. The serial gateway module provides a bridge between EIA-232 communications and the LonTalk network. Custom software for the serial gateway module must be written to implement the desired functionality.

The Ethernet/Serial cable contains a 3-wire EIA-232 serial communication channel that connects to a serial gateway module in the main pressure vessel. This module provides an EIA-232 to LonTalk network interface. Custom software for the serial gateway module must be written to implement the desired functionality. This connection would normally be used when installation of a serial gateway module in the payload is impractical.

The Ethernet/Serial cable also contains a 4-wire (two twisted pair) 10Base-T Ethernet channel. This is connected to a 10Base-T hub in the main pressure vessel. Either a cable or wireless Ethernet links the AUV to a surface vessel.

AUTONOMOUS UNDERSEA SYSTEMS INSTITUTE (AUSI) [40,41,42,43]

The Marine Systems Engineering Lab (MSEL) began at the University of New Hampshire (UNH) in 1976. MSEL personnel and facilities moved to the Marine Science Center of Northeastern University located in Nahant, Massachusetts in July 1993. In January 1996, the laboratory moved back to New Hampshire to continue its research activities as part of the Autonomous Undersea Systems Institute (AUSI).

AUSI has been funded mainly through grants from the ONR and the NSF. AUSI also provides its facilities and expertise to support research programs at other institutions. AUSI continues to organize and conduct International Symposia on Unmanned Untethered Submersible Technology.

AUSI, along with the Institute for Marine Technology Problems (IMTP) in Vladivostok, Russia, are investigating the characteristics and limitations of using solar energy as an energy source for a long-endurance AUV (figure 27). The prototype testbed is being used to evaluate the results of a number of analyses related to the solar-powered AUV. The ultimate objective is to develop a solar-powered AUV system for the marine community with endurance in excess of one year.

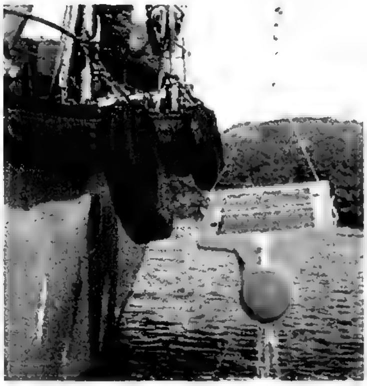


Figure 27. Recovery of Solar Powered AUV

Cooperative Distributed Problem Solving for Controlling Semi-Autonomous and Autonomous Oceanographic Sampling Networks (AOSNs). Successful deployment of AOSN systems will rely on coordinated, flexible, and adaptive behavior among the system's various participants. The Cooperative Behaviors project investigates such coordinated behavior. This project's goal is the development of protocols and mechanisms for intelligently planning and controlling AOSNs.

Cooperative Autonomous Underwater Vehicle Development Concept (CADCON). The AOSN concept is broad and far reaching. AOSN developers must deal with a huge list of intertwining issues. The technical problems associated with the design and development of such a complex system are many and varied; as a result, AUSI developed ideas relative to the sort of development environment that would better enable AOSN work. These ideas were formalized as the Cooperative AUV Development Concept (CADCON).

Development of Basic Autonomous Vehicle Behaviors. AUSI is developing and testing a prototypical set of behaviors which will provide a functionally robust mobile underwater vehicle. Initial research findings show that complex and robust behavior can arise from fairly simple heterogeneous neural networks. In short, this body of researchers has engendered a new branch in artificial intelligence/robotics that focuses on a bottom-up approach to the issue of autonomous agent behavior.

THE COMMISSION FOR GEOSCIENCES, ENVIRONMENT AND RESOURCES (CGER) [44]

The Commission for Geosciences, Environment, and Resources (CGER) oversees and coordinates the activities of the National Research Council in the broad areas of atmospheric sciences and climate, oceanography, solid-earth sciences, radioactive waste management, polar research, environmental science and toxicology, natural disasters, and water science. The National Research Council (NRC) is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering and serves as an independent advisor on scientific and technical questions of national importance. CGER manages the efforts of the following boards:

- Board on Atmospheric Sciences and Climate (BASC)
- Board on Earth Sciences and Resources (BESR)
- Board on Environmental Studies and Toxicology (BEST)
- Board on Radioactive Waste Management (BRWM)
- Natural Disasters Roundtable (NDR)
- Ocean Studies Board (OSB)
- Polar Research Board (PRB)
- Water Science and Technology Board (WSTB)

Of particular importance to AUV developments is the work performed under the leadership of the OSB. OSB was established by the NRC to advise the Federal government on issues of ocean science, engineering, and policy. In addition to exercising leadership within the ocean community, the OSB undertakes studies at the request of Federal agencies, Congress, or other sponsors, or upon its own initiative. The OSB explores the science, policies, and infrastructure needed to understand and protect coastal and marine environments and resources. The Board provides an open forum for those interested in ocean issues to bring technical and policy concerns for discussion and possible action. A primary responsibility of the Board is to initiate studies and ensure that they are carried out successfully. As appropriate, studies can be developed and overseen jointly with other NRC Boards. In selecting projects, the OSB attempts to be responsive to the requests of sponsors while also engaging in proactive activities related to ocean sciences, engineering, and policy.

A recent project completed is “Sea Floor Observatories: Challenges and Opportunities.” The final report entitled, "Illuminating the Hidden Planet: The Future of Sea Floor Observatory Science," discusses the scientific merit of, technical requirements for, and overall feasibility of establishing the infrastructure needed to implement a system of sea floor observatories. Recently, many sea floor observatory programs have been discussed or proposed. This study assesses the extent to which sea floor observatories will address future requirements for conducting multi-disciplinary ocean research and attempt to gauge the level of support for such programs within ocean science and the broader scientific community. This report highlights the use of AUVs in sea floor observatory projects.

OSB ACTIVITIES UNDER DEVELOPMENT

- Assessing Ambient Noise in the Ocean with Regard to Potential Impacts on Marine Mammals
- Carbon Sequestration Science
- Environmental Information for Naval Use
- Effects of Climate on Fisheries
- Environmental Considerations for Deep-Water Drilling
- Gas Hydrates in the Marine Environment
- Governance Structures for Publicly Owned Natural Resources
- Marine Biotechnology: Biosensors, Sentinel Species, and Marine Pharmaceuticals
- Representing and Reducing Uncertainty in Operational Ocean Models
- Reference Materials for Ocean Sciences
- The Role of Stock Enhancement in Fisheries Management
- Understanding and Managing Coastal Sediment Budgets

THE CONSORTIUM FOR OCEANOGRAPHIC RESEARCH AND EDUCATION (CORE) [45]

The Consortium for Oceanographic Research and Education (CORE) is an association of U.S. oceanographic research institutions, universities, laboratories, and aquaria organized to advance the science of oceanography.

CORE actively supports a wide range of issues and projects in research. The fundamental objective of this activity is to promote continued public and private investment in ocean research and to raise the awareness of the importance of this research to a spectrum of societal needs.

Education is a major component of CORE's mission. Facilitating the formulation of goals, policies, and objectives and providing advice and management for educational and research programs and facilities in oceanography and related fields are paramount. To foster an environment wherein oceanographic science and education are recognized as integral to U.S. policy goals in national security, economic development, quality of life, and education remains one of CORE's primary objectives.

THE MARINE TECHNOLOGY SOCIETY [46,47]

The Marine Technology Society (MTS) is dedicated to serving all people interested in the world's oceans. It is the only professional society committed to every sector of the ocean community: engineers, scientists, policymakers, educators, industry leaders, students, and concerned individuals. The MTS leads all its members to greater information and recognition. MTS is a network with a bounty of benefits.

Since its founding in 1963, MTS has been working toward the following goals:

- Disseminating marine science and technical knowledge
- Promoting and supporting education for marine scientists, engineers, and technicians
- Advancing the development of tools and procedures required to explore, study, and further the responsible and sustainable use of the oceans
- Providing services that promote a broader understanding of the relevance of the marine sciences to other technologies, arts, and human affairs

MTS's goals are accomplished by a variety of means, including conferences, workshops, committee meetings, and publications. The activities are enhanced by the diversity of the MTS membership, which is comprised of students and professionals involved in business, government, and academia who share an interest in ocean and marine science, engineering, and policy. The combination of the organized activities and the dynamic membership makes MTS a valuable forum for a rich exchange of ideas.

The MTS ROV Committee probably has one of the most dynamic pasts of any professional committee of the society. Its growth provides a good indication of the increasingly dynamic role of unmanned vehicles around the world. The parent MTS Undersea Vehicle Committee was essentially a manned submersible committee. Previous chairmen, such as R. McGrattan, John Pritzlaff, Joe Vadus, and R. Frank Busby nurtured it through its dynamic early days. Of particular note are the three MTS publications on manned submersible safety compiled by the Safety Standards Subcommittee led by Pritzlaff. These books were created by icons of the industry, although they did not reference unmanned vehicles, as the world was dominated by manned systems.

Unmanned vehicles arrived on the scene, making deeper penetrations into the manned vehicle realm, and the ROV Subcommittee was created in 1978, chaired by Drew Michel, who was followed by Robert Wernli from 1981 through 1991. As ROVs emerged in importance during that period, and with the timely theme of "A Technology Whose Time Has Come," the ROV subcommittee created the first unmanned vehicle conference--ROV '83--held in San Diego, California. Between ROV '83 and '84 conferences, the subcommittee produced the book "Operational Guidelines for Remotely Operated Vehicles," a needed follow-on to the three Pritzlaff-developed books. The ROV conferences and the Guidelines were successful. Along with the growing strength of the subcommittee, the Undersea Vehicle Committee became the largest committee in MTS. ROV '85 was again held in San Diego, and between 1985 and 1986, the Undersea Vehicle Committee again doubled in size to nearly 225 members. Because of the strength of the ROV industry and the size of the ROV committee (nearly twice the size of the next largest), the ROV Subcommittee was merged with the Undersea Vehicle Committee to become the Undersea Vehicle/ROV Committee.

ROV COMMITTEE MISSION

> "To promote the interchange of technical information between industrial, academic, defense, and other organizations on an international basis in the areas of ROVs, undersea robotics and artificial intelligence; provide speakers to academic institutions to increase the participation of students in the society and areas of ROV and undersea technology; produce technical publications related to ROV technology."

The **"Operational Effectiveness of Unmanned Underwater Systems"** CD-ROM is now available from MTS. Robert Wernli of First Centurion Enterprises announced that the final product is 700 pages with 390 photographs, charts, and diagrams.

For a demonstration of this CD-ROM see www.rov.org/rovdemo. The CD-ROM contains details about unmanned systems and their expected performance, including full descriptions and specifications, how they operate, where they are operating and how successfully, and what they can be expected to do in the future. The product has full CD-ROM search capability for key words in the basic text to related text and databases, as well as related photos and data sheets. Also included is a bibliography of past years of ROV/UI conference manuscripts, links to hundreds of ROV technology World Wide Web sites and a committee membership directory, including Internet addresses. The product is a truly interactive CD-ROM that offers needed information, accurately and rapidly.

THE NATIONAL UNDERSEA RESEARCH PROGRAM OF NOAA [48]

Progress in oceanography in the past quarter century has been greatly assisted by the development of undersea technology. The National Undersea Research Program (NURP), within NOAA, provides a unique national service by providing undersea scientists with the tools and expertise they need to work in the undersea environment. NOAA equips scientists with submersibles, ROVs or AUVs, mixed gas diving gear, and underwater laboratories and observatories.

NOAA research programs cover a range of undersea environments from the shoreline to the deep sea, capturing nearly all the scientific disciplines. A compendium of NURP's scientific studies illustrates the significance of gathering information from the ocean.

NURP's science programs are carried out by a series of regional centers around the nation. Projects are selected by peer-review, thus, opening up opportunities for undersea support to all of the nation's science community. Presently, the regional centers include (figure 28):

- Caribbean: Perry Foundation's Caribbean Marine Research Center
- Hawaii and the Western Pacific: University of Hawaii at Manoa, Hawaii Undersea Research Laboratory
- Mid-Atlantic Bight: Rutgers University
- West Coast and Polar Regions: University of Alaska at Fairbanks
- North Atlantic and Great Lakes: University of Connecticut-Avery Point
- Southeast and Gulf of Mexico: University of North Carolina at Wilmington

Figure 28. NURP Regional Centers

NURP operates undersea robots or remotely operated vehicles ROVs that are deployed from ships of opportunity. NURP provides access to a variety of ROVs, some leased and some owned by the program. NURP's ROVs have worked from the tropics to the Arctic and Antarctic. The manipulator arm of the Kraken, a Deep Sea Systems International MAXRover MK1, the largest of the center's ROVs with a depth capability of 940 meters (3,000 feet), works like the arms and hands of a human body to pick up specimens and place them in containers. Kraken's suction samplers collect algae, animals, and sediments. Three video cameras on the Kraken wide-angle, close-up, low-light, and 35-mm-film camera with a flash allow for high-resolution imaging and photography. A laser determines the size of objects underwater, and a scanning sonar uses sound to view objects and organisms outside the range of the cameras. NURP also operates smaller ROVs like the MiniRover and the Phantom S-2, which carry less weight and equipment in their dives to 230 meters (750 feet), but require only one support person above water.

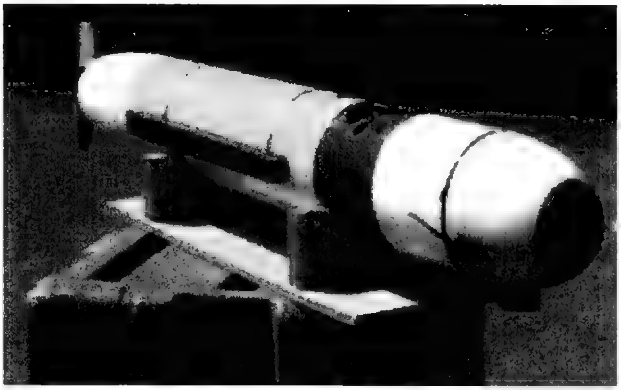


Figure 29. REMUS

AUVs are the most recent class of exploration technology. Independent of the surface, battery powered, and controlled by computers using various levels of artificial intelligence, these vehicles are programmed to carry out various underwater survey tasks. The REMUS AUV (figure 29) was developed by Woods Hole Oceanographic Institution for NURP's Mid-Atlantic Undersea Research Center to carry out wide-area continental shelf surveys. Designed for coastal monitoring and multiple vehicle survey operations, REMUS can operate in fresh or salt water. Though small in size, the vehicle is currently configured to support a variety of sensor packages.

LONG-TERM ECOSYSTEM OBSERVATORY [49]

An innovative approach is being demonstrated by Rutgers University and the Woods Hole Oceanographic Institution at a Long-term Ecosystem Observatory (LEO-15) at a 15-meter (48 foot) depth on the inner continental shelf of New Jersey. Most events in the ocean are missed because sensors are not in the ocean environment to continuously recording what happens there. As a result of this deficiency, LEO-15 is now the focus of a broad spectrum of research sponsored by NURP's Mid-Atlantic Research Center.

Since its inception, more than 50 projects at LEO-15 have been supported with funding from the NSF, NURP, and the National Ocean Partnership Program.

A dozen different sensors at LEO-15 provide real-time information (figure 30). LEO's Web site receives real-time data from satellites and the in situ sensors. An electro-fiber optic cable runs along the bottom of the ocean to two submerged nodes. The nodes are equipped with profiling instruments that move up and down in the water column, measuring temperature, salinity, and depth. Scientists can control the nodes via the Internet onshore. To get an idea of ocean events occurring between these nodes, two AUVs have been designed to travel between them measuring different oceanic processes.

LEO's capabilities will eventually extend to sites at 750 meters (2,400 feet) and at 2,500 meters (8,000 feet) offshore. Extensive studies have already taken place at the 2,500-meter site where six years of intensive sewage sludge dumping occurred. Having an observatory there would facilitate the study of the long-term effects of deep-ocean dumping on the ecosystem. This is an important consideration in light of the pressing need to find alternative sources for waste disposal. The development of other coastal observatories in places like Chesapeake and Monterey Bays, on Georges Bank, or in extreme environments, such as along mid-oceanic ridges, could also be sparked by LEO-15.

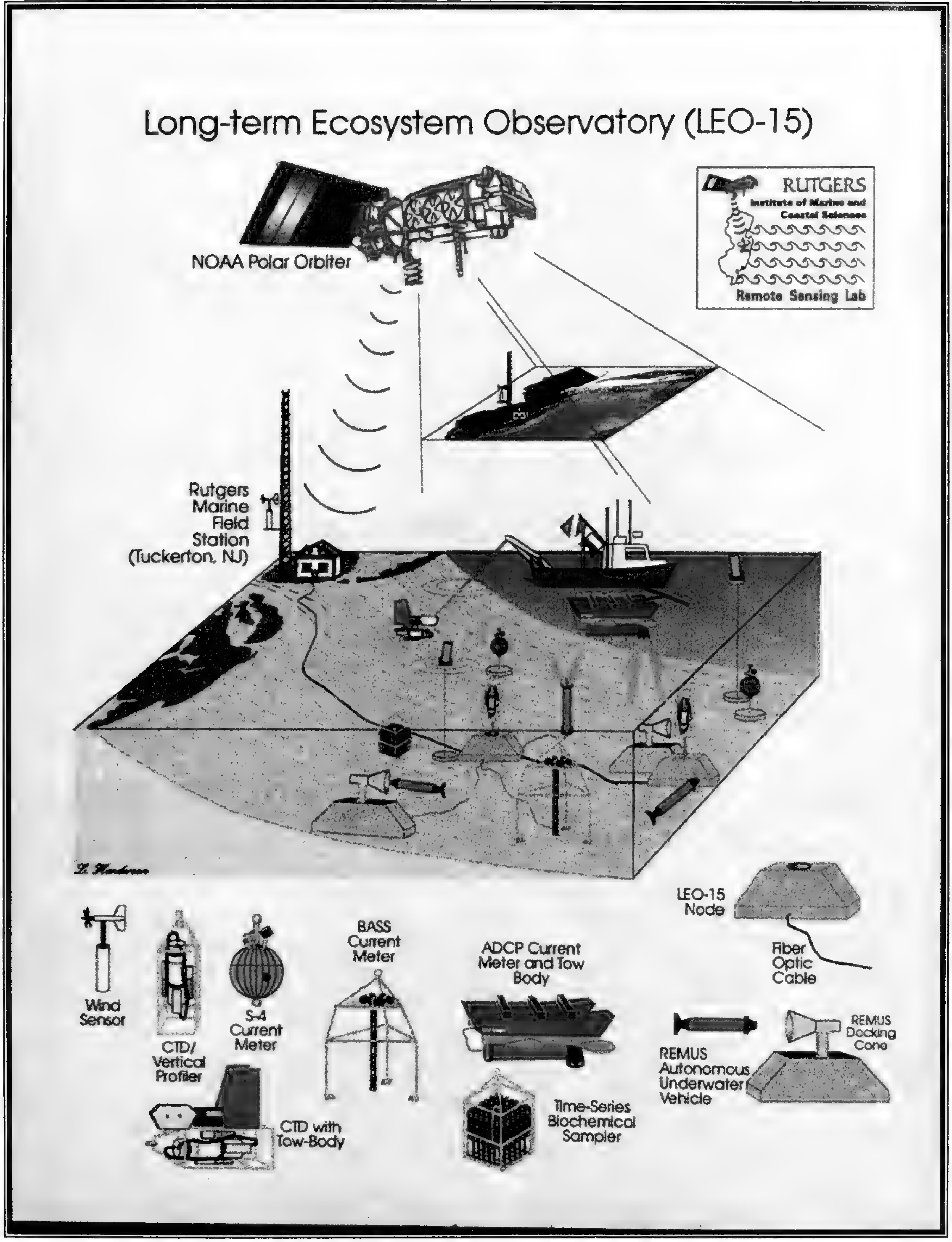


Figure 30. Long-term Ecosystem Observatory (LEO-15)

THE DEEP SUBMERGENCE SCIENCE COMMITTEE OF UNOLS [50,51]

The DEep Submergence Science Committee (DESSC) is a standing committee of the University National Oceanographic Laboratory System (UNOLS). DESSC provides advisory responsibilities for the National Deep Submergence Facility that includes ALVIN, Jason-Medea, ARGO-II, and the 120-kHz Side-Looking Sonar.

AUV MARKET FORECAST [52,53,54]

Sales of UUVs are expected to climb from $100 million in 2000 to over $330 million in 2004, and total $1.2 billion over the period. But growth in operational revenues during the same period will be greater, from $500 million to nearly $930 million, for a total of $3.5 billion (excluding support vessels).

The revenues found in figure 31 are part of the results of a major new study, *"The World UUV Report,"* on business prospects for Work-Class ROVs, and the "new" technology of AUVs launched by leading oil and marine analysts Douglas-Westwood at the Offshore Technology Conference in Houston.

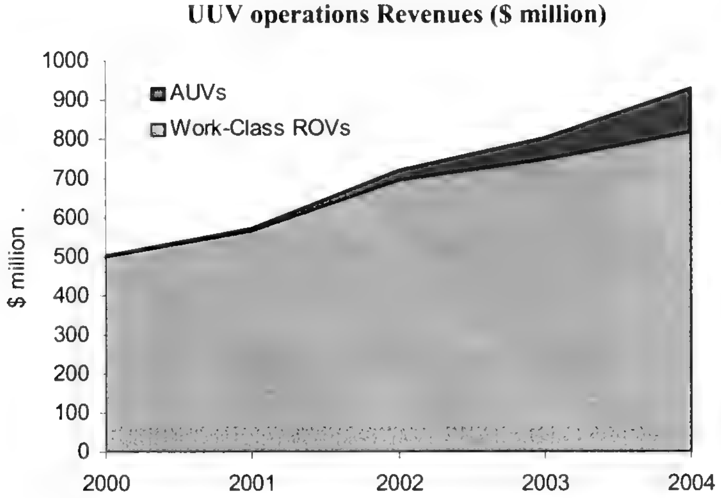


Figure 31. Strong Growth Forecast in UUV Market

Source: The World UUV Report (Douglas-Westwood Limited)

Over 3,000 ROVs of various types have been built to date, but the report concentrates on the high-price, high-earning Work-Class ROVs. There is currently a world fleet of 478 units for which the offshore oil and gas industry is the biggest customer.

According to the report, the year 2000 represents a cyclical low for the UUV manufacturing industry caused by the earlier oil price fall. In 1999, 61 Work-Class ROVs were delivered, but in 2000 only 38 deliveries were expected. However, with firm oil prices and growing deep-water activity, deliveries should climb to 118 units in 2004.

Over the period, the report's base-case analysis shows the Work-Class ROV fleet growing by nearly 50%. This growing fleet will require an increasing expenditure on ancillary equipment and replacement items with an estimated market value of $468 million over the five-year period.

While the offshore oil industry has been though a cyclical low, the submarine telecom cables sector has boomed. UUVs are used to survey, trench, and maintain cables, and the authors expect that cable work will account for 34% of UUV operational revenues over the period.

According to report joint author, John Westwood, the major technical challenges are "to reduce costs of ownership and to provide cost-effective systems for operations in ever-increasing water depths. One approach is the use of all-electric ROVs (most existing machines are electro-hydraulic systems) involving aerospace standard power systems and a total redesign to reduce component count and the numbers of electrical connections exposed to seawater."

AUVs, the new kids on the block, are true pre-programmed robots, increasingly capable of carrying out underwater survey and other missions without direct human control. AUVs entered commercial service in 2000, and if industry expectations are achieved, the authors believe that annual sales could grow to over 30 units in 2004 and AUVs account for 20% of UUV operations revenues. Two thirds of AUV revenues are expected from their use in seabed survey. (See Table 12.)

Financing UUV development remains a problem. Despite the growth of the telecommunications market, the major end-users of UUVs are the oil and gas companies. Their corporate objectives preclude most of them from direct investments in the development of new technology, regarding this as the role of the technology providers – the underwater service contractors.

Table 12. Report Projections of Growth

Operations ($m)	*2000*	*2001*	*2002*	*2003*	*2004*	*00-04*
Work-Class						
ROVs	501	565	695	747	817	3325
AUVs	2	9	26	59	112	207
total $m	503	574	720	806	928	3532

OBSERVATIONS AND RECOMMENDATIONS

The number of UUVs of various types has increased each year over the period of this report. The spectrum of vehicles includes those for military, scientific, and industrial uses. The complexity of missions, depth, range, and mission duration has increased over this period. Launch and recovery considerations, less glamorous than the UUVs themselves, have not received the deserved emphasis necessary to elevate the operational efficiency of UUV systems. Docking stations, designed to download data from UUVs, recharge batteries, and program the UUV for its next mission, are advancing quickly.

Industry, who earlier postponed interest in UUVs until they were confident in the technology, appears now to be reasonably comfortable in applying UUVs as tools. UUVs are now in use commercially in survey work. Commercial acceptance of UUVs has begun! The future for UUV use is great. Sensors and energy systems demand attention to speed the technical advances and operational uses of UUVs.

Bibliography

1. Mooney, J.B. et al., 1996. National Research Council Report, *Undersea Vehicles and National Needs*. National Academy Press

2. National Research Council, Naval Studies Board, 1997. *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st Century Force*, http://www.nas.edu/cpsma/nsb/tfnf.htm

3. Dunn, P.M., 28 Dec 1999, *The Navy Unmanned Undersea Vehicle (UUV) Master Plan*, Naval Undersea Warfare Center

4. CAPT Fiebeg, June 1998, Brief slides on *The Navy's Unmanned Undersea Vehicle (UUV) Program*

5. Near-Term Mine Reconnaissance System (NMRS) Office of Naval Research Web Page of 4 Sep 1997. http://www.onr.navy.mil/sci tech/ocean/jcm/nmrs.htm

6. Federation of American Scientist Web Page of 1 Jan 1999. http://www.fas.org/man/dod-101/sys/ship/weaps/nmrs.htm

7. Federation of American Scientist Web Page of 1 Jan 1999 http://www.fas.org/man/dod-101/sys/ ship/weaps/lmrs.htm

8. The Boeing Company Web Page of 2000. http://www.boeing.com/defense-space/infoelect/lmrs/

9. Naval Postgraduate Research Center for AUV Research Web Page, http://www.cs.nps.navy.mil/research/auv/about_auv.html

10. SonTeck Web Page of 3 June 2000. http://www.sontek.com/apps/auv-rov-uuv/advo-nps/advo-nps.htm

11. Walton, J., Nov 1992. NRaD Technical Report 1527, *Advanced Unmanned Search System (AUSS) Testbed - Search Demonstration Testing*

12. Jones, H.V., Nov 1992. NRaD Technical Report 1528, *Advanced Unmanned Search System (AUSS) Description*

13. Uhrich, R.W. & Walton, S.J.,. Nov 1992. NRaD Technical Report 1530, *Deep-Ocean Search Inspection: Advanced Unmanned Search System (AUSS) Concept of Operation*

14. McCracken, H.B., Nov 1992. NRaD Technical Report 1533, *Advanced Unmanned Search System (AUSS) Supervisor Command, Control, and Navigation*

15. Smith, K.L., Jr., R.C. Glatts, R.J. Baldwin, A.H. Uhlman, R.C. Horn, C.E. Reimers and S. E. Beaulieu. 1997. *An autonomous, bottom-transecting vehicle for making long time-series measurements of sediment community oxygen consumption to abyssal depths*, Limnol. Oceanogr., 42(7):1601-1612.

16. Ken Smith Laboratory Website, http://smithlab.ucsd.edu/

17. HUGIN 3000 Brochure, Kongsberg Simrad As

18. Kongsberg Simrad As Website, http://www.kongsberg-simrad.com

19. Northcutt, J.G., Kleiner, A.A. & Chance, T.S., May 2000. *A High-Resolution Survey AUV*, 2000 Offshore Technology Conference Paper OTC 12004

20. Chance, T.S., Kleiner, A.A., Northcutt, J.G., 2000. *The Autonomous Underwater Vehicle (AUV): A Cost-Effective Alternative to Deep-Towed Technology*, Integrated Coastal Zone Management 6th Ed. (pp. 65-69)

21. C&C Technologies, Inc., Web Page http://www.cctechnol.com/auv.htm

22. MIT Web Page. http://auvserv.mit.edu/0dysseyllb.html

23. Nadis, S. 28 March 1997. *Real-Time Oceanography Adapts to Sea Changes*, Science, Vol. 275 (pp. 1881-82)

24. Nadis, S. 28 March 1997. *Robotic Subs for Rapid-Response Science*, Science, Vol. 275 (p. 1881)

25. Kreider, J.R, February 1997. *UUVs for Underwater Work - Innovation or High Tech Toy?*, Sea Technology (pp. 51-57)

26. Levi, C., 29 January 1997. *MIT Sea Grant's Underwater Robot to Search for Giant Squid*, MIT Tech Talk

27. Niller, E., 19 February 1997. *Going Deep to Look for Real Live Giant Squid*, The San Diego Union-Tribune

28. Levi, C., Fall/Winter 1996. *Science at the Front*, MIT Sea Grant Nor'easter (pp. 16-19)

29. Bellingham, J.G., August 1997. *New Oceanographic Uses of Autonomous Underwater Vehicles*, DRAFT submitted to Marine Technology Review

30. MIT Web Page http://seagrant.mit.edu/loops.html

31. Lauerman, J.F., 1999. *The Little Yellow Sub That Could: Evolving Technologies Plumb the Oceans' Depths*, MIT Sea Grant Nor'easter

32. MIT Web Page hftp://auvserv.mit.edu/reports/HLbjg99.htm

33. MIT Web Page http://auvserv.mit.edu/aosn.htm

34. SPAWAR Web Page of 10 December 1999. http://www.nosc.mil/robots/undersea/dssn/dssn.html

35. Bellingham J.G., Schmidt H., & Chryssostomidis C., *AOSN MURI., Real-Time Oceanography With Autonomous Ocean Sampling Networks: A Center for Excellence*, MIT Sea Grant Program ONR Annual Report, also on Web Page http://auvserv.mit.edu/MURI/annual-report98.htm

36. MIT Web Page http://auvserv.mit.edu/CETUS.html

37. WHOI Web Page http://adcp.whoi.edu/REMUS/index.html

38. WHOI Web Page http://www.marine.whoi.edu/ships/auvs/abe_description.htm

39. FAU Web Site http://www.oe.fau.edu/research/ams.html

40. AUSI Web Site http://www.ausi.org/

41. AUSI, 21-22 January 2000, *Autonomous Undersea Systems Institute Board of Directors Meeting*

42. AUSI, 31 March 1998, A Strategic Plan for A AUS Consortium for the Research, Development, Utilization and Commercialization of Autonomous Undersea Vehicle Systems Technology, Version 1.4(rev)

43. AUSI Annual Report for Fiscal Year 1999

44. CGER Web Site hftp://www4.nas.edu/cger/cger.nsf

45. CORE Web Site http://core.cast.msstate.edu/

46. MTS Web Site http://www.mtsociety.org/

47. MTS ROV Committee Web Site http://www.rov.org/

48. NOAA National Undersea Research Center Web Site http://www.oar.noaa.gov/oceans/ocean_nurp.html#start

49. NOAA NURC Web Page http://marine.rutgers.edu/nurp/mabnurc.html

50. UNOLS Web Site http://www.unols.org/

51. UNOLS DESSC Web Site http://www.unols.org/dessc/

52. Westwood, J., 16 September 1999. *Future Prospects for AUVs*, presented Maridan 'PING' Symposium in Copenhagen

53. Douglas & Westwood, 1 May 2000. *Strong Growth Forecast in Underwater Vehicles Market*, Douglas-Westwood Limited News Release

54. Westwood, J., 2000. *Future Markets for UUVs*, Douglas-Westwood Associates