Technical Report 1529
November 1992

Evolution of a Search System:

Lessons Learned with the Advanced Unmanned Search System

J. Walton

Technical Report 1529
November 1992

Evolution of a Search System:

Lessons Learned with the Advanced Unmanned Search System

J. Walton

NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
Commanding Officer

R. T. SHEARER
Executive Director

ADMINISTRATIVE INFORMATION

This work was performed by the Ocean Engineering Division of the Naval Ocean Systems Center (currently known as the RDT&E Division of the Naval Command, Control and Ocean Surveillance Center). Sponsorship was provided by the Assistant Secretary of the Navy, Washington, DC 20350.

Further information on this subject is available in related reports that represent NRaD efforts through FY 1992. The bibliography is found at the end of this report.

Released by
N. B. Estabrook, Head
Ocean Engineering Division

Under authority of
I. P. Lemaire, Head
Engineering and
Computer Sciences Department

PK

OBJECTIVE

This document follows the evolution of the Advanced Unmanned Search System (AUSS) and the lessons learned. The events leading up to the development of the AUSS, the subsystem focus, systems engineering, and the interactive development and field testing are all included.

RESULTS

The AUSS supervisory controlled untethered search approach is unique, and has resulted in major advances in both underwater vehicle technology and search technology. AUSS broke free from the bounds of classic towed search systems to achieve drastic improvements. An unconventional but focused effort was applied employing system engineering, yet remaining flexible to RDT&E interactive evolution. This has allowed AUSS to break through a search technology barrier that has existed for decades. AUSS is a system that very effectively achieves its mission and surpasses its program goal.

CONTENTS

FIGURES

TERMINOLOGY

Terms, phrases, acronyms, and abbreviations peculiar tc ·earch and ocean technology endeavors will be used throughout this document. This section is devoted to explaining some of those terms and phrases.

Acoustic shadowing—a region of no return in a sonogram that results from the beam of an acoustic device being interrupted by a solid object.

Acoustic tracking system—a system that utilizes underwater acoustics to determine the relative positions of equipment in the water. Distances are determined by the time taken for sound to travel from one position to another.

Acoustic transponder—a device that responds to sound at one frequency by transmitting at another frequency.

AL—Acoustic Link.

AUV—Autonomous Underwater Vehicle.

Bit error rate—measure of accuracy in transmission of digital data; usually determined by the number of bits that are incorrect when received divided by the total number of bits transmitted.

Broad area search—rapid search of the ocean bottom by using a low-resolution sensor. Classification (identification) of contacts perceived with broad-area-search sensors is not usually possible. A typical broad-area-search sensor is a side-looking sonar.

BUMP—Benthic Untethered Multipurpose Platform. A free-descending, free-ascending test platform that tested the acoustic link used on AUSS in depths down to 15,000 feet.

Contact—a search sensor image perceived by the search system operator as an item of interest on the bottom of the ocean. Contacts may be real or "false" (i.e., not what is being sought).

Contact evaluation—close scrutiny of a contact to determine if it is a target of interest and, if it is, what are its characteristics. This normally involves the use of high-resolution sensors at close range to the contact.

Dockside Testing—testing of seagoing equipment where the undersea portion is in bay water and the surface support equipment is placed on a dock adjacent to the bay.

Doppler sonar—an acoustic sensor used to determine the velocity and position of a vehicle with respect to the bottom of the ocean.

EARS—External Acoustic Relay System. A towed system that was used as the surface acoustic link and acoustic tracking transducer platform.

EMI—Electromagnetic interference.

False target—a contact, although perceived by the search system operator as an item of interest, is not what is being sought.

False target density—the density of false targets perceived in the course of a search; normally in false targets per nmi^2.

FIFO—First in first out.

Fish-cycle acoustic tracking—a long baseline acoustic tracking technique that is used to determine (fix) the position of a "fish" (i.e., the AUSS vehicle).

FLS—Forward-Looking Sonar—an acoustic sensor that is used to scan the area forward of an underwater vehicle. For AUSS, the FLS has a mechanically scanned sonar "head" that transmits and receives a beam very similar to the beam of the SLS. A sonagram is developed representing the area in front of the vehicle as the head is mechanically scanned back and forth across the bow.

Holiday—the absence of required search data. SLS holidays are regions between successive scans for which no SLS data were collected.

Immediate contact evaluation—technique of stopping during a broad area search to perform a contact evaluation.

Lateral range function—target detection probability as a function of range.

LBL—Long baseline acoustic tracking—a technique by which the position of equipment in the water is determined in three dimensions. This is done by determining the distance from the equipment to at least three bottom-moored transponders (a transponder net) whose positions are known.

Multibus I—a computer architecture.

Multibus II—a computer architecture.

PLM—a computer programming language.

PTR—Portable Test Range. A subprogram of AUSS. The portable test range was used to produce side-looking-sonar performance data.

PWC—Public Works Center.

RMK—a realtime computer operating system.

RMX—a realtime computer operating system.

ROV—Remotely Operated Vehicle. This usually refers to a tethered vehicle.

RUWS—Remote Unmann. Work System.

SAR—Search And Recovery.

SBL—Short baseline acoustic tracking—a technique by which the position of equipment in the water is determined in three dimensions. This is done by determining the distance from the tracking vessel (usually a surface ship) to the underwater equipment and the depression and azimuth angles to the equipment.

SC—Surface console.

Scarp—an ocean bottom type characterized by steep sloping terrain.

Search area rate, or area search rate the rate at which a search system is able to search the ocean bottom; usually in nmi^2/hr.

SLS—Side-Looking Sonar—an acoustic search sensor used for searching from an underwater vehicle that is advancing in a straight line. Successive pings, (perpendicular to the track of the vehicle) sent out from the sonar, are narrow-beamed along the track of the vehicle, but are wide-beamed in the vertical. The times of return of these pings (along with the position and heading of the vehicle) are used to determine the position on the bottom from which the sound was reflected.

SOAS—State-of-The-Art Search—built or demonstrated hardware or technique used for search. Throughout the history of AUSS, the basis for state-of-the-art search has not changed. The state-of-the-art search consists of a search support ship towing a search vehicle with a long electromechanical cable.

Sonogram—a visual image of information collected by a sonar.

Supervisory control—control technique in which the human operator supervises the operation of a remote system. The human tells the vehicle what to do, not how to do it. The operator communicates with the remote system infrequently. In between these communications, the remote system performs a series of preprogrammed functions selected by the operator. When finished with a series of preprogrammed functions, the remote system awaits further instructions.

Swath width—overall coverage in one dimension of a search sensor. For instance, for side-looking sonar, each of two transducers (one port and one starboard) may cover a range of 1000 ft in a direction perpendicular to the track of the search vehicle. This results in a total swath width of 2000 ft.

Target—a contact.

Target detection probability—the probability of detecting a target with a specific search sensor used in a particular search scenario. The target is characterized by specific size, shape, and sonar target reflection characteristics.

TRANSDEC—Transducer Evaluation Center.

Type 0 control loop—a control loop in which the position error is finite.

Type 1 control loop—a control loop in which an attempt is made to drive the position error to zero. An integrator is applied to the position error. The integrated position error is then summed with the position error to produce the command signal.

UUV—Unmanned Underwater Vehicle.

NAVY LABORATORIES/CENTERS AND SUPPORT ACTIVITIES

MPL—Marine Physical Laboratory

NAVMAT—Naval Material Command

NAVOCEANO—Naval Oceanographic Office

NAVSEA—Naval Sea Systems Command

NAVSEC—Naval Sea Engineering Center

NCCOSC—Naval Command, Control and Ocean Surveillance Center

NOSC—Naval Oceans Systems Center

NRL—Naval Research Laboratory

NSRDC—Naval Surface Research and Development Center

SUBDEVGRUONE—Submarine Development Group One

WHOI—Woods Hole Oceanographic Institute

BACKGROUND

INTRODUCTION

The most visible aspect of the Advanced Unmanned Search System (AUSS) program is an untethered supervisory controlled underwater search vehicle. But the vehicle succeeds in its search mission only as part of a system. The system consists of the vehicle, human operators, an acoustic communications link, and surface support equipment. This system has been extensively demonstrated at sea. During sea tests, AUSS displayed a search capability that is, by far, superior to other present day state-of-the-art search systems.

The AUSS design and hardware are important contributions to Unmanned Underwater Vehicle (UUV) technology. The AUSS tactics and capabilities are important contributions to search. Documentation of AUSS evolution, system engineering, and lessons learned are of equal importance to the technology and search contributions.

The AUSS program evolution consists of several phases. It was born out of a need and predicated on expert contributions. Education in search and investigations of search were accomplished through analysis. The system was preliminarily developed with subsystem focus, further developed through systems engineering, and completed through interactive development/field testing. The collaboration of systems engineering and evolution, and the resulting lessons learned, are the subjects of this document.

This document does not adhere to a pure chronology of AUSS events. Instead, the major section titles follow the AUSS evolution. Subtitles (in italics) are for the most part lessons learned. An AUSS program history outline is presented in figure 1.

Search Study Phase	1973–1979
Search Performance Model	1974–1979
Portable Test Range Search Field Tests	1975–1978
Acoustic Link Development (BUMP)	1978–1981
AUSS Concept Definition	1980
AUSS Prototype Design	1980–1984
Search Demonstration Testing	1985–1987
Hardware Upgrade	1988–1990
AUSS System Testing/Demonstration	1990–1992

Figure 1. AUSS program history.

WHY SEARCH

The search and discovery of items lost at sea bring to mind the danger faced by brave and resourceful adventurers. Historically, not all undersea searches are glamorous, but the adventure, the adventurers, and the dangers are usually there. The Hollywood depiction of search may show helmeted aqua-persons moving about on the ocean floor and finding an intact treasure ship loaded with riches beyond belief. The modern-day search more typically involves a high-technology remote system in deep water involved in searching for a relatively small high-value item, or a field of debris on the bottom of the ocean. Much of the adventure is now in the development of the deep-ocean remote systems that are used to expedite the search. AUSS is the epitome of such systems.

Searches for items of high value (other than treasure) have been attempted for decades. A high-value item is one in which there is great interest. Areas of great interest to the United States include failure analysis, security, salvage, politics, and rescue. Of particular note are searches for the submarines USS *Thresher* and USS *Scorpion*, an H-Bomb near Spain, ordnance during the clearing of the Suez Canal, the Remote Unmanned Work System (RUWS), Korean Airlines Flight 007, the Air India Flight 182, and the United Airlines Flight 811 cargo door.

PROGRAM EVOLUTIONS AND LESSONS

GET THE EXPERTS INVOLVED

A High-Level Study Group Helps

The genesis of AUSS was in early 1973 after the searches for the USS *Thresher*, the USS *Scorpion*, and the H-Bomb provided evidence that a need existed to improve the U.S. Navy capability to conduct deep-ocean search. The literature was searched and studied, and the handful of people who had search experience were interviewed.

John Freund, then of NAVSEA 035, kicked off the AUSS program. At that time, he formed search-knowledgeable Navy and university personnel into a study group task team. Early in the program, the task team conducted a series of planning meetings that set the groundwork for the AUSS program. The task team consisted of representatives from NAVSEA, NAVMAT, NRL, NAVSEC, NAVOCEANO, NSRDC, SUBDEVGRU-ONE, MPL, WHOI, AND NOSC. John Freund continued to lead, fund, and champion the AUSS program from that time until the project termination in 1992.

The study group identified and documented several deficiencies in the existing state-of-the-art search. This study group, in total and in part, continued to participate and contribute to the AUSS program until three months prior to FY 77.

Nothing Rivals Experience

Two task team individuals emerged as the most knowledgeable in search theory and practice; C. L. "Bucky" Buchanan of NRL, and Dr. Fred Spiess of the Scripps Institution of Oceanography MPL. Both Spiess and Buchanan had extensive search operations experience, and were instrumental in the USS *Thresher* search. Both these individuals had taken responsibility of the onsite planning and implementation of search missions. They had overcome the existing search deficiencies to succeed and, in the process, had developed a number of ideas on how search could be improved.

After the official existence of the task team, Buchanan (January, 1977) produced a document that continues to be (as its title suggests) a good review of problems with state-of-the-art search systems. Buchanan (April, 1977) next produced a document in which he discussed many of the concepts and tactics eventually implemented in the successful AUSS program. It has taken 15 years to develop and prove many of the concepts that Buchanan discussed in this document and to know just how far-sighted this individual was in the field of search.

DEFINE THE NEED

The study group defined deep search as: "...to look for and find manmade objects at or near the bottom in depths of 20,000 ft any place in the world's oceans." Depths less than 2000 ft were not considered because they could be adequately accessed by existing technology systems.

Search Is Difficult

The consensus of the study group, based upon past search operations, was that the existing search capability could be characterized as: "...80% probability of finding a 2 1/2-ft-diameter object on a flat bottom area of 50 nmi^2 in 200 days," or, a search area rate of 0.25 nmi^2 per day! This, by present-day AUSS standards, is excruciatingly slow. The defined object size was, I believe, purposefully small. The bottom type was benign but typical of the deep ocean. The 80% probability does not show the kind of optimism that a multimillion dollar mission expenditure deserves.

Thus, the search problem in deep water is to search several square nautical miles during several hundred days with a crew who are vertically separated from the item of interest by (at best) several miles of seawater. The area ratio and volume ratio of the search cell to a 2 1/2-ft-diameter spherical object (assuming 20,000 ft of seawater and 50 nmi^2) are $4\text{x}10^7$ and $4\text{x}10^{11}$ respectively—(i.e., the needle in the haystack).

The Tow Cable Is Critical

A deep-ocean search system (real and imagined), in the days of the AUSS program inception, utilized a towed underwater search platform. The towed platform (towed vehicle) was equipped with sonar and/or photographic search sensors. The vehicle was towed by a long cable (at least 5 miles long if 20,000 ft depths were imagined) attached to a slow-moving surface ship. The control of the search vehicle could be accomplished by maneuvering the ship. Reversing the direction of the search vehicle (vehicle turnaround) could be accomplished by time-consuming turn maneuvers. Cables and cable reels for multimile deep towing are large, heavy, and cumbersome.

Many of the deficiencies flagged by the study group were related to the search tow cable. These deficiencies included search vehicle turnaround, vehicle control error, and vehicle navigation error. Turning, navigating (or tracking), and controlling an undersea vehicle connected to a surface platform by miles of cable is a tall order.

The turnaround costs the search mission many hours per turn. The tow ship must maneuver several miles past the end of the search lane to reverse direction and then return the vehicle to the next lane lined up for search. Typically, no searching is possible during turns. If search is accomplished during the turns, it is difficult to correlate towed vehicle position information with search sensor information. The vehicle may even touch the bottom during the turn. The vehicle turns on a smaller radius than the support ship. Upon touching the bottom, the cable may kink, and the cable is destroyed or the vehicle is lost.

Control error is the error between the track that the search vehicle is supposed to follow and the actual track followed. This is less of a problem for broad-area-search vehicle sensors with large sensor swaths than for contact evaluation vehicle sensors that typically have much smaller swath-width coverage. It is certainly evident that control error will be large when the surface ship is maneuvered to effect the track of an underwater vehicle connected to the ship by miles of tow cable. Dr. Spiess of MPL explained his frustration in frequently missing contact evaluations due to control error. He was particularly frustrated since the contact evaluations were attempted after investing hours in precontact evaluation turns.

Navigating (or tracking) the search vehicle refers to knowing the location of the vehicle. The important criteria here is knowing what territory the search vehicle sensor is covering, and what territory it has covered to avoid holidays in the sensor data collection. The state-of-the-art in search vehicle navigation is acoustic tracking, either long baseline (LBL) or short baseline (SBL). Navigation error amplifies the control error problem because it is characterized by position uncertainty and infrequent data. With towed systems in deep water, the use of either of these tracking systems for navigation forces the use of large overlap of search tracks.

The State-of-the-Art in Search (SOAS) Holds Inertia

Vought Corporation (1982) produced a report for the AUSS program in which a number of past searches were investigated. Of the 30 searches studied, the majority were conducted with towed systems and the rest were conducted using manned submersibles. These results are similar to what the AUSS task team found in 1973. If a similar study were done today, the same general result would occur, with a decrease in the number of searches conducted by manned submersibles.

The basic state-of-the-art in search has not changed in two decades! Searches are still conducted by using towed systems with long heavy cables and large bulky cable handling systems. Turnaround, control error, and navigation error are still major issues.

Time Is Money and SOAS Takes a Lot Of Time

Endicott and Kuhl (1992) produced a report for John Freund that identified two classes of search operation activity. The first class is where the search sensors are not actively searching and the probability of detection is not increasing. The second class is where the search sensors are actively searching and the probability of detection is increasing.

The first class includes items generic to all searches, such as planning, mobilization, and transit. It also includes descent, ascent, and turns. Mobilization of state-of-the-art towed systems can be slow due to the large cables and large deck gear. Descents and ascents, turns and turnarounds are time-consuming for towed systems.

State-of-the-art towed systems do not perform well in the second class because of low-broad-area-search rate, long contact evaluation times, control error, and navigation error. During broad area search, the search rate is limited by tow speeds. In deep water, the towed systems are restricted to 1 to 2 knots or the tow vehicle cannot be maintained at an altitude near the bottom. Contact evaluations with towed systems take hours to days depending upon the capability of the onsite search director to overcome the effects of control error and navigation error, and the ability to perform towed vehicle turns by using ship maneuvers.

Search mission time is the sum total of all times within the search and nonsearch classes. Search mission days cost from $10,000 to $100,000 and more. Efforts to improve all aspects of the search are warranted. Some major contributors to the daily rate are support ships, labor, and search-system support costs.

A Search Technology Gap Exists

C.E. Gunderson (1978), a member of the NOSC AUSS team, estimated the current state-of-the-art search rate at 0.045 nmi^2 per hour. This represented the current capability when using towed sensor platforms, and was established by analyzing past search operations. This was a significantly higher rate than the 0.25 nmi^2 per day (0.01 nmi^2 per hour) estimated by the study group. Gunderson's estimate was based upon towed and tethered search only, and did not include manned submersible searches. Gunderson stated that the search rate was primarily limited by a "technology gap."

The deficiencies in the existing search systems included low-broad-area-search rate, large control error, and long turnaround times; the same as stated by the study group five years previous. A major improvement in search technology would be a means to decouple the search vehicle from the effects of the cable.

EXPLORE THE COMPLEXITIES OF SEARCH

A number of deficiencies in the way traditional search was being performed had been identified. Bridging the technology gap meant finding a means to decouple the search vehicle from the effects of the tow cable. The problem was how the AUSS team could analyze search, analyze potential search systems approaches, and analyze potential search technologies. The interrelationships within these subjects and the search process itself is very complex. Search involves such factors as environment, target, surface support, and the search system used. To analyze search and to look at how search could be improved required development of sophisticated analytical tools.

Search Can Be Modeled

In FY 74, NAVSEA tasked NOSC[1] to develop a computer model of search as a product of the AUSS effort. The purpose of the computer model was to aid in the development and testing of new search concepts, to compare various search sensor performances, and to compare search systems approaches. In essence, the model would help handle the complexities of search. During the development of this model, the experience of and results of the studies conducted by the AUSS task team were transformed into algorithms. A few search computer programs already written at NRL and NSRDC were folded into the NOSC AUSS computer model.

The model was developed with an objective to compare systems and subsystems in a relative sense. It was never expected that exact performance of systems and subsystems would be predicted by the model. Instead, time to conduct a search mission and mean time to conduct a search mission were used to produce figures of merit. The figure of merit was used to compare the effectiveness of various mission profiles, tactics, systems approaches, and subsystems combinations. Figure 2 is a block diagram depicting the input and output parameters of the AUSS computer model.

[1]NOSC has since been renamed the Naval Command, Control and Ocean Surveillance Center, Research, Development, Test and Evaluation Division.

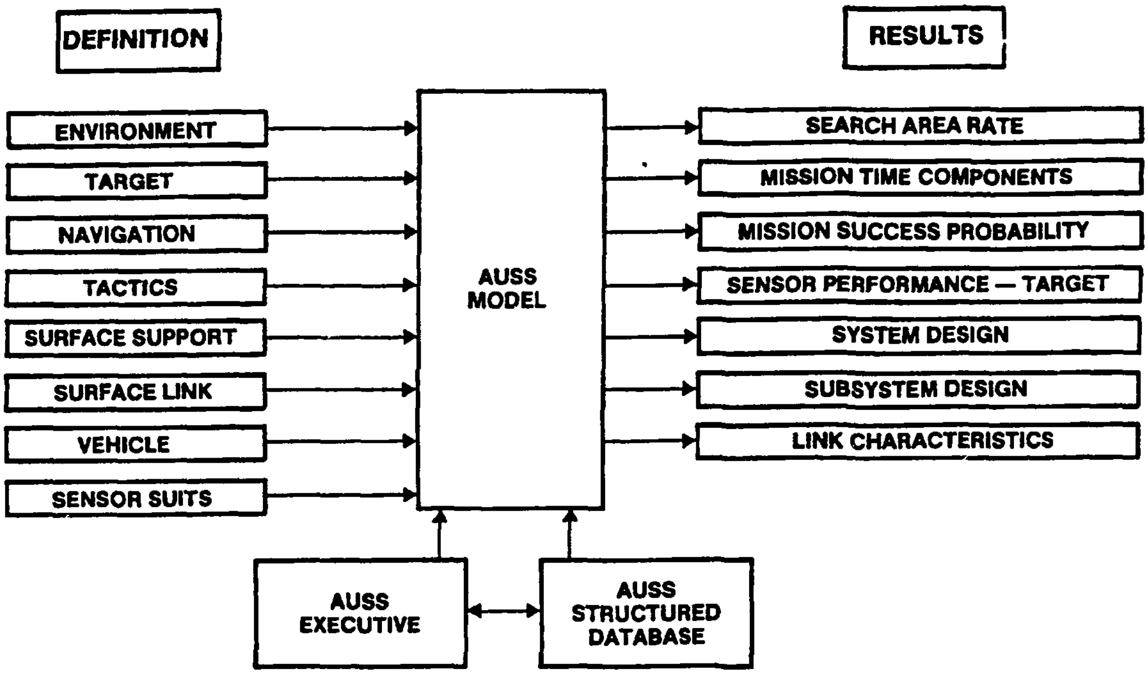

Figure 2. Input and output parameters of the AUSS computer model.

Search Field Testing Supports Search Modeling

Very limited search performance field data were available to support the development of the model. Building and fielding testbed search systems were considered, but preliminary designs determined this to be too expensive at that time. Instead, the Portable Test Range (PTR) program was initiated to collect target signatures by using different search sensors. The PTR program ran from the end of FY 76 until the middle of FY 78.

The long-range objective of PTR was to collect signatures of a variety of sensors for a variety of targets on a variety of bottom types. The short-term pared down objectives of PTR were (1) to determine the lateral range function (target detection probability as a function of range) for the side-looking sonar for two targets on two bottoms, and (2) to provide search mission cost breakdowns for use in the AUSS computer model.

Nothing Rivals Experience

Both short-term PTR objectives were met, and long-range objectives were not pursued. (Uhrich et al., 1978). Of equal importance to the two stated objectives, was the valuable experience gained by a group of young NOSC engineers in fielding state-of-the-art search technology. This same group of engineers later became part of the core AUSS team.

CONDUCT SYSTEMS PERFORMANCE ANALYSIS

During the same period the PTR testing occurred and until June 1979, the AUSS computer model was used for search systems analyses. The purposes of the search systems analyses were to (1) compare the performance of existing and advanced search systems, (2) identify critical technology areas for further development, and (3) exercise and verify the AUSS search performance model algorithms (Bryant, 1979).

Search Baseline Development Sets the Stage

With all the possible combinations of depth, target size, bottom type, and false target density, the task of using the model to analyze search for the full scope of scenarios was formidable. Because of this, three baseline search scenarios were defined and used. These cases were selected to encompass and bound the full range of anticipated scenarios. The cases were (1) shallow case (H-Bomb search at 2000 ft); (2) middle depth case (submarine search at 8400 ft); and (3) deep case (submarine search at 20,000 ft).

The H-Bomb dimensions were 1 ft radius by 10 ft long, and the submarine was 12.5 ft radius by 300 ft long. The bottom types assumed for the shallow, middle, and deep cases were scarp, smooth, and smooth respectively. The false target density assumed for the shallow, middle, and deep cases were 2.7, 0.13 and 0.13 targets per nmi^2 respectively. The shallow case constitutes a search for a small object in the worst terrain, and the middle and deep cases constitute searches for very large objects in the best terrain conditions.

A baseline deep-ocean search capability (i.e., a towed vehicle system) representing the current state-of-the-art was simulated. Simulations of several advanced search systems were derived from the baseline for comparison.

Candidate Systems Are Worth Considering

Originally, approximately 30 unmanned search system concepts were proposed for consideration. The number of systems for consideration was reduced to five during a series of engineering evaluation sessions. The main criteria for selection was that the system should offer significant improvement in mission rate over the baseline, and the system should consist of feasible (previously demonstrated or tested) technology. The five basic systems considered are shown in figure 3.

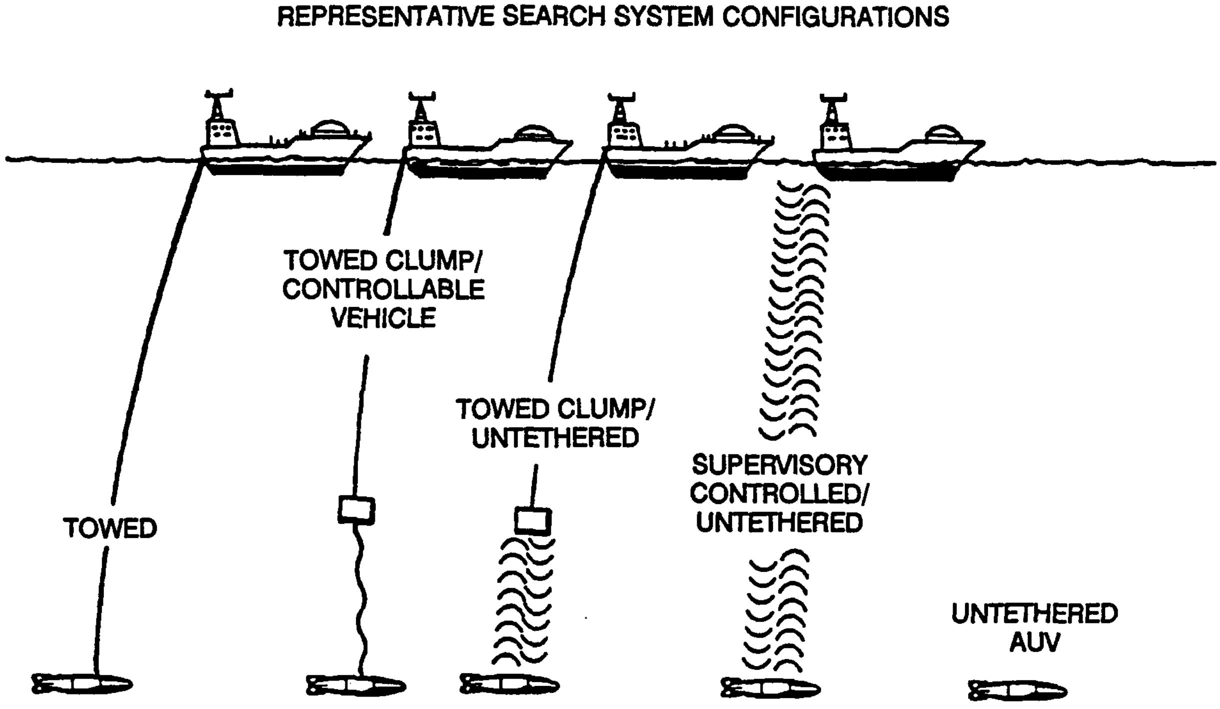

Figure 3. Search concepts studied.

Relative to the baseline system, the five systems featured a smaller control error, more precise navigation, and shorter launch time. Some important departures from SOAS were considered. For instance, a version of the towed system reduced the turn times to zero by using a rectangular spiral search pattern. A version of the towed system with decoupling clump reduced the navigation error to 0 during contact evaluation. This was done by using a scanning sonar mounted beneath the depressor clump to guide the vehicle to the target. Another version of the towed/clump system used a "trailer video" that could conduct immediate contact evaluations due to its lateral mobility. Decoupling the search system from the tow cable was a primary criteria.

Performance Improvements Are Possible

Every one of the five systems considered offered significant improvements over the baseline system. For the shallow case, improvements ranged from 2.7 to 10.8 times the baseline. In the deep case, improvements ranged from 4.6 to 37.6 times the baseline. Figure 4 shows relative performance curves for the five systems considered for the deep scenario. Deep scenario improvements exceeded shallow scenario improvements primarily because the towed baseline system becomes more and more burdened by the tow cable as the depth increases. The more freedom from the effects of the tow cable, the better the performance at great depths. Search systems are sensor limited in the shallow case.

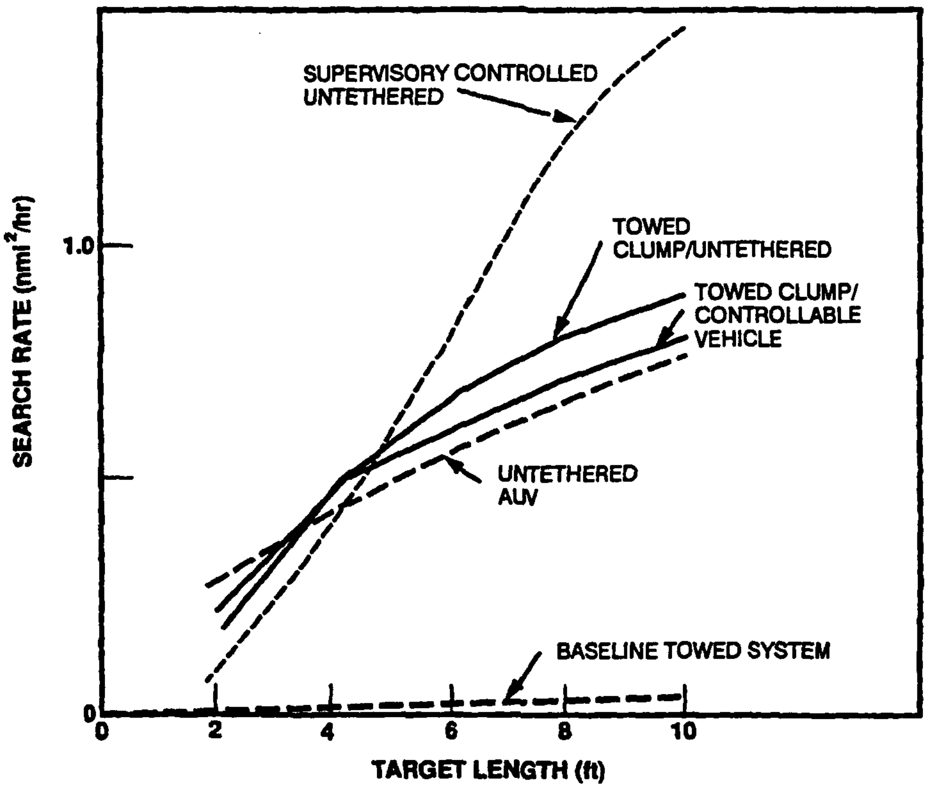

Figure 4. Relative performance curves for the five systems.

Supervisory Controlled Search Prevails

The highest overall performers, as seen in figure 4, are the supervisory controlled untethered systems. These systems are, of course, immune to the problems of the tow cable. The three major deficiency areas that repeatedly showed up in study after study (turnaround time, control error, and navigation error) can be, with the appropriate technology, minimized by using this type of system. Depth-independent search rates, which are limited only by the sensors, and the ability to perform immediate contact evaluations played very heavily in their superior performance.

A spot-scan version of the supervisory controlled system showed the highest performance advantage in the study. In the spot-scan search scenario, a sonar onboard the stationary vehicle would scan an area of the ocean bottom circular in plan view, transmit the data to the surface, and sprint to a new location where another circular spot scan would be conducted. A search area was to be covered by intersecting several of these circles in such a way that no holidays in the coverage existed. Eventually, this approach proved to be infeasible since a scanning sonar with the range and resolution necessary for the required system performance did not exist.

The final supervisory controlled, semiautonomous search system concept is depicted in figures 5, 6, and 7. In figure 5, the untethered vehicle is seen autonomously searching the bottom of the ocean with its broad-area-search sensor, SLS. The SLS image information is transmitted via an acoustic link (AL) to the surface for display to operators in near-realtime in the operator control van. When the operators see a contact of interest on their SLS screen, a command is sent over the AL to the vehicle to discontinue the SLS search. Next, as is seen in figure 6, commands are sent to the vehicle to GO to a position near the position of the SLS contact and to conduct a FLS scan. The FLS scan is transmitted through the AL to the operators where it is displayed on a sonar screen. The FLS scan is used to update the position of the contact. Finally, as depicted in figure 7, the operators send commands to the vehicle to GO to a position directly over the contact position and to image the contact optically. The optical image data are also transmitted through the AL to the operators. This process is repeated until the item(s) of interest are found, optically documented, and the position(s) determined.

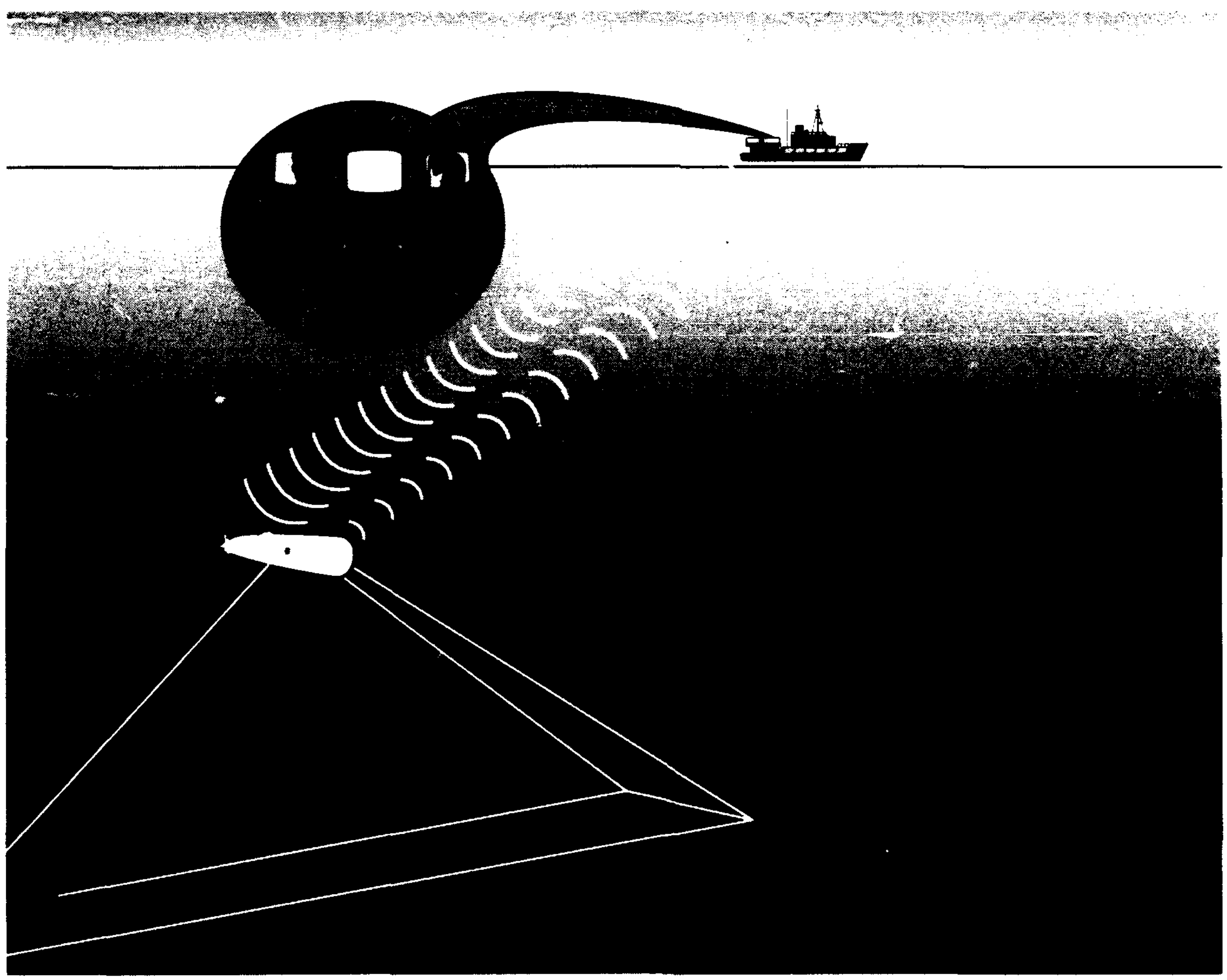

Figure 5. AUSS broad area search.

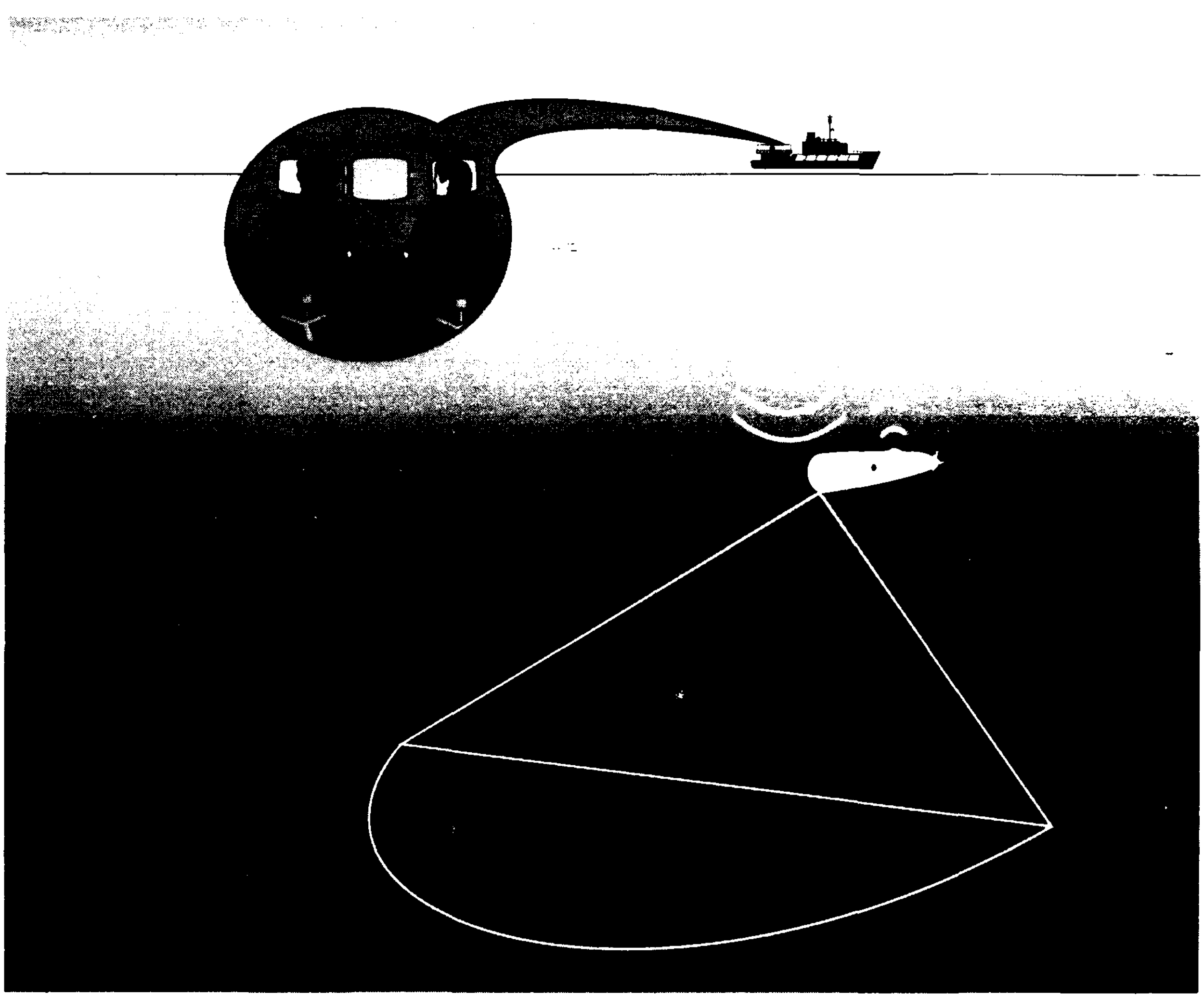

Figure 6. AUSS sonar target closing.

Figure 7. AUSS optical contact evaluation.

FIELD AND EVOLVE PROTOTYPE SYSTEM

A systems victory was achieved in the analysis of search by using a computer software model. This resulted in parametric representations from which a winning system emerged. The next step in a tangible improvement to the Navy's search capability was the system engineering and evolution of a prototype search system.

The purposes of the prototype were to provide a platform for evolution of required subsystems, to advance underdeveloped technologies required to implement the system, to demonstrate the feasibility of the system, and to eventually demonstrate the system's capability to significantly improve search. As lofty as this all sounds, the prototype eventually helped NOSC achieve all of these goals. Another goal defined for the prototype (to package the prototype for delivery as a search capability to the Navy) was never realized. In this document, the terms testbed and breadboard are often used to describe the prototype system. These terms are used to emphasize the preliminary nature of the prototype.

Anyone Can Build A Vehicle, So We Did

The Ocean Engineering Division at NOSC had been a pioneer in tethered vehicles (more recently referred to as ROVs) and had successfully fielded several. We were now in a position to develop a search system centered around an untethered vehicle. A number of required technology areas were well established in the division, such as state-of-the-art ocean technology, remote technology, hydrostatics, hydrodynamics, propulsion, energy conversion, communications, software development, and computer architecture.

The exciting pioneering areas in ocean technology required for the prototype search system included advanced composite pressure hull technology, acoustic telemetry, real-time operating and computing systems, and supervisory control of a remote undersea system.

The engineering design and manufacturing process produced a system centered around a vehicle (figure 8) that was small, compact, and able to operate to great ocean depths for a credible period of time (10- to 15-hours bottom time). A study into the efficiency of various candidate buoyancy concepts led to a pressure hull constructed of graphite epoxy with titanium end closures. The free-flooded forward and after compartments were constructed of fiberglass. The propulsion system utilized brush DC motors torque-coupled to the propellers via magnetic couplings. Silver zinc batteries were selected as the power source due to their high-energy density and proven track record.

For the most part, Multibus I computer architecture, the RMX operating system, and PLM programming language were used in the vehicle for the realtime operation and computing. Multibus I, RMX, and PLM were also used in the surface operations center, although a realtime environment was not required.

To support the vehicle operations, surface ship support equipment was designed and built. This consisted of a maintenance van, a control van, and a launch and recovery system. The maintenance van carried the vehicle and the required tools. The control van housed the electronics and operator interfaces required for at-sea operations. The launch and recovery system consisted of a launch and recovery ramp, a ship-mounted pivot assembly, and a transport system that overboarded and removed the launch ramp from the water astern of the support ship.

The launch and recovery system that was developed and fielded for the prototype AUSS set the standard for the UUV industry. The basic design has been used for the improved AUSS and several industry and military systems since its inception at NOSC.

AUSS VEHICLE

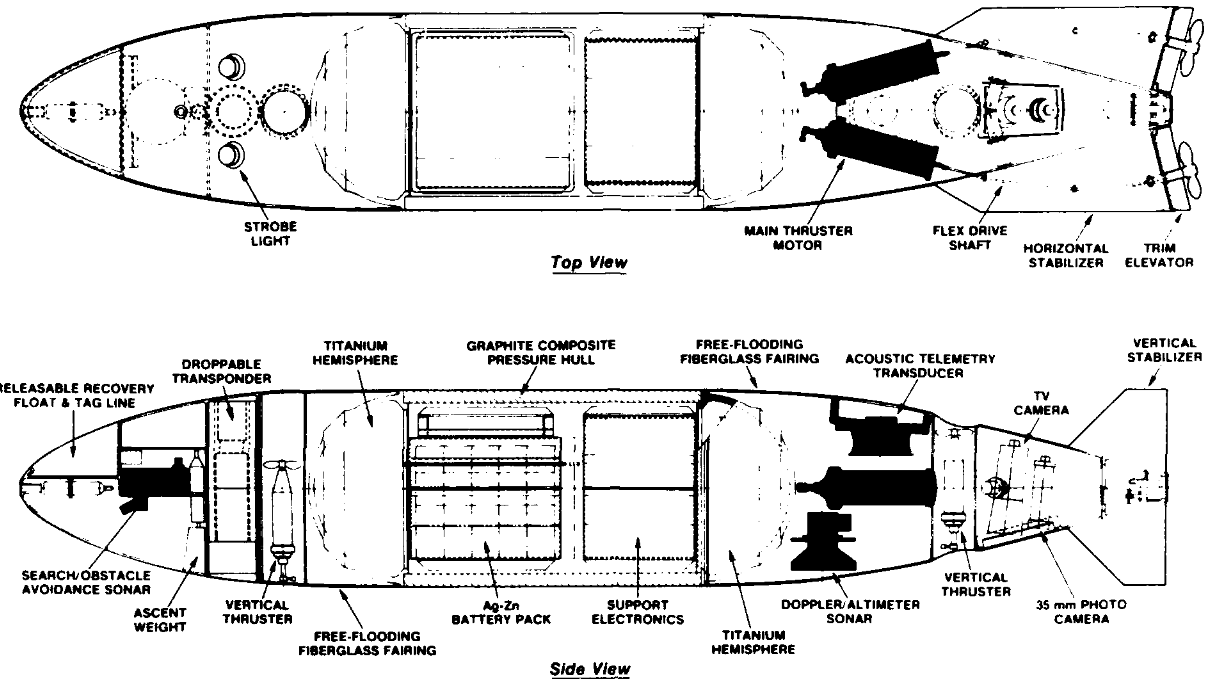

Figure 8. AUSS prototype vehicle.

Acknowledged frequently within the Ocean Engineering Division, somewhat tongue in cheek, is "anyone can build a vehicle." For us, the design and manufacturing process for AUSS was just the inauguration. The larger challenge was producing, in a first effort, a fully operational vehicle system that demonstrated a capability never before attempted.

Evolution Can Supplement System Engineering

Although it appeared that the prototype AUSS system was complete by 1985, it was not until 1987 that the system finally satisfied most of the objectives. A systems engineering approach was applied to the design and construction of the system. But it wasn't until the system was fielded, many lessons were learned, and the prototype evolution phase was complete that a systems feasibility was demonstrated and the system's potential to significantly improve search was demonstrated.

The prototype system was not expected to meet the objectives immediately upon fabrication. In fact, the vehicle was subjected to over 10 months, off and on, of dockside testing and 18 tethered dives before being allowed to swim free. (The tether was strictly a mechanical connection, and not a power or communications link). During the life of the prototype, tradeoff decisions were made in subsystem performance to best utilize the system to work on technical risk areas. Modifications were made to various subsystems at the expense of the performance of other subsystems. Many "quick fixes" were implemented in an effort to speed turnaround in answering technical and performance questions. The prototype served as a brassboard/breadboard system.

Prototype Deficiencies Must Become Engineering Problems

Few basic shipboard and operational problems or basic vehicle problems occurred during field testing, and any which existed were dealt with quickly. This was due to the extensive local experience in ocean technology and vehicles. The shipboard operations, logistics, equipment deployments, and vehicle launch and recovery quickly became routine. The vehicle hydrostatics, basic hydrodynamics, power, and propulsion systems remained static from the onset. Some mechanism problems continued to haunt us. But, from the very beginning of prototype field testing, a list of deficiencies in the technology development areas began to grow. These technology areas included the acoustic link, acoustic tracking, vehicle navigation, vehicle control, search sensors, and computers and software. A major aspect of the prototype system effort was identifying the system deficiencies and reducing them to engineering problems. Many of the deficiencies could not be tackled with the prototype, and were reduced to engineering problems only after another, improved system was created.

The Acoustic Link (AL) Worked Better on BUMP

The AL (figure 9) utilized for AUSS was first developed at NOSC and tested on the Benthic Untethered Multipurpose Platform (BUMP) in 1981 (figure 10). BUMP was a free-descending, free-ascending platform that could remain anchored to the bottom of the ocean for extended periods of time. From BUMP, the AL transmitted 4800 bits per second (bps) data from a depth of 15,000 feet. The 4800-bps data were received and decoded at a drifting surface ship with a bit error rate of 10^{-6}. This was accomplished across the full extent of a 45-degree half-angle vertical cone with its apex at BUMP (Mackelburg, 1991).

The performance of the AL system on the prototype AUSS was not up to the BUMP standard. The beam pattern appeared to have "holes" (regions of very high error rates). Also, measurements of noise in the vehicle AL system showed that the signal-to-noise ratio on the vehicle was near the operational limit for the 2500-ft depth where all prototype tests had been conducted. Operations at greater depths would not be possible without significantly reducing vehicle noise levels. Further, experiments directed toward the investigation of the beam pattern holes revealed a correlation between high error rates and small Doppler shift in the AL carrier frequency.

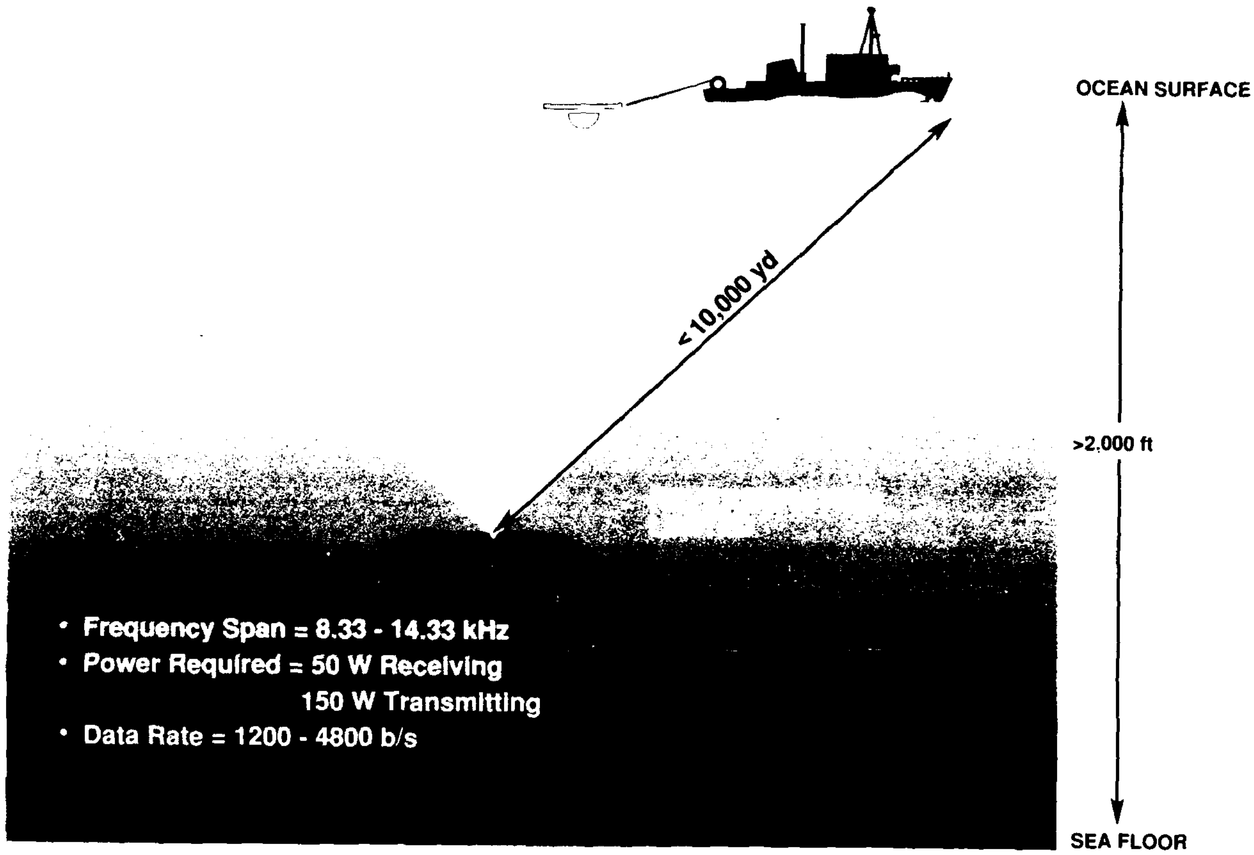

Figure 9. The acoustic link (AL).

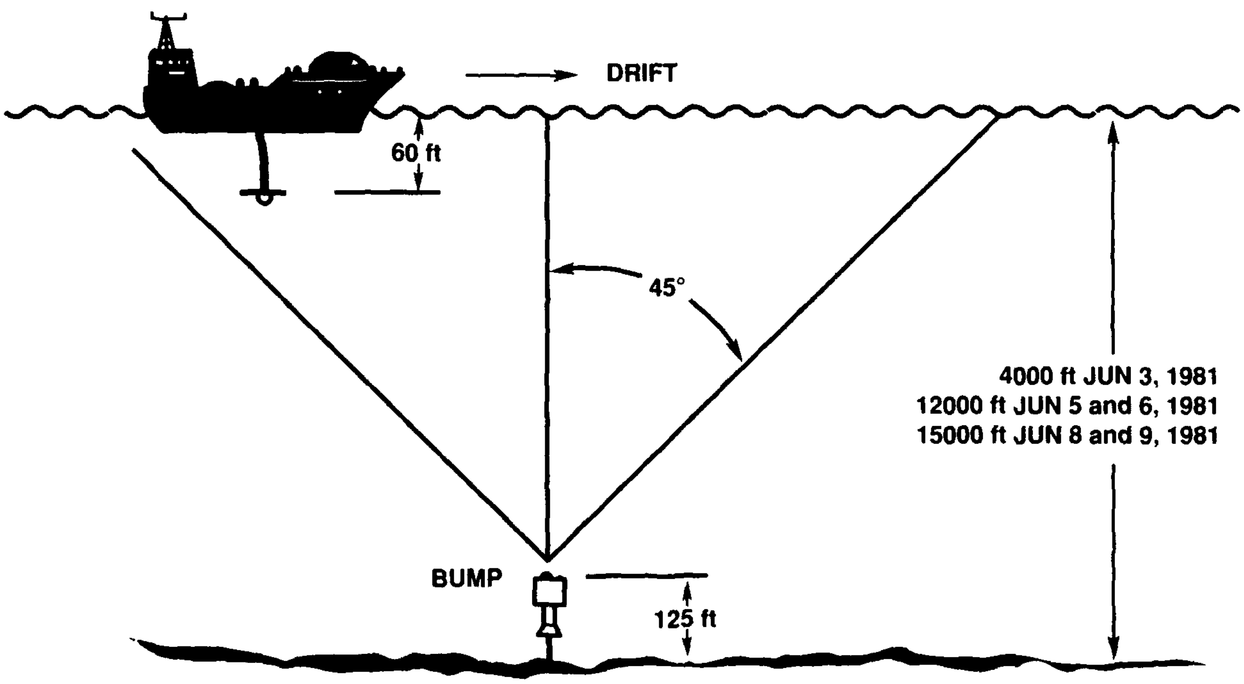

Figure 10. The AL tested on BUMP.

AL Deficiencies Are Definable

The Doppler shift in the AL was investigated both at sea and in the laboratory. The point at which the AL system was affected was at a carrier Doppler frequency shift corresponding to a relative velocity between the ship and the vehicle of 1 knot. A real-time Doppler correction technique was designed and implemented in the AUSS surface system. The main component of the Doppler corrector is a first in first out (FIFO) discrete circuit. The digitized AL signals are stored in the FIFO at the Doppler-shifted AL carrier frequency and read out into the AL system at the correct rate (11 kHz).

The AL performance was greatly improved with the implementation of the Doppler corrector. Because of this improvement, other sources of AL performance degradation were more visible and easier to analyze. The "holes" in the AL beam pattern, in particular a hole directly above the vehicle, were investigated both at sea and at NOSC's Transducer Evaluation Center (TRANSDEC). Observed were reverberations that occurred immediately after the direct-path return. These reverberations were determined to be from structure around the transducer. Although the reverberation situation was not improved upon in the prototype, the knowledge of its existence and cause were important products of the prototype effort.

Several noise-reduction "quick fixes" were developed and installed; however, the signal-to-noise ratio was not improved. The only way in which the noise problem could be dealt with would be during the system engineering design of an improved system.

AUSS Has Unique Acoustic Tracking Requirements

Vehicle tracking accuracy has been an issue of varying importance throughout AUSS history. Early on, when the system was expected to operate in the spot-scan mode, the accuracy of a SBL system was predicted as adequate. A high tracking accuracy was not required with the spot-scan approach because inaccuracy would be compensated for by overlap. With the spot-scan approach, the vehicle onboard navigation requirements were minimal, and pure dead reckoning was adequate to move from spot-scan center to spot-scan center.

The change from the spot scan to the SLS search concept changed the basic approach to vehicle tracking. It was expected that SBL tracking would not be adequate for the prototype SLS mission. Thus, the prototype system was fielded with SBL, LBL, and LBL fish-cycle systems. The LBL fish cycle was not dependable, so SBL became the primary prototype tracking system. SBL proved adequate in support of subsystem developments and testing. Along with other prototype subsystem testing, the LBL fish cycle was tested, investigated, and improved.

It Is Difficult to Net Fish-Cycle Gains

Sea testing with the prototype system brought to light many fish-cycle/autonomous vehicle characteristics. Almost no fish-cycle fixes were possible during vehicle transits.

Occasional fixes were possible with the vehicle hovering. The best vehicle altitudes for fish-cycle tracking were at the transponder net level and below. Increasing the width of the fish-cycle initiation pulse appeared to improve the percentage of successful fish cycles obtained.

The tracking investigations showed that a separate "stinger" transducer located behind the thrusters on the centerline of the vehicle provided the best performance of the fish cycle. The stinger improves the probability that a bottom transponder will respond to the direct path fish-cycle interrogation instead of the surface-reflected path by decreasing the possibility of bottom-mounted transponders being shadowed by the vehicle from the direct path of the vehicle-initiated interrogation pulse.

Eventually, the prototype fish-cycle tracking system was dependable for a hovering vehicle, and quite often the vehicle could be tracked in fish cycle while transiting.

EARS Could Be Simplified

The spot-scan search technique, as mentioned before, required only SBL for tracking. To support the SBL, and to also support the AL, a shallow-towed system was developed. This system, the External Acoustic Relay System (EARS), consisted of a tow winch and tow cable, a weighted depressor clump attached to the tow cable, and a streamlined towfish that was towed behind the depressor clump. The towfish contained the baffled AL transducer, SBL and LBL transducers, the SBL vertical reference unit, and a gyrocompass heading reference for the SBL.

The EARS provided a stable transducer platform that was decoupled from the ship motion. The EARS fish towed approximately 150 ft behind the ship, at approximately 150-ft depth. This tow position was meant to remove, as much as possible, the AL and tracking transducers from the noise of the ship.

The EARS allowed good SBL performance, but the focus shifted from SBL to LBL fish cycle as the spot-scan search was replaced with the SLS search. Also, tests that were conducted to see if the EARS towfish shaded the AL beam pattern in the forward and aft directions lead to the conclusion that the towfish was not needed for the AL or the LBL. The tests also showed that the suspected shading did not exist. The AL/LBL transducer was moved from the towfish to the clump, and the performance of both the systems remained the same.

All of the work with the EARS led us to the conclusion that the SBL (with acceptable performance degradation) could be operated on a transducer pole with its vertical reference unit and the gyrocompass onboard the ship, and the AL/LBL transducers could be operated from a towed depressor.

Vehicle Navigation Envelope Was Inadequate

The AUSS prototype vehicle navigation system consisted of a gyrocompass, a Doppler sonar, and software to produce components of vehicle velocity and vehicle position in a N/S, E/W coordinate system. During the prototype testing, this system operated properly only within two unacceptable constraints. The gyrocompass and the software performed properly, but the contractor-provided Doppler had a low speed threshold of 0.75 knot and a maximum operating altitude of 150 ft.

Sea testing provided data showing Doppler sonar electronics velocity outputs of 0 for actual vehicle velocities below 0.75 knot. This resulted in large calculated position errors during hovering and low-speed maneuvers. In fact, this threshold rendered hovering essentially impossible. Data gathered during sea tests also showed that the Doppler sonar data quality deteriorated when vehicle altitudes exceeded 150 ft. Attempts were made in vain to improve upon this threshold (AUSS search mission profiles include altitudes greater than 150 ft).

The prototype Doppler sonar was selected as the best available at the time, but it did not match up to its advertised performance. The bottom line is that the prototype Doppler sonar would not support the AUSS mission. The only solution was a better Doppler sonar.

Controlling the Vehicle Takes Diligence

The AUSS vehicle control system must be capable of controlling the vehicle in three-dimensional space, both while hovering and during transit. Yaw/heading control is accomplished by applying differential thrust on the horizontal thrusters in both hover and transit modes. Pitch is controlled by differential thrusts on forward and after vertical thrusters while in the hover mode. Dynamic depth/pitch is controlled by the elevator during transits. Depth control while in the hover mode is achieved by controlling the thrust on the vertical thrusters. Navigational control is achieved by issuing commands to the heading and depth control loops.

A simple computer model of the prototype vehicle and type 0 control routines were developed prior to the preliminary dockside testing. Both the model and the routines were refined until they were adequate for operating in the bay while on a tether. The vehicle's first few untethered at-sea operations showed that what worked well in the bay did not necessarily work well at sea. Using the information from the first few untethered dives, the control routines and the vehicle mathematical model were revised.

During the sea tests, it was seen that the type 0 yaw, depth, altitude, and pitch control loops resulted in unacceptably large offsets from the required values. The hover position and heading control routines, which use the Doppler velocity and position information, were found to be unstable in most cases, and drifted rapidly from the required location. The instability was due to the sample to sample noise in the velocity information. Also, as noted in the navigation section, the Doppler velocity information dropped out at velocities less than 0.75 knot. This dropout was a major cause for rapid drift of the vehicle while in hover.

A solution to the type 0 loop offset errors is to upgrade the control loops to type 1. The transit heading control routine was the first control routine to be converted to a type 1. With a type 1 control loop, the steady state error is zero. The trouble is that type 1 control loops are more difficult to stabilize. They require rate feedback to stabilize. In the prototype vehicle, digital differentiation was used to obtain rate feedback since there were no rate sensors. With some at-sea tuning of the control equation coefficients for the transit heading type 1, the control loop became stable with little offset from the commanded heading. The transit depth was also changed to a type 1 control routine, but stabilizing the loop was not possible. The mathematical model of the vehicle did not accurately model the transit depth mode of operation. Also, the use of differentiation of noisy depth and pitch sensors to provide rate feedback led to reduced stability of the loops.

Many important control system lessons were learned with the prototype. The transit heading control loop of the type 1 was tolerable, but would have been improved and simplified with the use of a yaw rate sensor. The transit depth control loop needed a more accurate pitch sensor and a pitch rate sensor to achieve the required control and stability. The hover and navigation control required a Doppler with zero or very small velocity dropout, and the Doppler sample to sample stability and noise was too large.

No One Makes AUSS Search Sensors

The AUSS concept employs both broad-area-search and contact evaluation sensors. The prototype broad-area-search sensors were port and starboard SLS. The contact evaluation sensor suite evolved to consist of an FLS, a 35-mm camera, a vidicon camera, and two strobe lights.

As stated before, the original preferred primary broad-area-search sensor for the prototype was a 360-degree scanning sonar to support spot-scan searching. An investigation into sonar developments showed hope that such a sonar having the range and resolution required for the AUSS mission would soon be available. With this in mind, the prototype was designed to demonstrate the spot-scan concept employing a FLS with a 180-degree scan and reduced range and resolution. As a result of an early design review and the strong urging of those in attendance, a SLS system was added. The SLS became the primary broad-area-search sensor due to its superior capability. The FLS was maintained as a target-closing sensor.

The FLS was originally procured from a contractor as a specially modified "Obstacle Avoidance Sonar." The modifications performed provided computer controlled interfaces to the standard wet-end and surface portions of the system. This was required for interfacing to the AUSS computers since the standard units are designed to operate on cabled systems. The processing and sampling were not flexible enough for the AUSS application. NOSC ultimately removed the contractor's computer interfaces, and designed a custom dedicated computer interface to the wet-end electronics. NOSC also replaced the contractor's surface PPI scan converter with surface computer display cards. The analog processing section of the sonar was heavily modified to provide improved pre-amp and detection electronics. The modifications resulted in an enhanced sonar. More sophisticated processing techniques were available with software under NOSC control.

The SLS and the FLS were supplied by the same contractor. The SLS electronics were similar to those of the FLS for which NOSC had already generated custom modifications. Only the transducers and front-end electronics were procured. The SLS front-end electronics were modified to duplicate the FLS electronics. A master-slave computer architecture was developed in which there was a master SLS computer to which slave port and starboard computers reported. With these extensive adaptations, these off-the-shelf sonars were made compatible with the AUSS.

The original ultracon video camera used on AUSS produced no usable pictures because its computer-controlled iris could not be adequately controlled when used with strobe illumination. As a result, a standard vidicon tube was installed in place of the ultracon tube. The vidicon provided usable images but with poor exposure control. Computer software was generated, which utilized the histogram of the digitized image in conjunction with linear contrast enhancement algorithms, to provide exposure and contrast control. The video and still cameras were synchronized with the firing of the strobe lights. The video images were frame-grabbed and digitized before transmission over the AL.

Onboard Recording Is Key to Sensor Mysteries

A vehicle onboard recording capability was implemented to analyze several prototype sonar and optical image problems. The onboard recorder originally consisted of a small reel-to-reel stereo audio recorder. Unprocessed sensor data were recorded in the vehicle and then analyzed after a completed mission. Unfortunately, the recorder had limited record time, was difficult to control, and provided poor postdive correlation of signals.

The reel-to-reel recorder was replaced by a hi-fi stereo video cassette recorder. The new recorder extended the amount and quality of data that could be recorded without incurring added weight or power penalties. In addition, video images obtained by the vehicle camera could be recorded.

The sonar interface electronics were modified to permit higher bandwidth and two channel simultaneous recording. The recorded sonar data were later used to provide a source of raw sonar data for signal and noise investigations, and laboratory testing of new sonar processing functions.

The "Black Hole" Mystery Is Solvable

A darkened centralized area of diminished sonar return on the FLS surface display was dubbed the "black hole." Extensive effort was expended to understand this problem so a solution could be found. Sonar signals were recorded onboard the vehicle and analyzed under a variety of controlled conditions. A major cause of the problem was a distortion introduced by the FLS acoustic-window nose section of the vehicle. The angle of incidence of the sonar wavefronts with the material of the acoustic window was non-normal and caused a refraction of both outgoing and returned sonar energy.

Experiments were conducted with the original FLS dome in place, with no dome, and with a specially fabricated hemispherical dome. The hemispherical dome significantly improved upon the original black hole, and the no-dome experiment eliminated the black hole. The FLS must be covered by a dome for hydrodynamic considerations, but the hemispherical dome actually worsened the hydrodynamics for the prototype vehicle shape. The only solution to this problem was a redesign of the vehicle shape that would include a hemispherical nose section.

Sensor Images Hide Behind Vehicle Noise

During FY 87, a major effort to increase the sonar signal-to-noise was pursued. It was found that a prime cause of the noise was the proximity of sensitive sonar electronics to motor controllers and high-current cabling. These wiring problems were primarily a result of the breadboard nature of the vehicle. Trunk lines for power were separated to isolate the sonar electronics from other portions of the vehicle system. In addition, DC-to-DC converters were added to further isolate the sensitive electronics and to permit more flexible grounding and shielding techniques.

As a result of the noise quieting efforts, the sonar capabilities were significantly improved. It became possible to detect weaker targets at greater ranges so that the sonars, both FLS and SLS, became marginally viable search sensors.

Prototype Computers Exhibit Flexibility

For the most part, the vehicle computer realtime operating system was RMX, and the backplane was Multibus I. The surface computers were a mix of commercial computers and NOSC-developed computer systems. The surface computer that interfaced directly with the vehicle, the surface console (SC) computer, was Multibus I, and used RMX and PLM. The surface overlays computer, and the surface flight recorder/ data logging computer were PC systems running under DOS.

To a large extent, each computer in the system operated independently of the other computers on designated, internally contained tasks. The tasks were allocated based upon function. This allowed the computer hardware and software to be developed independently as parallel efforts. A simple working system was integrated and tested as soon as possible, forming the baseline for further development. This was accomplished by focused parallel developments on only the five primary AUSS computers (the surface console computer, the main vehicle computer, the vehicle sensor processor, and the surface and vehicle AL computers). Once the baseline computers and software were proven in bay tests, enhancements to the five primary computers and development of the eight other noncommercial system computers were initiated.

The flexibility of the system development allowed enhancement implementations as at-sea operating lessons were learned. Some of these implementations included a GAIN command that allowed in-situ adjustments of the vehicle onboard control loop parameters via the AL, and a sensor processor utility command that provided the operator with a "user friendly" interface significantly increasing control of vehicle sensor operations. This laid the groundwork for numerous enhancements in sensor data handling; the ability to temporarily suspend the SLS transmissions to clear the acoustic channel for acoustic tracking fixes during vehicle turns; and the ability to retransmit video images at a higher resolution than originally transmitted.

An overlays computer was incorporated into the surface computer group to assist the operators in supervising the vehicle search operations. The overlays computer generated text and graphics that were merged with the pixel display output to form an annotated grid overlay. The operator was able to position a cursor over targets on the sonar display to mark those targets. The computer would calculate range and bearing to the marked targets. Also, a target closure algorithm calculated current drift from the apparent motion of the target between successive scans, and calculated recommended vehicle location and heading for an approach to the target from downstream.

A major shortcoming of the prototype system computers was their low reliability. Both the surface and vehicle computers used edge card connections. The use of parallel communications interfaces led to excessive interconnecting cables and excessive conductors in the cables. The software processing loads on the computers became unequal as at-sea system testing and evolution led to functional redefinitions. As might be expected with a testbed system, some of the computers reached the limit of their processing capabilities, while others remained underutilized.

The Prototype Could (Barely) Do a Search Demonstration

A search demonstration was conducted at the close of the AUSS FY 87 sea testing (Walton, Nov 1992). The demonstration was performed late in the prototype effort, just before prototype decommission, to benefit from earlier system improvement and risk reduction efforts. The demonstration was conducted in a well-developed operations area utilized for all previous AUSS dives. The area had a flat sandy silt bottom with a depth of 2500 ft. The operations area was a square of approximately 1 statute mile on a side. Targets had previously been deployed throughout the operations area.

The prototype system performance during the demonstration showed that the AUSS concept could significantly improve the state-of-the-art in search. The demonstration also showed that the prototype system had served its purpose, but was ready for retirement. Thirty-one percent of the search demonstration time was nonproductive time, resulting mostly from system failures. But, during the 3-hour and 45-minute mission, 3 targets were found and evaluated. The average time per contact evaluation was 30 minutes. The adjusted broad area SLS search rate (for SLS searching only, ignoring equipment failure times, operator error times and ignoring the 50% overlap used in the demonstration) was calculated at 0.4 nmi^2/hr. The adjusted overall search area rate (for all search time including contact evaluations, and again ignoring equipment failure time, operator error time, and ignoring the 50% overlap used in the demonstration), was 0.19 nmi^2/hr.

The testbed nature of the prototype and the many quick fixes required to produce the capabilities and performance required for the demonstration precluded fielding an optimized or even a near optimized system. Modifications to the testbed vehicle configuration to enhance the performance of subsystems were done at the expense of poor performance elsewhere.

The AL transducer and baffle were elevated above the body of the vehicle for good AL performance. The elevated transducer avoided acoustic shadowing previously experienced but adversely affected the vehicle hydrodynamics. The addition of the fish-cycle "stinger" transducer for improved tracking caused a static pitch trim problem. To compensate for the pitch trim offset, the still photograph 35-mm camera was removed, and counter balance weights were added in the appropriate locations.

The speed of the vehicle was limited to 1.6 knots to avoid along-track holidays (gaps) in the SLS data transmitted to the surface (maximum vehicle speed was near 5 knots). The prototype software was not sophisticated enough to assure that these holidays would not occur at higher speeds. The vehicle altitude was limited to 80 ft to avoid the Doppler sonar degradation that occurred at higher altitudes. The mission was designed to avoid vehicle velocities of less than 0.75 knot, which avoided the slow-speed Doppler dropout.

The search tracks selected were parallel to the water current. Water current transverse to the track of the vehicle could cause a transverse vehicle translation at a rate less than the 0.75 knot Doppler performance threshold, and would therefore go undetected. Short search legs were run to avoid large track-to-track error from the Doppler/gyrocompass system. The absolute magnitude of the Doppler/gyrocompass drift error increases as a function of time. An approximation of the actual track taken by the vehicle was determined not from the Doppler/gyrocompass system, but from LBL fish-cycle fixes taken of the vehicle whenever the vehicle was not advancing. The vehicle was slowly driven over target positions as pictures were taken for contact evaluations. This was done in lieu of hovering because the Doppler system would not support vehicle hovering.

RETIRE THE PROTOTYPE AND SYSTEM ENGINEER A REFINED MODEL

The prototype served the project well. Many technology areas had matured with the prototype. An acceptable approach to tailoring search sensors to the UUV search task had been established. Many system deficiencies had been defined, and some had been reduced to engineering problems. The search demonstration showed that the AUSS concept was a feasible approach to search, and that the potential existed to significantly improve search with the AUSS effort.

The Prototype Was a Tired Breadboard System

The law of diminishing returns forced the prototype system into retirement. It had been squeezed for all it was worth. The search demonstration showed a great search potential. But the prototype survived the short demonstration only through the efforts of the AUSS team, and several major system compromises. The prototype had become a product more of evolution than of its original system engineering. Post-design breadboard level implementations existed throughout, and an on-system upgrade program would have been monumental. The vehicle wiring was a major contributor to the poor signal-to-noise in the analog and digital systems onboard. The signal-to-noise in the AL system was such that the vehicle could not be expected to receive at depths much greater than 2500 ft. Unreliable edge card connections were standard in the system's Multibus I computers. Some of the computers processing capabilities were tapped out.

The prototype vehicle Doppler was inadequate for both hover and transit modes. The prototype vehicle was not stable enough for SLS operations. The shape of the vehicle required major changes to accommodate revised transducer installations and to avoid the FLS "black hole." The vehicle buoyancy consisted of an inadequate pressure vessel and many shaped pieces of syntactic foam. The pressure vessel did not support the vehicle buoyancy requirements, and was not capable of depths greater than 5,000 ft. The vehicle fiberglass fairings suffered from extensive modifications including holing, sawing, and gluing.

System Engineering and Team Experience Work Well Together

System engineering design, manufacturing, and fielding of an improved AUSS was the only logical way the program could continue to validate the concept and to advance SOAS. A particular advantage was that the prototype system developers who learned the AUSS prototype lessons could be the system developers of the improved system.

The core AUSS team was retained to design, build, and field the improved system. The system engineer held several team meetings to review the prototype lessons learned, the prototype deficiencies discovered, and to make and document decisions pertaining to the design of the improved model. Guidelines and design philosophy were defined, and meetings were held in which specific design issues were discussed. The system engineer led and arbitrated the discussions of the engineers of various engineering disciplines, and produced documents of design decisions for reference (Walton, 1988).

No Syntactic Foam Edict Allows Efficient Design

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

To maintain a small vehicle for 20,000-ft service, very efficient vehicle buoyancy was required. The graphite epoxy pressure vessel, as mentioned previously, was selected for its high displacement/weight ratio as compared to other 20,000-ft buoyancy-providing technologies. Syntactic foams for 20,000-ft service, on the other hand, are extremely inefficient, but are usually the best alternative as add-on buoyancy. As is the case for most undersea vehicles, syntactic foam was used extensively on the prototype. A commitment was made to avoid its use on the improved vehicle.

The commitment to relying solely on the graphite epoxy hull for buoyancy was met with the improved vehicle. The only syntactic foam in the system was the deployable nose float used for vehicle recovery. To meet this goal, several measures were taken. The graphite hull was the primary measure. Other measures were the use of Spectra™, a woven polyethylene material, for the free-flooded forward and after fairings; magnesium for the chassis inside the vehicle; Spectra™ for the battery packs; titanium for the wet connectors; and titanium and aluminum redesigns of various sensor housings.

The continuing NOSC pressure vessel program produced a graphite epoxy pressure vessel that tested adequate for 20,000-ft service. This was the fourth pressure vessel produced and tested for the AUSS effort. This final pressure vessel was manufactured using filament wound fibers pre-impregnated with epoxy. The change to the filament-wound construction rendered a pressure vessel that survived pressure testing that the previous broad goods constructed vessels could not survive (Stachiw, 1988). Spectra™ was selected for the free-flooded forward and aft fairing material. The Spectra™ has a specific gravity very close to that of sea water. Because of this, there is very little penalty in designing adequate structure into the fairings, and exotic lightening processes including shaving and lightening holing is not necessary. Figure 11 is a descriptive drawing of the improved vehicle.

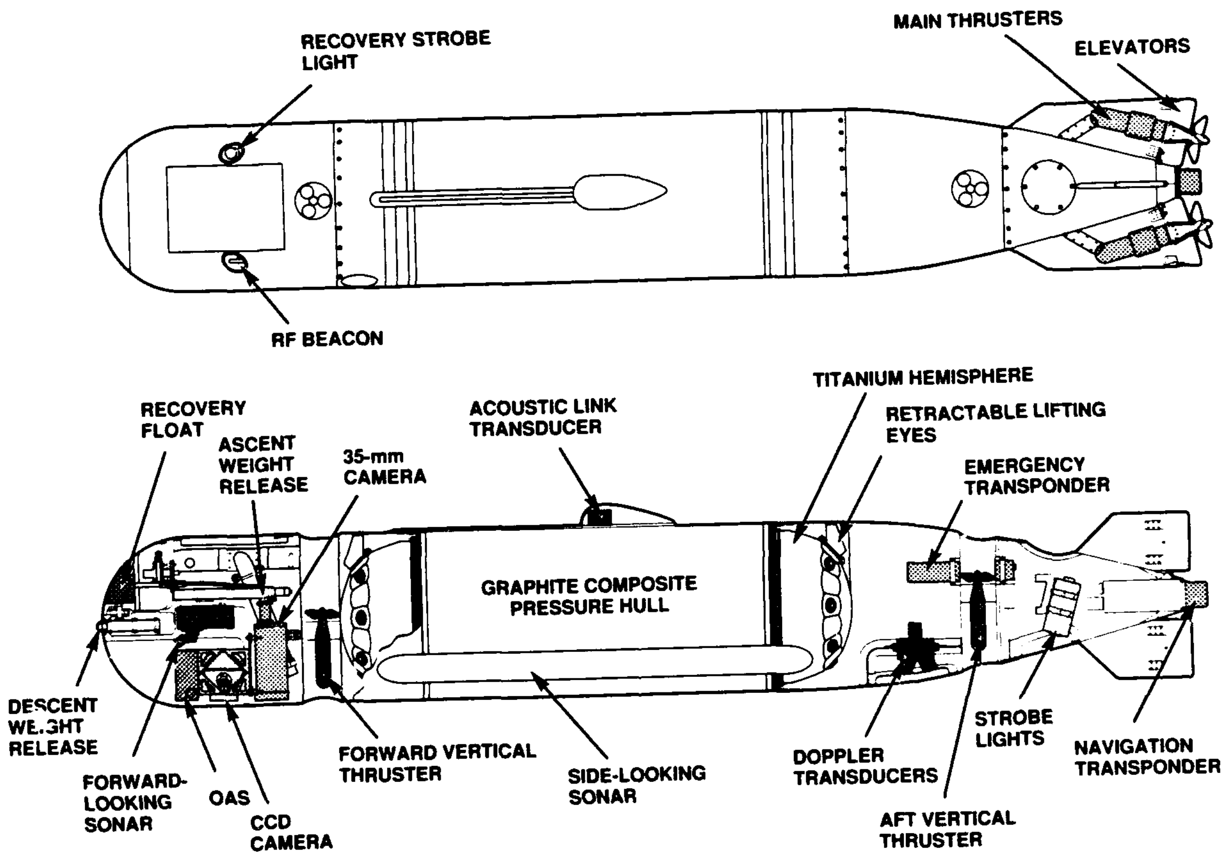

Figure 11. The improved vehicle.

The Improved System Benefited From Prototype Lessons Learned

The vehicle FLS was placed behind a polyethylene hemispherical half-dome cover. The cover was designed as part of the vehicle hydrodynamic shape. The vidicon camera was replaced by a cooled CCD camera for greater dynamic range, better sensitivity, and higher resolution. The prototype Doppler sonar was replaced by a Doppler sonar with higher accuracy, lower drift, much lower dropout, and higher operational altitude capability. A higher quality pendulometer and a rate sensor were added to improve the pitch transit loop, and a rate sensor was included in the yaw control loop. A much improved mathematical model of the vehicle was produced, and the latest software simulation tools were used to aid in the analysis of the control loops.

IBM PC hardware, the DOS operating system, and the C language were selected for the surface computers for ease of operator interface and existing hardware and software availability. Surface computer hardware was upgraded to industrialized 7552 PCs with PC cards adapted to pin and socket connectors. An in-depth review of the state-of-the-art in realtime systems led to a vehicle computer package consisting of the Multibus II backplane with pin and socket card connections, RMK operating system, and the PLM language. Serial communications were implemented, where possible, to decrease wiring. A "bit bus" serial communications system was selected for computer/sensor and computer/effecter communications.

The sonar electronics were designed from the ground up at NOSC, and the commercial transducers used on the prototype were retained. To improve upon the signal-to-noise in the sensors and the acoustic link, several equipment layout meetings were held wherein a commitment was made to arrange interior pressure hull components primarily based upon the noise environment. The design included extensive use of DC to DC converters for subsystem isolation.

The prototype's magnetically coupled brush dc motors were replaced by small brushless dc motors with integral motor controllers. The main propulsion motors/controllers were 3 inches in diameter. This allowed their placement in the horizontal stabilizer fins where they were directly connected to the propellers. This eliminates the use of inefficient drive trains and universal joints, eliminates wiring between the motor and controller, which may couple noise into other circuits, and places the entirety of the motor/controller function out in the water were it will not radiate noise into other circuitry.

To augment the AL sensor data transmission capability, a data compression system development effort was pursued. The first step in the effort was to define an approach. After research in the literature and analysis of the compression problem, a method based upon a two-dimensional cosine transform was developed. In this method, coefficients are produced by the transform and the most important coefficients are retained. Huffman and run-length coding are performed on these coefficients. Test software was written to test the transform and to perform compression and reconstruction of AUSS-type data. The test software was successfully applied to CCD camera files obtained through the camera manufacture and SLS image files obtained from AUSS prototype SLS analog data. Next, the compression algorithms were performed with commercially available digital signal processors. Due to dependability and availability problems, the digital signal processors were eliminated and the compression algorithms were handled by the AUSS system computers. The final compression configuration was set at this time.

The dependability, accuracy, and flexibility of the system acoustic tracking capability were improved by adding a new LBL tracking system. This addition provided the primary tracking capability during the subsystem development testing, but was used less during the search demonstrations. The new tracking capability consisted of a Sonatech NS11 transceiver, and a PC-based processor. NOSC-developed C language algorithms were implemented for transponder net surveys, tracking calculations, and integration of the surface and subsurface navigation and tracking systems.

The complex prototype EARS system was replaced by a transducer pole for the SBL, and a simple towed batfish depressor for the baffled AL LBL transducer. The launch and recovery system design was improved, mostly in the area of safety. All high-tension lines were eliminated. Onboard the ramp, 12-VDC power replaced both the pneumatics and the 220-VAC systems. A saddle/trolley system replaced a "tugger" system such that the vehicle is never free to sway or surge on hoist cables.

FIELD AND EVOLVE OPERATIONAL SYSTEM

The system engineering design of the improved AUSS was followed by detailed design and fabrication. The experience base of the AUSS team was even broader and deeper than before, so a stable system engineered AUSS emerged in hardware. Post manufacture evolutions on the improved system were predominantly expansions in capability, not additions and reworks.

Anyone Can Build Another AUSS Vehicle System

The improved AUSS vehicle (hereafter referred to as the vehicle) was manufactured and assembled on base at NRaD. The Spectra free-flooded forward and after fairings were manufactured to locally produced drawings by a contractor, and delivered to the on base Public Works Center (PWC) machine shop. At the machine shop, necessary machining was performed on the fairings, and NRaD designed hardware was built and installed in the fairings. Contractor-built sensors and devices were added to the fairings, and the fairings were mated with the graphite epoxy pressure vessel.

Electronics chassis were fabricated by the PWC machine shop per drawings developed by the AUSS team. The wiring on the chassis and backplanes on the chassis were completed by AUSS team technicians. About half of the circuit cards on the vehicle were specially designed, and the other half were standard commercially obtained cards. Card manufacturing occurred both on station and by contractors.

The surface vans were remodeled, and new control station equipment was fabricated and installed. The prototype launcher was reworked, and the new design features were added.

Large portions of the prototype vehicle software were salvaged, adapted to the new Multibus II/RMK environment, and supplemented with more software. New vehicle software was developed where necessary. The surface PLM software was rewritten in C, and a great deal of software was added to enhance the supervisory control capabilities of the operator.

Laboratory and Bay Testing Save Time And Money

Laboratory and dockside tethered test plans were prepared. The laboratory tests were prerequisite to the dockside tests, and the dockside tests were prerequisite to the sea testing. AUSS system engineering, team experience, and laboratory testing paid off. Only nine days of dockside testing were required prior to sea testing. Then, only two dives with a mechanical tether attached to the vehicle were conducted before the vehicle was set free.

As a result of the laboratory and dockside testing, command and control AL communications were checked through a wire, search sensor data AL transmissions and displays were checked through a wire, the Doppler was operational, the vehicle interior navigation sensors were calibrated, the Search and Recovery (SAR) system including weight releases was operational, the vehicle was trim, the propulsion system was operational, and all of the hover controls were operational.

The Dive Count Doesn't Count

The first dive with the improved AUSS employed a lightweight mechanical tether (nylon line) that suspended the vehicle 500 ft below a small boat. The AL and acoustic tracking systems were verified, and AL command release of the ascent weights was accomplished. Open-ocean launch and recovery was verified. The second dive with the system employed a lightweight mechanical tether (nylon line) that again ran from the small boat to the vehicle. This time, the vehicle was anchored 150 ft above the bottom (the bottom was at 2500 ft). AL and acoustic tracking performance at depth were evaluated. Vehicle onboard computers and subsystems were exercised. The ascent weights were dropped and the vehicle was released from its anchor by AL command.

The first two dives with the improved AUSS were subject to a mechanical tether. This compares to 18 tethered dives required with the prototype system. The third through the last dive, the 45th dive, were with the vehicle totally untethered. The emphasis of these dives was different from the prototype dives. During the prototype evolution, the concept of an untethered vehicle was still relatively new. Part of proving

AUSS technical viability depended upon showing that the vehicle could be deployed several times, do some operating, and be recovered. The prototype was subjected to 89 dives total (including the tethered dives), several times exposing the vehicle and the AUSS team to two dives in one week. The improved system was involved in 45 dives, and, during these dives, demonstrated a vast performance advancement over the prototype. The evolution and development of the improved AUSS set the pace for the at-sea test schedule. The criteria for a sea trip were clear test objectives made possible by completion of a specified list of system developments, subsystem integration, and repairs.

Subsystem Evolutions Support System Successes

From the beginning of the improved system sea testing until the final search demonstrations, operations provided catalysts for improved tactics, improved software implementations, and lessons learned in the area of supervisory controlled search.

Laboratory testing and TRANSDEC testing supplemented the at-sea testing. Whenever possible, subsystem problems were solved in environments other than at sea. But, as the system evolved to higher and higher levels of operational capability, it became more difficult to proof the capabilities and investigate subsystem problems in any other environment than at sea and with anything less than the complete operational system (Walton, December 1992).

Problem Propulsion Controllers Breed Creativity

The vendor supplied brushless DC propulsion motors/controllers on the improved AUSS vehicle were selected for all the right reasons as mentioned in the Systems Engineering section above. In reality, they were a real problem. Throughout the sea tests, motor controller failures accounted for more system down time than any other subsystem.

The first approach used to deal with the problem was to send units back to the vendor. The vendor improved upon some marginal designs in the circuitry. Motor systems continued to fail during operations, but once power was reset at the surface, the motors would run properly. This led to a theory that the controllers failed in some way due to the cold at 2500 ft. Lab tests were configured in which the motors/controllers were run in a chilled bath of water. Eventually, the chilled motors were also connected to a dynamometer. A protection circuit was discovered in the controllers, which tripped the motors out under the combined condition of cold and motor reversal under load. Also, the motor systems had vastly unmatched operating ranges with differing deadband regions and differing maximum performance points. A program of testing all AUSS motor systems was conducted where cold and room temperature dynamometer performances were documented. The documented test results were then sent to the vendor with the motor/controllers.

Motor systems with reasonable operational history and performance curves were retained to continue the AUSS at-sea testing. In time, the vendor was able to find fixes to the motor system problems. When repaired systems were returned and successfully retested, the remaining units were sent in for rework. Ultimately, the motor systems no longer bore the responsibility of terminating dives.

Operationally, the motor reliability situation offered several challenges. Operational decisions were made based upon whether or not the motor systems were supporting a mission. When a motor did fail during a mission, contingency plans focused upon tests that did not require the failed motor. For instance, transit control loops were tested after a vertical motor (not used in the transit control loops) had failed.

Our motor system problems were not limited to those of reliability. A controller operating frequency of 40 kHz was originally selected for the improved AUSS motor systems. The 40-kHz frequency and its harmonics would not have interfered with sonars or the AL on the vehicle. But, the motor controller frequency was not fixed at 40 kHz, and varied from motor to motor. Harmonics of the motor controllers showed up in the form of electromagnetic interference (EMI) in the sonar frequency bands.

Several steps were taken to mitigate the motor EMI in the sonars. Motor systems (motor/controller) were hand picked such that they would not have harmonics in the sonar operating bands. One of the most affected sonars was the FLS. The FLS frequency was changed to eliminate the harmful controller harmonics in its operating band. Also, filters were placed in the power lines to the motor controllers to decrease the conducted controller EMI that showed up in the power system.

The AL Performs Well

At the onset of the improved system testing, a satisfactory final approach to the AL baffle had not been found. In cooperation with the sea tests, AL tests were performed at NRaD's TRANSDEC facility. As in the prototype, reverberations from structure around the vehicle transducer continued to corrupt the AL signal. Finally, the transducer was moved to the top center of the graphite pressure vessel. This was a compromise in hydrodynamics, but was accepted because of the paramount importance of the AL. The method of mounting and the height of the transducer mount above the pressure vessel were critical. After several TRANSDEC evolutions, an acceptable configuration for the AL transducer on the pressure vessel was found. A major lesson learned was that a transducer and baffle configuration must be tested with the entire vehicle at TRANSDEC to determine the final system acoustic characteristics.

The improved electrical noise environment onboard the vehicle (improved over the prototype) was evidenced by some new problems. In the case of the AL, the improved signal-to-noise led to an AL "false carrier detect" and a "double ping."

These problems resulted because the more sensitive vehicle AL system "mistook" attenuated reverberated uplink transmissions as downlink transmissions.

The vehicle AL must periodically suspend transmissions (go quiet) and shift into the receive mode to listen for down transmissions. The presence of carrier is the means by which the AL "knows" there is a down transmission. When the vehicle detects the presence of the AL down channel carrier frequency, up transmissions are held off until the carrier goes away. Originally, the same frequency was used for up and down channel carrier. Reverberations from the up channel created a "false carrier detect" that would unnecessarily hold off uplink transmissions.

In navigation mode 3 (Osborne and Guerin, 1992), the vehicle sends out a ping to interrogate the bottom transponder field when the vehicle has completed an up transmission. When an up transmission was completed and a ping sent out, a reverberated carrier from the transmission was interpreted as a down transmission. Failure to obtain synchronization with the fictitious down transmission caused the vehicle to re-enter the receive mode and send out a ping. This occurred several times in a row and was referred to as a double ping.

To avoid the false carrier detect and the double ping, the single frequency AL was separated into two frequencies (11.33 kHz for the up channel and 10.989 kHz for the down channel). The reverberated signal no longer was mistaken for the down transmission and the problems disappeared.

Respectable AL performance was achieved due to the low vehicle noise environment, the implementation of the AL Doppler corrector, use of dual frequency, and the placement of the AL transducer on top of the pressure hull. Dependable 2400 bps communications supported operations from depths of 2500 ft to 12,000 ft. Communications of 4800 bps were not consistently used because the error rate increased with its use. Typically, one bit of transmission error resulted in the loss of 16 pixels in a compressed sensor image. Yet, some great performances were observed. For instance, an uncompressed 4800 bps CCD image contained only two errors for a 256 x 256 pixel x 8-bit resolution. This computes to a bit error rate of 3.8×10^{-6}, surpassing the project objective of 10^{-5} (Mackelburg, 1991).

Data Compression Complements the Acoustic Link

Sensor data compression was a boon to system performance. The criteria for performance is search area rate, and the rates at which SLS and CCD images are transmitted through the AL play heavily in the overall search area rate. High-resolution compressed CCD images were transmitted in less than 30 seconds throughout the improved system sea tests, tremendously enhancing contact evaluations. With compression, information preserving 1000-ft-range SLS images were obtained for vehicle advance speeds exceeding 4 knots with no along-track holidays. This performance resulted in SLS search area rates above 1 nmi^2/hr.

Artifacts originating during the transfer of data for compression in the vehicle occurred throughout the improved system sea testing. These errors generally corrupted part of a single 16 x 16 pixel sensor display block. The visual appearance of the artifacts was such that they became referred to as "worms." These worms were reduced to near extinction with the implementation of a technique that threw out and retransferred a section of compressed data if a check sum error was found within it (Watson, 1991; Uhrich and Watson, 1992).

Sensor Images Rise Above the Noise

The improved noise environment, the switch to a CCD camera, and the bottom up design of the sonar circuitry paid off handsomely. Exceptional sensor performance greatly enhanced the system search capability.

Good quality compressed CCD images of a World War II Dauntless bomber were transmitted through the AL and displayed for vehicle altitudes above the bomber as high as 65 ft. Another compressed CCD image was obtained of the canopy and cockpit of a Skyraider bomber where the CCD camera was approximately 3 ft above the canopy.

The SLS system provided a broad range of good images. Images as small as a desk drawer were clearly imaged out to 500 ft, and items such as the Dauntless bomber were clearly imaged at nearly 1000 ft. Successful 4 and 5 knot search patterns were run with no holidays and the SLS system scanning at the 1000-ft range scale.

Diligence Pays Off in Control

The AL, in conjunction with the vehicle onboard flight recorder, are invaluable tools in refining the control loops on the vehicle. The flight recorder records (in non-volatile memory and on a removable hard disk) vehicle data such as depth, altitude, pitch, roll, heading, Doppler velocity, and Doppler position. The flight-recorder non-volatile memory can be accessed and its data transmitted through the AL. Flight-recorder data obtained through the AL are plotted using an offline computer and plotter. Control systems performance is investigated in this fashion. To enhance this utility, control-system parameters such as loop gains and integrator limits can be adjusted at sea, and sent through the AL to the vehicle.

Dockside tests showed that the hover control loops were properly implemented and appeared to be stable. During the untethered at-sea tests, some instability and offset were observed in the hover system. In particular, the hover altitude jittered due to the noise from the sensor that the altitude loop is closed on, the Doppler. There were several feet of offset between the commanded hover depths and altitudes and the actual depths and altitudes respectively.

An improvement in the hover altitude control loop was accomplished by averaging the altitude over a 5-second period. Another improvement effectively closed the altitude loop on the depthometer instead of the Doppler altitude. The Doppler altitude and the vehicle depth were added to get a running average ocean bottom depth, and the vehicle depth was subtracted off to get an instantaneous altitude for closing the loop.

To eliminate the hover depth and hover altitude offsets (errors created by the net buoyancy of the vehicle) the depth and altitude loops were changed from type 0 to type 1. This is done by implementing limited integrators in the loops. Unfortunately, this resulted in some overshoot. The limited integrators integrated for too long and did not "de-integrate" until after the objective depth or altitude was passed. To correct this problem, "type switches" were implemented. The type switch is triggered by software that senses when the rate of change of depth/altitude decreases below a specified threshold. For rates above the threshold, the control loops are type 0, and for rates below the threshold, the control loops are type 1. This avoids the high values of integrated error fed back from the fulltime type 1 control loops.

The transit (underway) depth and altitude control loops worked well with a few exceptions. The altitude loop was subject to the Doppler noise, and both of the loops exhibited some overshoot. The Doppler noise problem for the transit loop was dealt with similarly to the Doppler noise problem in the hover loop. The overshoot was abated by adding pitch rate feedback to the depth and altitude outer loops.

The LBL Tail Wags the Mission Dog

The improved AUSS became more and more efficient at conducting search in the deep ocean as the development testing continued. Soon, AUSS search area rates were such that the area of a typical fish-cycle LBL transponder net could be searched within 1 to 2.5 hours. It is feasible to lay and survey a transponder net of this size within 10 hours. The AUSS single dive time is 10 hours, so about 4 times as much time would be spent deploying and surveying transponders as would be spent searching the areas during a mission. As the AUSS capability increased, the LBL tail began to wag the mission dog.

SBL integrated with a surface-ship tracking system, however, does not require the overhead of the transponder field deployment and survey. SBL is less accurate, especially as tracking geometry degrades with increasing depth.

The time disadvantage of the LBL led to some new thinking regarding the AUSS mission. Several successful AUSS search demonstrations in depths down to 5,000 ft were conducted without an LBL transponder net. The position of the vehicle was determined by using an average of several SBL tracking "fixes" for a hovering vehicle. Then the vehicle ran search patterns employing overlap sufficient to compensate for the track to track error of the Doppler gyrocompass navigation system. When a target was found and evaluated, the SBL was again used to fix the position of the hovering vehicle and, therefore, fix the position of the target. This technique was used to find and fix the position of two aircraft, a fishing boat, and several debris fields. One of the aircraft, the Dauntless bomber, was easily returned to on subsequent dives.

However, there were many novel UUV tracking techniques developed or demonstrated by using the NRaD tracking system. Most of these techniques relied upon the ship position being fixed by GPS. Two of these techniques were passive tracking and umbrella tracking. With passive tracking, the AUSS vehicle position was determined after a single ping was sent out from the vehicle to interrogate the transponder net. The advantages of the passive tracking technique were that the vehicle would not send out the ping until it "knew" the acoustic channel would be free, and it obtained a vehicle tracking fix with only one tracking cycle (fish-cycle tracking takes two cycles, which takes about twice as long).

With umbrella tracking, the position of a hovering vehicle was determined by using a collection of slant ranges to the vehicle from several ship positions. The position of the vehicle was the point of intersection between the depth plane of the vehicle and spheres with centers at the ship positions and radiuses equal to the corresponding slant ranges. Umbrella tracking, under some circumstances, may replace SBL as the tracking system of choice for an AUSS mission since it does not require a transponder net (Osborne and Guerin, 1992).

The Doppler Could Be Good Enough

Doppler/gyrocompass dead-reckoning vehicle navigation was successfully used to perform several search demonstrations. The Doppler position register was zeroed at the beginning of these demonstrations, and, although acoustic tracking fixes were obtained during some of the demonstrations, updates to the Doppler position were not deemed as necessary.

Unfortunately, the Doppler did not operate perfectly. Tests were constructed to determine what factors affected the Doppler. It was found that the Doppler scale factor was affected by the presence of its polyethylene cover and by the altitude at which the Doppler was operating. Also, increased dropouts in Doppler data occurred with increasing altitude. The Doppler drifted at a rate within 1 ft per minute when hovering at high altitudes or attached to its descent string (140-ft altitude) and this drift rate increased beyond 1 ft per minute during vehicle AL transmissions. Although greatly improved over the prototype Doppler, there is a minimum velocity dropout with the improved system Doppler. Without information on the level of and the cause of these effects, the amount of overlap required for AUSS vehicle search patterns is not accurately known. Search track overlap must be exaggerated, which decreases the overall search rate. The ultimate goal is to correct these deficiencies, and gain an understanding of the resulting Doppler performance.

The Doppler turned in some excellent performances in spite of the aforementioned deficiencies. Nearly all of the search demonstrations at the close of the AUSS testing were conducted with the Doppler/gyrocompass system as a dead reckoner with no updates required from the tracking system. During a particular test, the vehicle surveyed and marked a target in Doppler coordinates. The vehicle left this target for 4.5 hours, while it performed a number of search tasks, including photomosaic and SLS patterns with AL transmissions, and came back for another marking. The target marks in Doppler coordinates differed by only 157 ft. Ignoring any inaccuracies that might exist in the target marking itself, this computes to a "dynamic" drift rate of 0.58 ft per minute. To put this into perspective, if a typical AUSS search grid is 3 nmi x 3 nmi such that the lanes are 3 nmi long, the lane to lane overlap required due to this Doppler drift alone for the vehicle advancing at 5 knots would be only 21 ft.

Search Systems Revelations Are Rewarding

The improved AUSS benefited immensely from the prototype effort. It was system engineered from the ground up, leaning heavily upon the lessons learned during the prototype evolution. Many technical deficiencies were identified with the prototype. These deficiencies were reduced to engineering problems in both the prototype and improved system efforts. Most of the engineering problems were solved during the system engineering and evolution of the improved system. A high level of engineering refinement opened the door to many operational revelations, which led to further refinement and enhanced capabilities.

Nothing Rivals Experience

A dependable operationally improved system emerged from the system engineering and early sea-test efforts. With an operational system, the AUSS team was able to gain more experience with a supervisory controlled semi-autonomous search system. With the problem solving mostly behind them, the team was able to focus on operating the system, and enhancing the capabilities of the basic AUSS.

UUV Evolution Is Sea Test/Development Interactive

A major lesson learned was that a system such as AUSS must be developed interactively with the use of the deep ocean as a laboratory. The complex interactions between multiple acoustic devices and subsystems on board a UUV cannot be ultimately proofed elsewhere.

Tactics of the search mission with a UUV are best attempted, observed, and refined at sea. Many operational techniques were attempted and abandoned with AUSS, and observations of performance at sea led to improved tactics, improved hardware, and new capabilities.

More Autonomy Begets Depth Independence

The speed of sound in water affects the response time of the vehicle to supervisory commands. The speed of sound also affects the time taken for the supervisor to begin receiving sensor information. These times increase as the distance to the vehicle becomes greater. Supervisory commands will take a minimum of 4 seconds to reach the vehicle at 20,000 ft. It will take a minimum of 4 seconds for an image transmission to begin reaching the surface from 20,000 ft. System performance must be as insensitive as possible to the response time for supervisory commands or the transmission time for sensor images. Generally, if it is sensitive to these, the system performance is degraded as the depth is increased.

The AUSS operator is best suited to supervise vehicle activity where immediate vehicle response (within seconds) is not necessary. This restricts the operator to the area of major decision making. Operator decisions include definition of the search area to be covered, vehicle readiness at the onset of a mission, position of search initiation, search sensor image interpretation, target recognition, initiation of contact evaluations, extent of contact evaluations, termination of contact evaluations, continuation of a mission, and termination of a mission. In the time between these supervisory decisions, the vehicle must autonomously carry the mission.

The desired level of contact evaluation autonomy was not available with the prototype, but was realized with the improved system. During the prototype development testing and during early testing of the improved system, contact evaluations were conducted with the vehicle taking pictures of the target of interest while it glided over the target. There was only a short window of opportunity in which pictures of the target could be obtained. Optical acquisition and reacquisition of the target was time consuming.

The AUSS vehicle does not have side thrusters to negate a component of water current transverse to the path of the vehicle. Contact evaluations are best performed with the vehicle heading into the current. The prototype contact evaluation technique started by determining the local water current vector, and then approaching the target from downstream. The target was acquired with the FLS, and the vector from the target to the vehicle was determined from the displayed FLS surface image. The vehicle held its heading as it drifted with the current. A second FLS scan and a second vector were obtained. An off-line surface computer was used to determine the current vector from the two FLS vectors. The offline computer also provided a vehicle coordinate position down current from the target from which the vehicle could initiate its glide over the target. The human supervisor was required to "steer" the vehicle over the target, and command the taking of pictures at the appropriate time. This was marginally possible at 2500 ft. This technique would be much more difficult, and maybe impossible, at greater depths since the combined AL/supervisor reaction time would increase.

A hover at a radius routine was implemented during the improved vehicle evolution. This simple routine mimics a boat standing off from a buoy. The algorithm requires the vehicle to point at a position and maintain a given standoff from that position. The vehicle maintains the standoff and eventually "vanes" around to a heading into the current. The vehicle Doppler sonar (where the vehicle position is defined) is located approximately 10 ft behind the CCD and 35-mm cameras (where the pictures are taken). Using a standoff of 10 ft from an objective target for the hover at a radius routine theoretically maintains the cameras over the target. This is a completely autonomous routine that requires only one supervisory command to send the vehicle to a target. At the target position, the routine holds the cameras over the objective as the vehicle vanes into the current. The hover at a radius was also used during FLS scans. Hover at a radius has proven to be very depth insensitive and has been used effectively for depths between 2500 ft and 12,000 ft.

If it Works it Can Become Friendly

The improved AUSS demonstrated that broad area search and immediate contact evaluation could be accomplished dependably with a large improvement over the state-of-the-art search capabilities. The AUSS team was able to conceive of and implement innovative search system advances as the system became operational and more dependable. A number of these advances were aids that helped the human operator supervise the undersea vehicle operations. One of the advances was the hover at a radius capability mentioned above; another was target marking. The synergy of hover at a radius and target marking made a significant contribution to the efficiency of contact evaluations.

Target marking is a technique by which a cursor is placed over a sensor target image on the operator control console and a position for that target is automatically computed in the vehicle Doppler/gyrocompass coordinate system. Target marking was applied to SLS, FLS, and CCD portions of the mission.

The SLS target marking routine was conceived of and its basic implementation defined during the system engineering phase of the improved vehicle. The routine calculates a position for the target relative to the vehicle by using the cursor position on the SLS screen. From the cursor position, a slant range and a SLS ping line number are determined. Vehicle position, heading, and altitude at the time of the ping are determined by interpolation of data sent to the surface from the vehicle. From this information, the position of the target in vehicle coordinates is calculated.

The FLS routine used the cursor position on the FLS screen to determine the slant range and the angle of the FLS transducer head when the image under the cursor was obtained. The vehicle position, heading, and altitude are used with the slant range and transducer angle to calculate the position of the target in vehicle coordinates.

The CCD routine uses the cursor position on the CCD screen, vehicle altitude, vehicle heading, the distance between the camera and the Doppler, and the vehicle position to determine the position of the target under the cursor in vehicle coordinates.

A SLS target mark is used to determine a position for the vehicle to go to, hover at, and obtain an updated target mark with the FLS. FLS target mark is used to determine a position for the vehicle to go to, hover at, and obtain the first CCD image. The cursor is moved about on the CCD screen to determine positions for the vehicle to go to and obtain CCD image coverage of the target area.

DEMONSTRATE THE CAPABILITY

Supervisory Controlled Search Is Vindicated

Word of the impending end to traditional AUSS funding was received on 1 April 1992. This provided us an opportunity to obtain a snapshot of the system capability and "showcase" for a period of time. The 65 hours of bottom time during 8 dives in a 81-day time period between 5 April and 24 June produced some compelling results. SLS search rates up to 1.5 nmi^2/hr, contact evaluations typically taking between 10 and 15 minutes, "fully" operational dives between 2500 and 12,000 feet, depth-independent supervisory controlled search tactics, and excellent compression-enhanced acoustic link performance to 12,000 feet, were all demonstrated. This is where it all came together.

During a single dive at 4000 ft, consistent SLS search was conducted at speeds between 4.5 and 5 knots with a swath of 2000 ft. The area searched during the dive was 7.5 nmi^2, and the time to conduct SLS search plus contact evaluations was 8.5 hours. This demonstrates an SLS search rate better than 1.5 nmi^2/hr and an overall search rate (including contact evaluations) of 0.9 nmi^2/hr.

The passenger compartment of a 1940 Oldsmobile was searched for, found, and inspected (figures 12 and 13) during a dive at 12,000 ft. The vehicle operated at 12,000 ft for 11 hours. The images were transmitted through the acoustic link at 2400 bps.

Communications during the 12,000-ft dive were excellent, and search and contact evaluation tactics proved to be depth insensitive.

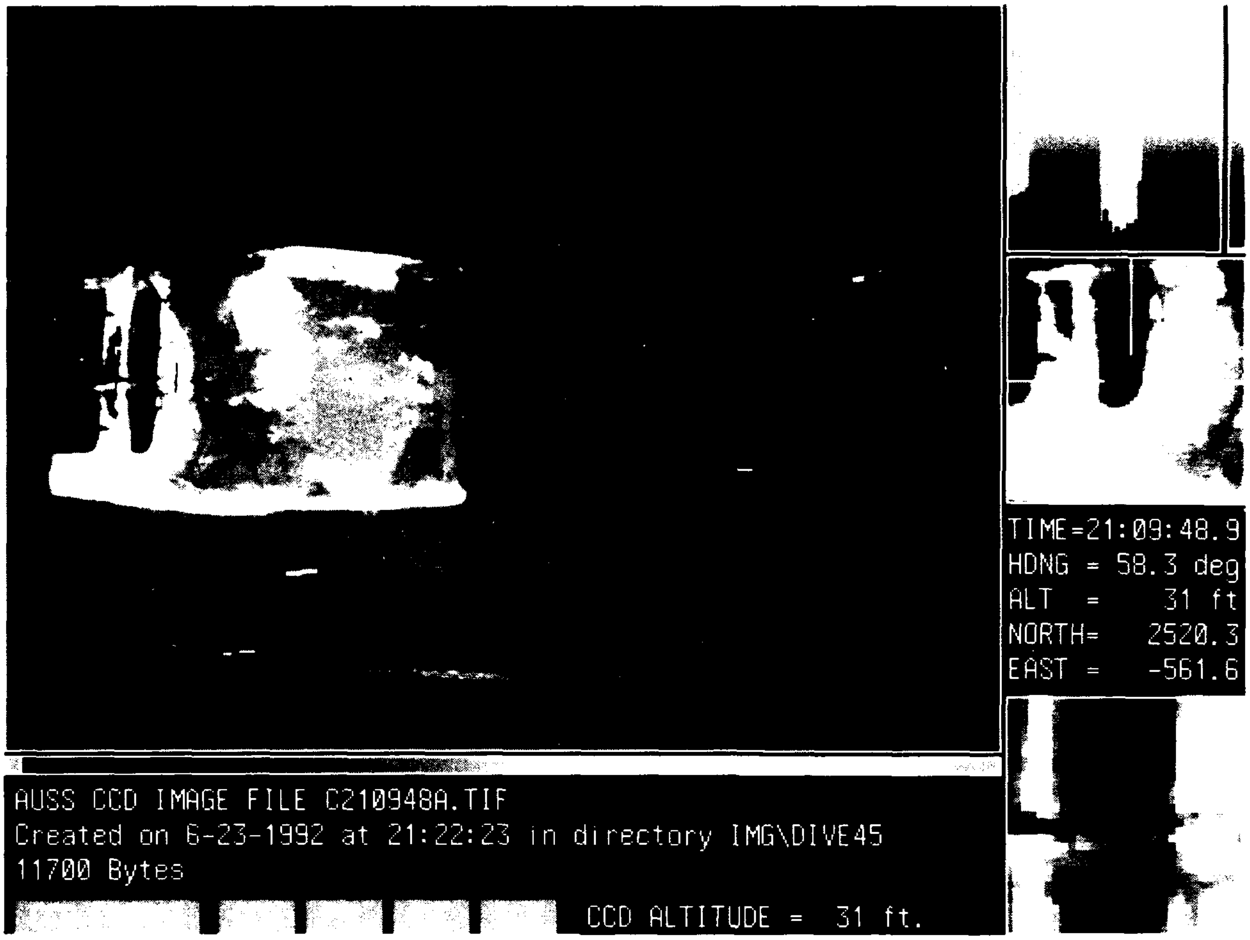

Figure 12. Acoustically transmitted image from 12,000 ft, 31-ft vehicle altitude.

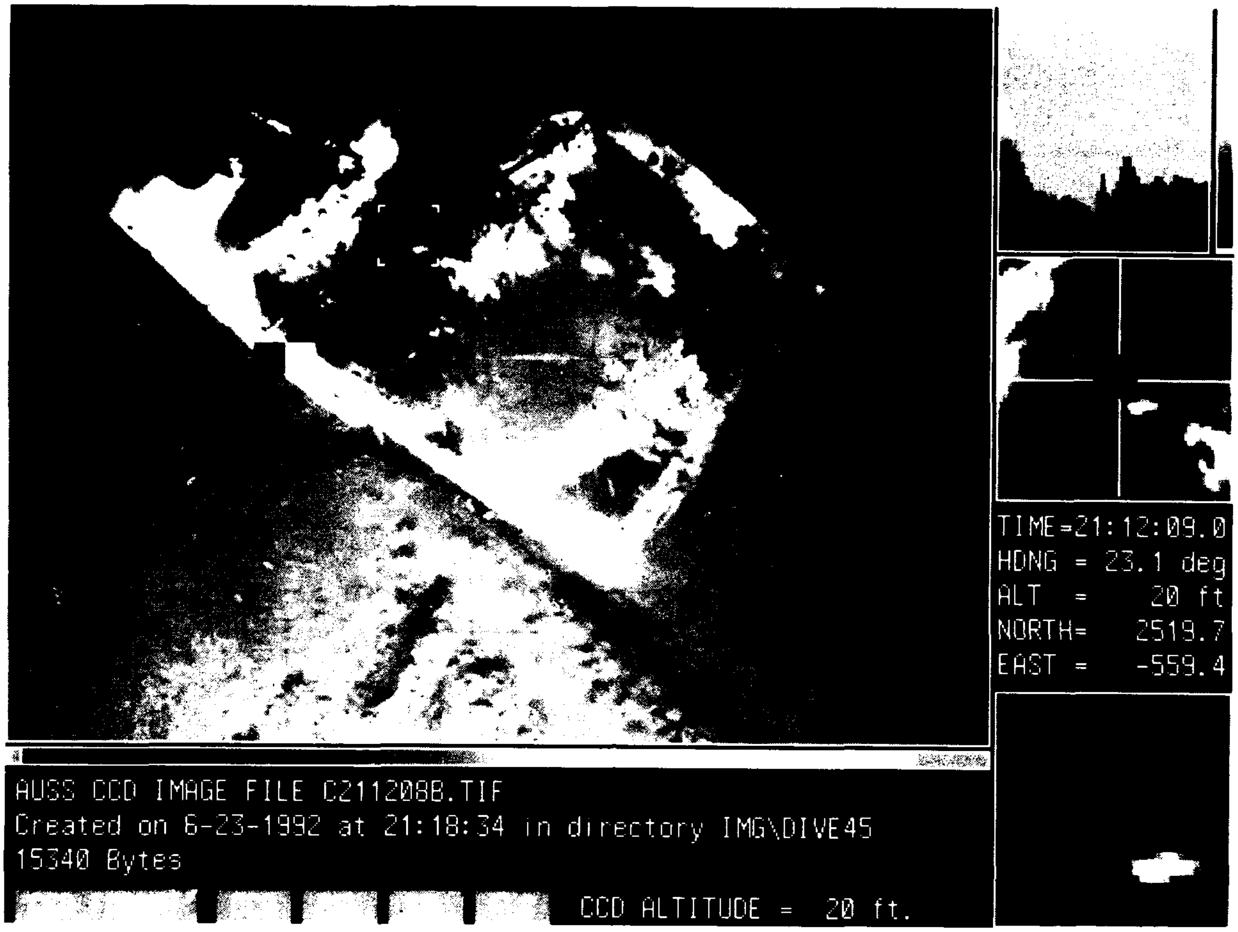

Figure 13. Acoustically transmitted image from 12,000 ft, 20-ft vehicle altitude.

Within a single 4000 ft dive, photomosaics of three target areas previously identified were conducted. A few of the acoustically transmitted low-resolution CCD images from the Dauntless Bomber mosaic can be seen in figures 14 through 17. The Doppler coordinate photomosaic pattern for the bomber is seen in figure 18. During this same dive, a 55-ft yacht and a Korean War vintage Skyraider night fighter aircraft were discovered with SLS, and inspected with CCD. Figure 19 is the FLS image of the yacht from the stern, and figure 20 is the CCD image taken from approximately the same position. Figures 21 and 22 are other CCD images of the yacht. Figures 23 through 25 are some of the CCD images of the aircraft. After finding, inspecting, and identifying the position of these targets, AUSS went on to cover 0.9 nmi^2 more search area. During this 14-hour dive, over 2.5 nmi^2 were searched, including several lengthy contact evaluations and three photomosaics.

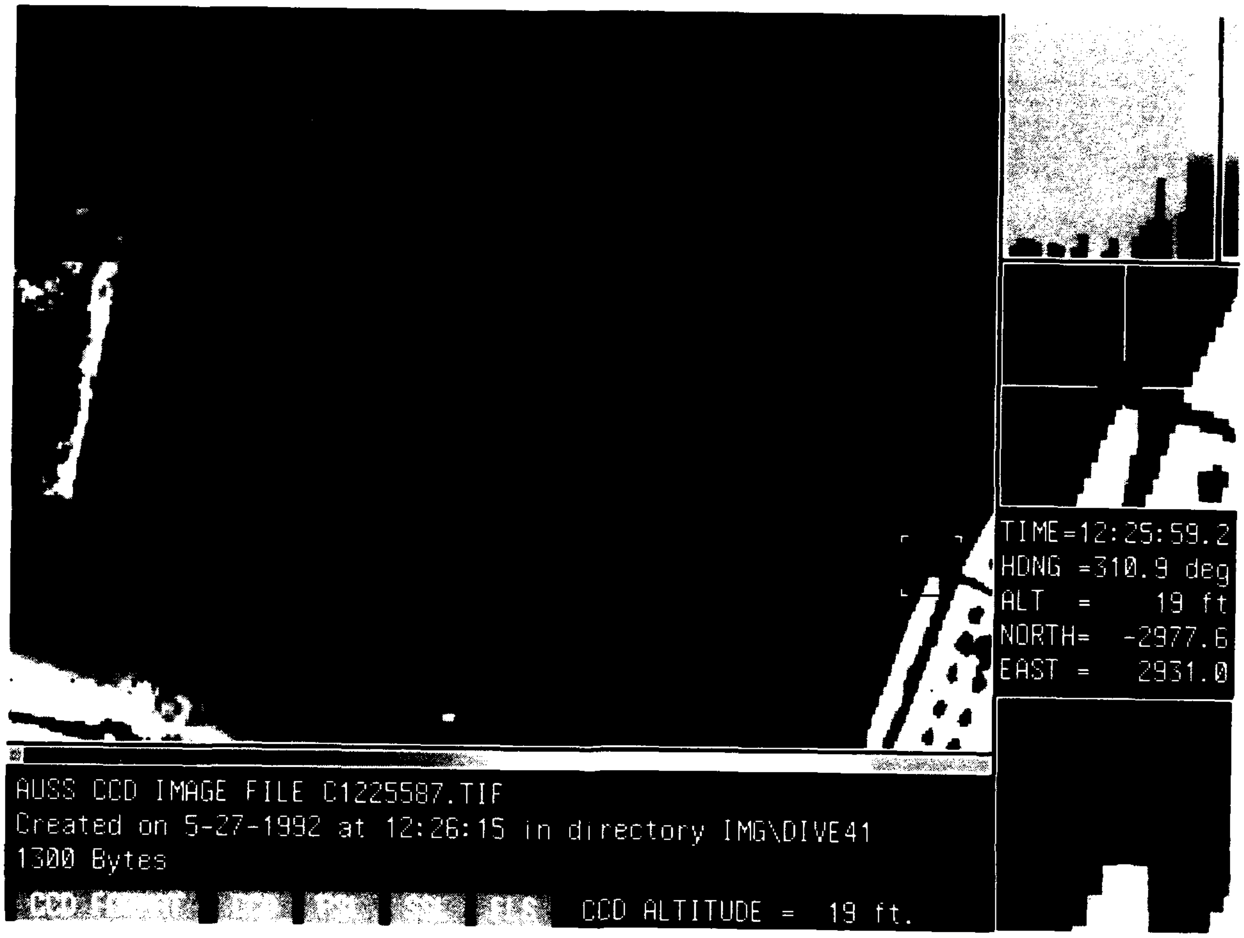

Figure 14. Very-low-resolution photomosaic image #1.

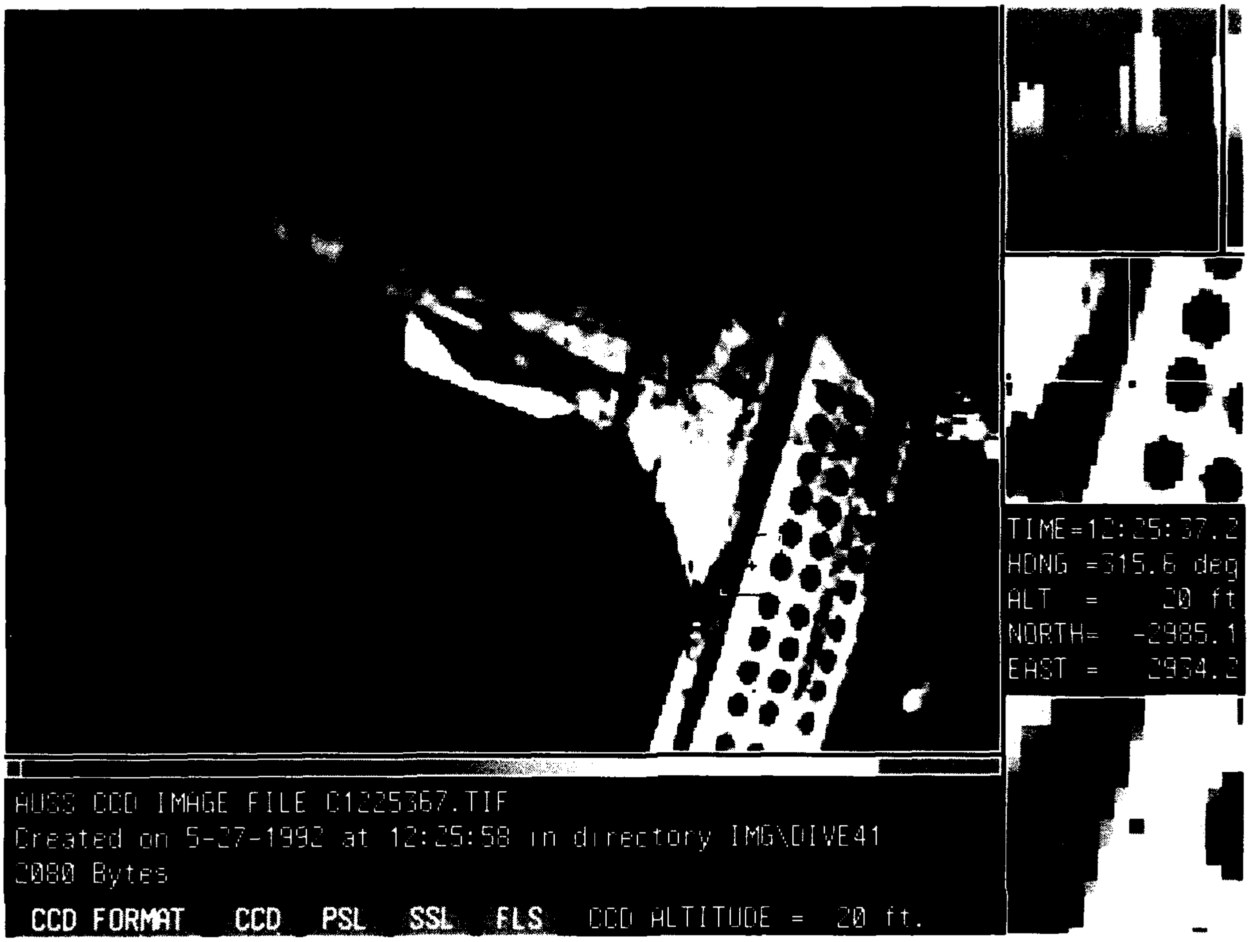

Figure 15. Very-low-resolution photomosaic image #2.

Figure 16. Very-low-resolution photomosaic image #3.

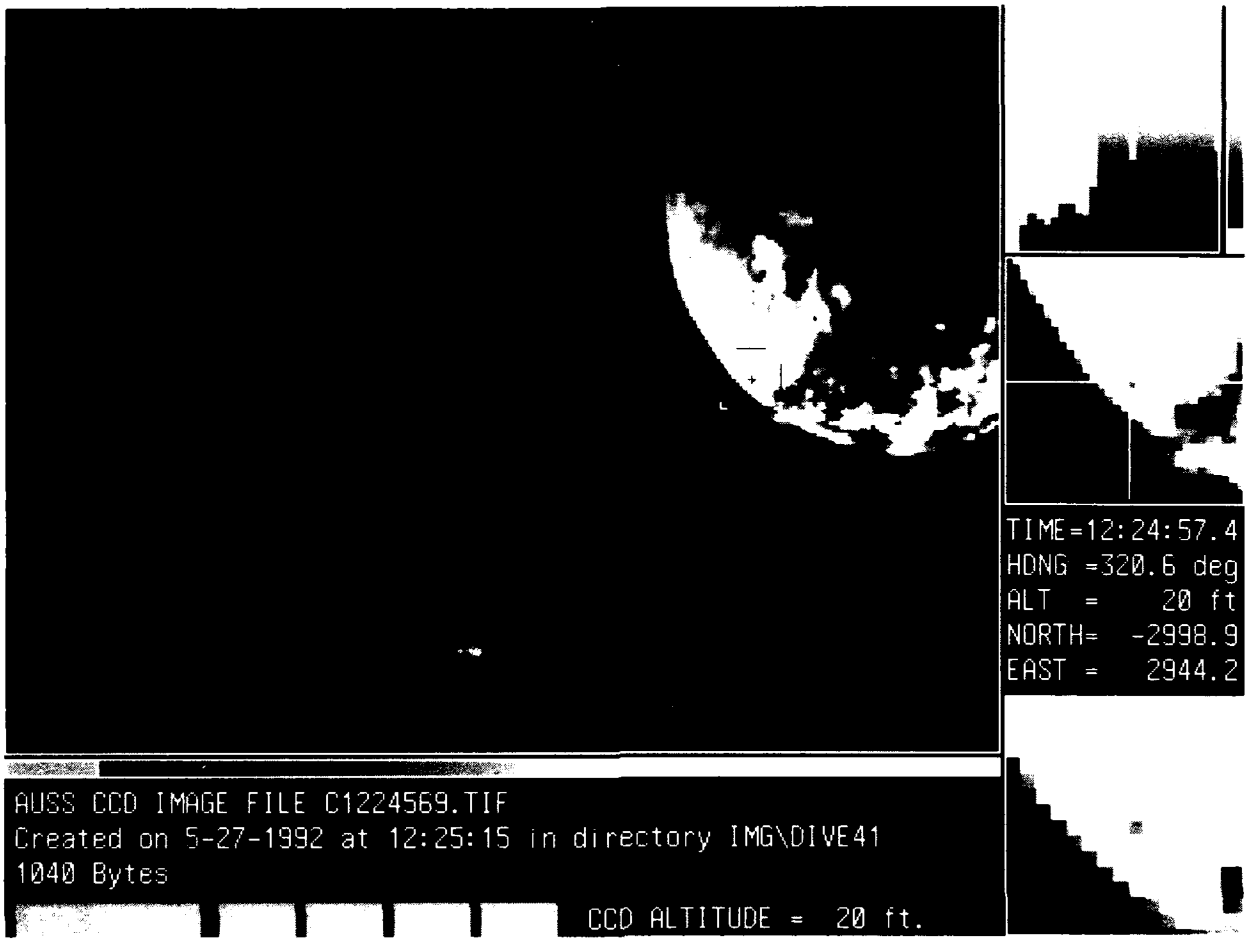

Figure 17. Very-low-resolution photomosaic image #4.

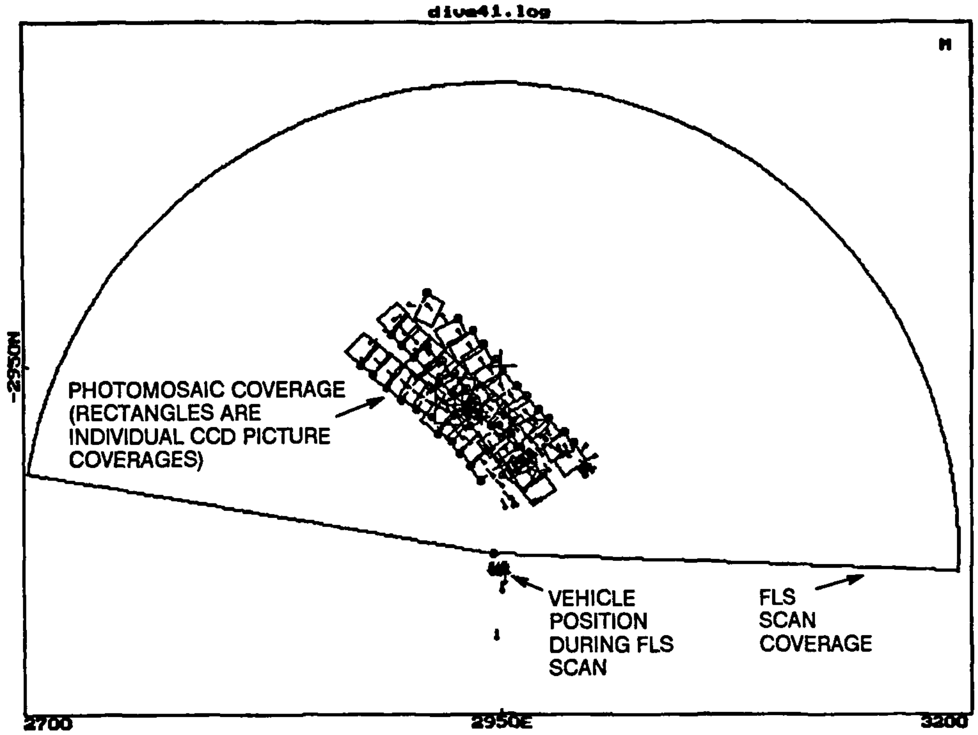

Figure 18. Bomber photomosaic.

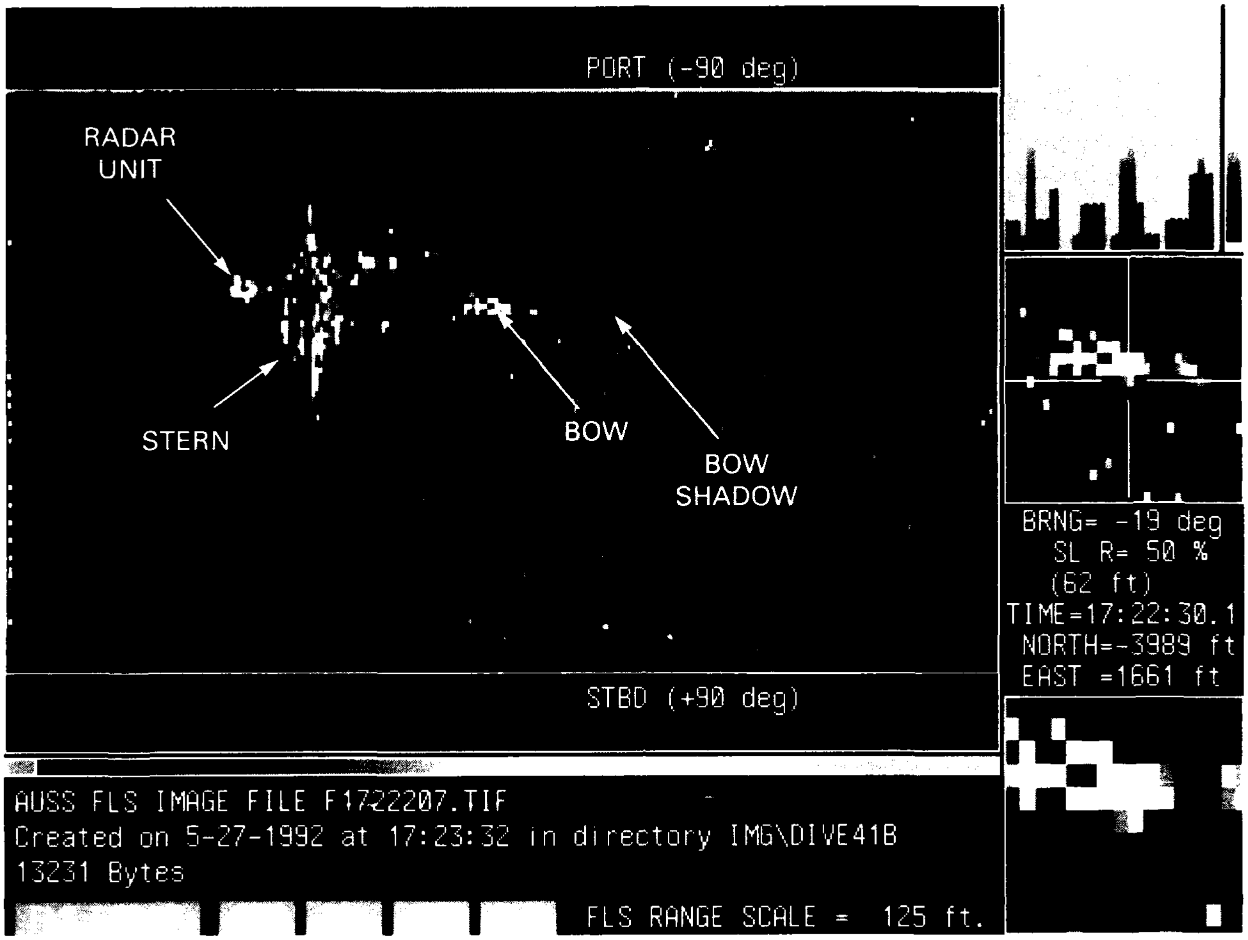

Figure 19. FLS image of 55-ft yacht.

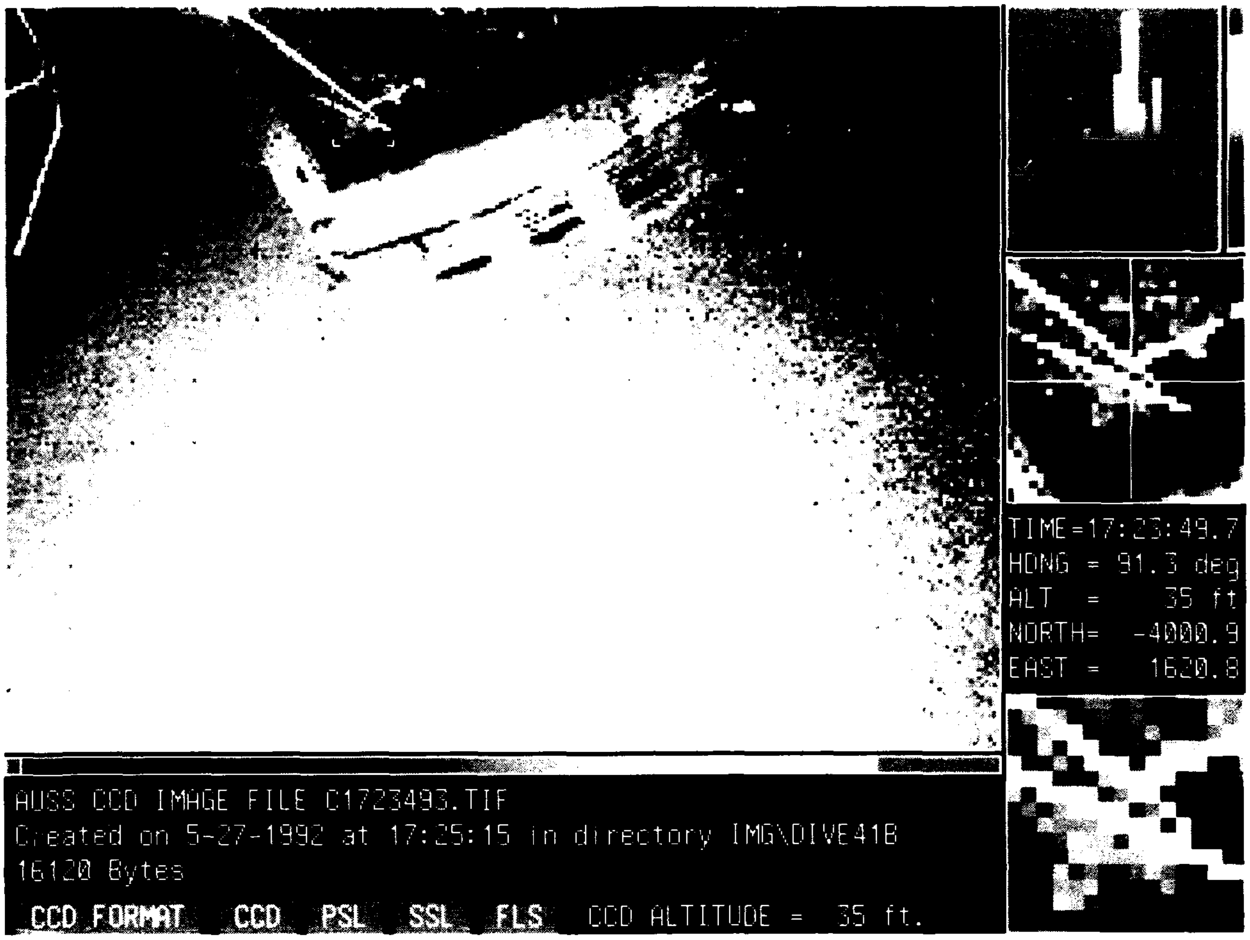

Figure 20. Stern of yacht (low resolution).

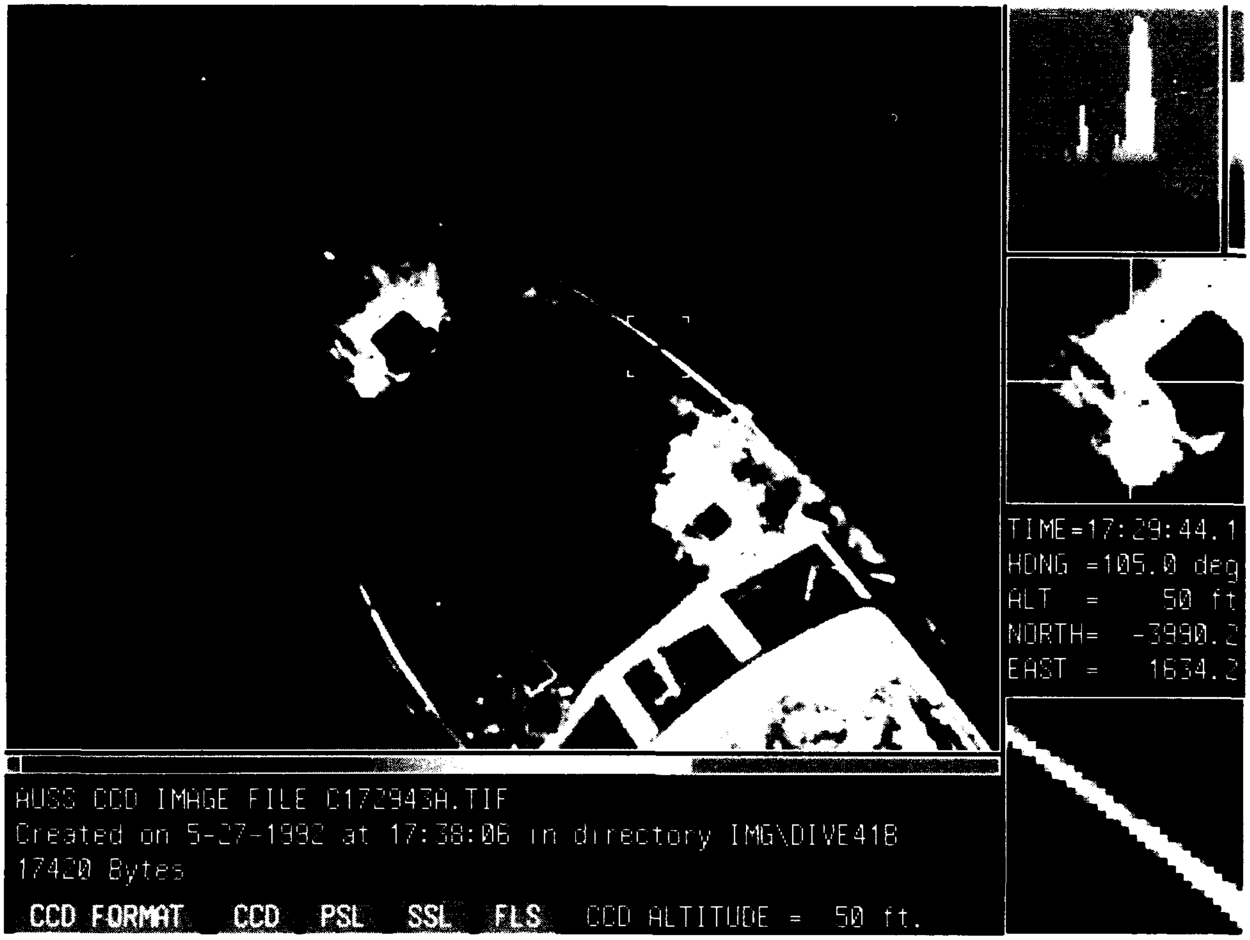

Figure 21. Bow of yacht.

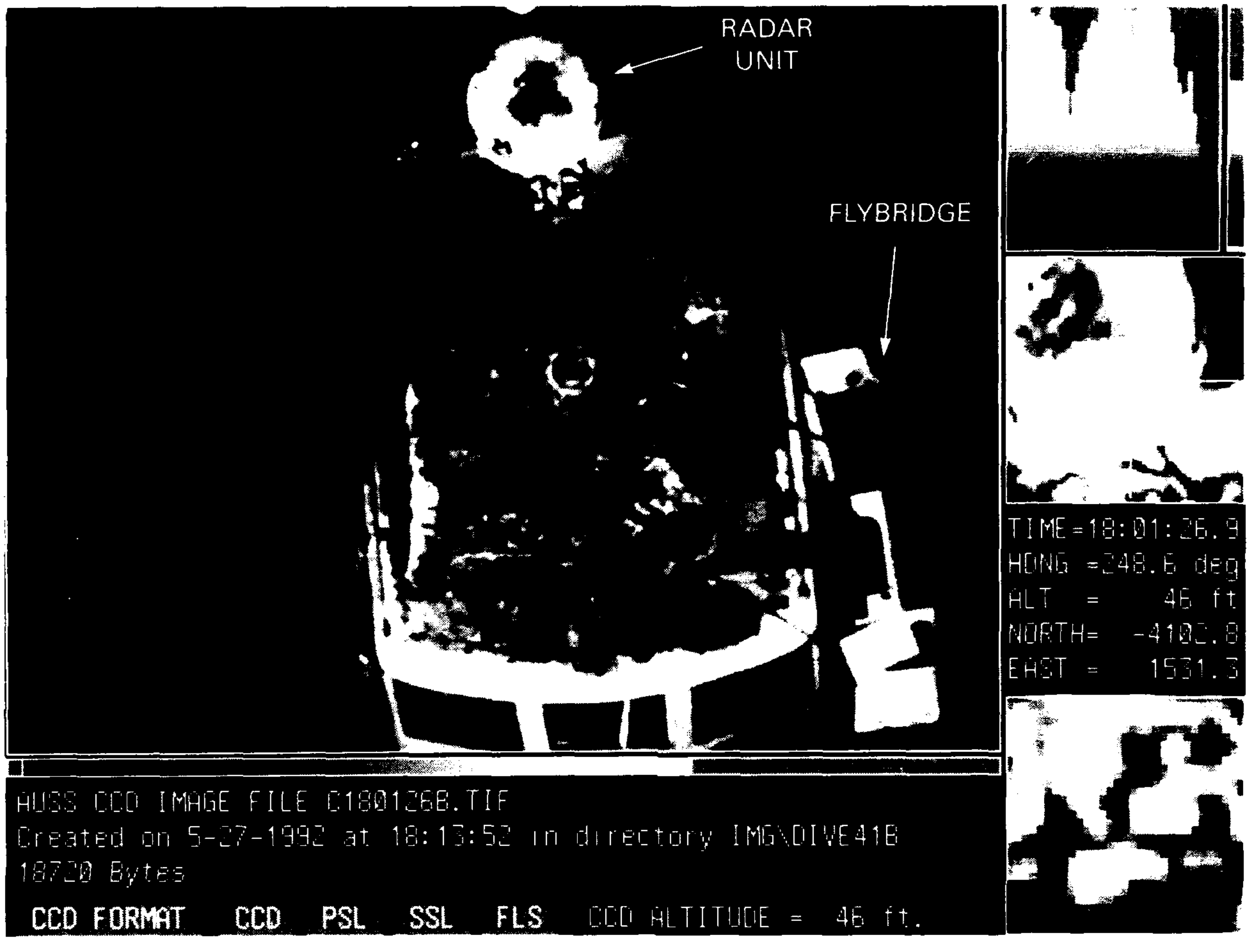

Figure 22. Midship of yacht.

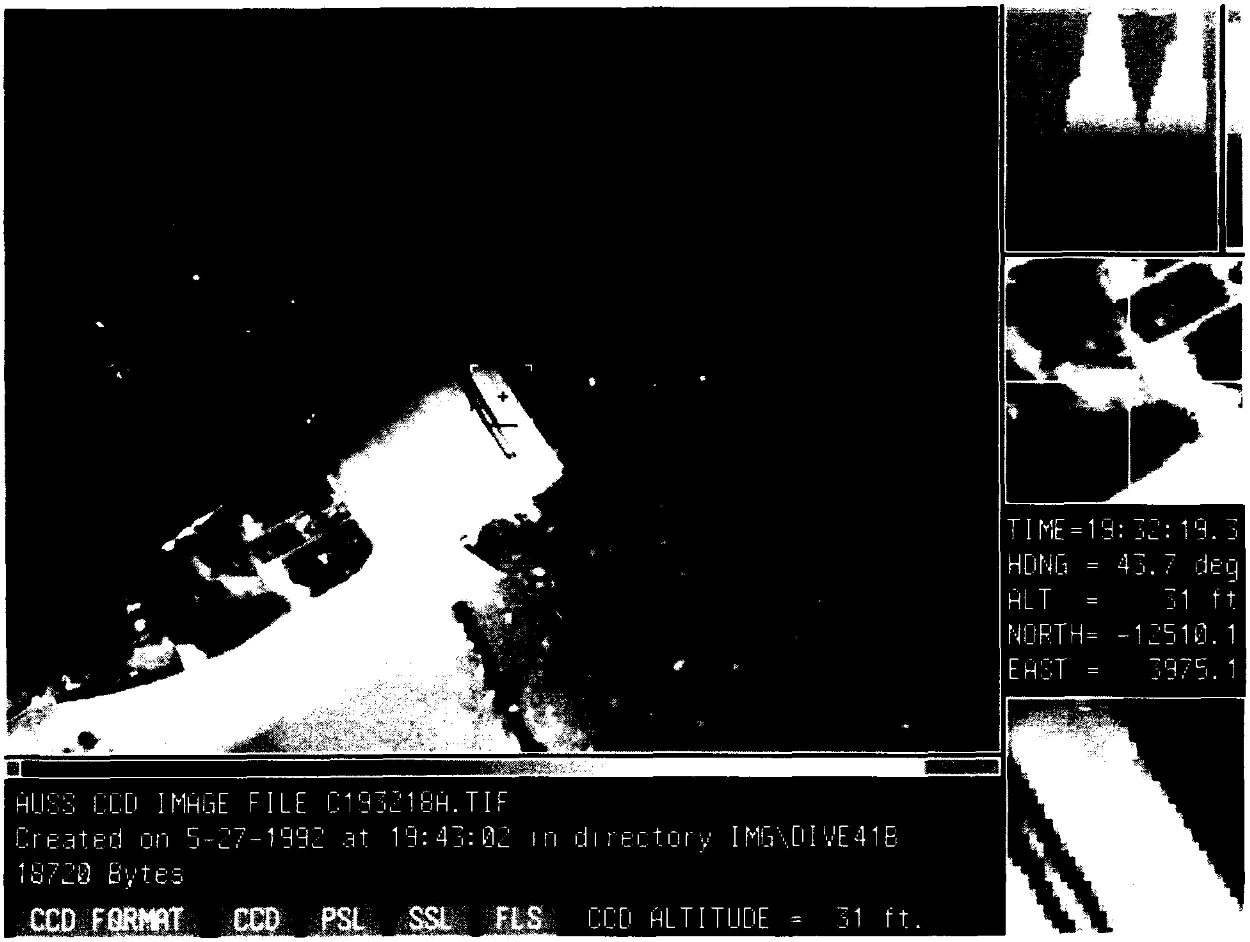

Figure 23. Skyraider nose.

Figure 24. Skyraider midsection.

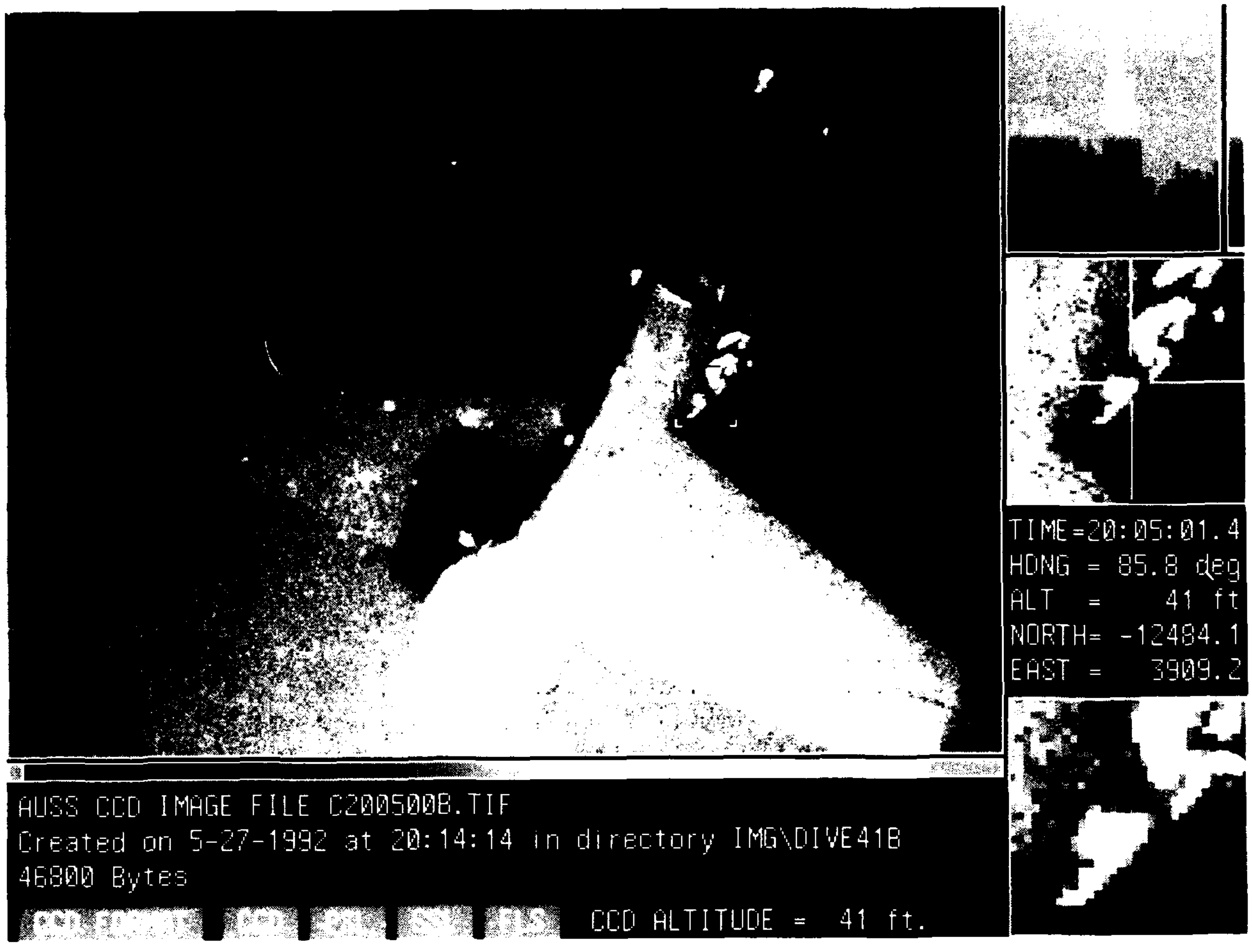

Figure 25. Skyraider tail.

AUSS Overall Search Mission Capability Is Excellent

During this time period, a World War II Dauntless dive bomber was searched for, found, and inspected. The bomber had been visited by other search systems on at least two previous occasions. Using conflicting coordinates from three different sources, three search areas were laid out. The three areas were prioritized based upon alleged accuracy of the fixes, and how recently the fixes were published. The three areas were 8000 ft on a side each, and overlapped slightly.

The first area searched produced two debris fields. Both were inspected thoroughly, and no bomber or bomber debris were found. The second area produced two large SLS targets, an apparent shipboard pipe structure (possibly an antenna mast), and a pile of wire rope (figure 26 is the transmitted FLS image showing the 25- to 30-ft diameter coils of wire rope). The operator's Doppler plot of the search pattern (in which the positions of the two aforementioned false targets are seen) is reproduced in figure 27. After two SLS pattern turns, a strong target return was seen on the starboard SLS image screen. Standard AUSS contact closure was conducted, and the target was found to be the bomber. The rest of the dive was devoted to further inspection of the bomber with CCD camera. The third area was never searched.

During a later dive, AUSS capability was demonstrated by using the bomber as the objective. The bomber, though, was treated as a false target (one which is not of primary interest). This was done to show the efficiency with which AUSS can prosecute a false target and resume search.

An AL supervisory command initiated the search demonstration. This command told the vehicle to advance at 4 knots at an altitude of 100 ft while performing SLS search on the 1000-ft range scale (2000 ft swath). The operators noticed a strong contact at about 900 ft on a port SLS image (figure 28). They immediately commanded the vehicle to interrupt the search and come to a stop. The image was marked to determine the Doppler coordinates of the contact. Next, the vehicle was commanded to go to a radius of 35 ft. When the vehicle reached that location, they ordered an FLS scan on the 250-ft range scale (figure 29). A new mark was obtained from the FLS image, and the vehicle was commanded to hover at a radius of 10 ft from the new coordinates. When the vehicle was in position, a single low-resolution CCD image was requested (figure 30). Ten minutes had passed since the contact, and only five commands had been issued. A sixth command was sent to resume the search. The vehicle returned to the search track and resumed sending SLS images. This false target had been evaluated in 14 minutes by using only six commands. Figure 31 is an annotated version of the Doppler plot that was presented to the operators during this demonstration. The operators plot includes the path of the vehicle, the FLS scan footprint, and the CCD image footprint.

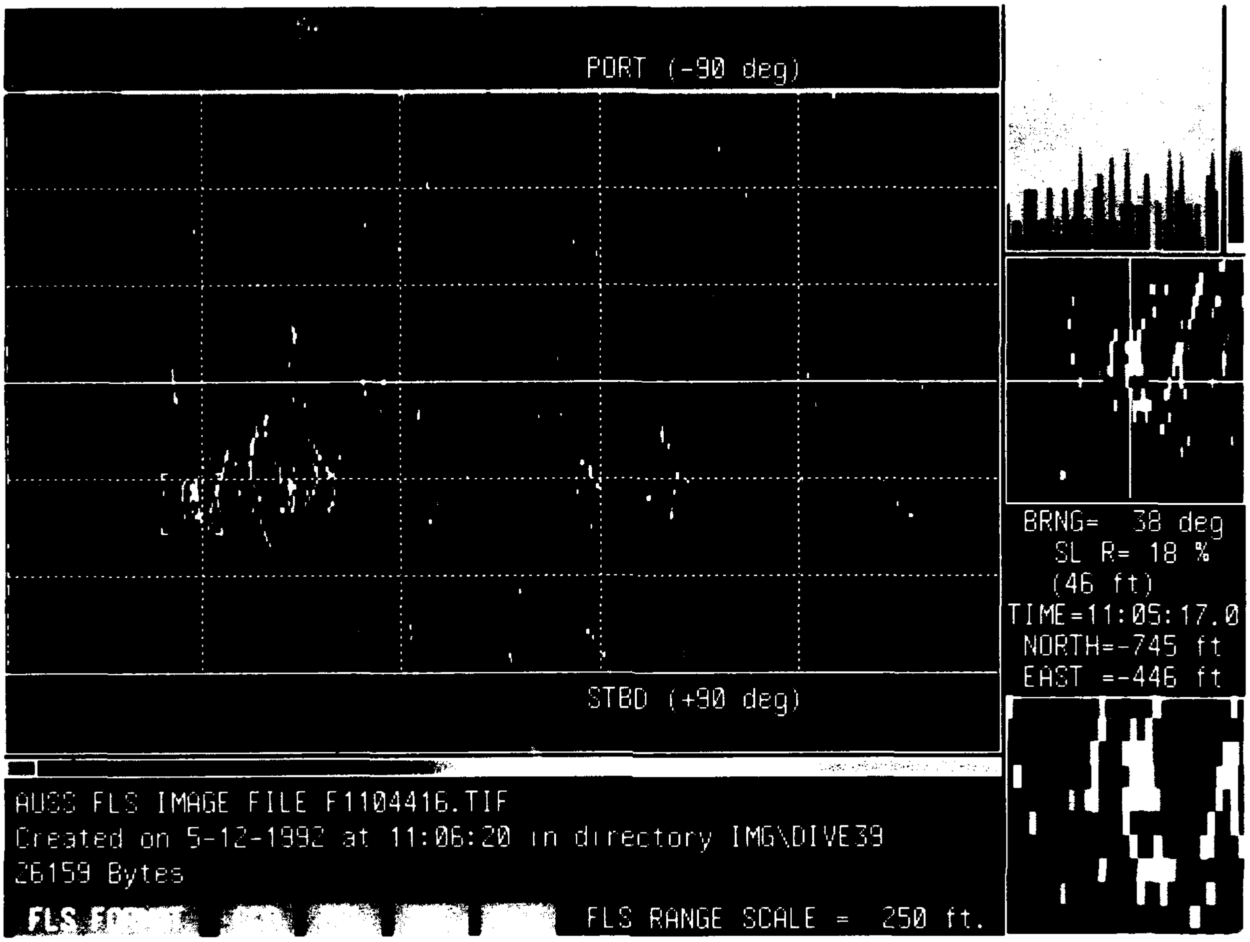

Figure 26. FLS image of wire rope.

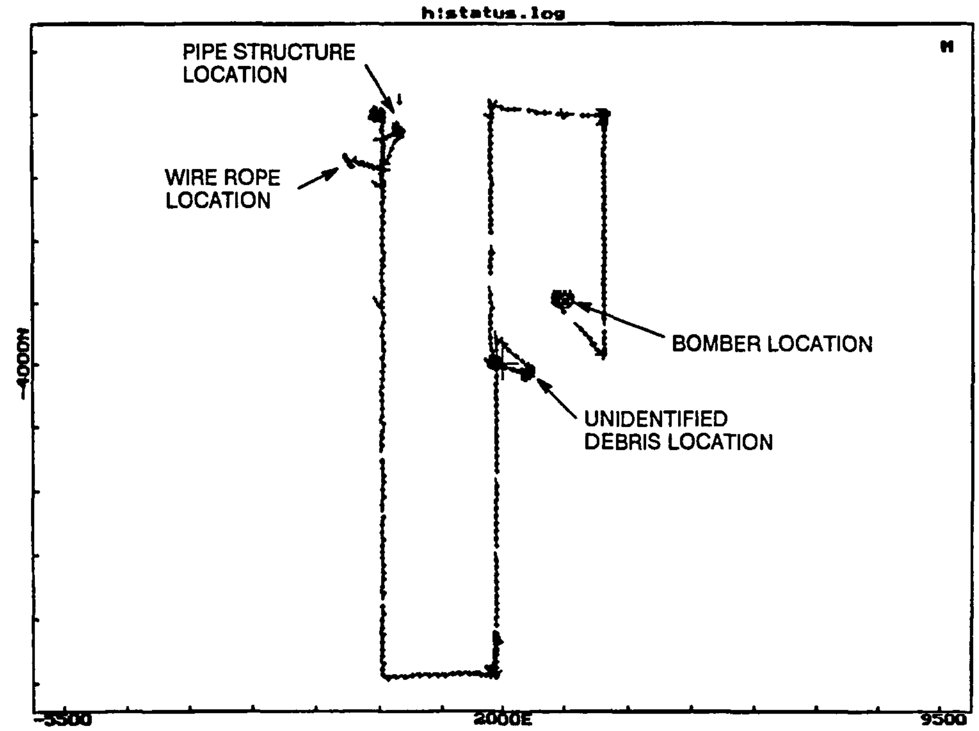

Figure 27. Doppler plot of bomber search.

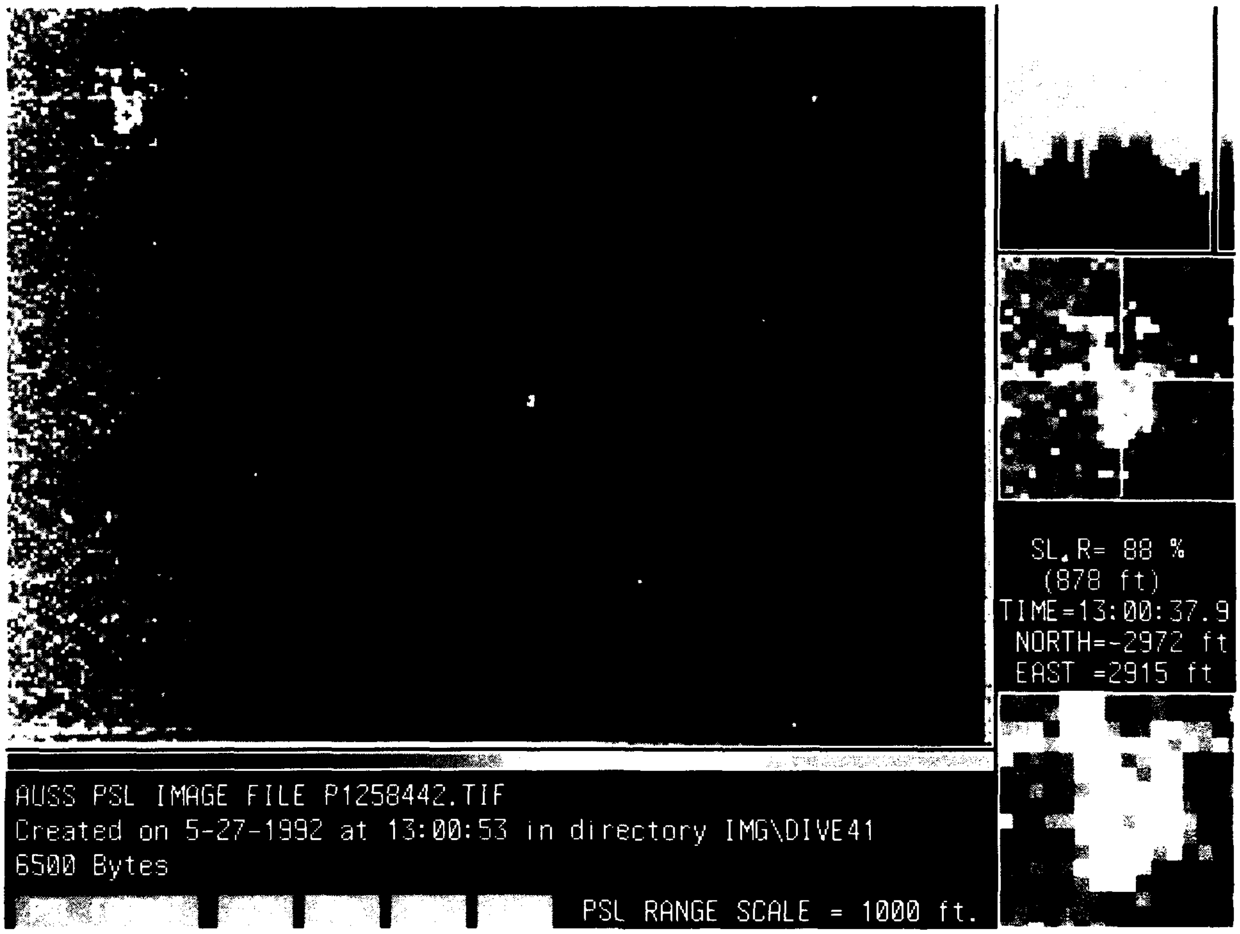

Figure 28. SLS image of bomber target.

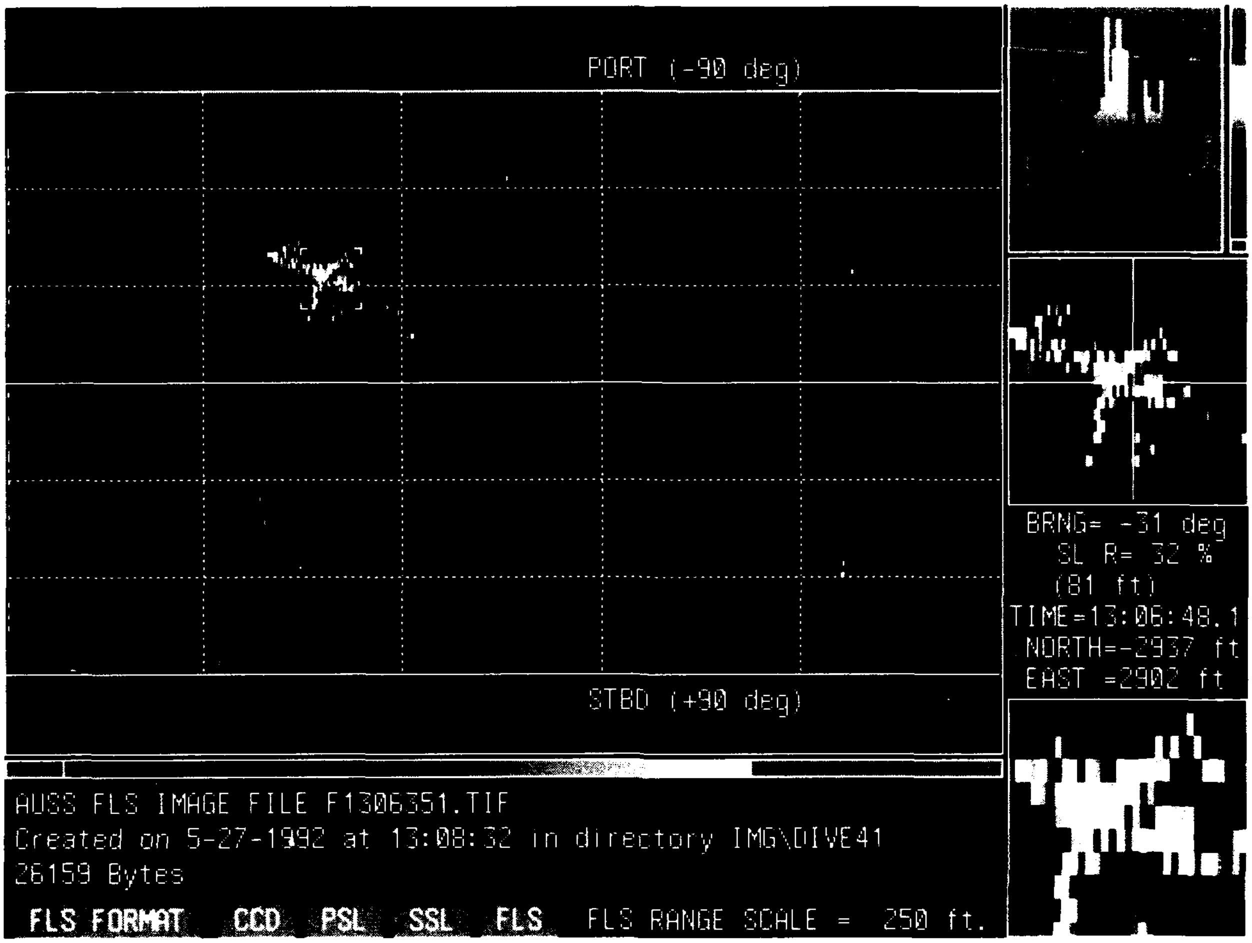

Figure 29. FLS image of bomber target.

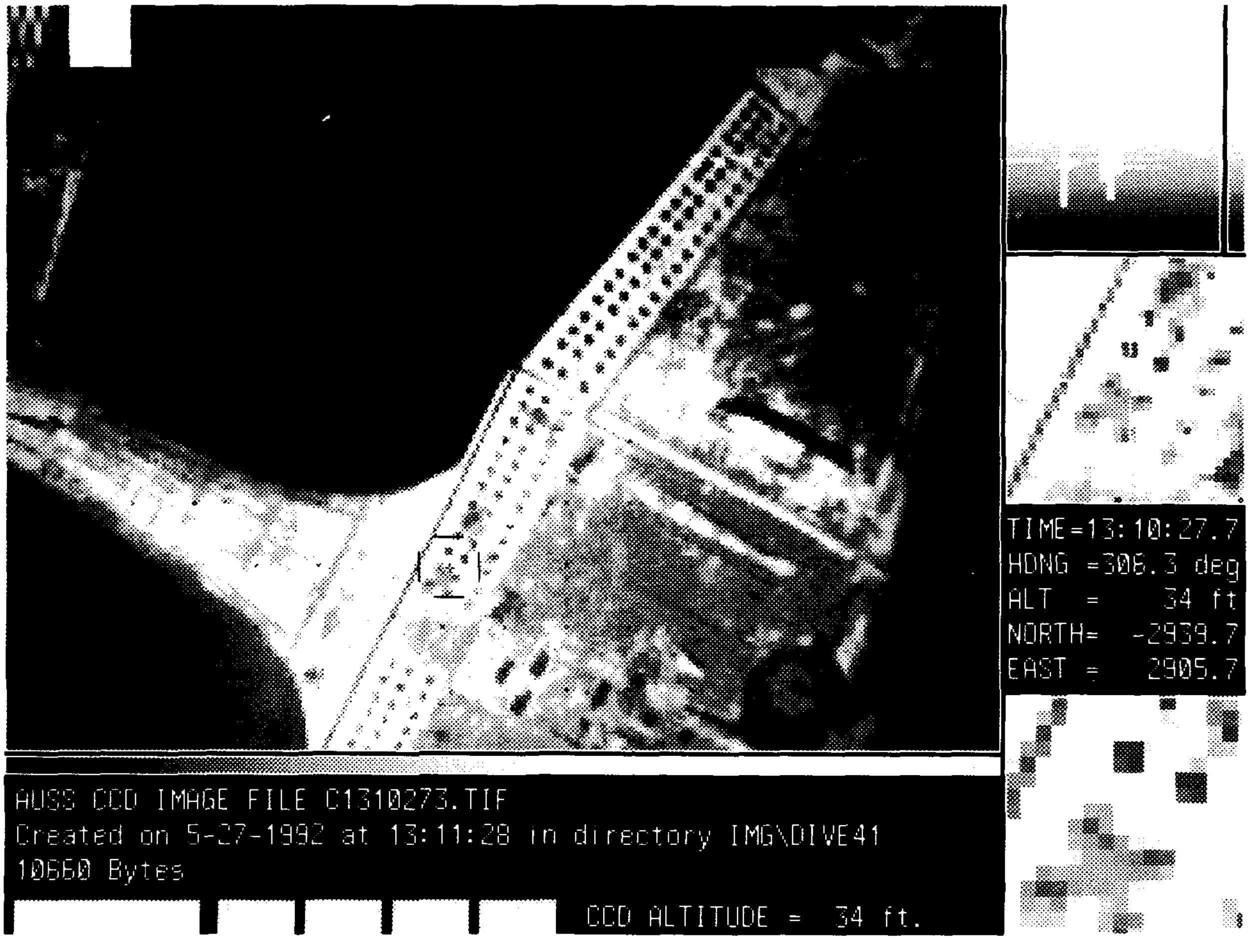

Figure 30. Low-resolution CCD image of bomber.

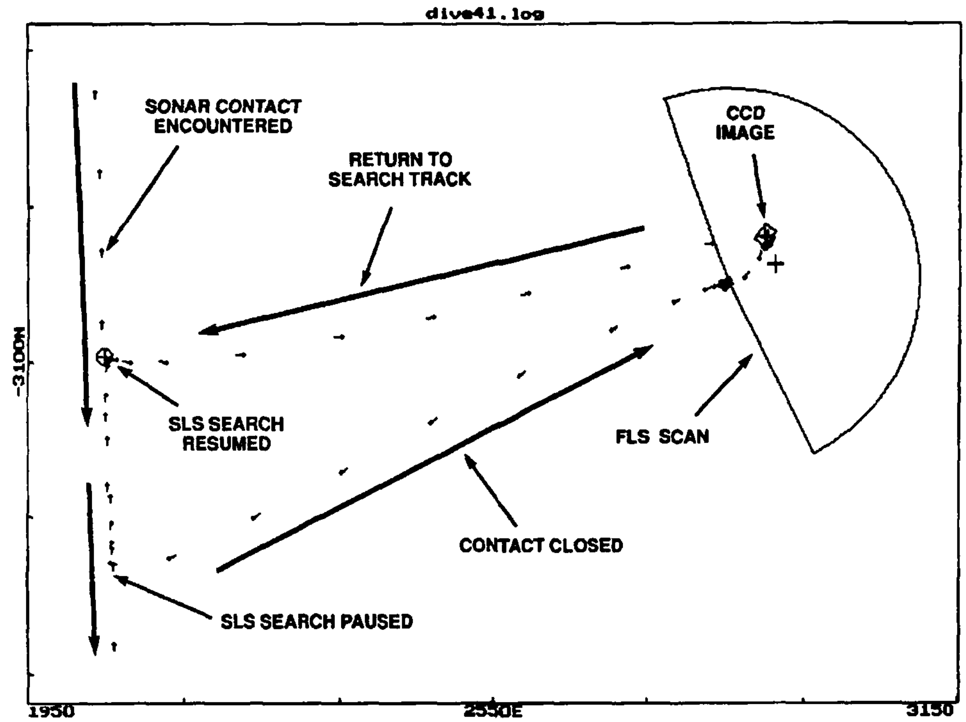

Figure 31. Plot of immediate contact evaluation.

Pictures (and Videos) Are Worth Thousands Of Words

A narrated video tape of the bomber immediate contact evaluation is available for viewing from the author. This realtime 14-minute tape shows the images as they were being received and fills in the time between images with realtime operator displays, Doppler position plots, and a computer simulation driven by data extracted from the vehicle flight recorder. The background audio is a realtime playback of the 8 to 14 kHz AL signals communicated between the surface and the vehicle. The tape is available in either super VHS or VHS, and provides excellent insight into the real operational capability of AUSS.

The variety of CCD and sonar images in this report were obtained by AUSS and acoustically transmitted to the surface via the acoustic link. These images demonstrate the effectiveness with which AUSS conducts search and contact evaluation.

CONCLUSION

The AUSS study group (1973) estimated the existing deep-search capability was about 0.01 nmi^2 per hour for a small target. Gunderson (1978) considered towed search systems only, and estimated the average state-of-the-art search rate was 0.045 nmi^2 per hour. The AUSS prototype demonstrated that SLS search rates of

0.4 nmi^2 per hour and contact evaluations of 30 minutes were possible. The improved AUSS demonstrated SLS search rates up to 1.5 nmi^2 per hour and contact evaluation times routinely between 10 and 20 minutes. With the improved system, overall search rates of 0.3 to 1.5 are expected, depending upon the terrain and the false target density.

AUSS Improves Search by More Than an Order Of Magnitude

The benefits of AUSS can be seen by applying two search scenario cases considered in the early AUSS performance analysis to the improved AUSS System. For both of these cases, 20,000-ft operation is assumed.

In the case of a small target (<10 ft) AUSS could search at 4.5 knots using the 1000-ft range scale (2000-ft swath). A conservative coverage is 110% such that the lane to lane spacing would be 1800 ft. Assuming, as did the AUSS performance analysis, a high false target environment (false target density of 2.7 targets per nmi^2), and also assuming 10 minutes per AUSS turn every 5 nmi^2 of track and 20 minutes per contact evaluation, the overall AUSS search rate would be 0.4 nmi per hour. This takes into account a conservative 4 hours of system cycle time every 10 hours (ascent, recovery, battery change, checkout, launch, and descent).

In the case of a large target (15-20 ft minimum) on a flat bottom, AUSS could search at 4.5 knots using the 2000-ft range scale (4000-ft swath). With 110% coverage, this results in a SLS search rate of 2.7 nmi^2 per hour. Assuming, as did the AUSS performance analysis, that the false target density is 0.13 target per nmi^2, and assuming that AUSS takes 20 minutes per contact evaluation, the overall search rate would be about 1.5 nmi^2 per hour (turn times again are 10 minutes every 5 nmi of track, and system cycle time is 4 hours every 10 hours).

AUSS overall deep search area rates of 0.4 and 1.5 nmi^2 per hour for the two cases considered are more than an order of magnitude improvement over the 0.01 and 0.045 nmi^2 per hour rates estimated for state-of-the-art search systems.

SUMMARY

The AUSS supervisory controlled untethered search approach is unique, and has resulted in major advances in both underwater vehicle technology and search technology. AUSS broke free from the bounds of classic towed search systems to achieve drastic improvements. An unconventional but focused effort was applied employing system engineering, yet remaining flexible to RDT&E interactive evolution. This has allowed AUSS to break through a search technology barrier that has existed for decades. AUSS is a system that very effectively achieves its mission and surpasses its program goal.

REFERENCES

Bryant, S. B. 1979. "Advanced Unmanned Search System (AUSS) Performance Analysis." NOSC TR 437 (July). Naval Ocean Systems Center, San Diego, CA.

Buchanan, C. L. 1977. "A Review of Problems with Current Search Systems and Solutions." R. B. Associates, Inc. (Jan).

Buchanan, C. L. 1977. "Free-Swimming Submersibles for Deep Sea Search Operations, Concepts, Problems, and Solutions." R. B. Associates, Inc. (April).

Endicott, D., Jr., and G. R. Kuhl. 1992. "The Fast Area Search System: A Feasibility Study." NRAD TR 1526 (Sep). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Gundersen, C. R. 1978. "Advanced Unmanned Search System (AUSS), Preliminary Search Systems Analysis." NOSC TR 375 (Dec). Naval Ocean Systems Center, San Diego, CA.

Mackelburg, G. R. 1991. "Acoustic Data Links for UUVs." IEEE/OES, Oceans '91 (Oct).

Mackelburg, G. R. 1992. "Advanced Unmanned Search System (AUSS) Acoustic Communication Link Development." NRAD TR 1531 (Nov). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Osborne, P. D., and C. C. Guerin. 1992. "Advanced Unmanned Search System (AUSS) Surface Navigation, Underwater Tracking, and Transponder Network Calibration." NRaD TR 1532 (Oct). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Stachiw, J. D. 1988. "Graphite Fiber-Reinforced Plastic Pressure Hull Mod 2 for the Advanced Unmanned Search System (AUSS)." NOSC TR 1245 (Aug). Naval Ocean Systems Center, San Diego, CA.

Uhrich, R. W., J. Walton, and S. J. Watson. 1978. "Portable Test Range and its Application to Side-Looking Sonar." NOSC TR 258 (Jan). Naval Ocean Systems Center, San Diego, CA.

Uhrich, R. W., and S. J. Watson. 1992. "Deep Ocean Search Inspection: Advanced Unmanned Search System (AUSS) Concept of Operation." NRaD TR 1530 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Vought Corporation Advanced Technology Center, Inc. 1982. "Operational and Logistics Analyses for Candidate Deep-Ocean Systems for the Advanced Deep Ocean Search System (AUSS)." NOSC CR 141 (Sep). Naval Ocean Systems Center, San Diego, CA.

Walton, J. M. 1988. "Synopsis of Documented AUSS Decisions." NOSC Memo 941/169-88 (Dec). Naval Ocean Systems Center, San Diego, CA.

Walton, J. M. 1991. "Advanced Unmanned Search System." IEEE/OES Oceans '91 (Oct).

Walton, J. M. 1992a. "Advanced Unmanned Search System (AUSS) Testbed: Search Demonstration Testing." NRaD TR 1527 (Nov). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Walton, J. M. 1992b. "Advanced Unmanned Search System (AUSS) At Sea Development Test Report." NRaD TR 1537 (Dec). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Watson, S. J. 1991. "Advanced Unmanned Search System Image Compression and Data Format." IEEE/OES, Oceans '91 (Oct).

BIBLIOGRAPHY

Acoustic Systems, Inc. 1992. "Definition of the Advanced Unmanned Search System (AUSS) Sonar Characteristics." NRaD TN 1704 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.*

Bryant, S. B. 1979. "Advanced Unmanned Search System (AUSS) Performance Analysis." NOSC TR 437 (Jul). Naval Ocean Systems Center, San Diego, CA.

Cooke, M. W. 1992. "Advanced Unmanned Search System (AUSS)." NRaD TD 2348 (Dec). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Endicott, D. L. Jr., and G. R. Kuhl. 1992. "Fast Area Search System (FASS): Feasibility Study Appendices." NRaD TN 1703 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.*

Endicott, D. L. Jr., and G. R. Kuhl. 1992. "The Fast Area Search System (FASS): A Feasibility Study." NRaD TR 1526 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Grace, D. R. 1992. "Brownian Reber Search Theory for the Advanced Unmanned Search System." NRaD TR 1534 (Oct). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Gunderson, C. R. 1978. "Advanced Unmanned Search System (AUSS), Preliminary Search Systems Analysis." NOSC TR 375 (Dec). Naval Ocean Systems Center, San Diego, CA.

Held, J. L. 1992. "Automatic Hovering Algorithms for the Advanced Unmanned Search System." NRaD TR 1535 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Held, J. L. and H. B. McCracken. 1993. "Automatic Transit Algorithms for the Advanced Unmanned Search System (AUSS)." NRaD TR 1536 (Jan). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Jones, H. V. 1992. "Advanced Unmanned Search System (AUSS) Description." NRaD TR 1528 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

* NRaD Technical Notes (TNs) are working documents and do not represent an official policy statement of the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD). For further information, contact the author(s).

Keil, T. J. 1992. "Advanced Unmanned Search System (AUSS) Deep Ocean Floor Search Performance Computer Model: Executive Summary." NRaD TN 1702 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.*

Kono, M. E. 1992. "Surface Computer System Architecture for the Advanced Unmanned Search System (AUSS)." NRaD TR 1538 (Dec). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Mackelburg, G. R., S. J. Watson, and W. D. Bryan. 1992. "Advanced Unmanned Search System (AUSS) Acoustic Communication Link Development." NRaD TR 1531 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

McCracken, H. B. 1992. "Advanced Unmanned Search System (AUSS) Supervisory Command, Control and Navigation." NRaD TR 1533 (Nov). Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Osborne, P. D., and C. C. Geurin. 1992. "Advanced Unmanned Search System (AUSS) Surface Navigation, Underwater Tracking, and Transponder Network Calibration." NRaD TR 1532 (Oct). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Rasmussen, M. E. 1992. "Advanced Unmanned Search System (AUSS) Battery Monitor/Charging Systems." NRaD TR 1539 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Schwager, M., and J. Stangle (SAIC). 1992. "Advanced Unmanned Search System (AUSS) Software Description: Vol I Surface SW/Vol II Vehicle SW." NRaD TN 1705 (Dec). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.*

SEACO, Inc. 1992. "Development of the Acoustic Telemetry System." NRaD TD 2336 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Stachiw J. D. 1984. "Graphite-Reinforced Plastic Pressure Hull for the Advanced Unmanned Search System (AUSS) (U)." NOSC TR 999 (Oct). Naval Ocean Systems Center, San Diego, CA.

Stachiw J. D. 1986. "Graphite-Fiber-Reinforced Plastic Pressure Hull Mod 1 for the Advanced Unmanned Search System (AUSS)." NOSC TR 1182 (Dec). Naval Ocean Systems Center, San Diego, CA.

* NRaD Technical Notes (TNs) are working documents and do not represent an official policy statement of the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD). For further information, contact the author(s).

Stachiw J. D. 1988. "Graphite-Fiber-Reinforced Plastic Pressure Hull Mod 2 for the Advanced Unmanned Search System (AUSS)." NOSC TR 1245 (Aug). Naval Ocean Systems Center, San Diego, CA.

Uhrich, R. W., J. Walton, and S. J. Watson. 1978. "Portable Test Range and its Application to Side-Looking Sonar." NOSC TR 258 (Jan). Naval Ocean Systems Center, San Diego, CA.

Uhrich, R. W., and S. J. Watson. 1992. "Deep-Ocean Search and Inspection: Advanced Unmanned Search System (AUSS) Concept of Operation." NRaD TR 1530 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Uhrich, R. W., S. J. Watson, and G. R. Mackelburg (Eds.). 1992. "Advanced Unmanned Search System (AUSS) Surface Acoustic Link Description." NRaD TN 1706 (Oct). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.*

Vought Corporation. 1992. "Design Analysis and Operations Research for the Advanced Unmanned Search System (AUSS)." NRaD TD 2337 (Sep). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Walton, J. 1992. "Advanced Unmanned Search System (AUSS) At-Sea Development Test Report." NRaD TR 1537 (Dec). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Walton, J. 1992. "Advanced Unmanned Search System (AUSS) Testbed: FY 1987 Development Testing." NRaD TR 1525 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Walton, J. 1992. "Advanced Unmanned Search System (AUSS) Testbed: Search Demonstration Testing." NRaD TR 1527 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Walton, J. 1992. "Evolution of a Search System: Lessons Learned with the Advanced Unmanned Search System." NRaD TR 1529 (Nov). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

* NRaD Technical Notes (TNs) are working documents and do not represent an official policy statement of the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD). For further information, contact the author(s).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1992	Final: September 1992

4. TITLE AND SUBTITLE

EVOLUTION OF A SEARCH SYSTEM:
Lessons Learned with the Advanced Unmanned Search System

5. FUNDING NUMBERS

PE: 0603713N
Access No.: DN588521
Proj: S0397

6. AUTHOR(S)

J. Walton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division (NRaD)
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

NRaD TR 1529

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Assistant Secretary of the Navy
Research and Development (PMO–403)
Washington, DC 20350

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This document follows the evolution of the Advanced Unmanned Search System (AUSS) and the lessons learned. The events leading up to the development of the AUSS, the subsystem focus, systems engineering, and the interactive development and field testing are all included.

14. SUBJECT TERMS

acoustic link
prototype
state-of-the-art search
autonomous underwater vehicles
technology gap
underwater vehicles
supervisory control

15. NUMBER OF PAGES

84

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(Include Area Code)*	21c. OFFICE SYMBOL
J. Walton	(619) 553-1879	Code 941