NAVAL POSTGRADUATE SCHOOL
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RESEARCH PROPOSAL

Submitted to: **Office of Naval Research**
ATTN: ONR Code 32: AO FNC
BCT-1, Room 407
800 North Quincy Street
Arlington, VA 22217-5660

SUMMARY

1. **Title:** ***COMMAND AND CONTROL DEMONSTRATIONS WITH COOPERATING VEHICLES***

2. **Period of Research:** October 1, 2001- September 30, 2005 (4 years)

3. **Total Estimated Cost for Period:** $2,827,214 for 4 years

4. **Principal Investigator:** Anthony J. Healey, Professor of Mechanical Engineering
Director, Center for Research on Autonomous Underwater Vehicles

5. **Brief Description:** This proposal is in response to ONR BAA 01-012, "DEMONSTRATION OF UNDERSEA, AUTONOMOUS OPERATION CAPABILITIES AND RELATED TECHNOLOGY DEVELOPMENT." It proposes 4 main thrusts, command and control between multiple vehicles, Ultra high-speed acoustic modem communications, Sonar based navigation, and 3D visualization of results. The proposal includes faculty from the Physics and the Mechanical Engineering Departments and the Underwater Warfare group. It will involve the ARIES AUV as a major system integrator for networked vehicles.

6. **Key Words:**

Underwater Robotics, Robust Control, Ocean Science, Shallow Water, Autonomous Systems.

7. **Recommend Approval:**

____________________	____________________	____________
Terry R. McNelley Chair, Mechanical Engineering	William B. Maier II, Chair, Physics Department	Clyde Scandrett Chair, UW Group

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LCDR Chris Eagle
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Dated _______

8. **Reviewed:**

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9. **Approved:**

Dated _______

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Dean of Research

BAA 01-012, DEMONSTRATION OF UNDERSEA, AUTONOMOUS OPERATION CAPABILITIES AND RELATED TECHNOLOGY DEVELOPMENT

Subject Areas

Maritime Reconnaisance

Communications / Navigation Aids

Undersea Search and Survey

Naval Postgraduate School
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"COMMAND AND CONTROL DEMONSTRATIONS WITH COOPERATING VEHICLES"

ABSTRACT

This proposal addresses the need for autonomous command and control for multiple underwater vehicles operating in challenging underwater environments. NPS is well suited to provide service to ONR demonstrating command and control technologies. The proposal addresses four major themes each with short term, mid term, and long term goals. NPS has an ideal platform in the ARIES vehicle for demonstrating advances in command and control, high speed acoustic communications between vehicles, sonar based navigation technologies, and data visualization. The ARIES is equipped with an acoustic modem for underwater communications, radio modems for communications when surfaced, and navigation based on a Doppler aided inertial, compass and DGPS system. The ARIES is used as a mobile gateway system node that may be commanded to move into close proximity with working vehicles. Close proximity allows for higher data transfer rate underwater . Cooperative engagement demonstrations will be developed with other vehicles to provide shipboard / shore-base command station communications links to the underway underwater vehicles at moderately high rates. The ARIES will gather and transmit AUV status, locations, and target information including (in later years), image snippets. The system will be used for remote re-tasking of the working vehicles. NPS experience with integrating UUV data into the Navy's MEDAL tactical decision aid will also be a part of the system of demonstrations with the continual goal of reducing the latency of data gathering to the fleet. This work builds on previous success of NPS at UUV demonstrations including the recent KB01 exercise at Camp Pendleton in which we demonstrated a radio communications link for image snippet transfer from the ARIES via a PELICAN aircraft to the ONR base. Separately and additionally, NPS will demonstrate the use of forward look sonar in obstacle avoidance strategies, for example, in harbor entrances and very shallow water conditions, and further the development of computer visualization of data gathered.

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Summary Information

The Naval Postgraduate School (NPS) is pleased to submit this proposal to the Office of Naval Research (ONR) in the support of the Autonomous Operations (AO) Future Naval Capabilities (FNC). The NPS Center for AUV Research has been involved with underwater autonomous systems for over 13 years and has awarded Master Degrees to over 150 Naval Officers who have written theses in this subject area. Central to the NPS effort has been the (Acoustic Radio Interactive Exploratory Server) ARIES, a third generation Unmanned Underwater Vehicle (UUV) designed for command and control, acoustic communications and sonar experimentation. The vehicle has performed numerous in-water experiments in a variety of fields. (see http://www.nps.navy.mil/research/auv/auvframes.html).

The proposal focuses under four major themes. They are Command and Control, Ultra High Frequency (UHF) Data Transfer, Sonar Based Navigation Technology and Data Visualization. Each of the specialized areas is presented with near-term, mid-term and longer-term goals for the yearly Fleet Battle Experiment Exercises and AO FNC Underwater Search and Surveillance and Communications/Navigation Aid and Maritime Reconnaissance demonstrations. Throughout this proposal, the NPS Center for AUV Research adheres to several principles that focus on the strength of the Navy's University and it's unique position to facilitate development of UUV capabilities. We believe these are particularly relevant to the AO FNC effort:

1. **System Integration**. The Center has a unique ability to perform studies and experiments to ensure that a wide range of UUVs can function cooperatively. The center is non-proprietary in nature and can provide various programs the ability to ensure interoperability among various classes of vehicles. Areas addressed within the proposal that demonstrate this "system of systems" integration approach include acoustic underwater communications and data collection and dissemination.

2. **Development of Advanced Engineering Concepts**. The goal of the center is to select specific engineering projects that have applicability to the widest range of UUV vehicles. The goal is to establish close ties with existing UUV acquisition programs in order to bring Naval officers closer to the developmental process.

3. **ARIES as the UUV Test Bed**. The NPS vehicle is an ideal platform for development of computer architecture, software, sensors and navigational hardware for small to medium sized autonomous systems. The ARIES has an open architecture computer system that permits data input from a wide variety of sensors and modems. The size of the ARIES permits a range of internal configurations to accommodate advanced design concepts. From its inception, the ARIES has completed research and testing on a numerous sensor systems. Most recently, the ARIES has been testing Inertial Navigation Systems (INS) for advanced navigational techniques.

4. **Ground Zero Development for Naval UUV Expertise**. We bring Naval Officers into the engineering developmental effort so that they are familiarized with the direction of future technology. NPS is the development source for the next operational commanders and acquisition program managers that may use the UUV technology.

Early exposure to the strengths and weakness of the technology is critical to realizing full potential of the vehicles.

Recent Achievements

The NPS Center for UUV Research has contributed to the UUV development efforts from the earliest stage. Using the early Phoenix robot, we developed sea way wave compensation methods for shallow water station keeping behavior. In AUVFEST 1998 and 1999, we demonstrated products concerning directional sea state estimation and dynamic station keeping control (Reidel, Ph. D. Dissertation 1999). In the most recent Fleet Battle Experiment (FBE) HOTEL and Kernal Blitz 2001 (KB01) exercise at Camp Pendleton, we integrated the Navy's MEDAL (Mine-warfare Environmental Decision Aids Library) with an automated data server (ADS) to permit a UUVs to report littoral mine warfare data into the Global Command and Control System – Maritime.. During the last year we have extensively operated the ARIES, as a communications server vehicle. In the KB01 exercise, we successfully demonstrated high speed file transfer (30,000 bits / sec.) from a surfaced UUV through an aerial vehicle using radio modem wireless technology to the ONR base. This is a preliminary step to network control.

This summer, NPS and the University of Lisbon, and the University of the Azores are jointly participating in an exercise at the San Joao de Carlos bank off Terceira island in the Azores. The objective is to examine the data sharing aspects of two autonomous vehicles. IST has an autonomous surface vessel (DELPHIM) and the NPS ARIES is the underwater vehicle. The mission uses both vehicles to find and locate shallow water vents. The DELPHIM locates a cluster of vent activity using its own sonar and passes GPS positions of cluster areas to the ARIES via an acoustic modem. The acoustic modem has already been installed and tested on the ARIES (see below). ARIES will then perform a local area search and gather video imagery. The use of cooperative data sharing between two autonomous vehicles is new.

NPS ARIES UUV

FAU Modem Installed on ARIES

Figure 1 The NPS ARIES and the Acoustic Modem

While great strides have been accomplished in UUV technology there is still a great deal to complete. For example, the minefield reconnaissance work of KB01 showed that information gathered from UUV assets is not timely; it can be several hours before planners receive the data. It is possible to dramatically reduced reporting times. We believe the most effective method of doing this is through the use of multiple vehicles and communications networks

Main Proposal Introduction

Improving Undersea Search And Survey Capabilities. The ability to search and classify the bottom type for Mine Warfare and Amphibious Operations has been demonstrated with several UUV systems. The difficulty with existing capabilities is in the timely recovery of the data and the coverage rate of UUVs. For the vehicles to be fully utilized, two things need to occur. First the data should be available to the operational command in near real time and the search rate should be maximized. The best way to improve both detection and coverage rates is to simultaneously use multiple vehicles. It then becomes an issue as to the best method to control and retrieve information from multiple vehicles operating simultaneously. We recognize the requirement for a Communications/Navigation Aid (C/NA) for in-stride data gathering and transmitting including dynamic navigational modifications to multiple UUVs. NPS proposes to use the ARIES vehicle as C/NA Vehicle for this purpose.

The ARIES vehicle has inherent capabilities to serve as the ideal enabling undersea node of the Net-centric Warfare Sensor Grid. It is configured as a server/gateway vehicle, this combined with its open architecture computer hardware and software makes it ideal for this role. ARIES currently has an installed FAU modem and has the capability of installing several additional modems. This would permit the ARIES to serve as a C2 vehicle for a variety of UUVs in the shallow and very shallow water regimes (including sea crawlers***). The ARIES can carry multiple modems at the same time so that, in the absence of an interoperability standard, communications between different vehicles in the same mission is possible.***

The ARIES is equipped with a radio modem for communications when surfaced, and navigation based on Doppler aided inertial units, compass, and a Differential GPS (DGPS) system. NPS has perfected the capability to use DGPS corrections to navigational solutions with surface pop-up maneuvering. Position errors can be bounded by 10m. most of the time *without* using beacons. The ARIES is used as a mobile gateway system node that may be commanded to move into close proximity of working vehicles / fixed nodes. Close proximity allows for higher error free data transfer rates than long range acoustic communication links permit. The work described here, involving the development of command and control software for cooperative engagement demonstrations, will be developed keeping other vehicles in mind to provide shipboard / shore-base command station communications links at ever high rates (ultimately up to 1 Mbps from typically 10,000bps), to operating underwater vehicles (REMUS). The ARIES will gather and transmit UUV status, locations, and target information including (in later years), image snippets from working vehicles. ARIES will also interact with ongoing work in Seaweb as a data truck and C2N aid.

High Speed Short Range UHF Underwater Modems. We propose to introduce a new paradigm for underwater network communications. In acoustic modem technology, the stress has been to increase both data rate and range - two competing objectives in the solution of vehicle network communications. Rather than increasing power and size of acoustic modems for long-range error free transmission, NPS proposes to investigate short-range communications at high rates between vehicles that can be in close proximity with each other. Close proximity is enabled through the use of a mobile node - a gateway node that would be capable of moving in close to a working vehicle to perform the close in high-speed data transfer. The ARIES vehicle exemplifies such a node.

NPS proposes to develop a high-speed (with bit rates of several hundreds of kilo bits/sec to 1 Mbps) underwater data transfer system based on short range in the order of 10 meters. It is interesting to note that recent modem research has led to goals of achieving long range data flows at moderately high rates up to tens of kilobits per second in shallow waters while what we would like to see is hundreds of kilobits per second at short range. Short-range links are made possible by using multi vehicle strategies. In particular, using a gateway vehicle such as ARIES, rendezvous behaviors could be developed by which one vehicle tracks closely to another (within a closing range of 10 m) so that either high-speed acoustic or electromagnetic communications are enabled. Depth separation prevents collisions.

An initial study indicates that acoustic energy in the 3-5MHz. will travel up to 10 meters in range allowing for a 60db transmission loss. Even using simple coding schemes, it appears that 1 Mbps is possible at that short range. Electromagnetic energy would have less range for the frequencies considered, and laser communication systems suffer from the requirements of pointing accuracy. We are convinced that laser communications could be accomplished between stationary points, but the relative motions existing between 2 vehicles in the ocean would prohibit such as system.

Sonar Based Navigation Technologies. As a separate area of development, NPS will develop algorithms and strategies for Sonar Based Navigation behaviors for UUVs using forward look sonar. For example, in harbor entrances and very shallow conditions the possibility of shoaling occurs and seeking and tracking inside ship channels will be required. Avoidance of uncharted obstacles such as ship wrecks or well heads and normal shipping will need attention to both obstacle detection technologies as well as UUV response / track modifications.

NPS has studied obstacle avoidance algorithms and track control behavior in the work of Cottle, (1995) in which a controller added curvature to the commanded path determined by proximity to the sensed obstacle. In computer simulation studies of land-based robots for the EOD BUGS program, we simulated obstacle avoidance behaviors employed by the Foster Miller Lemming, the ISR Pebbles vehicle and the Draper Laboratories Rover vehicle. Each vehicle had different control strategies, but the Draper Rover had sonar beams that detected an obstacle, and then, based on the sector in which the obstacle was detected, an added turn command allowed the vehicle to <u>avoid the obstacle as well as map its location</u>. These methods, summarized in (Kim, 1999), fall into the category of reactive obstacle avoidance rather than the planned category such as the "Circle World" (see Brutzman Ph. D. Dissertation) which performs efficient A* algorithmic searches.

Combined localization and mapping will be now possible using scanning sonar on a UUV. The ARIES vehicle is equipped with a Tritec 725, 725KHz. 24-degree vertical beam, mechanically scanned sonar which can be used for experiments with the development of obstacle avoidance algorithms. NPS has developed sonar algorithms for integrating the TRITEC scanning sonar into the vehicle control system allowing for contacts to be recognized in term of range and bearing. This feature was demonstrated at UUV Fest 1998 and details including the scan line analysis which leads to clustering and contact identification are given in the mini-report in **Appendix III**. A wide variety of obstacle avoidance algorithms have been developed by NPS in past simulation work but none has yet been tested in water. The reduction of sonar data to range and bearing information for vehicle control is highly dependent on the specific sonar used and the goal of this work would be to transfer this work to The Navy's small to medium sized UUVs in development. For the development of algorithms, the ARIES vehicle with the TRITEC scanning sonar would be used in in-water obstacle avoidance experiments. In Monterey Bay, there are many natural obstacles including harbor walls, pier pilings, and underwater objects such as sunken boats that would be used in experimental studies.

Use of 3-D graphics as a Visualization Tool for MEDAL Data

3D graphics is a powerful tool for visualization of many kinds of underwater data. Because the underwater environment is typically not visible to operators, current geographic 2D displays must greatly simplify interactions among vehicles, sonars, water-column properties, bottom bathymetry, targets of interest, obscuring contacts and a myriad of other data. The goal of our underwater virtual world research is to show that such diverse inputs can be individually modeled, automatically generated and scaled and integrated over the World Wide Web. Compatibly augmenting existing fleet systems is a primary design capability.

There are three components to the 3D graphics visualization effort:

1. Data collection and conversion for use by the MEDAL system,
2. Ongoing production of a 3D model library, and
3. Data-driven auto-generation of 3D virtual environments.

Data Collection and Conversion. NPS has implemented the AUV Data Server (ADS), which integrates multiple software capabilities as follows.

- Reads AUV telemetry files in tabular-number or exercise-approved data formats
- Alternatively can accept continuous telemetry streams as input
- Converts Asset, Bathymetry and Contact reports to Message Text Format (MTF) messages, the baseline format for all DOD message systems
- Transfers messages to MEDAL, providing integrated 2D viewing in fleet systems
- Auto-generate 3D virtual-world playback of reported AUV telemetry, using ISO-standard Virtual Reality Modeling Language (VRML) and Extensible 3D (X3D) Graphics
- Archives data results
- Open-source Java code producing open-format output results.

The ADS system operates in concert with Mine Warfare Environment Decision Aids Library (MEDAL). MEDAL is actively used in fleet mine-warfare exercises. MEDAL is part of the Global Command and Control System – Maritime Component (GCCS-M) software architecture.

Ongoing Production of a 3D Model Library. Due to the high cost, proprietary constraints and mutually incompatible nature of available 3D models, NPS has begun building and collecting 3D models in an open library as part of the Scenario Authoring and Visualization for Advanced Graphical Environments (Savage) project. These VRML/X3D models and sub-components, created by students and staff, now number in the hundreds and are available online at http://web.nps.navy.mil/~brutzman/Savage/toc.html

The 3D models themselves are typically produced using the locally developed *X3D-Edit* authoring tool, available free for unrestricted use. *X3D-Edit* produces X3D/VRML models by following a scene-graph paradigm. Each node and attribute in a scene is provided with local tool tips for context-based help. The use of Extensible Markup Language (XML) as the basis for X3D ensures that syntax errors are automatically detected, ensuring that incorrectly formed scenes are not allowed to escape into (and possibly corrupt) larger 3D virtual environments. The current model inventory includes several dozen ships, aircraft, amphibious assault vehicles, submersibles, terrain data-sets, and various visualization prototypes for scene integration.

Data-driven Auto-generation of 3D Virtual Environments. Ongoing UUV work has shown that pre-mission rehearsal and post-mission analysis are essential capabilities for operational planning and interpretation of results. Because underwater vehicle interactions are inherently spatial, it can be very difficult to understand the precise causes of imprecision or error without some sort of animated 3D visualization. While such techniques have been attempted for some time, it is only recently that scalable Web-based approaches to modeling and simulation have become practical and scalable**. Numerous examples of these new capabilities are given in Appendix IV.**

Several medium-scale simulations have shown the value of this approach. Composing individual models along with visualization and authoring tools lets us verify interoperability among models, their corresponding physics and various embedded user-interface prototypes. The first two major scenarios in the SAVAGE project are:

- Amphibious raid at Camp Pendleton's Red Beach
- Collision between USS GREENVILLE and MV EHIME MARU

We are now experimenting with the automatic generation of virtual environments using ADS. In addition to auto-generation of MTF reports for asset track, bathymetry and contact imagery, we are creating larger scenes modeling the same data in spatial form within a 3D version of the same operating areas. Thanks to the multi-year NPS DIS-Java-VRML project performed together with the Web3D Consortium, we are further able to share such simulations in real time over the network via the IEEE Distributed Interactive Simulation (DIS) standard, using a variety of physics-based protocol data unit (PDU) formats. With continued progress, we soon expect to analyze independent AUV control of track paths and sensor response for consistency with both observed and historical data. Our forthcoming auto-generation of tracks corresponding to Fleet Battle Experiment Hotel (FBE-H) off Panama City Florida in Spring 2000, and Exercise Kernel Blitz off Camp Pendleton in Spring 2001, will demonstrate both post-mission and in-stride visualization capabilities.

NPS experience with integrating UUV data into the Navy's MEDAL tactical decision aid will also be a part of the system of demonstrations with the continual goal of reducing the latency of data gathering to the fleet. This work builds on previous success of NPS at UUV demonstrations including the recent KB01 exercise in which we demonstrated a radio communications link for image snippet transfer from the ARIES via a PELICAN aircraft to the ONR base at Camp Pendleton. The aerial relay link was provided by the PELICAN aircraft which was flying the AROSS sensor package during the exercise. However, for system demonstrations on a regular basis in Monterey Bay, we propose to use an aircraft of opportunity from the NPS Flying Club. This could expand later on to the use of radio controlled assets using Dr. Issac Kaminar's work at NPS.

Technical Tasks

This proposal brings together the expertise of NPS staff and students in the areas of AUV Command and Control. Not only do we know about the problems facing the Navy in Autonomous Systems, but we also have Naval Officer students who are involved by thesis work in the subject. The officer students represent the future leadership of the Navy and will be exposed to the new technologies at this early stage if this work is funded. Four thrusts are described here each with near term, mid term and longer term goals that correspond roughly to each of three years as an initial program linked to demonstrations of capability during each year.

The description of tasks is shown together in Figures 2 to 4 as to their relation to each year's goals. What follows is a more detailed description of the tasks that broadly follows the layout in each of the Figures 2 to 4.

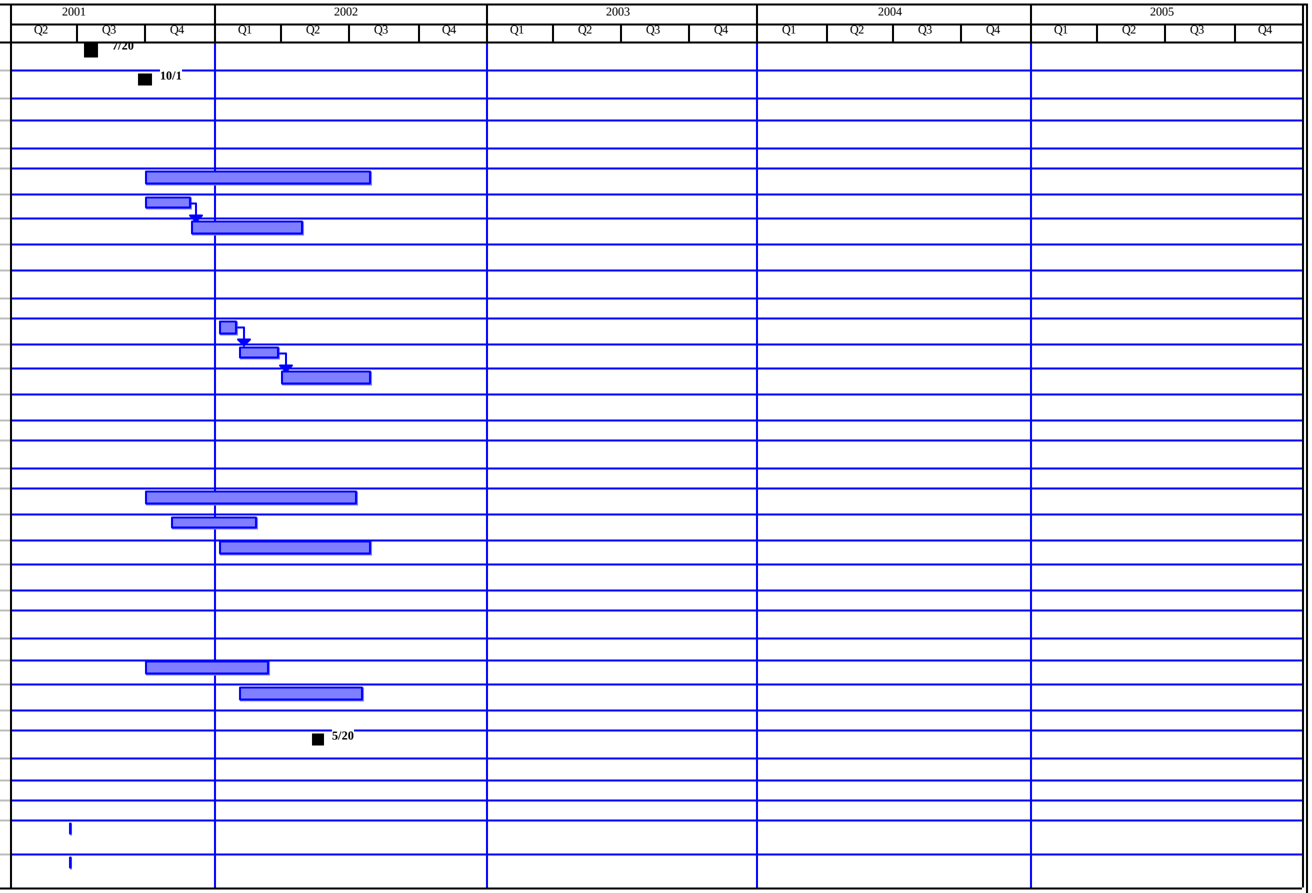
Thrust I Advances and Experiments in Command and Control

Near Term Goals

Figure 5 shows the current situation regarding our command and control system for the ARIES AUV. As a routine matter, NPS has command and control authority over the ARIES when surfaced. Data files are retrieved using a whaler as a relay station. With the current configuration, about a 4-6 mile range is possible with data transfer rates to 30,000 bits/sec. This could be increased if the relay station was not used, but then the range would be limited to less than 1 km depending highly on sea state. As an example, in Monterey Bay we frequently have to operate in 6-9 feet swells. At the present time, this rate allows for data files up to 40,000 Bytes to be transferred in 13 seconds using a Z-Modem protocol on the base station PC with Kermit running in the ARIES QNXT processor. Details of the ARIES computer controller are available in (Marco, 2000), in which a dual processor solution is used allowing for both internal and external network solutions. The vehicle is capable of performing altitude control, depth control, tracking control, speed control heading control, waypoint control, and can be made **to loiter about a fixed point if needed.** Communications links are serial, although in a new development using "Tiny Bridge", we are beginning to implement IP protocols through the radio serial connections. Radio communication speeds to date are very adequate for transferring data files and processing navigational track, GPS data, vehicle battery status, Doppler and IMU data, depth and altitude results. Video files from the on board DV recorder are not transferable at this time through the radio link. They have to wait for the vehicle to be recovered. This configuration was that used in the KB01 exercise in March 2001 at Camp Pendleton.

With a view to achieving the longer-term goals of developing rendezvous maneuvers, the work will begin with simulations of general rendezvous behaviors for the ARIES vehicle as a server vehicle assuming that the worker vehicle (i.e. REMUS) is conducting a normal survey. **We will first simulate rendezvous around a fixed node using the loiter behavior, and then rendezvous to a moving vehicle performing trajectory control behavior**. The rendezvous will be based on a pre-planned rendezvous point so that the ARIES will have a new behavior - that of arriving at a defined place in space and time. This type of planning is solved using dynamic programming, or other two-point boundary value problem solution method. The planning approach obviates the new for the ARIES to "catch up' with REMUS. It will simply be at the right place and time as REMUS comes by. This is the first task in Figure 2.

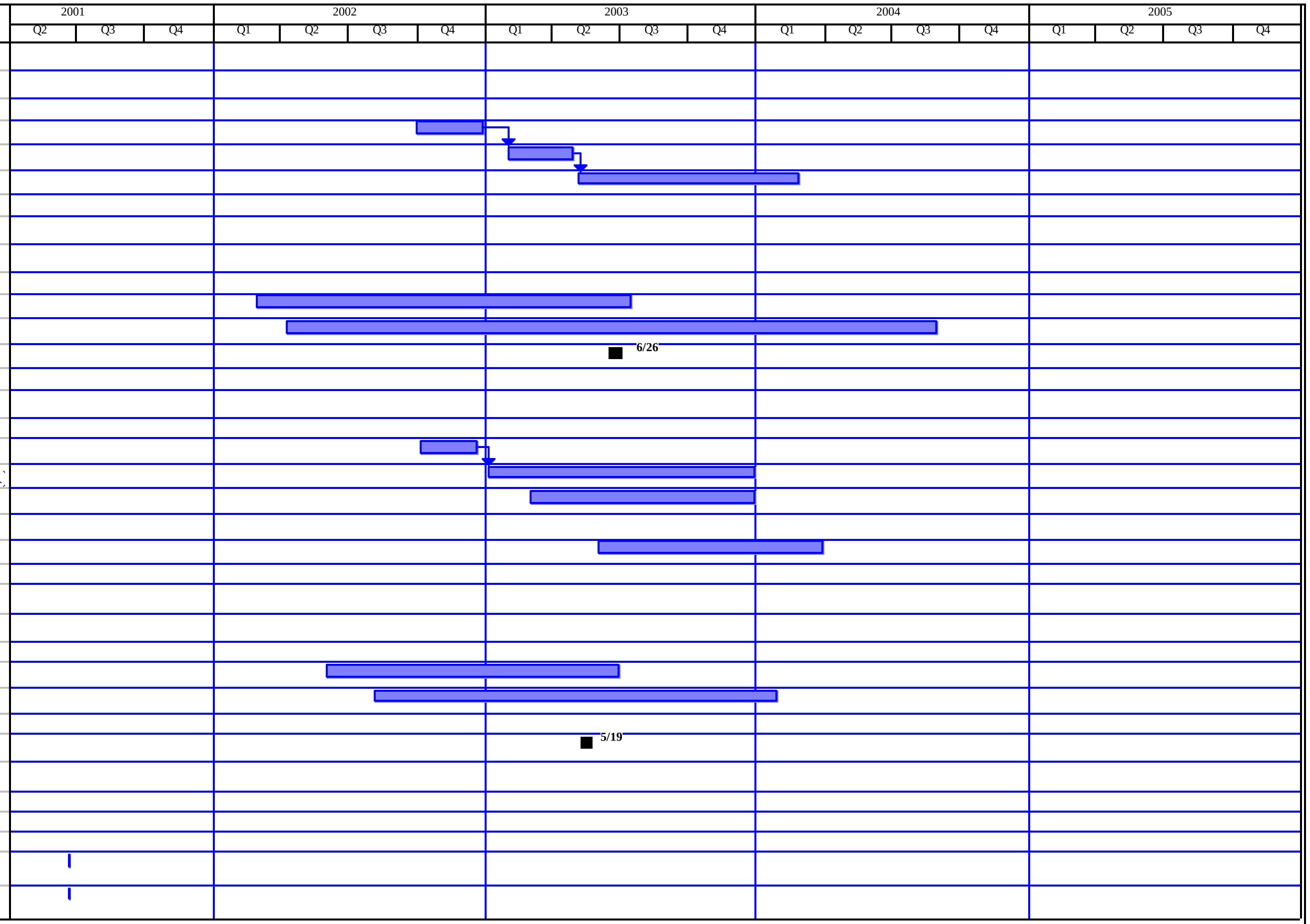
ID	Task Name
1	**Proposal Due**
2	**Funds Obligated**
3	
4	**1 Near Term Command and Control**
5	
6	Perform Simulations for Rendevous Maneuvers-(USS)
7	Software Extension to accommodate Other Modems-(USS)
8	Radio/Acoustic Link with FAU Modem-(USS)
9	
10	**2 Near Term Comms FAU- ARIES-WHOI**
11	
12	Install WHOI Micro Modem-(USS)
13	Test Whoi Micro Modem with ARIES / Whaler-(USS)
14	Test WHOI Modem and FAU Modem-(USS)
15	on ARIES
16	
17	**3 Near Term Obstacle Avoidance Technology**
18	
19	Obstacle Avoidance Scenario Simulations-(MR)
20	Select and purchase appropriate Forward Look Sonar-(MR)
21	Tests using Fwd Look Sonar mode(bottom and surface)-(MR)
22	
23	
24	**4 Near Term Visualization**
25	
26	Visualize Acoustic Beam Data Transfer-(MR)
27	Visualize Multi-Vehicle Tracking-(USS)
28	
29	**FBE-K(Experiments with Remus / ARIES / FAU)**
30	
31	
32	
33	**Figure 2. Near Term Tasks**
34	**October 2001 - September 2002**



Project: AFONC_plan
Date: Thu 7/19/01

Task | Milestone | Rolled Up Split | External Tasks | Deadline
Split | Summary | Rolled Up Milestone | Project Summary
Progress | Rolled Up Task | Rolled Up Progress | External Milestone

ID	Task Name
35	**1 Mid term Command and Control**
36	**-ARIES to a Sea-Web Node**
37	
38	Purchase and Install Benthos Sea Web Node-(USS)
39	Test with ARIES and a Commercial sea web node-downlink-(USS)
40	ARIES first Stationary and then Loitering -(USS)
41	
42	**2 Mid term Modem Development-**
43	**Stationary UHF Acoustics**
44	
45	UHF Transmission Stationary Characterisation-(MR/USS)
46	Prototype Modem Development Stationary-(MR/USS)
47	CDR Marr Graduation
48	
49	**3 Mid term Obstacle Avoidance**
50	
51	Integrate processed sonar returns into Navigation Process-(MR)
52	Dynamic O/A Experiments with Scanning Sonar(Channel Centering)-(MR`
53	Tests with scanning sonar against an object structure-
54	characterise returns-(USS)
55	Conduct experiments to avoid an object-(MR)
56	
57	**4 Mid term Visualization-Data Links with**
58	**ADS / Medal**
59	
60	Visualize Sea Web Networking-(USS)
61	Visualize Obstacle Avoidance Decision Making-(MR)
62	
63	**FBE-M Demonstrate Sea Web**
64	**Bi-Directional Communications With ARIES**
65	
66	
67	
68	**Figure 3. Mid Term Tasks**
69	**October 2002 - September 2003**



Project: AFONC_plan
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Task		Milestone		Rolled Up Split		External Tasks		Deadline	
Split		Summary		Rolled Up Milestone		Project Summary			
Progress		Rolled Up Task		Rolled Up Progress		External Milestone			

ID	Task Name
70	**1 Long Term Command and Control**
71	
72	Install USB sensor for ARIES
73	Equip NPS REMUS(from DURIP)
74	Experimental Validation of Rendevous Maneuver(Stationary Point)-(USS)
75	Experimental Validation of Rendevous (Moving Vehicle)-(USS)
76	
77	**2 Long Term UHF Acoustic Comms**
78	
79	ARIES with a High Speed Sea-Web Node -Data Uplink-(USS)
80	Experiments with new UHF Modem on ARIES-(MR/USS)
81	
82	**3 Long Term Obstacle Avoidance**
83	
84	Harbor Entrance Experiments-(MR)
85	Channel Centering Experiments(Moss Landing)-(MR)
86	Multiple Contact Field Avoidance Demonstrations-(MR)
87	
88	**4 Long Term Visualization**
89	
90	Network Distributed Visualization-(USS)
91	In stride Data Collection visualization-(MR/USS)
92	
93	**FBE-O Multi Vehicle Rendevous and**
94	**Data Transfer**
95	
96	
97	**Figure 4. Longer Term Tasks**
98	**October 2003 - September 2004**

Project: AFONC_plan
Date: Thu 7/19/01

Task	Milestone	Rolled Up Split	External Tasks	Deadline
Split	Summary	Rolled Up Milestone	Project Summary	
Progress	Rolled Up Task	Rolled Up Progress	External Milestone	

We have installed an FAU acoustic modem (LeBlanc, et. al., 2000) that allows communication links to be made between the Whaler relay station and the ARIES when underwater. The acoustic modem system has already been tested in the Monterey harbor with success. A range of 300 m was used for this test, and reliable transmission and reply was given even with only 0.1 full power. This configuration also will be tested during this summer period in a joint exercise with the University of Lisbon in the Azores. This is a cooperative exercise using the acoustic modem to receive data from the University of Lisbon DELPHIM vehicle. In this exercise, the DELPHIM will send a limited set of commands to ARIES through the acoustic channel and task the ARIES to obtain video pictures of shallow water vents. Later in this task, the work will extend our software processes to accommodate more than one modem as the WHOI micro modem is planned for installation.

In the first year, and with the objective to reduce data latency, we propose to install a WHOI modem (see emails in appendix) that would upgrade our capabilities enabling us to communicate with the REMUS vehicles. This development will provide us with the capability of sending queries and commands to any REMUS within range of the ARIES. Assuming that this modem has a 1000m range in shallow water, experiments will be conducted in which data files will be transferred from a working REMUS vehicle as shown by the concept in Figure 6. With REMUS vehicles in the working area, data such as contact locations and status will be passed to ARIES which will then be free to surface and radio back to the command base. To conduct these experiments NPS would prefer to have a working REMUS vehicle available in MontereyWe plan to submit a DURIP proposal to purchase a REMUS vehicle. With DURIP funds to purchase our own REMUS, these communications experiments will be easier to conduct locally in Monterey. Other options include MOA's with other universities and conduct experiments in San Diego with VSWMCM Detachment. Meanwhile, yet other options will be to "model" the working REMUS vehicle using the Whaler to carry the "pair" modem to that installed on the ARIES. This will certainly demonstrate that the communication links are in place and a demonstration plan with both REMUS and FAU vehicles during the FBE -K experiments (assumed to take place during the summer of 2002) will be developed as shown in the plan in Figure 2. One of the key points of this work, and the NPS approach is that ***ARIES may carry BOTH modems.***. While an interoperability standard is still being worked out, this enables NPS to communicate ***with both REMUS and FAU vehicles in the same mission***.

Interactions with Sea Web:

We also plan to interface with the Sea Web activities explained in Appendix II. The first emphasis applies C3N functions being developed by other projects to the ARIES vehicle. These C3N functions provide an underlying functionality for ARIES operation in a networked context, and they permit interoperable, cooperative operations with other fixed and mobile nodes in the Seaweb network. This means that we will purchase and install and test a commercial telesonar node for ARIES in additional to the WHOI micro-modem.

The second emphasis involves high-data-rate links permitting ARIES to service or download an undersea sensor network that nominally functions in a low-data-rate manner. For example, a surveillance network operating in a clandestine, energy-conserving, low-data-rate manner may make periodic synopsis reports through the fixed network, retaining raw data in memory for post-processing. If the command center deems the synopsis report to be of high interest, ARIES would visit the remote sensor and download associated raw data at close range, with high data rate and low source level. ARIES would transport the downloaded data to a gateway node and upload the data through that gateway to the command center, again at close range, with high data rate and low source level. The high-data-rate transfers would employ coherently processed telesonar signaling using a daughter board demodulator associated with the standard telesonar modem. This high-data-rate capability will apply the products of a recently awarded STTR contract with Benthos, Inc, and will extend the STTR-developed capability to support operations in the undersea network context. This capability will be combined with ARIES' ability to hover near an adjacent node. The aim of this work is to make an initial foray into using high-data-rate, close-range acoustic communications and learn operational lessons that will guide the development of a new, very-high-frequency, high-bandwidth telesonar modem. The very-high-frequency, clandestine modem will operate at frequencies greater than 100 kHz and less than 1.5 MHz, with the actual spectral band to be determined by an integrated link-budget analysis and concept-of-operations analysis.

FY02 SEA WEB MILESTONES

1. Deliver basic telesonar modem, deck unit, and commercial version of firmware.
2. Support integration of telesonar modem electronics and transducer into ARIES.
3. Support integration and testing of commercial (non-seaweb) ATM885 modem firmware into ARIES and deck unit.
4. Support demonstration of basic, non-networked C3N using a telesonar deck unit as a remote ARIES terminal.
5. Issue Seaweb 2002 experiment plan, including implementation details for FY03 ARIES C3N capabilities.
6. Deliver telesonar modem hardware upgrade including a high-data-rate daughter board with Sharc processors.

Mid Term Goals

Mid term goals in command and control are illustrated in Figure 3 and will demonstrate the ability of ARIES to loiter around a ***fixed node*** such as that in a 'sea web' network (Butler et. al., 2000). A sea web (See Appendix II for additional information) is a set of fixed transponders / modems that are self-surveying and record contact data in water depths from 300 feet and shallower. It is planned to eventually demonstrate the data transfer for both up-link at higher data rates as well as down-link at low data rates between the ARIES - a mobile node - and a Sea Web fixed node. We will program ARIES to loiter around the fixed node and receive data acoustically which will then be transmitted by surfacing and using the radio modem to link to a base command station. The data formats can be put into US MTF for import in MEDAL.

FY03 SEA WEB / ARIES MILESTONES

1. Incorporate high-data-rate modulation and demodulation for ARIES data-packet transfers in the context of Seaweb 2002 networking protocols.
2. Perform networked command/control of ARIES, including cellular handoff as ARIES moves throughout fixed distributed network.
3. Perform low-data-rate networked transfer of CTD data, other onboard sensor data, ARIES system data, and/or any other desired data payloads from ARIES to seaweb database ashore.
4. Test and refine low-data-rate downloads of data from a remote fixed node to ARIES and from ARIES to a deck-unit modem.
5. Track subsurface location of ARIES relative to undersea network nodes using server-initiated telesonar ranging measurements.

6. Experiment with homing algorithm using single fixed node (leveraging Benthos STTR).
7. Support the identification of collaborations between NPS and other AUV developers for cross-system AUV operations, and fold these collaborative activities into FY04 demonstration planning.
8. Issue Seaweb 2003 experiment plan, including implementation details for FY04 ARIES C3N capabilities.
9. Work with ONR 322 and ONR 36 to develop a new SBIR or STTR topic for close-range, very-high-frequency, large-bandwidth acoustic modem for clandestine data transfers. The aim of this SBIR/STTR topic is identifying an industry partner funded with ONR 36 industrial program dollars to team with us in FY04 and FY05.
10. Execute Seaweb 2003 Experiment (Summer 2003, probably Buzzards Bay).

It is proposed that we will develop a mini test sea-web system in Monterey Bay for the purposes of testing with ARIES since it would be added expense to join the Annual Sea web experiments. In this regard the budget calls for a **sub contract to SSCSD** who will provide funds identified in the budget for supporting **the contract with Benthos** to continue the development of the high-speed feature to their ATM-885 commercial modem.

Long Term Goals

The long term development of command and control technologies will focus on command and control linkages using both acoustic and radio modems, **where high data rates will be enabled through close range rendezvous**. Since we will have already demonstrated communications with a fixed node, and the loitering behavior, this year will focus on communications with a moving node. Ultimately, we expect to perform rendezvous with a moving vehicle as shown in Figure 7.

Figure 7 shows the scenario where a close in rendezvous will be enabled using accurate navigation of ARIES (within 10m) which will track a REMUS vehicle using Ultra Short Baseline sensors as well as its own navigation sensors. The cross track error guidance algorithms used in ARIES (Marco, 2000), will be extended to close along track errors as well as cross track errors. The resulting controller is called a "trajectory" controller. This type of control will place the slave vehicle (ARIES) in the close vicinity of the master vehicle (REMUS). This 2-vehicle rendezvous behavior is a project that NPS will begin to study immediately. We believe that it is quite feasible with the current state of vehicle development**. The slower speed of ARIES is not a problem** since we will use a preplanned rendezvous point that represents a feasible plan for both vehicles to arrive at the rendezvous point along the original REMUS track at the prescribed point in time. The problem requires an on board dynamic planning capability built into ARIES that allows it to be at a specified place and time. The REMUS vehicle will not need to change its path plan at all. However, we may require the REMUS to slow to 3 knots during the rendezvous operation, which will only take a short distance. The rendezvous area will be defined by an initial call from the master (REMUS) to communicate data files of large magnitude. Such data files would be sonar image files of larger magnitude than the small "snippet" files we currently use, which are in the order of 20K Bytes. ARIES would then perform the rendezvous plan and indicate to REMUS using the WHOI Micro-modem where the rendezvous is to take place. The two vehicles arrive at the appointed place and time but on different altitude paths. We plan to use a small USB (Ultra Short Baseline) sensor on ARIES to sense bearing angles to the REMUS. Based on a down bearing command, and flying at prescribed altitude, the closing maneuver behavior will be guaranteed stable. When in close range, the data handshake and file transfer would be accomplished. With a rendezvous time of 10 seconds and a 1Mbps data rate, we can transfer a 10Mbit file in that short time. The top speed of ARIES is 3.5 knots which would only have to maintained for a short period while the rendezvous is accomplished. This task will include verification of maneuvering to a fixed point as well as to a moving vehicle. We may choose to define the 'moving vehicle' at first as a towed body using our whaler support boat, but later the use of a REMUS vehicle for these tests is the goal.

Longer Term Goals Sea Web Interactions

As part of the long-term goals in command and control, we have specific goals related to the interactions with sea web. These are,

FY04 MILESTONES

1. Upgrade high-data-rate modem hardware with more advanced capability building on lessons learned from the Benthos STTR.
2. Support ARIES participation in FY04 Fleet Battle Experiment or other demonstration opportunity identified by Autonomous Operations FNC Program.
3. Demonstrate ARIES networked operations in conjunction with 688-class submarine, DADS, Hydra, and Racom; show cross-system interoperability.
4. Track subsurface location of ARIES relative to fixed network.
5. Support ARIES performance of autonomous mission utilizing fixed network for navigation waypoints and data telemetry.
6. Issue Seaweb 2004 experiment plan, including implementation details for FY05 ARIES C3N capabilities.
7. Execute Seaweb 2004 Experiment, (Summer 2004, site TBD)
8. Support ARIES implementation of a 15-20 kHz transducer for compatibility with telesonar directional transducers.
9. Support the identification of collaborations between NPS and other AUV developers for cross-system AUV operations, and fold these collaborative activities into FY05 planning.
10. Perform ARIES to other AUV comms/nav as part of AO FNC demonstration network.
11. Demonstrate coordinated operations involving ARIES and other AUV.
12. Refine previously tested capabilities.
13. Implement geo-localization algorithms in seaweb server using GPS input from ARIES.
14. Select SBIR/STTR contractor for very-high-frequency modem development.

FY05 Milestones

1. Support ARIES performance in FY05 Fleet Battle Experiment or other sea trial designated by the Autonomous Operations FNC Program.
2. Demonstrate various cross-mission, cross-system uses of ARIES in conjunction with other networked systems.
3. Implement refinements and other capabilities identified by project to ensure transition of ARIES as an integral part of future Naval capabilities involving autonomous operations.
4. Integrate prototype very high frequency modem into ARIES UUV and test at sea.

In summary, we plan a graduated development for using the high-speed data link, starting with communications with fixed nodes, loitering with a mobile node around a fixed node, and finally communicating between two moving nodes. The above discussion elaborates our plan for work under the thrust of COMMAND and CONTROL.

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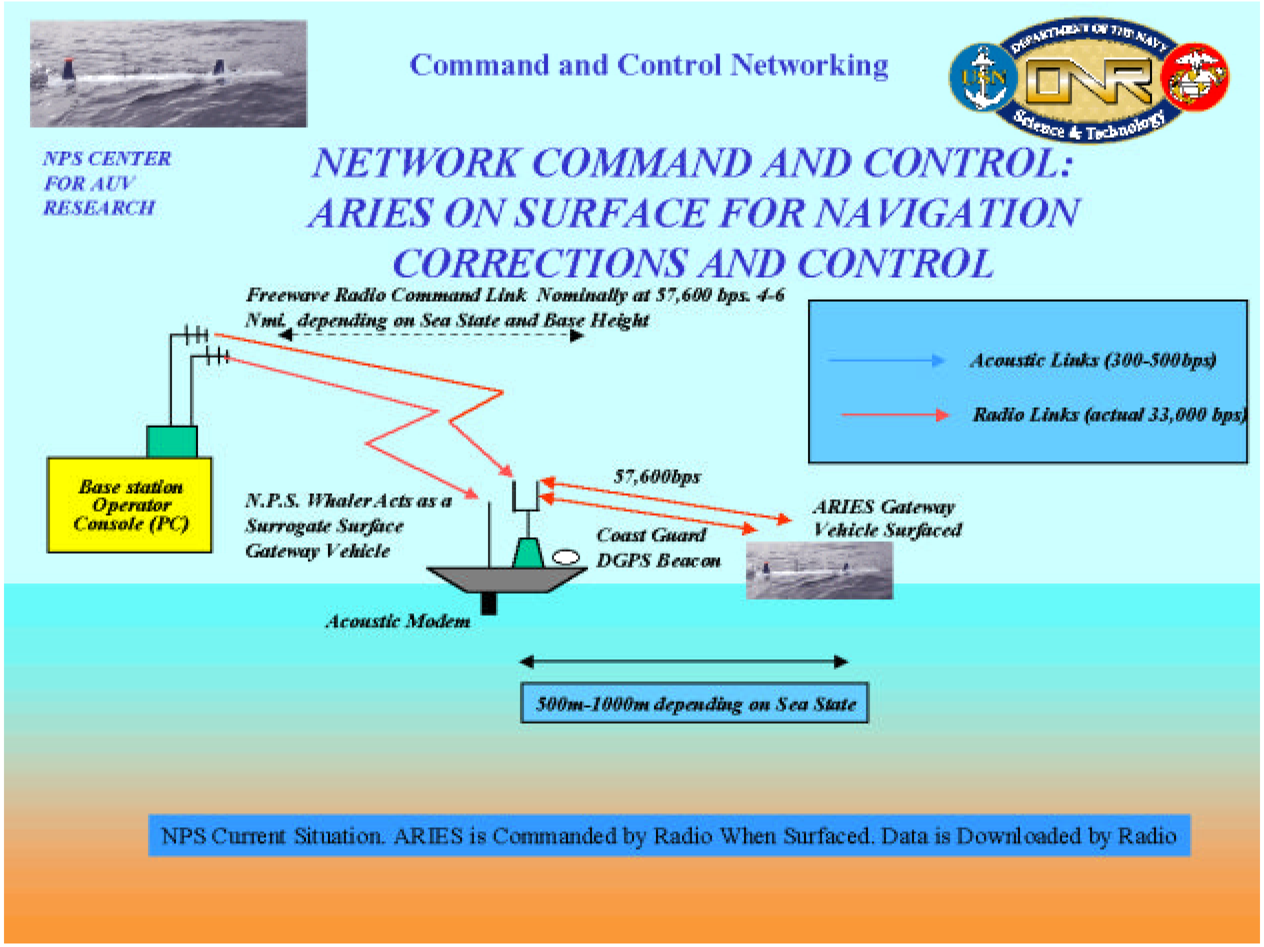

Figure 5. NPS Current System. The Whaler acts as a Communications Relay Station For Navigation and Control of the ARIES.

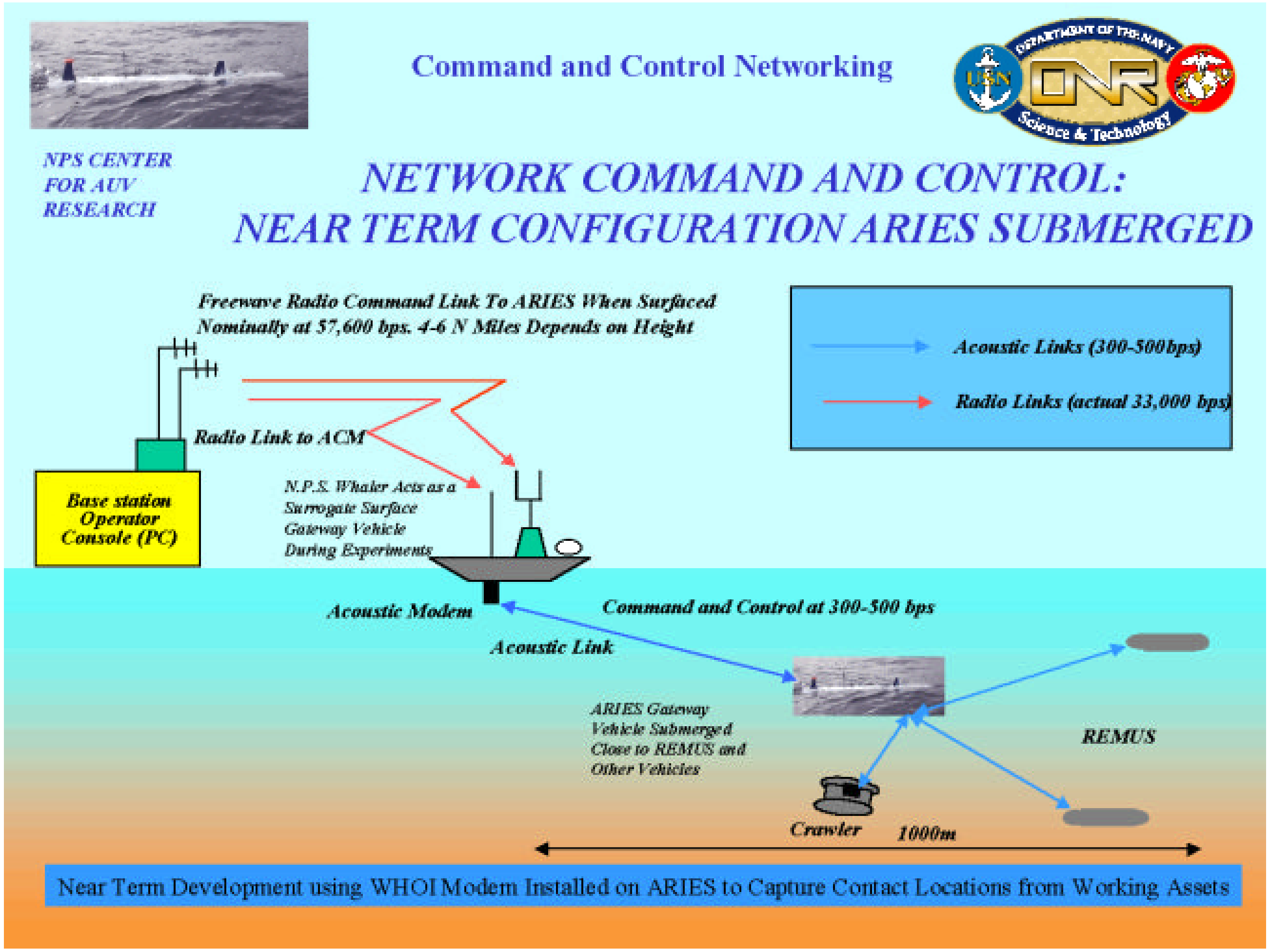

Figure 6. System Configuration With Acoustic Modem Working ARIES Communicates with other Vehicles as they move into the area for data Transfer.

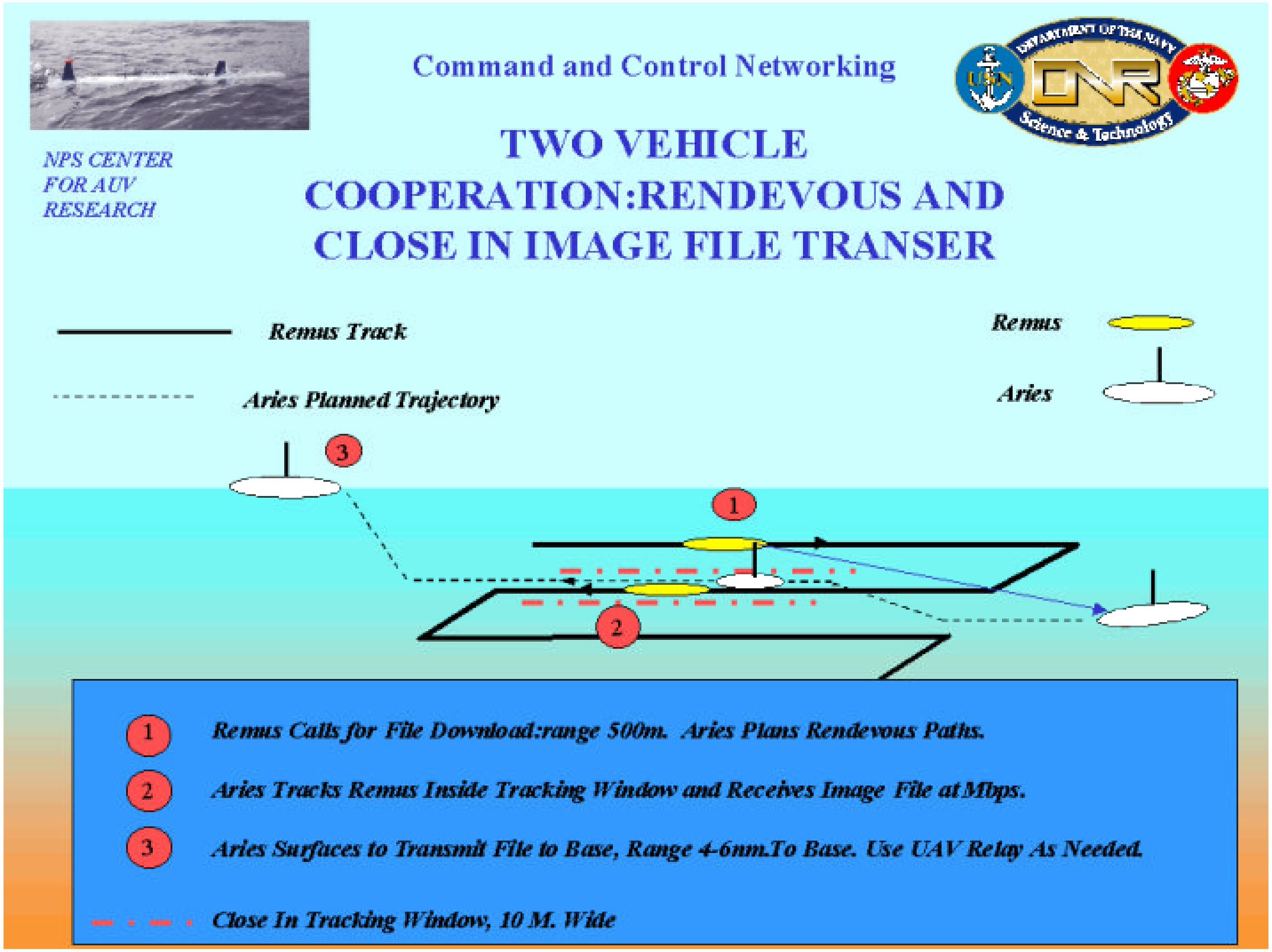

Figure 7a, Outgoing Year Goals to Perform Close In Rendezvous Between REMUS and ARIES for High Speed Data Transfer. REMUS slows to 3 knots During Rendezvous (10-15 sec.), ARIES Plans the Rendezvous Point and Maintains Contact (3 knots, at Separate Altitude Paths)

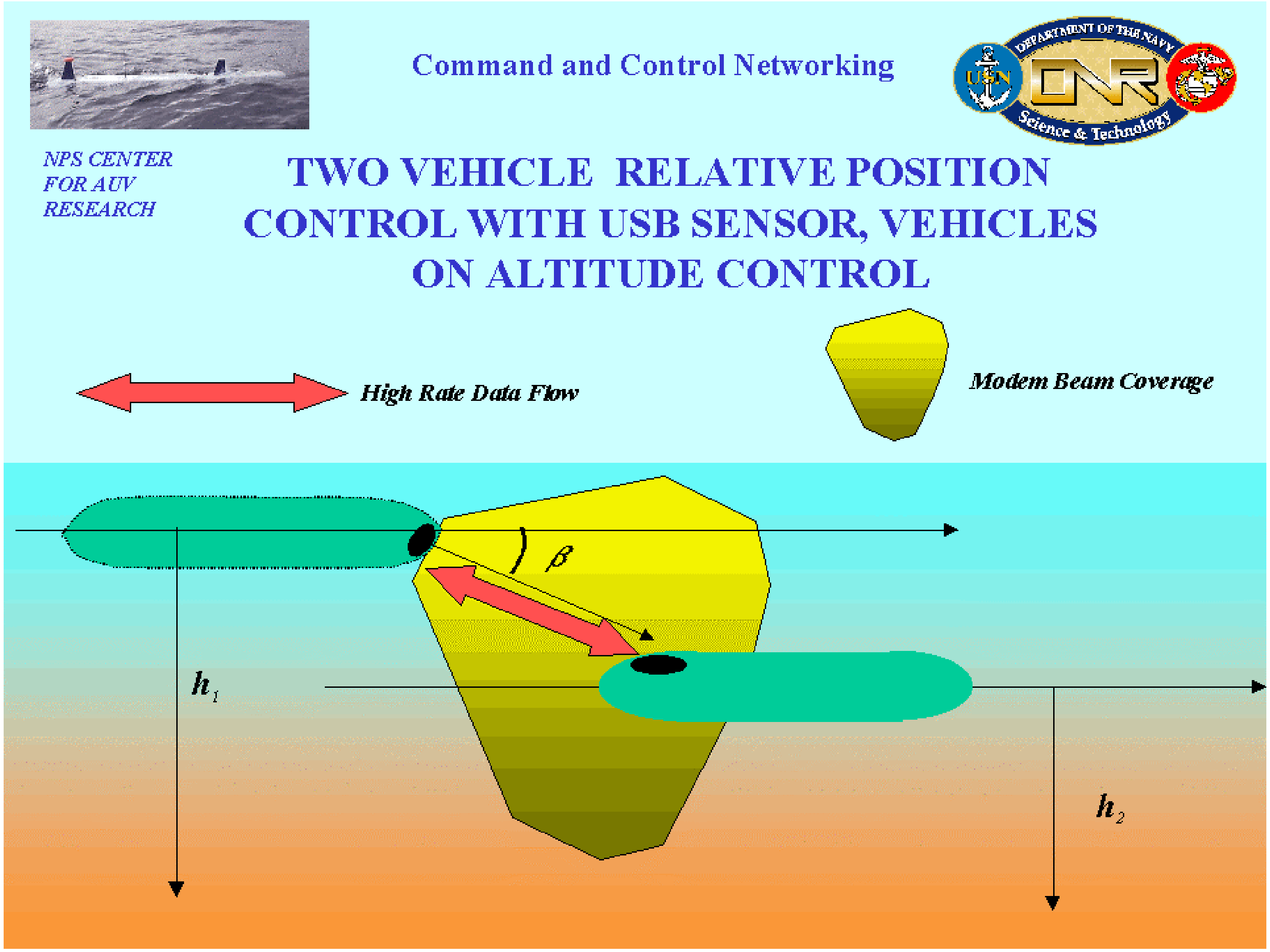

Figure 7 b Diagram Showing Use of USB sensor to Home in to Close Range Trajectory Tracking. UHF Data Transfer Takes Place When Master and Slave Vehicles are Tracking.

Thrust II New Ultrasonic UHF Modem and U/W Communications

Discussion of UHF Modem Concepts

The second thrust is to work on a short range high data rate modem using ultra high frequency acoustics. The next few sections elaborate on our thoughts about the development of an ultra high frequency modem with short range that could communicate large data files between close in vehicles. We have studied the issues surrounding the use of ultra-sonics, VHF electro-magnetic, and electro-optic communication links. Electro-optic links suffer from the problem of pointing accuracy with a moving vehicle that suffers from pitch and roll motions. Sensor stabilization and pointing problems are deemed to be too difficult to overcome. Electro-magnetic range is much lower than acoustic range for the same frequency and therefore does not compete well for high data rate at small ranges. For instance, at 1 MHz., the electromagnetic attenuation in sea water would be about 20 db /meter, so for a 100 db loss (a reasonable heuristic for a communication system) a range of only 5 meters would be achieved. This is to be compared to a range of 60 meters for acoustic signals at that frequency. Sound transmission in the ocean has been well studied at lower frequencies but little research has been done concerning communications underwater in the ultrasonic range. Theoretical bandwidths in the ultrasonic range exceed currently achievable underwater data bit rates by two orders of magnitude, up to megabits per second. At these high transfer rates, real time data, including images, can be collected in stride from underwater search assets, passed to the ARIES (operating as a mobile node), and ultimately sent to the command center when the ARIES surfaces. This capability will provide crucial, near real-time data to the war fighters, including positions of underwater threats and, eventually, video of mine-like contacts for appropriate prosecution. Using ARIES as a mobile network C^3 node, we will first do studies to verify that such communication is possible followed by testing in progressively more realistic environments with the ultimate goal of communicating between two AUVs while underway and passing the data back to the command center.

Data Encoding and Link Layer Data Protocol

The theoretical analysis in the last section supports the conclusion that a bandwidth of 2-4 MHz may be available in the underwater environment being considered. To efficiently translate this seemingly large amount of raw bandwidth into effective data throughput, two areas of concern must be addressed. These are (1) data encoding, the method of representing information by physical signals, and (2) the selection, or if necessary, the development of the most appropriate data link protocol to enable recovery of the data in the midst of adverse environmental conditions

1. Data Encoding

The objective of the proposed system is the delivery of computer data between underwater platforms. The data, sequences of binary “bits,” must be encoded as physical signals that efficiently use the available bandwidth of the physical medium. If bits are encoded into digital signals made of discrete, discontinuous pulses, the process is called data encoding.

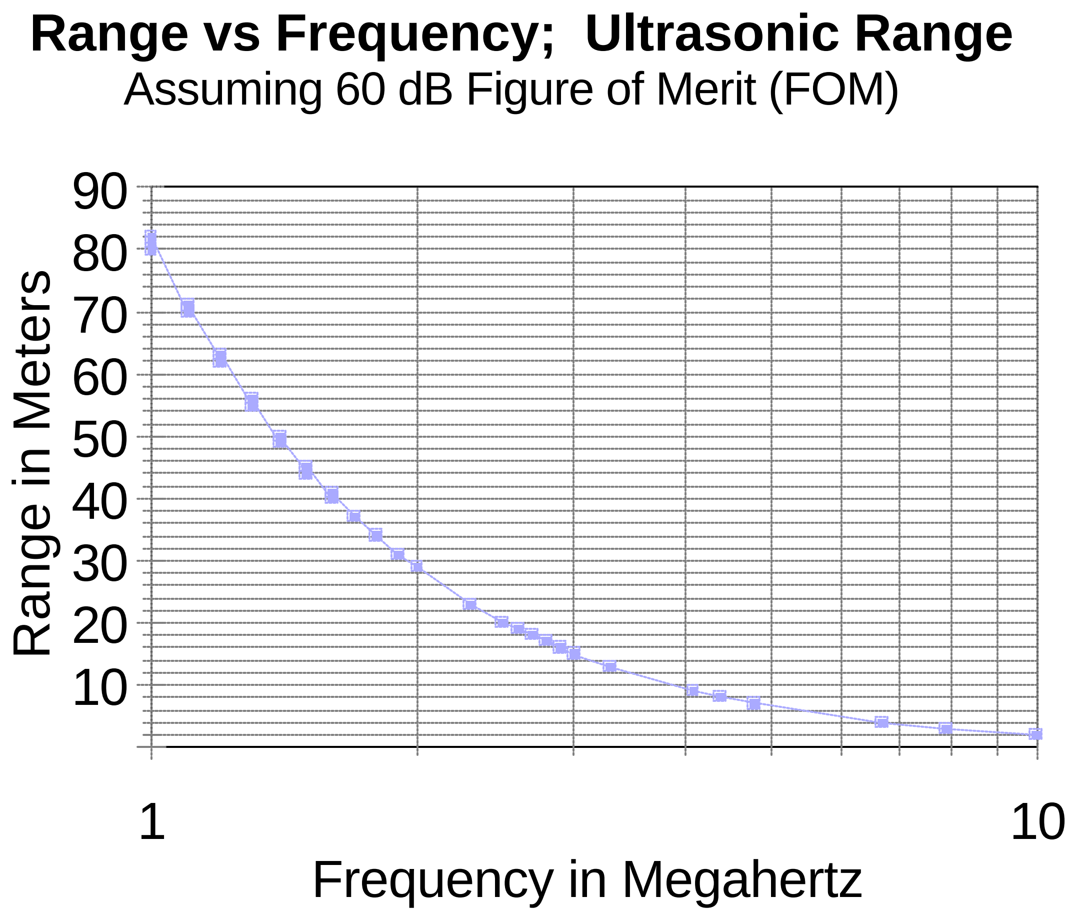

Figure 8. Range vs Frequency for Acoustic Transmission Based on a 60 db Loss Factor. 3 MHz. Shows a Viable Range of 15 Meters

We propose the use of digital signals for communication between the ultrasonic modems of the two underwater platforms. Digital signaling components are widely available. Additionally, it is relatively inexpensive to build customized digital circuits when necessary. The challenge is to find an encoding scheme that is most suitable to the physical environment. The suitability of a particular data-encoding scheme is typically measured by three metrics:

1) Achievable bit rate
2) Resistance to noises and other transmission impairments, and
3) Cost to implement (including power consumption).

There is a theoretical bound on the maximum achievable bit rate with any data-encoding scheme. Shannon's Theorem provides a well known and widely accepted calculation of that limit. Denote *B* to be the available bandwidth of a communication channel, and *C* the achievable bit rate for that channel. Shannon's limit can be expressed as follows:

$$C \leq B \log_2(1 + SNR),$$

where *SNR* is the limiting signal-to-noise ratio [Stallings2000]. For example, if *B* is 3 MHz and the SNR is 100, which corresponds to 20db, the theoretical upper bound on achievable bit rate is approximately 20 Mbps. While this rate is much more than expected, even a 20% efficiency leads to a rate of 1 Mbps.

We will experiment with the Manchester data-encoding method, as it performs well with respect to the first metric. The Manchester encoding method is widely used as part of the 10-Mbps, 10BaseT, Ethernet standard (IEEE 802.3). It makes efficient use of channel bandwidth, achieving a bit rate of 10 Mbps from a signal spectrum between 5 and 10 MHz [Couch1987]. We project a bit rate of 2-4 Mbps using Manchester encoding in the underwater environment, given the available channel bandwidth of 2-4 MHz.

Additional study evaluating the performance of Manchester encoding with respect to the other two metrics will also be performed. In particular, we want to make sure that the encoding method is resistant to the types of noise and transmission impairments characteristic of the underwater environment. One particular concern is the ringing effect caused by transmitting a pulse signal with a mechanical transducer. The physical medium may need to be damped to reduce this reverberation effect.

2. Link Layer Data Protocol

Bit errors are inevitable for any physical medium. The problem is particularly severe for underwater acoustic channels [Curtin, 1993, Sozer, 2000]. Therefore, a link layer data protocol is required for the proposed system to ensure reliable delivery of computer data between the underwater platforms.

The most important performance metric for a link layer protocol is the achievable channel utilization. Consider a channel with a raw bit rate of 3 Mbps. If the link layer protocol could utilize the channel only 10% of the time, the effective data throughput over that channel would be just 300 Kbps!

The achievable utilization of a link layer protocol (denoted by U) depends on several system parameters. These are: the raw bit rate of the channel (denoted by C), the data frame size in bits (denoted by F)[1], the one-way signal propagation latency (denoted by t_{prop}), and the uncorrectable frame error rate (P). Three link layer protocol candidates bear consideration for the proposed system.

2.1 Forward Error Correction (FEC)

The first protocol would add Forward Error Correction (FEC) code to each data frame so that the receiver can correct almost all bit errors in the frame. The transmitter sends out data frames continuously, and as rapidly as possible. The receiver may either process incoming frames at the same rate as they are received or buffer some of the frames for later processing. The main advantage of this protocol is that it works with a **unidirectional channel**. It has been demonstrated that Hamming codes perform well for an underwater acoustic channel [Reimers, 1995]. The principal disadvantage is that it is not 100% reliable. It cannot be used to deliver critical textual or numerical data. Even for still-image data that may not require 100% reliability, a small number of uncorrectable bit errors may degrade the quality significantly when the image is compressed or should the errors cluster about the portion of the image of greatest interest to the user. FEC codes also incur communication overhead as they incorporate redundancy in the

[1] For ease of presentation, we assume a fixed frame size.

data. For this reason they have a negative impact on the attainable data throughput. For example, if each frame's FEC code were one quarter of the total frame size, then the actual data throughput would never exceed 75% of the channel capacity, even if the channel utilization approaches 100%. For a specific reliability target, such as limiting uncorrectable frame error rate below 1%, the required FEC code size increases as the bit error rate of the physical medium rises.[2] Since the bit error rate in our system is expected to be high, the communication overhead of FEC codes can be a major problem. Unless we must deal with a simplex channel, we plan to explore alternatives that may prove to be more efficient than depending entirely on FEC codes for error control.

2.2 Stop and Wait ARQ

The second protocol of interest is Stop-and-Wait ARQ (Automatic Repeat reQuest). No FEC code is required, although sometimes a FEC code may be used to reduce the uncorrectable frame error rate (P). Error control is predominantly implemented by way of retransmissions. The receiver must acknowledge to the sender the receipt of each data frame that is free of errors. It may also send a negative acknowledgement for an incoming frame with errors. The sender cannot send a new data frame until the current frame is positively acknowledged. Upon receiving a negative acknowledgement or in the absence of positive acknowledgement within a specific time period, the sender will retransmit the current frame.

This protocol has two major advantages. First, the protocol can achieve **100% reliability**. Second, it works with a **half-duplex (simplex) channel**. The main drawback is that it may not be able to achieve high channel utilization in some system environments. Specifically, the achievable channel utilization of Stop-and-Wait ARQ, according to [Stallings2000], is bounded as follows

$$U \le \frac{1-P}{1+\dfrac{2t_{prop}}{(F/C)}}.$$

Consider our target system where C is approximately 3 Mbps and t_{prop} is typically 6.7 milliseconds[3]. As P approaches 0 the utilization is maximized for a given frame size (F) and channel capacity. From the formula above, the frame size (F) would have to be larger than 25 Kbytes in order to achieve channel utilization larger than 83%. Given the high bit error rate in our system, this frame size may be too large to assure a small P value. From the same formula, a large P value would clearly have a negative impact on U. This problem would be exacerbated if C decreased or t_{prop} increased.

2.3 Sliding Window

The third protocol bearing consideration is the Sliding Window protocol, which improves on Stop-and-Wait ARQ and is the basis of the popular TCP protocol. Specifically, the sender may send multiple frames at a time as long as the total number of unacknowledged frames is not larger than a particular window size. The window size is determined either by the buffer space at the receiver or by the number of outstanding frames the receiver can track [Balakrishnan, 2001],

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[2] The required FEC code size also jumps when the correlation of bit errors increases.
[3] Time it takes a sound wave to travel 10 meters [Sozer2000].

as well as other system parameters. The receiver acknowledges the frames that it has received correctly. These acknowledgements will reduce the number of unacknowledged frames and prompt the sender to transmit new data frames. The sender will also retransmit a frame for which there is no acknowledgement within a given period of time. The main advantage of the Sliding Window protocol is that it can achieve **very high channel utilization**, specifically $1 - P$, without requiring a large data frame size [Stallings, 2000]. The principal disadvantage is that it can only work with a **duplex channel**. In other words, there must be a back channel for the receiver to send acknowledgements to the sender while the sender is transmitting data frames.

We plan to implement a Sliding Window based link layer protocol for the target communication system. We also plan to incorporate a small FEC code into each data frame to reduce the uncorrectable error rate *(P)*. The requirement of a concurrent back channel needs further study. It should be noted that the back channel does not have to be high speed as the acknowledgement data is very small in size. Nor does the back channel have to be 100% reliable. In particular, the acknowledgements may be made cumulative so that occasional losses of acknowledgements would have no significant impact on channel utilization [Balakrishnan2001]. We believe that the existing acoustic modems on the target underwater platforms would be adequate to create a back channel for our link layer protocol. To implement this, the acknowledgements may be piggybacked with the control data exchanged by the underwater platforms via the acoustic modems (e.g., for tracking and positioning purposes). Additionally, we will investigate possible designs for the new ultrasonic modems to support an asymmetric duplex channel.

We now will discuss the tasks and work plan relative to this thrust.

Near Term Goals

While the ultimate goal in this concept of operations is for the ARIES to rendezvous with other underwater vehicles such as the REMUS and use an ultrasonic modem to conduct a high speed download of sidescan and other images without disrupting the search, initial goals will be much simpler. As shown in Figure 2, we initially focus on the installation of a WHOI modem so that we can exercise communication links at low rates between two different vehicles. The importance of using the ARIES vehicle is that it has the space and weight capacity to carry two different modems so that control can be effected to both REMUS and FAU vehicles without the interoperability standard being in place. Experiments with multiple different vehicles will then be part of the FBE exercise at the end of the first year.

Mid Term Goals

As seen in Figure 3, the ultra high speed modem thrust really begins in FY 2002 with a characterization of the concept with stationary elements. This work will be part of the Doctoral dissertation of CDR W. J. Marr, USN, and will include

UHF Transmission Characterization: We will design, build, and procure transducers with our desired specifications (hemispherical omni-directional point source resonant at about 4-5 MHz). Companies such as International Transducer Corporation (ITC) already produce spherical omni-directional transducers with the directivity pattern desired (but not at the frequencies desired). Other companies such as Ultrasonic Transducers and Etalon manufacture immersion transducers in the frequencies desired.

Test the transducers and verify the theoretical range in a controlled laboratory setting using a signal generator, power amp, transmitter, receiver, pre-amp, and oscilloscope. This step will require purchase of a 100-200 W amplifier for the transmitter and a pre-amplifier for the signal out of the receiver.

Prototype Development Use the system to pass data in a controlled laboratory setting. At this point, a simple coding scheme using Manchester coding is preferred.

Long Term Goals

Experiment with New UHF Modem on ARIES We will install and conduct field tests pier side in Monterey Bay, with a prototype modem including the passing of data; conduct tests in open water with one unit installed on the ARIES vehicle and the other attached to our Boston Whaler. The experiments will be used to send image snippet using ultrasonic modem while operating with the ARIES vehicle and the Boston Whaler in Monterey Bay. Send the file by free wave to the command post once ARIES reaches the surface. It is likely that we work with ONR to develop an SBIR contract aimed at building a prototype UHF modem - possibly building on the Benthos work in sea web

Thrust III   Sonar Navigation Technologies (Obstacle Avoidance)

The goal with Sonar Navigation is to take data received from a forward-looking or side-scan sonar and use that information to assist the vehicle in navigation. This can broken down into several distinct but related projects: Prominent Terrain Featured Navigation, Prominent Feature-Based Navigational Updates and Obstacle Avoidance. The premise is to take the batch files created by the sonar and have the computer look for sonar return patterns, which, once achieving a required confidence threshold, would be used to modify the UUV navigational algorithm.

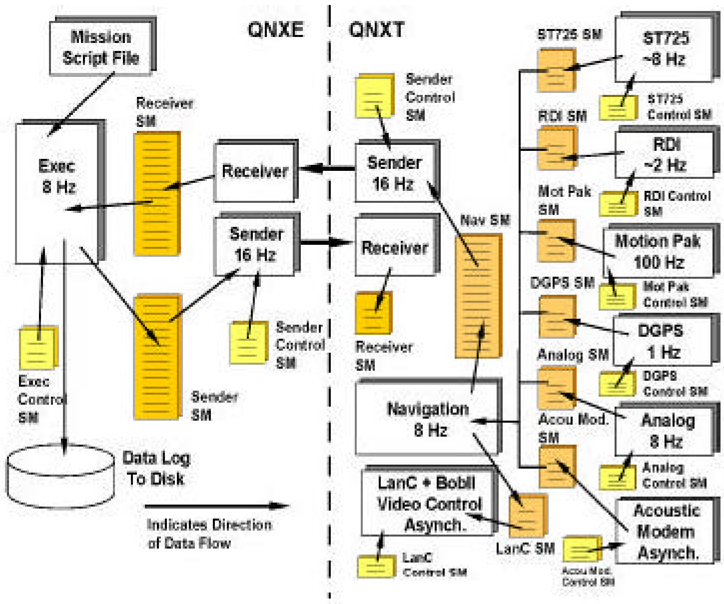
Prominent Terrain Featured Navigation. SEAL Delivery Vehicles (a manned underwater wet submersible) have forward-looking sonar for their submersibles. When conducting missions in harbor areas, SEALs use visual sonar display to navigate in constricted areas. For example, when traveling up a harbor entrance, they can frequently see a hard sonar return from the dredged harbor channel walls. They will use this information to navigate close to the harbor channel wall and avoid shipping. For the Maritime Reconnaissance operations, we propose to automate the process with the ARIES forward-looking sonar. This will assist other navigational systems (ie. INS, DVL, GPS) to facilitate navigation in constricted littoral areas.

Prominent Feature-Based Navigational Updates. A UUV can be programmed to pass by known underwater man-made obstacles during Maritime Reconnaissance operations in harbor and littoral areas. With an a priori knowledge of the underwater shape of the object, this information can be used to update the position of the UUV. This reduces the number of times a UUV would need to surface and reacquire a GPS navigational fix and in turn reduce the chance of compromising the mission. Distinct angular objects like concrete piers are ideal and the focus of the work would be to extend that capability to a wider group of objects. In later years, this capability would be extended to more general terrain based navigation (See Leonard 199X).

Obstacle Avoidance. The obstacle avoidance thrust is aimed at developing algorithms and their experimental validations leading to the ability to autonomously drive an UUV up a ship channel (channel centering) and avoid specific contacts (well heads, structures, islands, other ships). Channel centering would be an extension of the prominent terrain based navigation. This time the ARIES mechanically scanning forward-looking sonar would seek to retrieve the hard sonar returns from both sides of the harbor channel and use that information to update the navigational algorithm and center the UUV in the channel. The more difficult problem is the avoidance of moving targets like ships in the harbor. The difficulty is associated with receiving enough reliable sonar returns to distinguish between the noise and clutter of an obstacle. This is exacerbated by decreasing distance over time between the UUV and an oncoming ship. We propose to initiate experiments with fixed obstacles first and then extend this work to incorporate moving targets. This work would result in an algorithm for Obstacle Avoidance.

The ARIES is an ideal test bed platform to conduct experiments in sonar navigation techniques. The computer hardware architecture is diagrammed in Figure 9. It is designed to operate a single computer processor or two independent cooperating processes. For the purposes of the AO FNC demonstrations, we initially recommend a centrally designed system utilizing the QNXT processor. The ARIES also features a Tritech 725, 725KHz 24 degree mechanical scanning forward-looking sonar. It is directly linked to a QNXT processor running a QNX Operating System. The direct link from the sensor to the processor facilitates navigational updates from the processed batch sonar files. Additionally, navigational sensors such as an

Inertial Navigational System and Doppler Velocity Log and Differential GPS are all combined effectively using extended Kalman Filters.



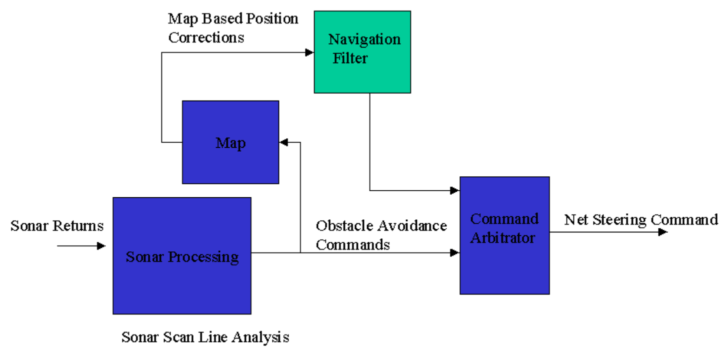


Figure 9 Computer Architecture and Sonar Navigation Block Diagram

Sonar Navigation Technology Experiments and Demonstrations

Near Term Goals

Obstacle Avoidance Scenario Simulations. In this task we will develop a simulation of a UUV vehicle with its steering parameters together with a simulation of the forward-looking sonar returns that would be used to control the track of the vehicle. This involves the integration of the simulated sonar returns together with the algorithms used to produce range and bearing information of contacts as used by the vehicle navigational command system.

In these simulations, we will address how to deviate the path of the vehicle for the purpose of obstacle avoidance in a similar way to that described in (Cottle, 1995). Other simpler schemes will be explored such as those developed in the EOD BUGS program from our earlier work with random and semi-random searching (Kim, 1999). The simulation will be capable of testing algorithms for channel centering, contact detection and localization, and contact avoidance.

Tests using the Forward Look Sonar with Bottom and Surface Returns. In this task we will perform experimental missions where the ARIES vehicle is equipped with its forward-looking sonar, and study the returns found from the sonar using scan lines analysis to determine the quality of returns from the sea surface and bottom. These are preliminary to the study of those returns when the vehicle maneuvers close to a hard contact such as a structure / wall / or concrete block.

Next, a nominal trajectory path will be chosen along which the AUV will be guided using a series of way points. As the forward-look sonar detects contacts, path guidance will be adjusted to center the path between contacts. Contacts in these experiments will mostly come from channel walls, pier pilings and harbor concrete walls. Harbor entrance experiments will be conducted in Monterey Harbor. To study channel centering further, we will attempt to drive the ARIES vehicle up Moss Landing Entrance. The challenge here will be to manage the variable buoyancy caused by fresh water run off, and to steer to the deeper areas of the channel.

Mid Term Goals

Obstacle Avoidance. The mid-term tasking in obstacle avoidance will concentrate on the integration of sonar returns as processed by the forward-looking sonar system into the navigation filter process such that the information can be used in the vehicle tracking controller. In principle, the processed sonar returns produce additive heading commands to those predetermined by the vehicle control. Heading commands will be arbitrated between those from the normal track following controller with those required to avoid the obstacle contacts to produce a combined heading command that will both avoid the contact and then return to the original path when the contact is passed. Command arbitration will be accomplished using similar methods to those outlined in (Kim, 1999) for land-based robots. The mid term tasking will be broken down into to four following major tasks:

1. Integrate Processed Returns into Navigation Processes. Software will be expanded to integrate the results of scan line analysis into contact information such as range and bearing that can be used in the vehicle navigation process.

2. Implement a navigation algorithm that uses sonar to navigate a dredged harbor wall. This will be demonstrated in the first AO FNC demonstration.

3. Implement a algorithm aboard the ARIES which uses a concrete pier with strong angular sonar returns to update the navigational algorithm. This will be demonstrated in the first AO FNC demonstration.

3. Dynamic O/A Experiments with Forward Look Sonar. This work will focus on the analysis of typical returns as seen by the forward look sonar.

4. Test the Forward Look Sonar against Object Structure-Characterization of returns. This work will provide field evaluation of the above concepts.

5. Conduct Experiments to avoid an object. This work will give the proof of concept and a demonstration of the technology developed for the first AO FNC demonstration.

Long Term Goals

The mid and long term goal of the development of the sonar navigation techniques is to transfer the technology to a larger group of UUVs. We propose to implement the developed algorithms in ONR identified small to medium sized UUVs and test functionality among different platforms. The goal is to develop algorithms which various forward look and side scan sonars can implement. Key to this demonstration is the participation of NAVSEA acquisition program managers to permit and encourage access to developmental vehicles. The NPS Center for AUV Research will also submit a 2002 ONR DURIP proposal for the express purpose of testing command and control between classes of UUVs (WHOI SAHRV and Foster Miller Lemmings) and transferring and testing of newly designed hardware and software among recommended UUVs programs. We propose the following demonstrations for the second AO FNC demonstration:

1. Multiple Contact Field Avoidance Demonstrations. Using the results generated by the development of the sonar-guided algorithms, we will further explore guidance through multiple contact fields. The goal of the demonstration would be the avoidance of simulated mines in a shallow/very shallow water inert minefield.

2. Terrain based navigation. Given a priori chart data (DTED2) the ARIES is able to demonstrate accurate navigation in a restricted littoral area. This would be an extension of the mid-term goal of resetting from a known underwater obstacle. This may be extended to accurately navigate using terrain based navigation *without* a priori knowledge of the underwater seabed.

Thrust IV 3-D Graphics Viewers for AUV DATA

Near Term Goals

Near term goals related to the previous three thrust will be follow by visualization efforts that will lead the way to defining parameters to assist the experimental work. This work will include

- Visualize Acoustic Beam Data Transfer

Data Transfer Algorithms will be simulated and visualized in complete detail. All parameters of interest will be viewable individually or in combination, so that basic correctness and robustness in the presence of noise can be evaluated fully. Diverse parameters include, range, beam pattern, signal strength, background noise, transmission mode and data rate.

- Visualize Multi-Vehicle Tracking

We will develop simulations and visualize the control performance of multi-vehicle tracking including the relation to data transfer issues.

Mid Term Goals

- Visualize Sea Web Networking

The Seaweb network will be visualized through the full extent of its search area. This includes the bottom fixed nodes and radio gateway links to shore.

- Visualize Obstacle Avoidance Behaviors

Detailed visualization of vehicle / object interaction will be used to tune and evaluate obstacle avoidance algorithms.

Longer Term Goals

- Networked Distributed Visualization

- In Stride Data Collection Visualization

These tasks will be developed to support in water experiments within the framework of the FBE experiments. Network distributed visualization means that these 3D products will be used simultaneously by FBE partners connected across the network. In stride data collection will yield 3D products immediately from relayed ARIES server telemetry.

In performing these goals , the following sub goals will be pursued

- Pre-visualization and post-mission analysis of operations conducted during this work
- Comparative evaluation of tracking, obstacle-avoidance and navigational algorithms

- Build physically based sonar representations using sound speed profile (SSP) databases, sonar propagation models, and real-time collision detection for a sonar-return server
- Visualize acoustic communications physics, beam paths, error modes and effectiveness
- Continued work on converting large bathymetric data sets into usable, viewable terrain
- Simplification of multi-user networking using DIS-Java-VRML in order to facilitate shared virtual environments among separate research teams
- Implement IEEE DIS PDUs for network communication of sonar transmissions and time-varying state of searched minefields
- Automatic generation of visualization archives in stride with AUV operations using relayed telemetry with ADS
- Continue to improve augmentation of MEDAL capabilities with 3D views

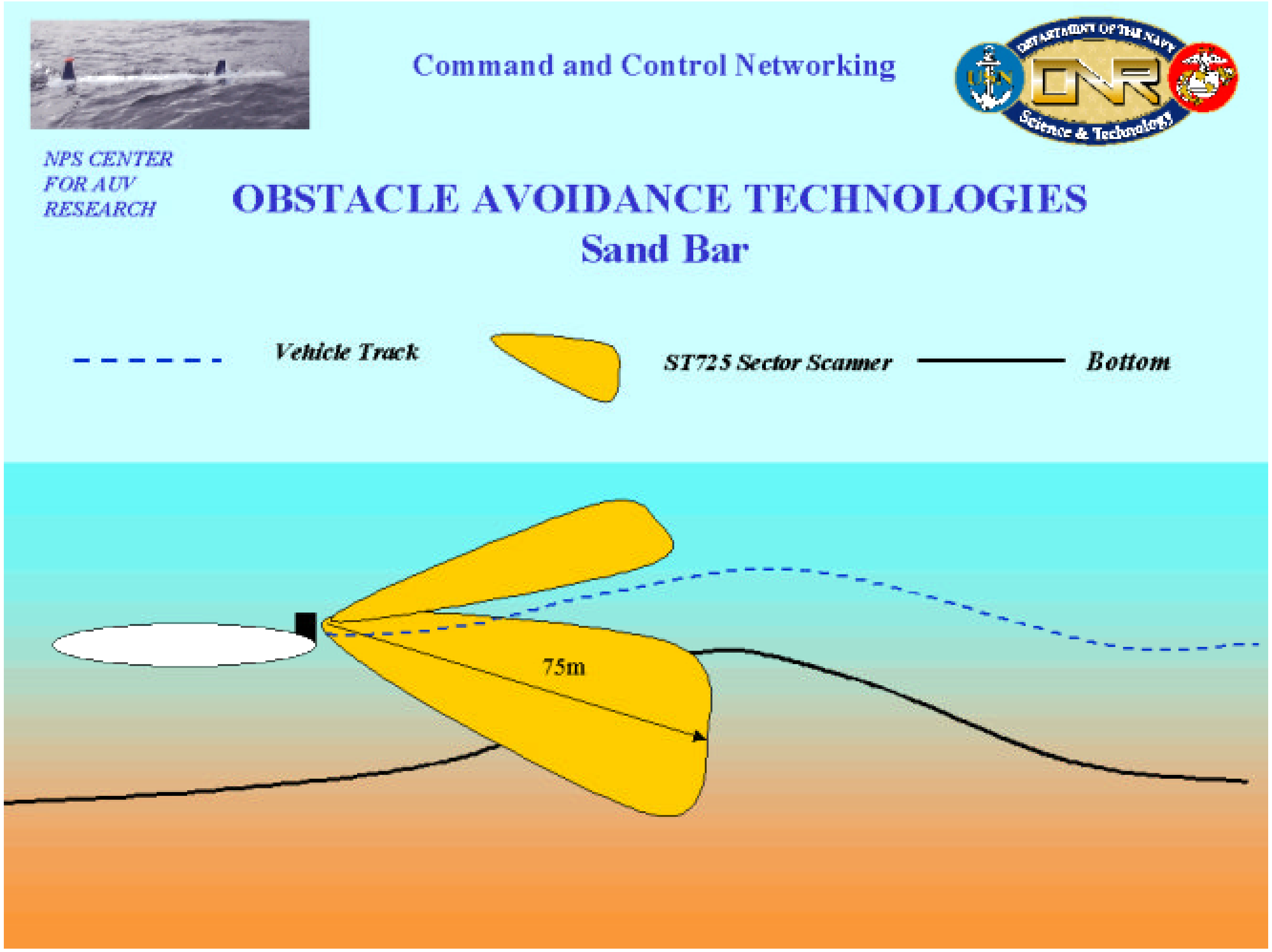


Figure 10 Bottom Shoaling Detections

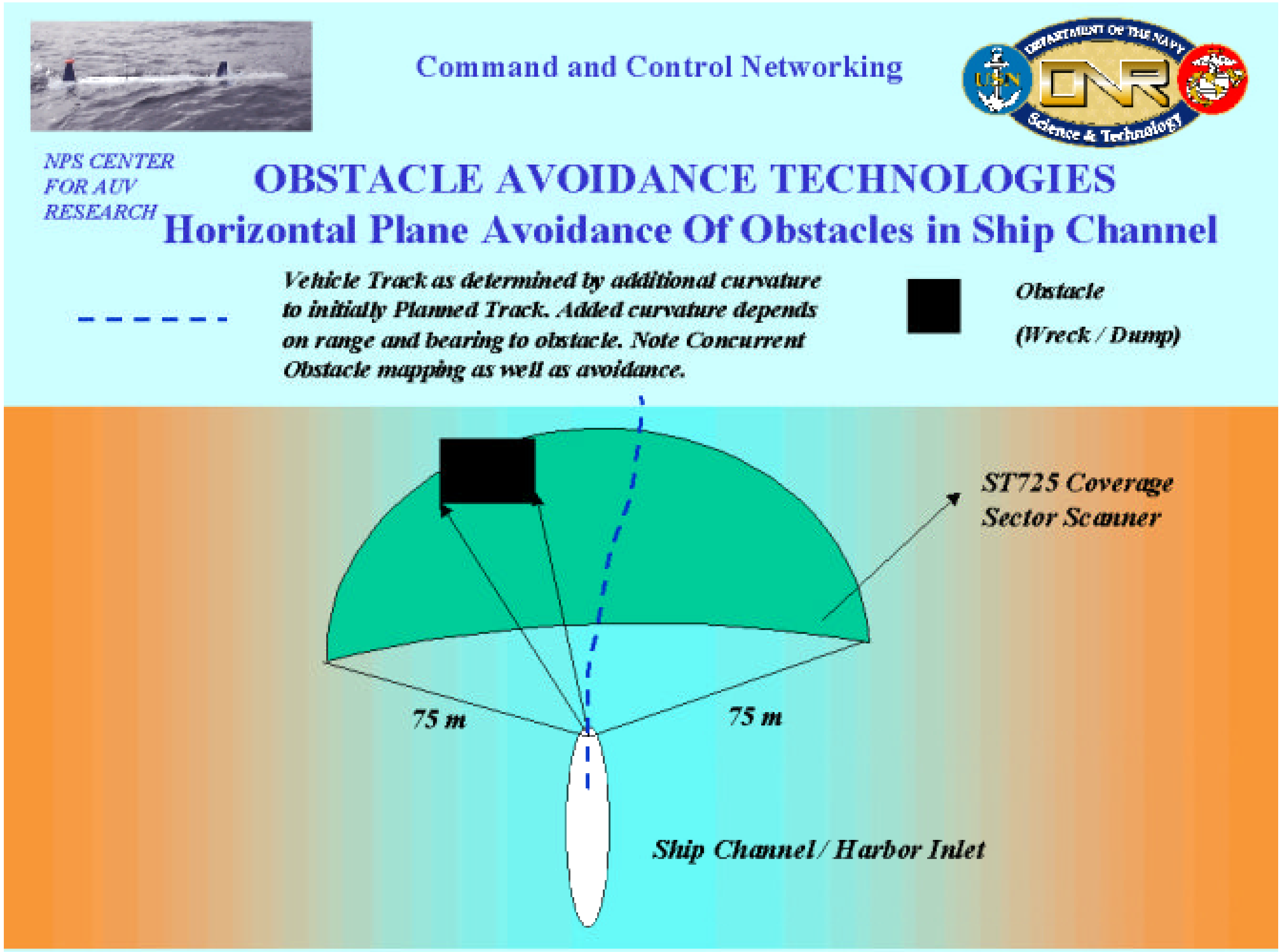


Figure 11 Contact Detected and Navigational Path is Modified by Combining Sonar Return Data With Navigational Commands

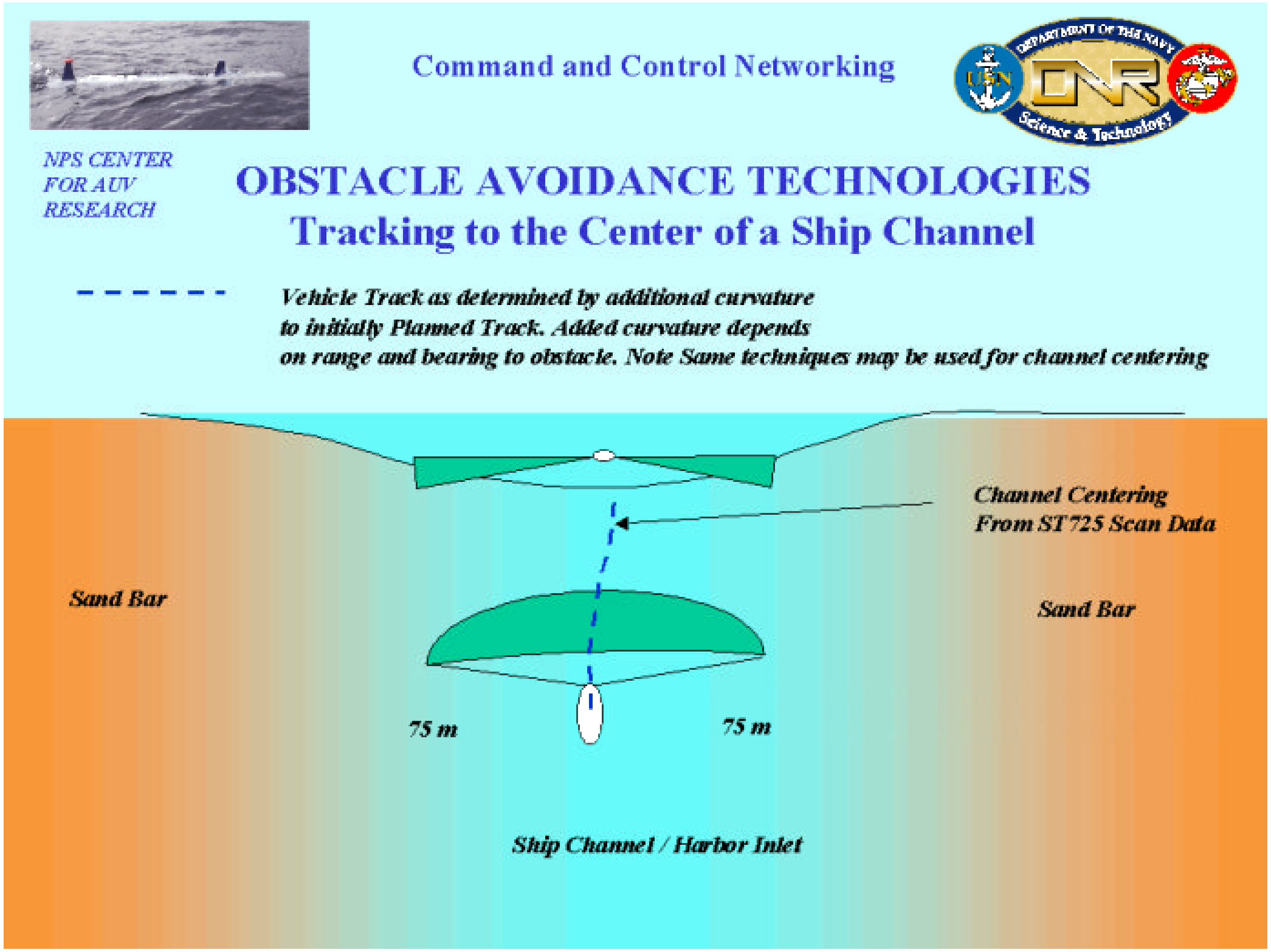


Figure 12 Channel Centering Using Sonar Returens From Side Walls

MANAGEMENT

The Project will be in the Center for AUV Research at the Naval Postgraduate School. It will be managed by Professor A. J. Healey, Director of the Center for AUV Research as the Principle Investigator. Dr. Healey, Dr. Marco, and Mr. Robert Dayap will be responsible for Vehicle Operations and Experimental work. CDR W. J. Marr will be responsible for developments with the UHF Modem as part of his Ph. D. Dissertation and needs no additional salary support.

Dr. D. P. Brutzman will be responsible for the entire thrust on Visualization. Mr. D. Horner will be responsible for assisting in the coordination of obstacle avoidance and Command and Control activities, and will be pursuing his Doctoral work in the area of "Agent Based Algorithms for Robotic Control and Visualization". Their effort is part time as indicated in the budget plan.

Dr. J. Rice will be responsible for work dealing with the cooperation with Sea Web and any coordination necessary between use of ARIES and the SEA WEB node experiment. He will be covered by contracts to SSCSD as shown in the budget breakdown and also for the management of the ongoing contract to Benthos for the high speed Sea Wed node developments. His travel expenses are covered within the contract to SSCSD.

Dr. Geoff Xie will provide expertise in networking considerations and will assist in coding schemes for the UHF Modem development.

The contract to Rowlands allows for software support during the course of the project.

The Equipment costs in the first year provides for the purchase of the WHOI Micro modem, an IMU upgrade to the Honeywell HG 1700 system to replace the current system (Systron Donner / Kearfott KG2001), and a commercial sea web telesonar modem for ARIES. Note that additional hardware from Benthos is covered in the ongoing contract through SSCSD.

The budget breakdown for Sea web Interactions in Years 2002,2003,2004,2005 is

	FY2002	**FY2003**	**FY2004**	**FY2005**
SSCSD	**50K**	**125K**	**125K**	**75K**
Benthos	**100K**	**100K**	**100K**	**100K**

Proposed Budget FY 2002 - FY 2005

ITEM	FY 2002	FY 2003	FY 2004	FY 2005
I. LABOR				
a. Faculty Labor	290,000	304,500	319,725	335,711
Faculty Name AJHealey, 2 qtrs				
Doug Horner 1 qtr				
Dave Marco, 2 qtrs				
Don Brutzman, 1 qtr				
Geoff Xie, 1 qtr				
b. Support Labor, R. Dayap				
c. TOTAL LABOR	**290000.00**	**304500.00**	**319725.00**	**335711.25**
II. NON-LABOR				
a. Travel	40,000	40,000	40,000	40,000
b. Equipment/Supplies	30,000	30,000	30,000	30,000
HG1700 (IMU upgrade)	19,000			
Scanning Sonar	25,000			
Benthos Modem Pair	19,000			
WHOI Modem	12,000			
c. TOTAL NON-LABOR	**145,000**	**70,000**	**70,000**	**70,000**
	0			
III. OTHER DIRECT COSTS				
a. Contracts-MIPR to SSCSD for Sea Web Demonstrations	150000	225000	225000	175,000
b. Contracts-IPA	0			
c. Contracts-To Rowlands for Software Support	50,000	50,000	50,000	50,000
d. TOTAL OTHER DIRECT COSTS	**200000**	**275000**	**275000**	**225000**
	0			
IV. INDIRECT COSTS	**57371**	**60240**	**63252**	**66414**
V. TOTAL PROJECT	**692371**	**709740**	**727977**	**697126**

LOGISTICS

The logistics tail is uncertain at this time. The proposal deals with developmental assets and logistical trails have not been forecast.

CAPABILITIES

The Center and the Naval Postgraduate School is well equipped to perform the research needed by the ONR in this program. We have the ARIES AUV vehicle that is an open architecture test bed vehicle shown below. The details concerning the ARIES vehicle are given in Marco,(2000) and are available on the web at , http://web.nps.navy.mil/~me/healey/papers/Oceans2000.pdf. The system capability at NPS also includes the use of a Boston Whaler, equipped with a marine radio, radio modem repeater stations, and could be upgraded to carry its own GPS positioning devices if needed.

NPS also has an active stand-alone HP C3600 workstation, configured as a stand alone unclassified MEDAL station suited for software development and integration. It has been used to gather and collect AUV data at FBE hotel and KB01, and sends MTF message formatted data to Fleet MEDAL stations.

These are described in the attached flyers.

ARIES - Acoustic Radio Interactive Exploratory Server

NPS POC:

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ONR POC:

Tom Swean, Jr.
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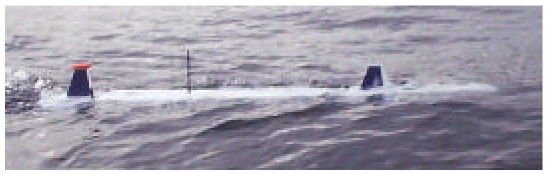


The ARIES AUV is under development as a communications server vehicle. The vehicle is an outgrowth of the NPS Phoenix AUV which has been used as a test bed for AUV control systems and Command and Control research. The vehicle is also used to develop low cost underwater navigation capabilities using DGPS when surfaced. When equipped with an underwater video camera, it may be used as a reacquisition and ID vehicle for minelike contacts. In particular, when surfaced, **it both corrects navigational error and acts as a communications server** for file transfer and underwater vehicle redirect. Extended operating range are obtained using communications links through an aerial relay vehicle (Pelican).

The vehicle has a top speed of almost 4 knots, an operating depth of 50 meters, and an endurance up to 4 hours with the current battery set. It has a bottom following capability, track following, and (not installed yet) a station keeping and bottom sitting capability.

Physical Characteristics:

Length 120” (304 cm)
Width 10”x16” (25x 40cm)
Weight 490 lbs (220 kg)

Sensor Packages:

Acoustic Doppler Current, Video Camera

Navigation Means:

Acoustic Ground Locked Doppler, IMU,Compass, Dead Reckoning, GPS correction when surfaced

Dynamic Tracking:

When surfacing

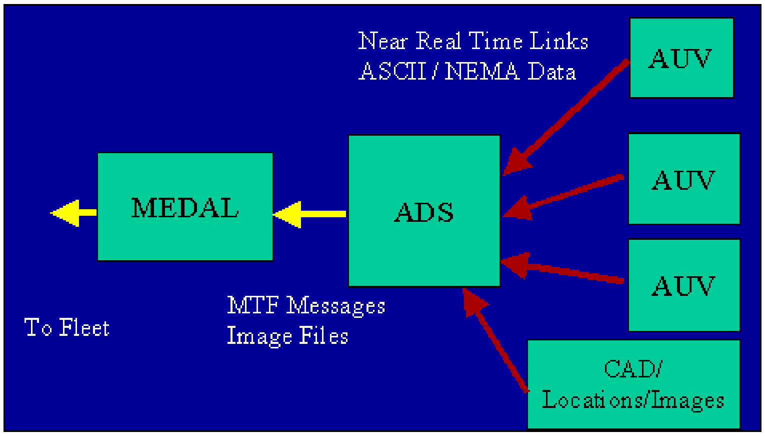
In Development:

Acoustic Communications, Communications Network Server

Office of Naval Research

NPS-Tactical Decision Aids for AUVs

Naval Postgraduate School, Center for AUV Research



NPS POC:

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Team Leader
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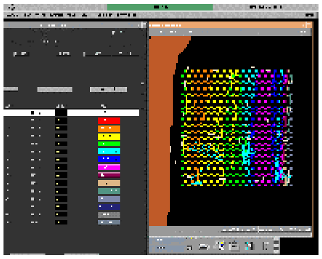
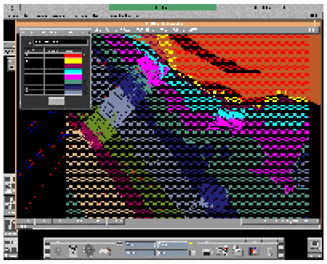
sweant@onr.navy.mil

The Tactical Decision Aid(TDA) for AUVs is a software package that runs on a laptop PC with the purpose of obtaining mission relevant data from AUVs operating in the area and displaying the data in a common operating environment that the Navy's decision makers are used to seeing. In particular the data includes vehicles' positions, bathymetry data as measured by the AUVs, contact locations from sonar analysis, and image snippets(acoustic plus video).

Ocean current and other hydrographic data may also be displayed. The common environment for Naval operators is the GCCS-M system and its Mine Warfare Decision Aids Library (MEDAL).

The NPS TDA embodies an automated data server (ADS) which gathers data through radio or LAN connections to the AUVs. The ADS archives and translates information into a common language (USMTF) and transmits messages to be viewed in a MEDAL screen (runs on an HP workstation). The data can be transmitted through tape or disc into classified secret MEDAL stations for dissemination to the fleet.





800 NORTH QUINCY STREET ARLINGTON, VA 22217-5660
http://www.onr.navy.mil

APPENDIX I
Emails from WHOI

Tony,

Yes, we are still very interested in getting a modem onto your vehicle.

We'd like to put the micro-modem on rather than the utility modem since it is smaller, lower power, cheaper, etc.

The software is still being ported from the utility modem to the micro-modem, but the hardware is all ready. The software should be done sometime this summer.

The micro-modem uses the FH-FSK interoperability standard that we wrote. I think FAU has written the transmitter for the standard but I don't know about the receiver.

I'll get together a spec package for you, both mechanical and electrical.

Did you want an external housing or did you want to mount it inside your vehicle?

The external housing is 2.5" OD, about 10" long plus connectors and bend radii. We are going to make a version with low-profile right-angle connectors fairly soon in order to minimize the length.

Lee

--

Lee Freitag, Senior Engineer
Mail Stop 18
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508.289.3285
508.457.2195 (fax)

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Lee

--

Lee Freitag, Senior Engineer
Mail Stop 18
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508.289.3285
508.457.2195 (fax)

Tony,

The micro-modem is also being integrated into the REMUS/SAHRV as it moves from R&D to pre-procurement via a P3I program (pre-planned product improvements sponsored by PMS325).
So, yes, the two vehicles would be able to communicate.

Biographies

Anthony J. Healey, Principle Investigator

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Professor Healey obtained his undergraduate degree at Kings College, London University, and his Ph.D in Mechanical Engineering at the University of Sheffield. His specialty is in Dynamic Systems and Control. He has taught at Penn State University, MIT, the University of Texas at Austin, and has been Chairman of the Mechanical Engineering Department at the Naval Postgraduate School, 1986-1992. He is currently Professor in the Mechanical Engineering Department and Director of the Center for AUV Research, with the aims of developing AUV technology for naval applications of AUVs. He has written many papers on the subject and has graduated numerous Masters and Ph.D students.

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Dr. D. P. Brutzman

Don Brutzman is a computer scientist and Associate Professor working in the Interdisciplinary Academic Group at the Naval Postgraduate School. He holds a B.S.E.E. from the U.S. Naval Academy in 1978, is a qualified engineer aboard nuclear submarines, and earned a Ph.D. in Computer Science from the Naval Postgraduate School in 1994. He is a member in the Undersea Warfare Academic Group, the Modeling Virtual Environments & Simulation (MOVES) Academic Group, and the NPS Center for Autonomous Underwater Vehicle (AUV) Research. His research interests include underwater robotics, real-time 3D computer graphics, artificial intelligence and high-performance networking. He is a member of the Institute of Electrical and Electronic Engineers (IEEE), the Association for Computing Machinery (ACM) Special Interest Group on Graphics (SIGGRAPH) and the American Association for Artificial Intelligence (AAAI). He is a board member of non-profit Sea Lab Monterey Bay, which is designing and building a youth-oriented year-round residential science camp. He is a founding member of the non-profit Web3D Consortium Board of Directors and leads the VRML 200x / Extensible 3D (X3D) Specification Task Group. He represents Web3D as the Advisory Committee Representative to the World Wide Web Consortium (W3C). He is a retired submarine officer who has conducted testing of advanced capability underwater equipment. His research work includes the development of underwater robot software, in combination with comprehensive virtual-world modeling of underwater hydrodynamics, sonar and robot hardware response. His duties include MOVES Technical Director for Networked Virtual Environments and 3D Visual

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Mr. Doug Horner

Doug Horner is a Research Analyst at Rolands and Associates Inc. His principle areas of interest include Web-based 3D graphics for military applications, development and implementation of computer simulation systems, and software interfaces for Autonomous Underwater Vehicles (AUVs). He served 12 years in the U.S. Navy as a Naval Special Warfare (SEAL) officer. His last duty station was at the Naval Sea Systems Command where he served as the Program Manager for the Special Operations Unmanned Underwater Vehicle, SAHRV. Mr. Horner received his B.A./B.S. in Economics and Mathematics at Boston University, a M.S. in Applied Mathematics and M.A. in National Security Affairs.

Geoffrey G. Xie

obtained his Ph.D. degree in computer science from the University of Texas at Austin in 1996. He is currently an Assistant Professor in the Department of Computer Science at the Naval Postgraduate School, Monterey, California. His main research focus is in the areas of computer networking, especially in the design of integrated services packet networks for transport of quality of service sensitive data. He is a regular reviewer for IEEE/ACM Transactions on Networking, the National Science Foundation, and several leading technical conferences, specialized on quality of service routing and traffic management issues. He serves on the program committees of two leading computer communication conferences: IEEE INFOCOM and IEEE International Conference on Network Protocols (IEEE ICNP).

Dr Xie began his career in computer networks in 1990 as a research assistant in the Networking Research Laboratory at the University of Texas at Austin. From 1991 to 1994, he worked full time as a project engineer developing distributed applications at Schlumberger Austin Research Center. He is currently the PI for the SAAM project (http://www.saamnet.org) under the DARPA's Next Generation Internet Initiative. The project is also funded by NASA. He is also a PI in the NSF Gigabits ATM Switch Distribution Program and the main architect of a time-driven crypto-key sequencing method that enables very high speed software-based packet level origin authentication and data integrity. Dr. Xie's technical publications are available on line from: http://www.cs.nps.navy.mil/people/faculty/xie/pub.

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APPENDIX II

SEA WEB DETAIL

The Seaweb Communications Network for Autonomous Undersea Vehicle Operations

(BAA-01-012)

SPAWARSYSCEN San Diego D857 (Acoustic Branch)
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1. Seaweb and telesonar, a demonstrated ocean acoustic network

The seaweb and telesonar development projects have worked closely with ONR (often with ONR as sponsor) to develop

- viable hardware and modulation schemes to support robust underwater acoustic networked communications in the full range of littoral ocean environments
- a series of demonstrations and field experiments closely folded into the seaweb-capability development cycle that provide steady incremental increases in capability, moving toward

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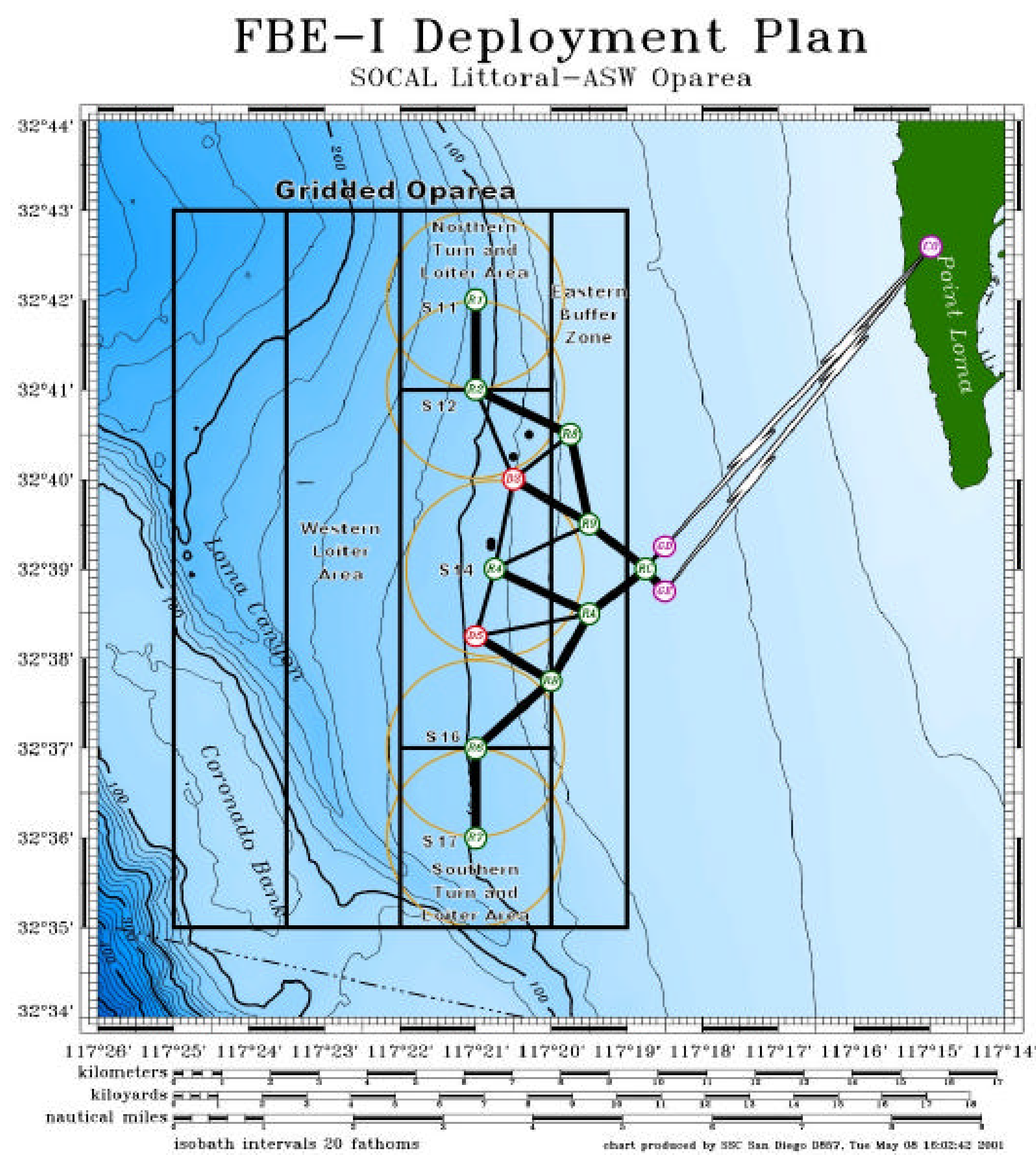

Another seaweb capability demonstrated in FBE India (in addition to multiple prior field experiments) was intrinsic comms-system ranging from node-to-node using telesonar time-of-flight. All FBE India nodes performed ranging, and the seaweb ranging capability was successfully used in the Sublink 2000 experiment to develop navigation updates for the maneuvering node (USS *Dolphin*). The seaweb ranging capability thus provides a natural integrated navigation aid to UUVs or mobile nodes equipped with telesonar.

This successful participation of seaweb/telesonar in a major fleet development experiment demonstrates the maturity of seaweb networking, with additional capability necessary for the exit criteria of BAA 01-012 either already included in the seaweb development plan or covered under this proposal. Telesonar mo dem hardware are readily available, inexpensive, SBIR-developed COTS items.

2. Seaweb development (2001)

Seaweb 2001 will occur during August and September 2001 on the Loma Shelf west of Point Loma, San Diego, CA. It is the fourth in an annual series of such experiments in undersea digital wireless networking. The long-term goal of these experiments is an adaptive telesonar network automatically responsive to diverse and dynamic environments, network geometries, node types, and mission requirements. The near-term goal is planned, stepwise progress toward reaching the full seaweb capability while applying current seaweb state-of-the-art undersea acoustic network capability to a growing number of application systems.

Seaweb networks support asynchronous data communications from autonomous nodes to command centers. On the backlink, seaweb allows remote command and control of instruments associated with the autonomous nodes. Additionally, network activity supports acoustic navigation and geolocalization of undersea nodes as a by-product of telesonar ranging signals. More generally, seaweb networking permits wireless transmissions between member nodes in the network using established routes or via an intervening cellular node. Hence, seaweb technology provides an undersea C3N[4] capability for various applications.

Seaweb is intended for future Naval capabilities in littoral ASW[5] and undersea autonomous operations. A significant dual-use of seaweb is C3N for general oceanographic applications. A benefit of the technology is cross-system, cross-platform, cross-mission interoperability, providing enormous added value to otherwise solitary systems. Seaweb is the underlying fabric of an expeditionary sensor grid, and is imperative for dynamic interoperable connectivity. For example, a UUV[6] mobile node operating within a grid of fixed sensor nodes benefits from the established network topology for battlespace awareness, navigation, and communications via gateway nodes to distant command centers. Conversely, UUVs add value to the fixed grid for sensor deployment, search, survey, water-column sampling, pop-up Racom[7] gateway communications, etc.

Seaweb development balances the desire for rapid increases in capability, the need for stable operation in support of applications that are themselves developmental, and the constraints of reasonable budgets. This balance is achieved by an annual cycle. Seaweb research conducted by several contributing projects occurs during the first three quarters of the fiscal year. Integration, implementation, test, and evaluation occur during a *Seaweb experiment* in the fourth quarter. The products of the annual Seaweb experiment are major capability upgrades for seaweb server software, telesonar modem seaweb firmware, and telesonar modem hardware. The annual Seaweb experiment also transitions these upgrades into participating application systems such as DADS[8], Hydra, FRONT[9], Sublink, Racom, μDADS, and SeaLAN[10]. At the conclusion of the experiment, the upgraded seaweb capability reaches stability suitable for use with the continuing development of the various application systems during the following year, in parallel with research and preparations for the next Seaweb experiment.

This development cycle provides a natural tradeoff between "comms-oriented development" and "application integration of comms" in order to retain seamless compatibility across a range of applications and "user" systems. This approach thus fulfills the SPAWAR charter to provide overarching integration of communication functions while simultaneously providing a geometric capability increase in the Navy "system of systems" by enabling interoperability through intelligent information exchange.

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[4] C3N = Command, Control, Communication and Navigation
[5] ASW = Anti-Submarine Warfare
[6] UUV = Unmanned Undersea Vehicle
[7] Racom = Radio/Acoustic Communications
[8] DADS = Deployable Autonomous Distributed System
[9] FRONT = Front-Resolving Observational Network with Telemetry
[10] SeaLAN = Undersea Local Area Network

The first phase of Seaweb 2001 will be performed in the laboratory. Personnel will implement extensions to the seaweb firmware executing on the TMS320C5410 DSP[11] aboard the telesonar modem and will test network performance in the air. Seaweb 2001 will introduce specific new network capabilities to be integrated into seaweb firmware and implemented on telesonar modem hardware. In addition, a graphical user interface called the *seaweb server* will gain new capabilities for managing the network and providing seamless client access to application systems.

The latter phases of Seaweb 2001 will involve exercising the Seaweb 2001 firmware at sea using multiple autonomous nodes, each equipped with a telesonar modem. One or more gateway nodes are buoys providing line-of-sight digital radio and/or cellular modem links to an ashore seaweb server. Many repeater nodes will be deployed on the seafloor with acoustic releases. Sensor nodes will include commercial oceanographic instruments serving as data sources. Experiment events are designed to stress the network for refining and debugging the Seaweb 2001 firmware. As the firmware is stabilized, specific networking performance experiments will ensue. In the final phase of Seaweb 2001, a Hydra surveillance array with in situ matched-field processing will function as an ASW sensor node, and will operate against the *USS Dolphin* diesel-electric submarine transiting through the area as a surrogate threat target.

For purposes of National Environmental Policy Act compliance, Seaweb 2001 and associated testing may be performed under a Categorical Exclusion (CATEX) on file at SPAWARSYSCEN San Diego.

3. The importance of system interoperability

SPAWARSYSCEN San Diego is chartered with developing communications systems for the Navy and ensuring interoperability through overarching integration and network-centric development and compatibility. Seaweb fulfills this charter for the developing field of networked underwater acoustic communications for the Navy. This charter is particularly important for this field due to the increasing realization of the need for general underwater wireless connectivity, driving development of acoustic comms systems, which in turn drives development of ever-increasing applications functions. Without attention to system interoperability and overarching integration as manifested in seaweb, a tangled snarl of incompatible systems, signaling techniques, and modulations will quickly arise. A classic example is provided by the early days of the electric light, which quickly resulted in over 175 different, incompatible thread designs for sockets and light bulbs on the market.

Undersea acoustic communications is by nature bandwidth-limited [1]. This fact alone greatly increases the danger of incompatible systems producing serious consequences. For example, in an entirely feasible worst-case scenario a UUV using an incompatible underwater comms system enters a deployed Littoral ASW (LASW) field area, and both UUV comms and LASW comms become unusable due to mutual interference. As the mildest consequence of incompatibility, UUV comms, LASW comms and other (platform) undersea comms may be forced to sacrifice low-probability of exploitation in order to overcome mutual interference in a conflict for required operating SNR.

Seaweb has stressed and continues to stress the network aspects of undersea acoustic comms. The seaweb communications network is fundamentally designed to incorporate different modulation schemes for data packets depending on mission and channel parameters, including high-data-rate adaptive techniques such as developed and demonstrated during the ACOMMS ATD. Channel-reliable high data rate signaling is being incorporated in the next phase of seaweb development and can include ACOMMS modulations. However, maintaining compatible network structure across systems as seaweb is designed from first principle to do is extremely important. The ONR Signalex project is identifying the appropriate modulation methods for use in particular environments. Signalex results will be the basis for telesonar adaptive modulation algorithms where data packets will be transmitted in a channel-adaptive format. The existing Seaweb protocols already anticipate this development in their use of MAC-layer handshaking and network-layer information assurance.

In another benefit of seaweb integration, SPAWARSYSCEN San Diego top-level management has formed the Dynamic Interoperable Connectivity Imperative, a center-wide cross-project cross-mission coordination structure to provide tight integration of seaweb into the Navy-wide command and control support structure, such as GCCS-M. Seaweb also allows synergistic, cost-effective development of communications network capabilities through the

[11] DSP = digital signal processor chip

Imperative, with an individual project receiving more benefit than its own investment dollars alone could provide. For example, by participating in seaweb the Autonomous Operations FNC would be leveraging its comms investment with money and resources from the LASW FNC, the National Ocean-ographic Partnership Program, Navy RF systems, and other seaweb/Imperative participants.

4. Seaweb Server (network control and diagnostic software)

The Seaweb server is a set of software functions and a graphical user interface that interprets, formats, and routes downlink traffic destined for undersea nodes. On the uplink, it archives information produced by the network, retrieves the information for an operator, and provides database access for client users. The server manages Seaweb gateways and member nodes. It monitors, displays, and logs the network status. The server manages the network routing tables and neighbor tables and ensures network interoperability. As of Seaweb '99, telesonar modem firmware permitted the server to remotely reconfigure routing topologies in anticipation of future self-configuration and dynamic network control. One important function of server network control was dramatically illustrated in Seaweb '99 when operators bypassed server oversight and inadvertently produced a circular routing where a trio of nodes continuously passed a packet between themselves in an infinite loop until battery depletion.

Currently, the Seaweb server executes as a graphical set of virtual instruments implemented under Linux or Windows NT on a laptop PC or other Intel-based system. The recent successful port of the server to Linux greatly improved server uptime reliability and server software currently has been tested to run for months with no failures. As seaweb develops, some server functions will be integrated at node level while retaining the overall server network interface.

A conceptual diagram of the seaweb server control and interlink role is illustrated in figure 2.

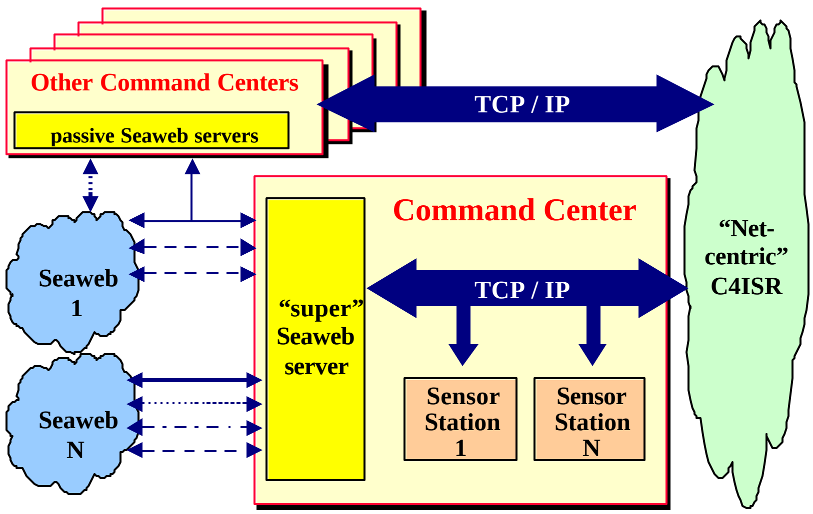

Fig. 2. Seaweb extends modern "net-centric" interconnectivity to the undersea realm. Wireless underwater networks include gateway nodes with radio, acoustic, wire, or fiber links to manned command centers where a Seaweb server provides the required user interface. Command centers may be aboard ship, submarine, aircraft, or ashore. They may be geographically distant and connected to the gateway node via space satellite or terrestrial internet. At the designated command center a "super" Seaweb server manages and controls the undersea network. All Seaweb servers archive Seaweb packets and provide data access to client stations.

Demonstrating seaweb network external interface flexibility, in Seaweb '99 the server simultaneously linked with a Verizon cellular digital packet data (CDPD) gateway node via the internet and with the packet-radio Racom gateway link via a serial port. A demonstrated milestone was the establishment of a complete gateway-to-gateway route through the undersea network using the seaweb server, exercised successfully via the internet with live demonstrations at the remote OCEANS 2000 conference.

Another test examined networking of automatic uplink sensor packets while simultaneously issuing server-generated downlink commands to deliberately poll sensors. In preparation for the "Front-Resolving Observation Network with Telemetry" (FRONT) [2] telesonar application, large acoustic Doppler current profiler (ADCP) packets were synthesized and passed through the network with TDMA scheduling.

For every packet received by a Seaweb '99 node, the modem appended link metrics such as bit-error rate (BER), automatic gain control (AGC), and SNR. These diagnostics aided post-mortem system analysis. Performance correlated strongly with environmental factors such as refraction, bathymetry, wind, and shipping although no attempt was made to quantify these relationships in Seaweb 99.

5. Seaweb networks

Telesonar wireless acoustic links interconnect distributed undersea assets, potentially integrating them as a unified resource and extending net-centric operations into the undersea environment.

Seaweb is the realization of such an undersea wireless network [3] of fixed and mobile nodes, including intelligent master nodes and various interfaces to command centers. It provides the command, control, and communications infrastructure for coordinating appropriate assets to accomplish a given mission in an arbitrary ocean environment.

The seaweb is a set of autonomous, stationary nodes (*e.g.*, deployable surveillance sensors, sea mines, relay stations), mobile nodes (*e.g.*, UUVs, including swimmers and crawlers) and specialized nodes (*e.g.*, bi-static sonar projectors).

Seaweb *gateways* provide connections to command centers submerged, afloat, aloft, and ashore. Telesonar-equipped gateway nodes interface Seaweb to terrestrial, airborne, and space-based networks. For example, a telesonobuoy serves as a radio/acoustic interface permitting satellites and maritime patrol aircraft to access submerged, autonomous systems. Similarly, submarines can access Seaweb with telesonar signaling in the WQC-2 underwater telephone band or by using other organic sonars. Seaweb provides the submarine commander several options for secure, digital connectivity at speed and depth, including bi-directional access to all Seaweb-linked resources and distant gateways.

A seaweb *server* resides at manned command centers or specialized nodes and is an interface to the undersea network. The server archives all incoming data packets and provides read-only access to client stations via internet. A single designated "super" server controls and reconfigures the network.

Seaweb quality of service is limited by low-bandwidth, half-duplex, high-latency telesonar links. Occasional outages from poor propagation or elevated noise levels can disrupt telesonar links [4]. Ultimately, the available energy supply dictates service life and battery-limited nodes must be energy conserving [5]. Moreover, Seaweb must ensure transmission security by operating with low bit-energy per noise-spectral-density (E_b/N_0) and by otherwise limiting interception by unauthorized receivers. Seaweb must therefore be a revolutionary information system bound by these constraints.

The Seaweb architecture of interest includes the physical layer, the media-access-control (MAC) layer, and the network layer. These most fundamental layers of communications functionality support higher layers that will tend to be application specific.

Simplicity, efficiency, reliability, and security are the governing design principles. Half-duplex handshaking [6] asynchronously establishes adaptive telesonar links [7]. The initiating node transmits a request-to-send (RTS) waveform with a frequency-hopped, spread-spectrum (FHSS) [8] series or direct-sequence spread-spectrum (DSSS) [9] pseudo-random carrier uniquely addressing the intended receiver. (Alternatively, the initiating node may transmit a universal pattern for broadcasting or when establishing links with unknown nodes.) The addressed node detects the request and awakens from a low-power sleep state to demodulate. Further processing of the request signal provides an estimate of the channel scattering function and signal excess. The addressed node then acknowledges receipt with a FHSS or DSSS acoustic reply. This clear-to-send (CTS) reply specifies appropriate modulation parameters for the ensuing message packets based upon the measured channel conditions. Following this RTS/CTS handshake, the initiating node transmits the data packet(s) with nearly optimal bit-rate, modulation, coding, and source level.

At the physical layer, an understanding of the transmission channel is obtained through at-sea measurements and numerical propagation models. Knowledge of the fundamental constraints on telesonar signaling translates into increasingly sophisticated modems. DSP-based modulators and demodulators permit the application of modern digital communications techniques to exploit the unique aspects of the underwater channel. Directional transducers further enhance the performance of these devices [10].

The MAC layer supports secure, low-power, point-to-point connectivity, and the telesonar handshake protocol is uniquely suited to wireless half-duplex networking with slowly propagating channels. Handshaking permits addressing, ranging, channel estimation, adaptive modulation, and power control. The Seaweb philosophy mandates that telesonar links be environmentally adaptive [11], with provision for bi-directional asymmetry.

Spread-spectrum modulation is consistent with the desire for asynchronous multiple-access to the physical channel using code-division multiple-access (CDMA) networking [12]. Nevertheless, the Seaweb concept does not exclude time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) methods and is in fact pursuing hybrid schemes suited to the physical-layer constraints. In a data transfer, for example, the RTS/CTS exchange might occur as an asynchronous CDMA dialog in which the data packets are queued for transmission during a time slot or within a frequency band such that collisions are avoided altogether.

Optimized network topologies are configured and maintained under the supervision of master nodes [13]. Seaweb provides for graceful failure of network nodes, addition of new nodes, and assimilation of mobile nodes. Essential by-products of the telesonar link are range measurement, range-rate measurement, and clock-synchronization. Collectively, these features support initialization, navigation, and network optimization.

6. ATM885 undersea acoustic modems

The ATM885 modem depicted in Fig. 3 improves on prior modems with the incorporation of a more powerful DSP and additional memory. Telesonar firmware formerly encoded by necessity as efficient machine language is reprogrammed on the ATM885 as a more structured set of algorithms. The ForeFRONT-1 (Nov. 1999), FRONT-1 (Dec. 1999), ForeFRONT-2 (April 2000), Sublink 2000 (May 2000), and FRONT-2 (June 2000) experiments hastened the successful transition of Seaweb 99 firmware from the ATM875 to the ATM885. These intervening Seaweb applications were stepping stones toward achieving basic ATM885 hardware readiness prior to instituting Seaweb 2000 upgrades.

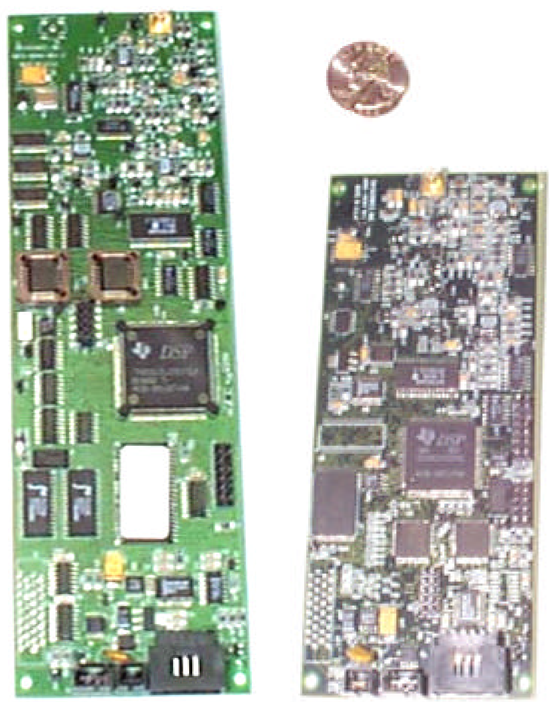

Fig. 3. The TMS320C5410-based ATM885 telesonar modem overcomes the hardware limitations of the TMS320C50-based ATM875s. The ATM875s served Seaweb 98 and 99. Seaweb 2000 used ATM885s, benefiting from faster processing, lower power draw, and increased memory. The ATM885 supports 100 MIPs and 320K words of memory compared with 25 MIPs and 74K available from the ATM875.

Seaweb 2000 implemented in firmware the core features of a compact, structured protocol. The protocol efficiently maps network-layer and MAC-layer functionality onto a physical layer based on channel-tolerant, 64-bit utility packets and channel-adaptive, arbitrary-length data packets. Seven utility packet types are implemented for Seaweb 2000. These packet types permit data transfers and node-to-node ranging. A richer set of available utility packets is being investigated with OPNET simulations, but the seven core utility packets provide substantial networking capability.

The initial handshake consists of the transmitter sending an RTS packet and the receiver replying with a CTS packet. This round trip establishes the communications link and probes the channel in order to assess optimal transmission power. Future enhancements to the protocol will support a choice of data modulation methods, with selection based on channel estimates derived from the RTS role as a probe signal. A "busy" packet is issued in response to an RTS when the receiver node decides to defer data reception in favor of other traffic. Following a successful RTS/CTS handshake, the data packet(s) are sent. The Seaweb 2000 core protocol provides for acknowledgments, either positive or negative, of a data message. The choice of acknowledgment type will depend on the traffic patterns associated with a particular network mission.

A "ping" utility packet initiates node-to-node and node-to-multi-node identification and ranging. An "echo" packet is the usual response to a received ping.

In Seaweb 2000, hybrid CDMA/TDMA architectures were investigated as methods for avoiding mutual interference compared to FDMA. FDMA methods sacrifice precious bandwidth and prolong the duration of a transmission, often aggravating MAI rather than resisting it. Furthermore, the use of a small number of frequency sets is viewed as an overly restrictive networking solution. It should be noted that all of these drawbacks are well known and FDMA was employed in Seawebs 98 and 99 primarily for ease of implementation as a simple extension to the rigid ATM875 telesonar machine code. The ATM885 permits a break from those restrictions.

Seaweb 2000 execution fully incorporated the experimental approach tried in Seaweb 99 of establishing two parallel networks—one in air at the command center and one in the waters of Buzzards Bay. This approach minimized time-consuming field upgrades by providing a convenient network for troubleshooting deployed firmware and testing code changes prior to at-sea downloads.

As a further analysis aid, all modems now include a data-logging feature. All output generated by the ATM885 and normally available via direct serial connection is logged to an internal buffer. Thus, the behavior of autonomous nodes can be studied in great detail after recovery from sea. To take maximum advantage of this capability, Seaweb 2000 code included additional diagnostics. These included channel estimation (*e.g.*, SNR, multipath spread, Doppler spread, range rate, etc.), demodulation statistics (*e.g.*, bit-error rate, automatic gain control, intermediate decoding results, power level, etc.), and networking (*e.g.*, data packet source, data packet sink, routing path, etc.). For Seaweb applications, the data-logging feature can also support the archiving of data until such time that an adjacent node is able to download the data. For example, a designated *sink* node operating without access to a gateway node can collect all packets forwarded from the network and telemeter them to a command center when interrogated by a gateway (such as a ship arriving on station for just such a data download).

Increasing the value of diagnostic data, the C5410 real-time clock time is maintained even during sleep state. Although this clock may not have the stability required for certain future network applications, its availability permits initial development of in-water clock-synchronization techniques.

The ATM885 modem also includes provision for a *watchdog* function hosted aboard a microchip independent of the C5410 DSP. The watchdog resets the C5410 DSP upon detection of supply voltage drops or upon cessation of DSP activity pulses. The watchdog provides a high level of fault tolerance and permits experimental modems to continue functioning in spite of system errors. A watchdog reset triggers the logging of additional diagnostics for thorough troubleshooting after modem recovery.

The ATM885, developed through the joint development effort of SSC San Diego, Delphi Communications Systems, Inc, and Benthos, Inc., is commercially available from Benthos, Inc. Continuous improvements to modem capability are added through the seaweb development cycle.

Summary of Acoustic Comms Performance Goals

An operational complement of UUVs will be equipped with ATM885 modems (or successors) and appropriate interfaces. A "master node" and a specialized Com/Nav aid vehicle will also be equipped with modems and with additional capability to meet specialized functions as servers and control nodes. Sequential upgrades, fitting into the existing seaweb/telesonar development cycle, will add high-data-rate and LPE/LPI modulations to the existing telesonar modulation suite. Combining simulation and experiment, optimal seaweb networks will be defined and implemented for the UUV swarm and specialized Com/Nav aid and master node. The acoustic network will be interfaced to RF in a manner similar to current telesonar implementations, with ultimate appropriate formatting and interfacing to integrate with external military networks. The modems will be commercially available to the Navy from Benthos after demonstration, providing easy transition to direct and/or related follow-on acquisition programs.

The ultimate end product will be hardware and software appropriate to integrate seaweb networks into the Undersea Search and Survey and Com/Nav Aid missions, and appropriate sea tests to demonstrate that the communications exit criteria specified for USS are met and exceeded by this network. Because the implemented acoustic network will be embedded in the seaweb network and cooperate in the seaweb development plan, the acoustic comms UUV support network will not be just another stand-alone, incompatible system, but will be interoperable with other deployed surveillance systems and platforms. This will enable potential information sharing and a geometric gain in usefulness from full participation in the forcenet.

Programs, related programs, transitions

DADS (Deployable Autonomous Distributed Systems)
μDADS (proposed DADS-derived lightweight deployables)
Hydra and other sensing programs (ONR Deployables program)
ADS (Advanced Deployable System)
UCQxx (Underwater Telephone system, telesonar already demonstrated for this)

Resumes

Mr. Joseph A. Rice is the principal investigator of the Telesonar Technology Project, the SubLink Project, the Seaweb project, and the former PI of the Telesonar Channel Models Project. Since 1981, he has performed basic and applied research for the U.S. Navy involving digital signal processing and the undersea acoustic transmission channel. He holds a bachelor of arts in mathematics, a bachelor of science in engineering science, and a masters of science in electrical engineering from the University of California San Diego. He has coordinated and been a prime driver of research in developing networked underwater acoustic communications over the last five years, working with Datasonics Inc., Benthos Inc., and Delphi Communications Inc., among others. He has acted as technical oversight on a number of acoustic comms SBIRs, and has presented multiple papers at government, national, and international conferences and forums. In 2000, Mr. Rice was appointed to the Engineering Acoustics Chair at the Naval Postgraduate School. He continues to direct the telesonar and seaweb projects as an SSCSD project manager while detailed to NPS.

Dr. C. David Rees attained his PhD at the University of Washington physics department in 1984. After a postdoc at Fermi National Accelerator Laboratory he joined SSCSD. At SSCSD he has worked in underwater acoustics, including propagation modeling, signal processing algorithms and applications, matched field processing, numerical optimization, real-time processing, and other areas in this field. He is currently head of the Acoustic Branch, noted for cutting-edge research and development in underwater acoustic communications, signal processing, and light weight ocean technology. He makes multiple presentations to sponsors and in technical information briefs every year, attends national and international conferences presenting talks, and is an author on over 30 papers.

Related Government funded projects

Project	*Project Lead*	*Sponsor*
Telesonar Technology Project (Seaweb Lead)	SSC San Diego	ONR 321 6.2
Deployable Autonomous Undersea Surveillance Project	SSC San Diego	ONR 321 6.2
DADS Intra-Field Data Fusion Project	SSC San Diego	ONR 321 6.2
Telesonar Channel Project	SSC San Diego	ILIR
Front-Resolving Observational Network with Telemetry	U. Conn.	NOPP
DADS Demonstration Project	SSC San Diego	ONR 321 6.3
Signalex Project	SSC San Diego	ONR 322 6.2
Dynamic Interoperability Connectivity Imperative	SSC San Diego	SSC San Diego
Sublink (May and June only)	SSC San Diego	NWDC

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APPENDIX III

Acoustic Range Background Calculations

The equation for underwater transmission is found in Urick's book, *The Principles of Underwater Sound*. The figure of merit (FOM) is defined as the maximum allowable one-way transmission loss.

$$\mathrm{FOM} = \mathrm{SL} - (\mathrm{NL} - \mathrm{DI} + \mathrm{DT})$$

Where SL is source level, NL is the noise level, DI is the receiver directivity index, and DT is the detection threshold. Using very conservative values, we anticipate an FOM of 60 dB. Thus, as long as the FOM does not exceed the transmission loss (TL), we are capable of transmitting/receiving signals. Underwater transmission loss is governed by spherical spreading and absorption due to attenuation. The expression for TL from Medwin & Clay (*Acoustical Oceanography*) is:

$$\mathrm{TL} = 20 \log_{10}(\mathrm{R}/\mathrm{R}_o) + \alpha(\mathrm{R} - \mathrm{R}_o)\ \mathrm{dB}$$

where α (dB/m) is the attenuation rate, R is the range traveled, and R_o is the reference distance (1 meter).

The attenuation rate is also defined as:

$$\alpha_s = (1.71x10^8)(4\mu_F/3 + \mu_F')f^2/(\rho_F c_F^3) + \text{relaxation terms}$$

where α is the attenuation rate, μ_F is the dynamic coefficient of shear viscosity, μ_F' is the dynamic coefficient of bulk viscosity, *c* is the speed of sound in water (m/s), and *f* is the frequency in KHz. Note that at frequencies just above 1 MHz, the attenuation rate is the same in fresh and salt water.

The following figure of range versus frequency in the ultrasonic range was computed and produced based on very conservative values. From a theoretical analysis, we should be capable of transmitting and receiving underwater signals in the 4 MHz range from a distance of about 10 meters.

APPENDIX IV

DETAILS ON THE ST 725 SONAR SCAN LINE ANALYSIS FROM THE AUV 98 EXERCISE

Automatic Sonar Target Recognition Experiments

One of the objectives of the AUV Fest experiments involved testing a recently developed sonar target recognition software module. The software is designed to process the sonar returns in real time and provide a reduced data set from the large amounts of data gathered. From the data, the centers of concentrations of high intensity sonar returns are identified and their locations stored during mission time, which requires no post processing. The location information can be then be used for post mission analysis or path re-planning to return to these areas for further study during the same mission. High intensity concentrations suggest underwater objects or structures, while areas of low intensity do not. Since the majority of the open ocean is clear, only a small amount of the data gathered is meaningful, and this approach greatly reduces the data storage requirements of the onboard computer system. The following will give a brief description the sonar used, the identification algorithm, and finally the results from one of the missions.

Sonar Head General Description

The NPS Phoenix is equipped with two mechanically scannable high frequency sonar heads built by Tritech Corp. One is an ST725 scanning sonar and the other is an ST1000 profiler sonar. Each head can be scanned continuously through 360 degrees of rotation or swept through any defined angular sector around the central axis of the unit. During normal operation, the head will ping, wait for return echoes to process, and then rotate a specified angular width and repeat. Step widths of 0.9^{o}, 1.8^{o}, and 3.6^{o} are computer selectable.

All missions performed at AUV Fest used the ST725 which operates at a frequency of 725 kilohertz and emits an acoustic beam 2.5^{o} wide in the horizontal plane by 24^{o} wide in the vertical plane. This device is described as a scanning sonar due to the nature of the range and intensity information returned for each ping. A scanning sonar operates by placing the intensities of the echoes from each ping into discrete segments of range called range bins. For this sonar, the number of range bins is nominally 128, but for operating ranges of 10 meters or less, the number of range bins is reduced to 64. The maximum operating range of the ST725 is 100 meters with a minimum operating range of 6 meters, and provides a resolution of (Maximum Range)/128 or (Maximum Range)/64, depending on the range setting used. The range setting used in the Gulf was 20 meters, which gave a resolution of approximately 15 cm.

In order to more clearly analyze the returns, the data can be thresholded to analyze only returns above a certain intensity level so that significant objects/structures can be seen, while other less significant entities (e. g. suspended particles in the water column, weak multi-path echoes, noise, etc.), are excluded. Combining thresholding with an appropriate power setting for the transducer, high quality results can be achieved.

Sonar Cluster Identification Program

The identification algorithm is designed to recognize areas of contiguous high intensity sonar returns. Below is a section of a test case showing sonar scanlines that have been thresholded to record intensities above 10.

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 **11 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **11 13 12 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **11 13 15 13 12 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 **12 11** 0 **14 13 12 12 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **12 13 14 14 13 12 12 11** 0 0 0 0 0 0 0 0 0 **11** 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **13 13 14 15 14 12 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **13 13** 0 **15 15 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 **12 13 14 13** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 **11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 **12 13 14 13 14** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 **11 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 **12 12** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 **13 13** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 **14 14** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 **11 11** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 **12 12** 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

The algorithm records the centroid (X, Y pairs) of each cluster of high intensity returns, while ignoring noise or small concentrations such as the 14, 13 group shown above. Several parameters are selectable to tune the algorithm for target identification such as maximum cluster width, breadth, number of non-contiguous contacts, etc. The following presents the results of the identification algorithm from a run at AUV Fest.

Results form AUV Fest

Since there were no submerged targets in the area where the Phoenix operated, the chase boat served as a suitable target. Figure 1 shows the targets identified (chase boat) with the centroid of each marked with a cross-hair. The trajectory of the Phoenix is shown with a solid line while the sonar returns with an intensity above 10 are shown with asterisks. Figure 2 shows the lower right target cluster with the centroid clearly identified by the algorithm. Since the AUV Fest results were very positive, further experiments will be conducted in Monterey Bay in the early summer of 1999.

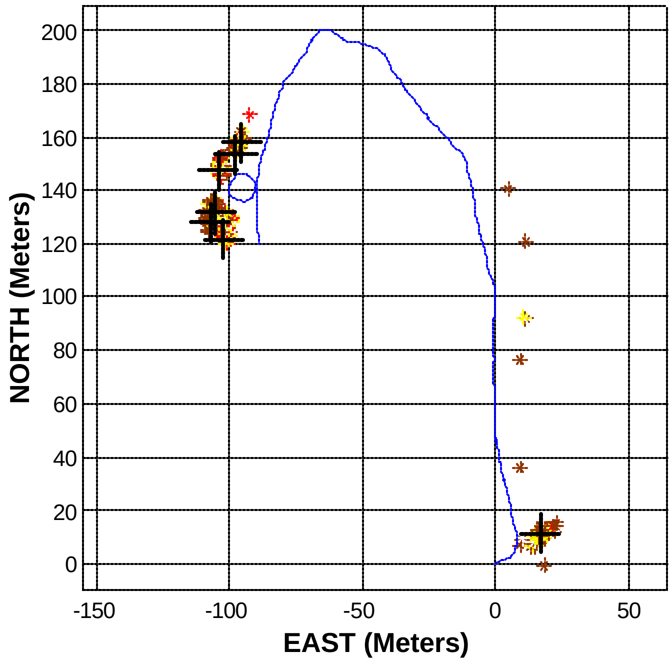

Figure 1. Clusters Identified.

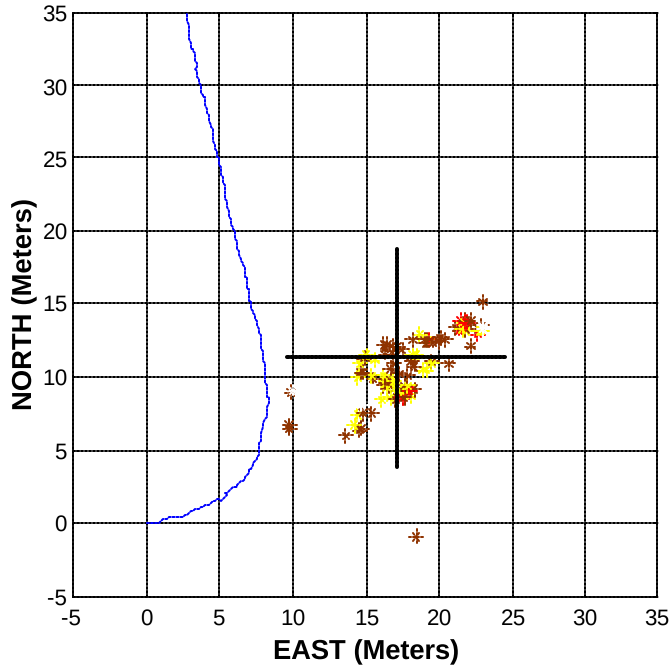

Figure 2. Lower right cluster with centroid.

APPENDIX V

EXAMPLES OF GRAPHICS FROM VISUALIZATION STUDIES

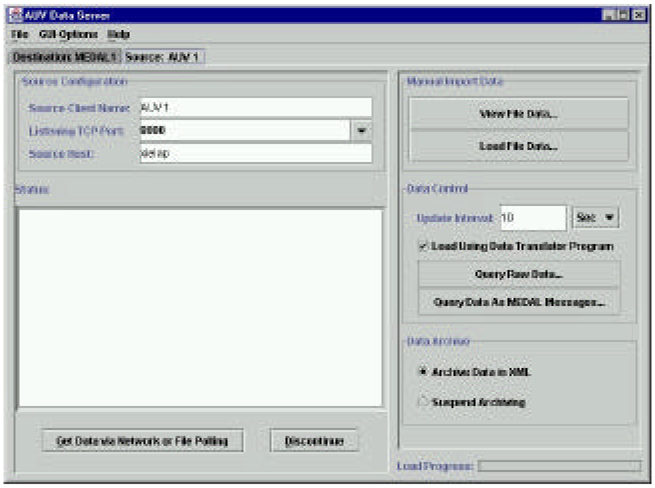

Figure 1. AUV Data Server (ADS) accepts a variety of telemetry asset, bathymetry and contact reports for conversion and transmission to the MEDAL system. ADS can run via user interface or command line.

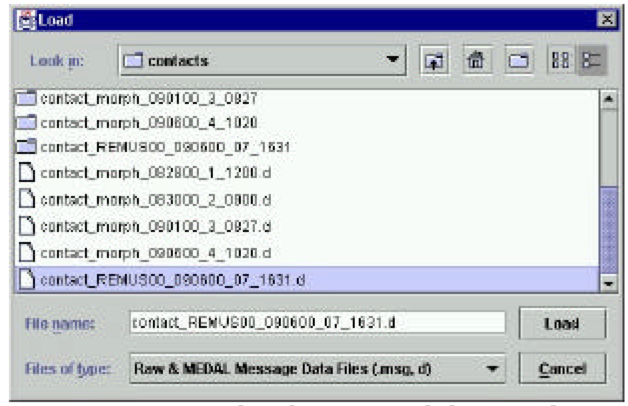

Figure 2. ADS has been tested during Fleet Battle Experiments with multiple underwater vehicles. Tested AUVs include WHOI's REMUS, FAU's MORPHEUS and NPS ARIES.

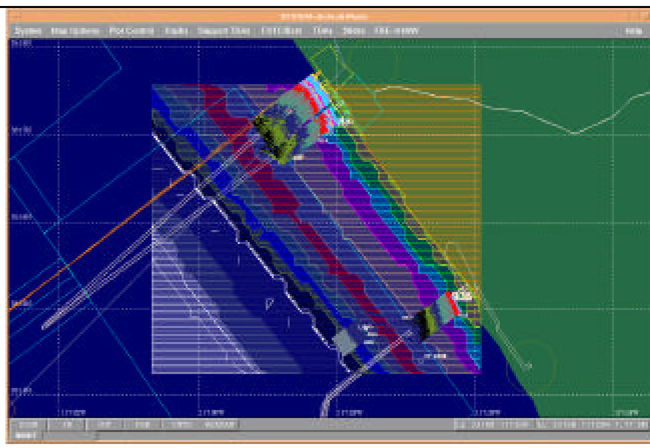

Figure 3. Aggregate plot showing multiple AUV tracks and bathymetry results overlaid with historical and exercise data. Bathymetry update overlays indicate detection of significant seasonal changes in bottom slope.

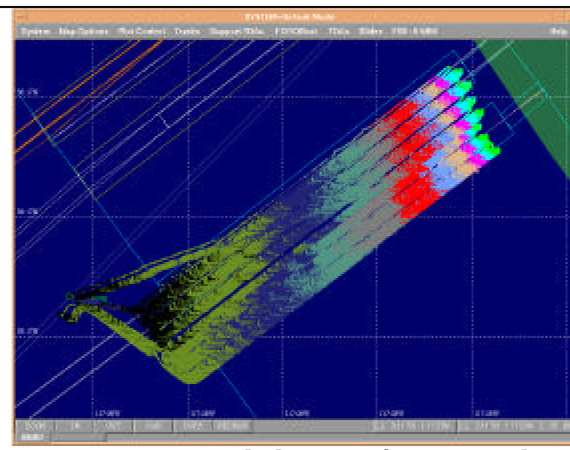

Figure 4. Detailed view of AUV track, bathymetry and contact data overlays using MEDAL.

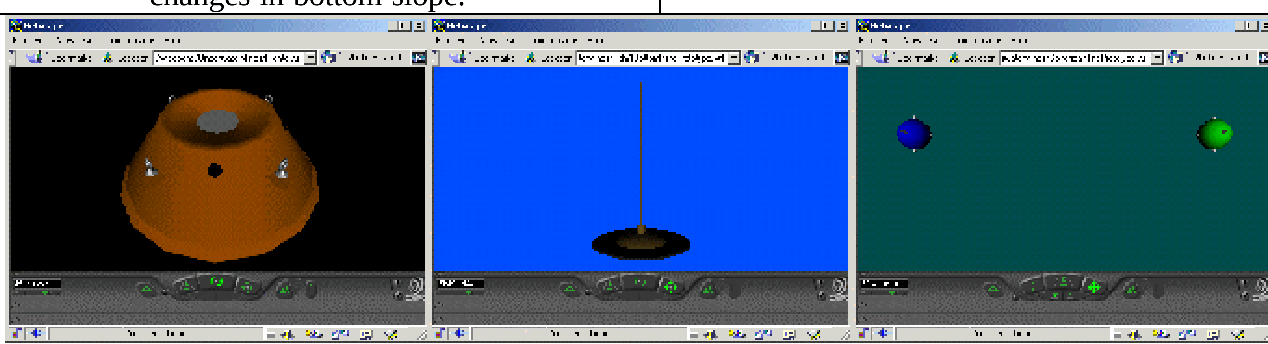

Figure 5. Manta, PDM-1 and spherical underwater mine models.

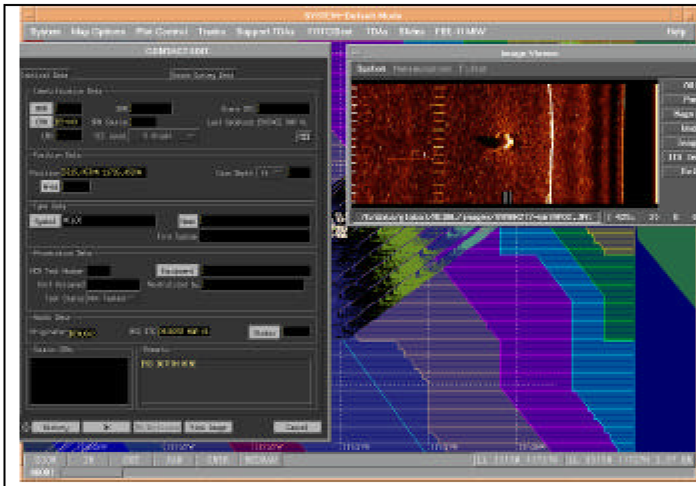

Figure 6. MEDAL further enables viewing AUV-reported contact imagery via a geographic database.

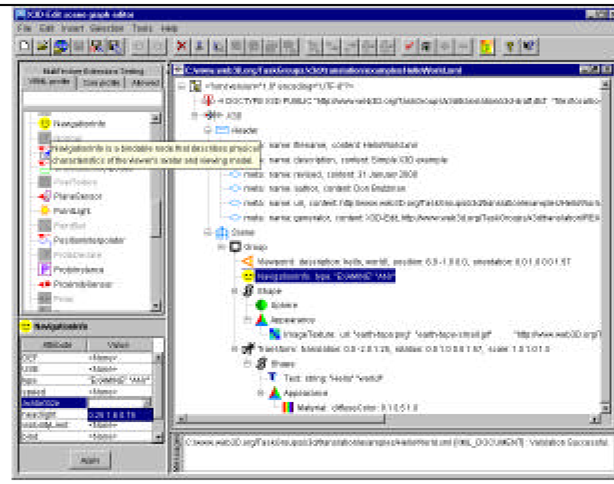

Figure 7. X3D-Edit provides context-sensitive help & automatic error checks for 3D model construction.

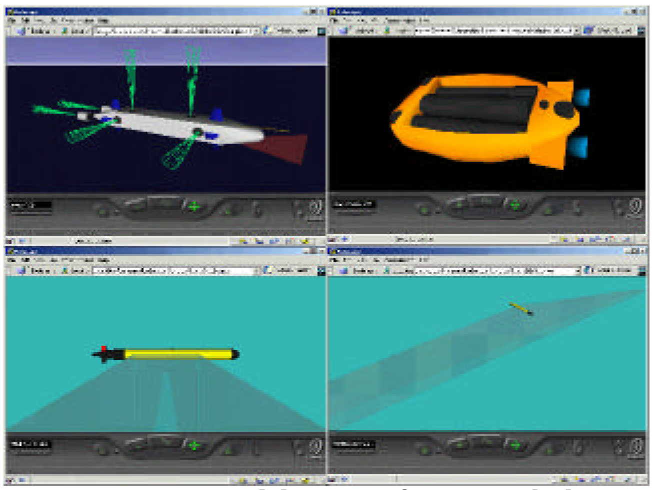

Figure 8. AUV model views of Aries with thruster flow and ahead-looking sonar, Cetus, & Remus with sidescan sonar.

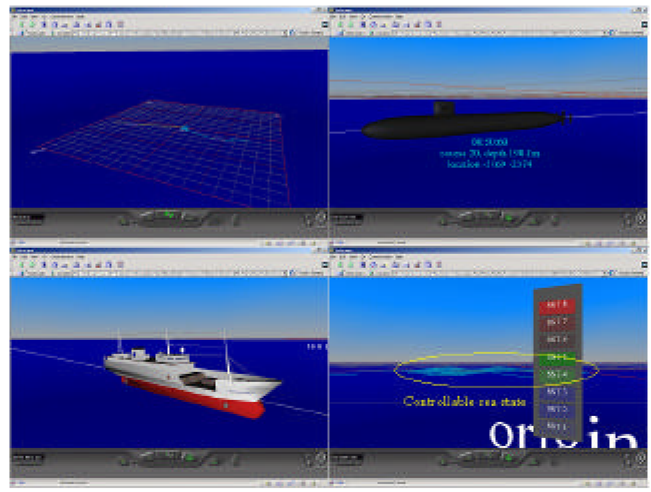

Figure 9. Various model views in USS GREENVILLE - MV EHIME MARU collision scenario.

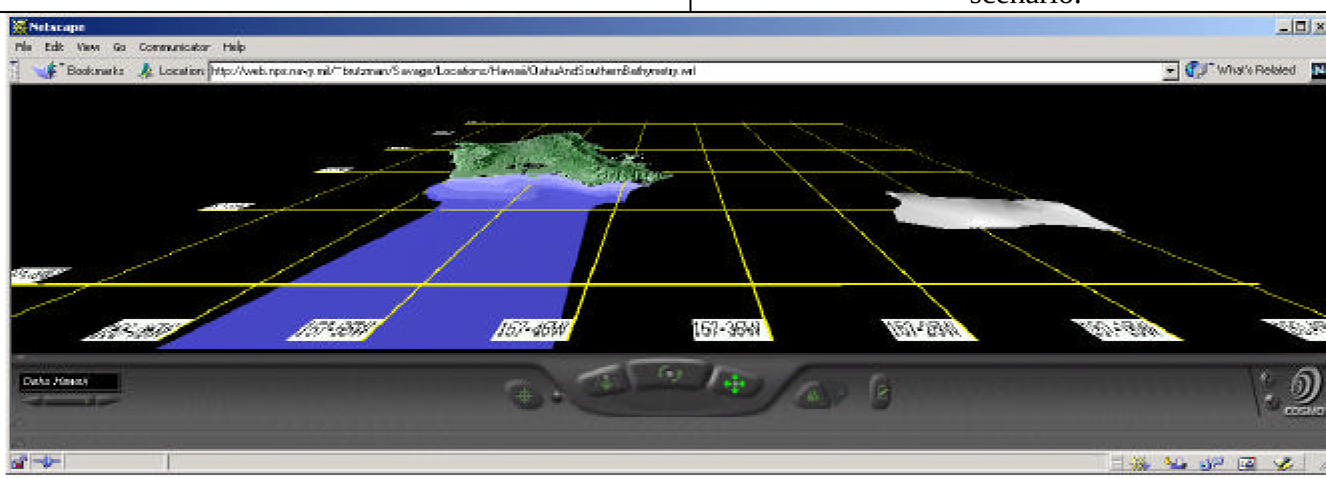

Figure 10. Derived hi-resolution terrain and bathymetry for Oahu and Molokai Hawaii, seen from southern aspect.

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