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The Supervisor of Diving and Salvage (NAVSEA 00C) funded the Ocean Technology Division of the Naval Ocean Research and Development Activity (NORDA) to conduct a competitive selection and demonstration of commercially produced, field-proven, acoustic tracking equipment that could be used as an Under-the-Hull Diver Location System (UHDLS). After competition, NORDA selected two contractors that produce commercially available acoustic position and tracking equipment to demonstrate their equipment experimentally in a test environment provided by the U.S. Government. The equipment was demonstrated in three environments: a pool, a lock, and dockside under the vessel "Pearl River."

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There is an error on page 6. In the left column where it mentions salinity range, the measurement should be in parts per thousand(^{0}/oo) instead of percentage (%).

Naval Ocean Research and Development Activity.
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Under-the-Hull Diver Location System: Report of Test Results.

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Ocean Acoustics and Technology Directorate

Foreword

Ships' hulls must be inspected periodically to determine structural integrity, results of collision damage, and to identify maintenance requirements. The most significant problem in an underwater inspection (especially for large ships) is in locating the desired inspection points or areas. Hull inspections are typically performed while the ship is either dockside or anchored in a harbor environment. This report describes the results of tests conducted on two systems that would track a diver's movements in relation to known points on a ship's hull.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

Executive summary

The Supervisor of Diving and Salvage (NAVSEA 00C) funded the Ocean Technology Division of the Naval Ocean Research and Development Activity (NORDA) to conduct a competitive selection and demonstration of commercially produced, field-proven, acoustic tracking equipment that could be used as an Under-the-Hull Diver Location System (UHDLS). After competition, NORDA selected two contractors that produce commercially available acoustic position and tracking equipment to demonstrate their equipment experimentally in a test environment provided by the U.S. Government. The equipment was demonstrated in three environments: a pool, a lock, and dockside under the vessel "Pearl River."

The demonstration determined that both systems could track a diver in the highly reverberant, multipath environment under the hull of a ship. The accuracy with which they could track the diver and the maturity of the software to present the results were the major differences. One system demonstrated used a general-purpose computer, and the other used a personal computer for the Diver Supervisor Display Unit. A Diver Supervisor Display Unit capable of withstanding the environment that would be encountered aboard ship would have to be developed for UHDLS.

This report recommends that option 3 (adaptation of underwater tracking equipment to a limited capability UHDLS in accordance with reference 3) of the demonstration contract be exercised to procure the Sonardyne equipment. This action will effectively procure the development of the Diver Supervisor Display Unit with menu-driven software for the unit.

Acknowledgments

This work was funded through Program Element 63721N, Dale Uhler, program manager.

Contents

Under-the-Hull Diver Location System: Report of test results

1.0 Introduction

The integrity of a ship's hull is of paramount importance to safety at sea. Hulls are continually subjected to a variety of forces that tend to reduce integrity, e.g., corrosion, fatigue due to vibration, collision with waterborne objects, or running aground. The many manifestations of these forces frequently require that hulls be inspected. In-water inspections are the most cost-effective because the expense of a dry-docking operation is often avoided.

2.0 Background

Ships' hulls must be inspected periodically to determine structural integrity and results of collision damage, and to identify maintenance requirements. The most significant problem in an underwater inspection (especially for large ships) is in locating the desired inspection points or areas. Hull inspections are typically performed while the ship is either dockside, anchored in a harbor, or anchored at sea.

Hull inspections can be roughly divided into two types, point survey and area survey. For point surveys, the diver is usually asked to determine the status of a hull fitting, a seam, a sea chest, or a similar specific item. The problem for the diver (and the Diving Supervisor) is first to find the item, then to ensure that it is the correct one and, finally, to inspect it and not a similar item nearby. For area surveys, the diver must inspect the total area and be able to relate inspection results to specific hull locations. For a large area containing numerous damage sites, it is impossible to ascertain their physical relationships without a fairly precise navigation system.

The solution to this under-the-hull navigation problem is a diver location system that tracks the diver's movements in relation to known points on the hull. The system must display the resulting information topside to the Diving Supervisor in a format that permits efficient vectoring of the diver from one desired location to another.

The Supervisor of Diving and Salvage (NAVSEA 00C) funded the Ocean Technology Division of the Naval Ocean Research and Development Activity (NORDA) to perform a feasibility study of techniques for locating and tracking a diver under the hull of a ship being inspected. The results of this study are documented in System Definition Study [1].

Key issues addressed by the study included the following.

- The acoustic environment and the risk that large errors will result from the inability to distinguish between direct acoustic arrivals and multiple reflections between the hull and the harbor floor.
- Design implications of the acoustic environment, including the need for high signal-to-noise ratios and the need for self-checking measurement techniques.
- Definition of the series of measurements and calculations that must be performed to determine the diver's position relative to a desired inspection point (i.e., the relative locations of multiple tracking sensors, the location and orientation of the hull relative to the array of tracking sensors, the location and course of the diver relative to the array of tracking sensors, the location of the inspection point in ship's hull coordinates, and the comparison of all of this information in a common coordinate system).
- Functional requirements for data acquisition, processing, and display.
- Specific examples of system configurations, including operational scenarios.

The U.S. Government competitively selected two contractors to demonstrate experimentally, in test environments provided by the government, that commercially produced, field-proven acoustic tracking equipment can be adapted to meet the performance requirements of an Under-the-Hull Diver Location System (UHDLS).

3.0 Test environment description

Reference 2 describes the proposed UHDLS Field Test Plan. The following describes the actual test procedures.

3.1 Pool test

The pool tests (see Fig. 1) were conducted in Picayune, Mississippi. These tests permitted accurate positioning of all acoustic tracking projectors/transducers and complete control over geometry in a highly reverberant environment.

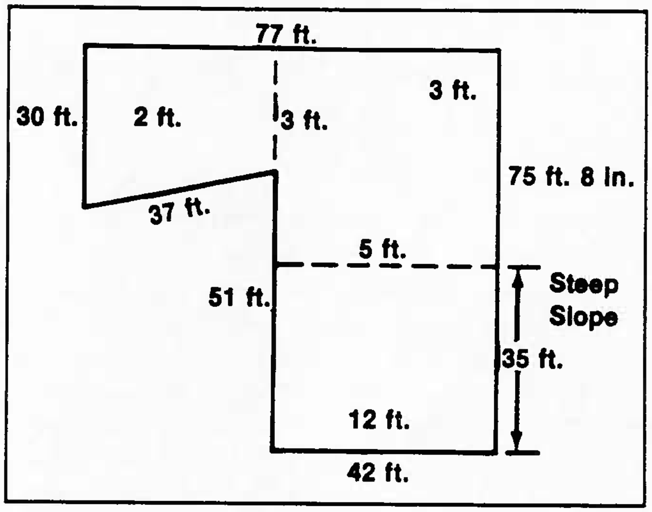

Figure 1. Test pool, Picayune, Mississippi.

The purpose of these tests was to demonstrate the system's ability to

- locate a target when all devices are in the deep end of the pool,
- locate a target that has been moved to the shallow end of the pool,
- track a target that is moving about the pool.

To accomplish these tests, several positions were measured by tape to determine their exact locations. The diver transducer was then moved to these locations. A comparison of positions measured by tape with those measured acoustically is discussed in Section 5.0.

3.2 Lock test

The lock tests (Fig. 2) were conducted at NSTL, Mississippi. These tests permitted slightly less accurate

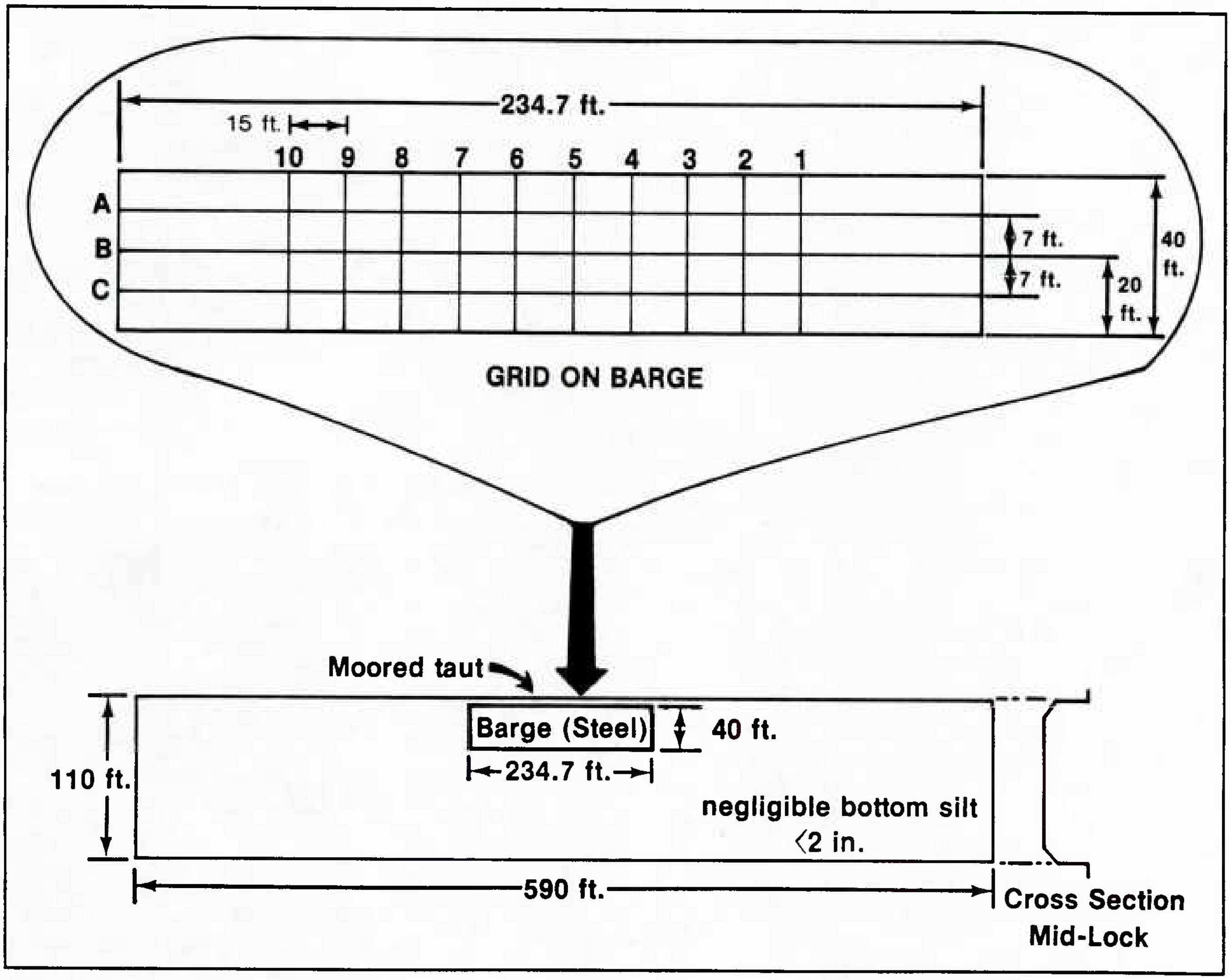

Figure 2. Lock.

positioning of tracking projectors/transponders in a controlled geometry for a less difficult (in most cases) reverberant environment than the pool test. The purpose of these tests was to demonstrate the system's ability to

- locate a target placed on the bottom of a barge,
- track a target which is moving about under the barge hull.

To accomplish these tests, a barge was placed in the lock at NSTL in approximately 24 feet of water. Ten lines were placed around the barge at a 15-foot spacing, and three lines were placed around the barge from bow to stern at a 7-foot spacing; one line was positioned down the center of the barge. This grid is shown in Figure 2. The locations of this grid were determined by a measuring tape, and these positions are considered to be the actual locations. To obtain precise measurements of diver position, the Diver-Mounted Sensor Package was moved along the edge of the barge to the grid locations. These positions were then compared with results obtained from the UHDLS. A comparison of these positions is included in Section 5.0. After completion of these tests, a diver-vectoring test was conducted. The first diver-vectoring tests consisted of instructing the diver to follow known paths under the barge and then tracking the diver's position along those paths. The second diver-vectoring tests consisted of vectoring the diver to known locations under the barge.

3.3 Dockside test

The dockside tests (see Fig. 3) were conducted under the barge "Pearl River," which was moored at the canal docks located at NSTL. These tests were similar in geometry to the lock test, but in a less demanding reverberation environment because of absorption by the soft harbor bottom and the reduced multipath reflections from a curved hull. The purpose of these tests was to demonstrate the system's ability to

- locate a target placed at known locations on the ship's hull,
- track a target that is moving about under the hull of the ship.

To accomplish these tests, the "Pearl River" was tightly moored at the NSTL dock area in approximately 15 feet of water. Positions were measured around the edge of the "Pearl River" using a measuring tape. The Diver-Mounted Sensor Package was then moved along the edge of the barge to each of the locations, and its position was measured acoustically. After completion of these tests, diver vectoring tests were conducted.

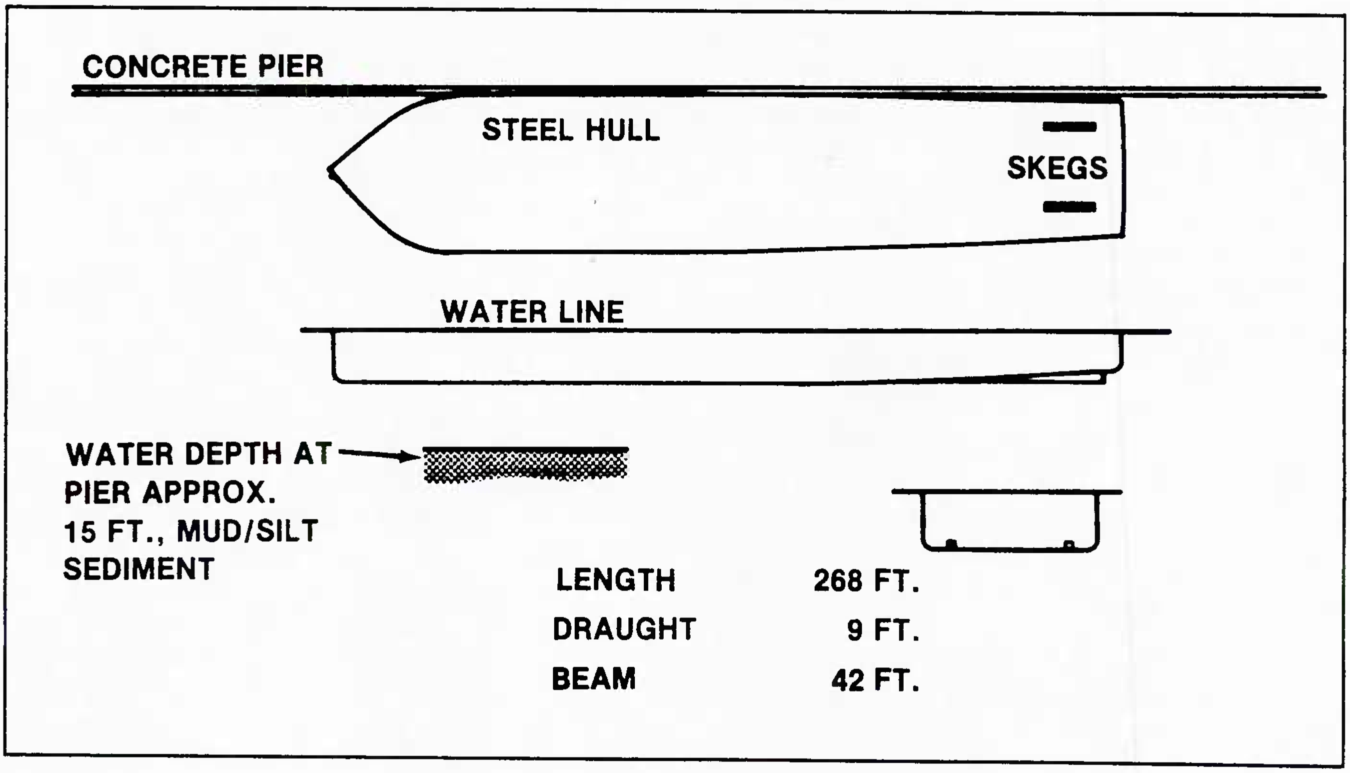

Figure 3. Ship.

The diver vector tests were an attempt to vector a diver to a known location under the hull. A magnet was attached to the hull by the diver, marking the location for the supervisor. The diver would then depart the area and the supervisor would attempt to vector the diver back to the magnet.

4.0 Equipment description

This section describes each of the systems demonstrated.

4.1 Sonardyne

A block diagram of the Sonardyne equipment is shown in Figure 4. The following description of equipment was taken from Sonardyne's response to the solicitation.

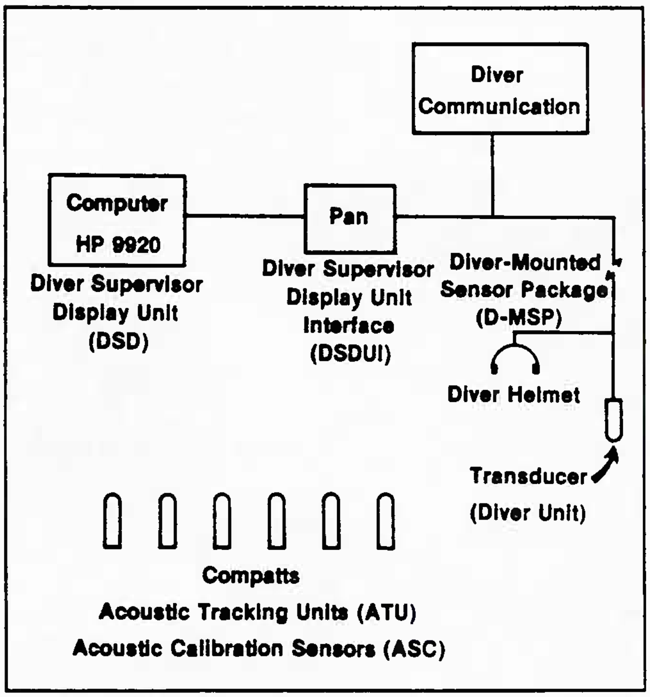

Figure 4. Sonardyne system block diagram.

4.1.1 Acoustic Tracking Units

The Acoustic Tracking Units are a type 7363 "Midi"-Compatt HF Intelligent Transponder. The compatt can be used in two interrogation modes: simultaneous mode for normal navigation and sequential mode for range measurements of the highest possible accuracy. In simultaneous mode the Diver-Mounted Sensor Package interrogates on Common Interrogation Frequency and all enabled compatts reply, each on its Individual Channel Frequency. When any enabled compatt is interrogated on its Individual Channel Frequency, it replies on Common Reply Frequency. The type 7363 compatt has 10 Individual Channel Frequencies available.

Using an acoustic command from the Programmable Acoustic Navigator, the operator can direct any compatt to change its reply frequency to any of the channel frequencies. This capability reduces inventory requirements and helps overcome interference problems. If any array is laid and interference occurs on a particular channel in use, it is a simple matter to change the compatt to another channel. Each compatt carries a label which gives its "Address." This label is a number that identifies both the Individual Channel Frequency channel number and an address code. Up to 960 individually addressable compatts may be used in proximity. A compatt may be prevented from replying to interrogations by a "Disable" command for conserving battery life, for security, or to avoid confusion when two or more compatts can reply on the same frequency. "Enable" is performed by three commands, each of which sets a different telemetry data rate into the compatt. The difference noticed by an operator controlling compatts by Programmable Acoustic Navigator is that each command is acknowledged by a unique message.

All the advanced commands result in data that must be transmitted from the compatt back to the Programmable Acoustic Navigator. Digital transmission always identifies which compatt is transmitting and what command has been executed. The data is high resolution—13 bits for analog sensor outputs and much higher for ranges or digital sensor outputs. The most significant improvement in the long-baseline navigation is the ability to measure baselines between transponders directly as an aid to rapid, accurate self-calibration. Any compatt may be commanded to interrogate and measure the range to any other compatt in the array using sequential mode for highest accuracy. The range-time data is telemetered back to the Programmable Acoustic Navigator without loss of resolution or accuracy. Baselines may be measured to an accuracy of better than 4–5 cm at the system operating frequency, providing the velocity of sound at the seabed is accurately known. Compatts can be provided with a temperature and pressure sensor to allow the sound velocity to be calculated by using an empirical equation such as "Medwin's." The compatt may be fitted with a Data Acquisition System to digitize the outputs of various sensors. The most popular sensors are a platinum resistance thermometer and a strain gauge depth sensor. Accuracies better than 0.2°C for temperature and 0.2% for depth are maintained under field conditions, provided atmospheric pressure variations are taken into account. Compatts fitted with a Data Acquisition System can also report their exact battery voltage to a Programmable Acoustic Navigator. To speed up other operations compatts have a facility called "Cycle Mode." Up to eight commands may be stacked in a compatt's memory, say, six baseline measurements plus temperature and depth. A single "Cycle" command will cause the compatt to cycle through all eight commands, telemetering each parameter immediately after measurement. Each compatt has built-in self-test hardware and software. This capability allows transmitter frequency and power level, receiver tuning, and bandwidths to be checked before deployment. This checkout can be done on deck using a test transducer without opening the pressure housing.

Brief specifications

Dimensions

Overall length: 700 mm
Largest diameter: 127 mm
Weight in air: 10 kg
Weight in water: 3 kg
Depth rating: 500 m

Acoustic parameters

Frequency range: 33–65 kHz
Receiving sensitivity: 80 dB re 1 μPa
Source level: 190 dB re 1 μPa at 1 m
Pulse length: 1.5 msec
Turnaround delay: programmable from 32.5 msec
Timing resolution, digital: 16.25 μsec
Listening life: nicad, 1 month; alkaline, 6 months
Replies: nicad, 3 x 10^5; alkaline, 7 x 10^5

4.1.2 Acoustic Calibration Sensors

The type 7363 compatt, as described, can be used as an Acoustic Calibration Sensor.

4.1.3 Diver Supervisor Display Unit Interface

A Programmable Acoustic Navigator is used as a Diver Supervisor Display Unit Interface. The Programmable Acoustic Navigator is a microcomputer-controlled unit dedicated to transmitting, receiving, and decoding acoustic signals. The Programmable Acoustic Navigator is controlled by a computer terminal or a master computer via an RS-232C serial data link or IEEE-488 (HPIB) parallel interface. Two transducer ports are available, switchable by software. A front panel keyboard and 32-character alphanumeric display provide local input and display.

The Programmable Acoustic Navigator operates as an advanced acoustic transceiver, computes ranges between seabed transponders, and passes these data to a separate computer for position computation. The number of ranges passed to the computer is limited only by the number of receiver channels within the Programmable Acoustic Navigator and the number of transponders on the seabed. The Programmable Acoustic Navigator acts as the surface control unit for the transmission of commands to compatts and the reception and display of the reply. Compatts reply to all commands with an acknowledgment and a data value where appropriate. The PAN displays the reply and scales the data where necessary. Errors detected in the compatt reply are also listed.

Controlling the Programmable Acoustic Navigator from a master computer allows the measurements made by the Programmable Acoustic Navigator to be used in complex calculation routines. The Sonardyne Software Package, currently available for the Hewlett-Packard HP 9836 and HP 9826 computers, contains the following computation routines.

- Auto-Calibration provides a relative transponder array calibration from seabed baseline measurements.
- Acoustic Long-Baseline Position Calculation provides a position for the transponder connected to a Programmable Acoustic Navigator from up to 10 ranges to seabed transponders.
- Positioning of a Mobile Compatt within a transponder array by the simultaneous measurement of seabed baselines from compatt to each transponder.

Basic specifications

Dimensions

Standard Model: 444 mm wide, 203 mm high, 279 mm deep. The unit is fully sealed and provided with a pressure relief which must be opened for air transport.

Weight: 10 kg

Transit Case: 300 mm wide, 500 mm high, 740 mm long

Shipping weight: 42 kg

Dunking transducer: 130 mm dia, 400 mm long, 8 kg in air

100 m cable/drum: 400 mm dia, 230 mm wide, 20 kg in air

Shipping weight: 47 kg

Power: 110/220 VAC, maximum current 0.2/0.1 amp

Performance

Transducer beamshape: hemispherical as standard directional transducers available

Frequency: 33–65 kHz
Rx sensitivity: 80 dB re 1 μPa
Interrogation source level: 189 dB re 1 μPa at 1 m
Pulse length: 1.5 msec
Timing resolution: 6.4 μsec
Number of independent navigation channels: 10
Telemetry data rates: 25, 50, 100, 250 Baud

4.1.4 Diver-Mounted Sensor Package

The Diver-Mounted Sensor Package is a remote interrogation transducer for the Programmable Acoustic Navigator, designed to mount onto a diver's twin-cylinder aqualung. The Diver-Mounted Sensor Package is connected to the Programmable Acoustic Navigator by a 300-m umbilical of 0.375 inch diameter. This umbilical has a Kevlar center strain member, 7 conductors plus shield, and a polyurethane sheath. The umbilical is connected to the Diver-Mounted Sensor Package by an E-O connector. The Diver-Mounted Sensor Package receives the transmit signal generated by the Programmable Acoustic Navigator via the umbilical. In addition, a preamplifer is incorporated in the Diver-Mounted Sensor Package to boost the received signals for transmission up the umbilical to the Programmable Acoustic Navigator's multichannel receiver. The Diver-Mounted Sensor Package has a second E-O connector for a diver's earpiece and the speech input/output is provided by a Voice-Communications Surface Unit interposed between the umbilical's surface end and the Programmable Acoustic Navigator.

4.1.5 Diver Supervisor Display Unit

The Diver Supervisor Display Unit used by Sonardyne was a standard HP 9920 computer. The HP 9920 was interfaced with an HP 82913A 13-inch monitor, an HP 217G printer, and an HP 9921D dual disc drive. The software used by Sonardyne runs on the HP series 200 family of computers. A minimum system consists of a processor unit, a mass storage device for storing programs, a cathrode-ray tube, and a keyboard. The cathode-ray tube has a standard character display for displaying data in alphanumeric format and a graphics display for showing information in chart or diagram form. For most applications, a nonvolatile graphics capability is very useful.

4.1.6 Temperature/Depth/Sound Velocity Sensor Package

The Temperature/Depth/Sound Velocity Sensor Package used was an Electronics Instruments Limited model 5005, with the following specifications.

Temperature
- Accuracy: ±0.01°C
- Range: −1 to 30°C

Salinity
- Accuracy: ±0.05%
- Range: 0.5 to 39.5%

4.1.7 System Software

The Acoustic Positioning System Software is an easy-to-use, menu-driven program intended for use by hydrographic surveyors carrying out surveys by long-baseline techniques. It carries out a number of important functions.

- Database handling
- Programmable Acoustic Navigator/Compatt command interpretation
- Array Calibration
- Navigation of vessels or other objects by varying ranging from a transducer
- Navigation of an object using a "simultaneous mode" compatt
- Navigation of an object by sequential interrogation of a transponder from an array of compatts
- Navigation of an object by tracking a relay transponder

Graphic displays on the monitor are used to illustrate progress of the calibration procedure and to illustrate the tracking of a diver. The operator does not need to know the language used by the Programmable Acoustic Navigator acoustic transceiver or that used by the intelligent compatt transponder, although he will quickly learn the language by seeing the commands that are sent to the equipment.

4.1.7.1 Structure and general operation of software

The program is written in BASIC and runs under the HP BASIC 3.0 operating system for HP Series 200 computers. This program is a "structured" BASIC with many extensions particular to the Series 200 family for such functions as real-time I/O, matrix math, string handling, mass storage, real-time clock, and graphics. The interpreter does prerun checks on structure of token variables and labels to increase operating speed.

Generally, the operating system and program are stored on 3.5-inch microflexible disk mass storage media, although it is possible to store it on an optional EPROM card fitted inside the processor box. The first task the Acoustic Positioning System Software does is to load the existing database and poll all the devices that it can use to warn the operator of any configuration or hardware errors. The MODE menu is then displayed on the cathode-ray tube. Program operation is based on the tree structure, and the MODE menu is the first branching point. This point has eight options of which three, Database, Calibration, and Trackship, are central in any operation. At the top of this list is the Database, which has seven options or branches. The first option is Transponder Data, which has five options. Before the Calibration option can be entered, the operator must return to the MODE menu via each level, in this case, two levels. It is made easy because a return to the last level is always the default option. This procedure makes program operation easy because it reduces the rules to learn to the absolute minimum. Data is presented in a spread-sheet format and editing is done by controlling a cursor to underline the entry (word or character) that needs entering or editing.

4.1.8 Typical deployment and system operation

A logical sequence follows.

- Decide where to deploy the transponders to ensure line of sight between them and to minimize interference.
- Deploy the transponders. The array can be purely relative, it may be tied to known positions by fixing a compatt to a known point, or it may be an addition to an existing array.
- Power-up the system, load the operating system and program.
- Use the Database option to
  - enter any fixed transponder coordinates;
  - enter provisional coordinates for free transponders;
  - measure the depth, temperature and salinity from each compatt to compute the sound velocity at the seabed;
  - get the transponder status;
  - exit back to MODE menu.
- The Calibration option is called and the Auto-Cal option selected. The operator enters an estimate of the accuracy of the current transponder coordinates. Assigning a high accuracy tends to fix a transponder in its current position. A low accuracy will allow the adjustment process to move it in preference to higher accuracy locations. The program automatically collects the baseline length data from each compatt in the array. A predetermined number of telemetry error-free measurements are made in each direction. If the data for a baseline has a standard deviation greater than a preset value, a histogram of the data is drawn on the screen and the operator can manipulate the data. Once the baseline data is accepted, a ''variation of coordinates'' adjustment is performed to determine the best fit transponder coordinates.
- The transponder data base is updated and the program is returned to the MODE menu.
- The Database option is re-entered and operational data entered such as diver transducer depth. Further options allow waypoints to be entered or points entered that define a structure such as the underside of a ship.
- Return to MODE menu and choose the Track Ship option (Track Diver in this case). The transponder is then tracked by the array. Special function keys are available for a number of functions, such as
  -control of scale zoom up/down (Zoom),
  -overlay,
  -redraw plot,
  -navigation filter ON/OFF,
  -waypoint-range and bearing,
  -exit to MODE menu.

In addition, some keys on the keyboard have some extra functions.

R) causes display of Range data in inverse video at the bottom of the screen.

K) causes the key function to be displayed.

D) causes Data to be written in inverse video at the bottom of the screen.

4.2 Datasonics

A block diagram of the Datasonics equipment is shown in Figure 5. The following description of equipment was taken from the response to the solicitation by Datasonics.

4.2.1 Acoustic Tracking Units

The Acoustic Tracking Units are Model UAT-372 transponders for deployment as a position reference array.

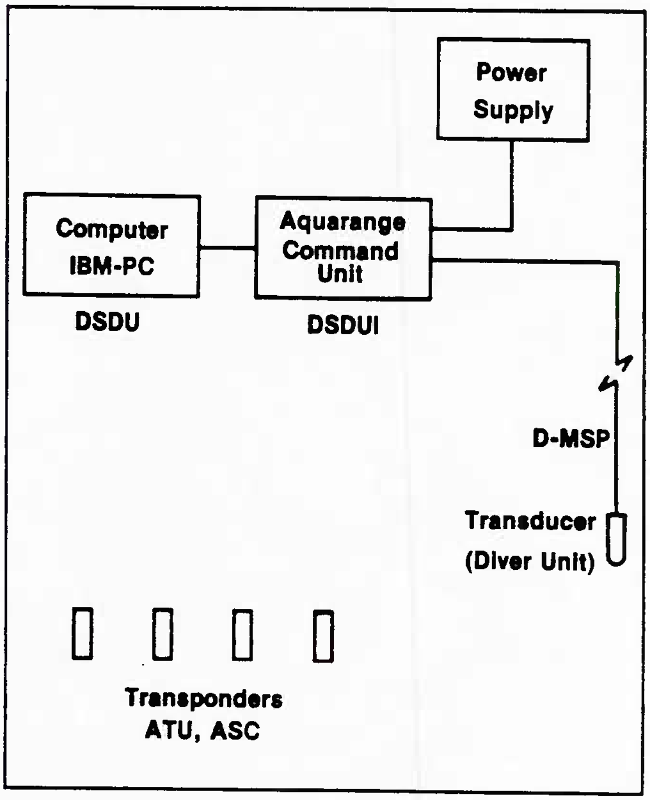

Figure 5. Datasonics system block diagram.

These units will operate in the 35 kHz band and are based on the standard off-the-shelf, 100 kHz, side-scan sonar target transponders.

Brief specifications

Dimensions
- Overall length: 330 mm
- Largest diameter: 89 mm
- Weight: 4.5 kg
- Depth rating: 305 m

Acoustic parameters
- Frequency range: 28–38 kHz
- Rx sensitivity: 80 dB re 1 μPa
- Power output: 100 W
- Pulse length: 1.0 msec
- Turnaround delay: Selectable
- Operating life: 12 months
- Number of channels: 6

4.2.2 Acoustic Calibration Sensors

The Acoustic Calibration Sensors are also a Model UAT-372 transponder. The Acoustic Calibration Sensors can be attached to a ship's hull with magnetic hull attachments or with line.

4.2.3 Diver Supervisor Display Unit Interface

The Diver Supervisor Display Unit Interface is an Aquarange Model ACU-298 8-channel interrogator/receiver with RS-232 Serial/GPIO parallel input/output interface.

Brief specifications

Dimensions
- Length: 483 mm
- Height: 133 mm
- Width: 457 mm
- Weight: 14 kg
- Power: 24 VDC or 110 VAC to DC converter (supplied with unit)

Acoustic parameters
- Frequency range: 35 kHz band
- Source level: 195 dB re 1 μPa at 1 m
- Pulse length: 200 μsec

4.2.4 Diver-Mounted Sensor Package

The Diver-Mounted Sensor Package is a Model AT-477 transmit/receive "Diver" transducer with 500 feet of Kevlar-reinforced cable.

4.2.5 Diver Supervisor Display Unit

The Diver Supervisor Display Unit is an IBM portable computer with 256k memory, integral keyboard, cathode-ray tube display, and dual floppy disk drives. An OKI DATA u92 Printer provides a hardcopy capability for data output.

4.2.6 Temperature/Depth/Sound Velocity Sensor Package

This separate system measured the water temperature. The Temperature/Depth/Sound Velocity Sensor Package was also used to calculate the sound velocity.

4.2.7 System Software

The System Software provided included limited calibration and navigation functions. This System Software used two range circles for the navigation fix. The third range was used to determine ambiguity. The system did not have the capability of providing a hardcopy of plots, which made it difficult to quickly determine the spread in data of more than one track. The system did not have the capability of self-calibration, and the range between Acoustic Tracking Units was input to the system. The System Software then fixed the navigation net.

5.0 Test results

5.1 Sonardyne

The results of the Sonardyne tests are divided into the results at each location: pool, lock, and dockside.

5.1.1 Sonardyne pool tests

The pool tests, described in paragraph 3.1, were completed on 18 November 1985 using the Sonardyne system. Four Acoustic Tracking Units were placed at the locations noted in Figure 6. The system was then calibrated. The Diver-Mounted Sensor Package was tied to a float

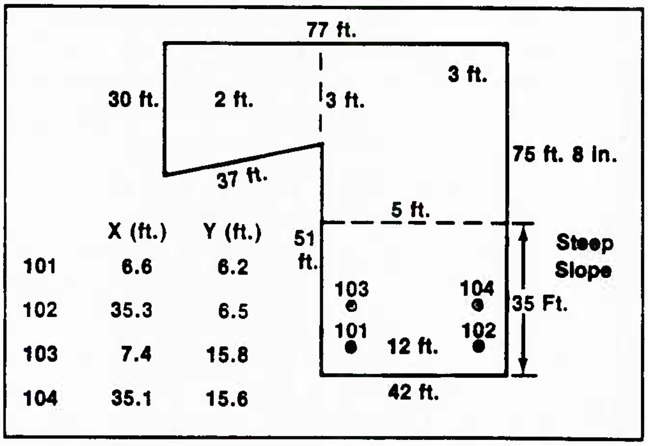

Figure 6. Sonardyne pool test, Picayune, Mississippi.

and positioned in several known locations about the pool. A comparison of the data is shown in Table 1. The final phase of the test consisted of a diver swimming around the pool while pushing the Diver-Mounted Sensor Package attached to the float. The plot generated by the Sonardyne computer system is shown in Figure 7. This system was capable of filtering the ranges that would be acceptable for the tracking calculations. The purpose of the filter was to try to eliminate false fixes in a multipath or interference environment. This filter was set very tight (very small range errors allowed) initially. The close filter setting caused the track fixes to be separated in time, as fix criteria were not satisfied for each and every ping. Experimentation with the filter adjustment gave a good compromise between eliminating data and keeping a close track of the diver. Several swims around the pool adjusting the filter settings were required to obtain the optimum results. After adjusting the filter very few dropouts were observed on the display. Most of the dropouts occurred as the swimmer went between the Acoustic Tracking Unit and the wall of the pool. The pool tests were considered extremely successful; only marginal results were expected in this highly reverberant noise environment.

Table 1. Sonardyne pool test.

Measured by Tape (m)		Measured by System (m)		Error (m)
X	Y	X	Y	R
8.33	1.76	8.38	1.66	0.086
4.69	3.78	4.59	3.55	0.25

Statics for Test
n = 2
R = 0.17
σ = 0.08

5.1.2 Sonardyne lock tests

The lock tests, described in paragraph 3.2, were conducted 19–22 November 1985. Four Acoustic Tracking Units were placed off the edges of the barge and two were attached to the barge, as shown in Figure 8. Recall that for this system Acoustic Tracking Units and Acoustic Calibration Sensors are interchangeable. Two methods were attempted for attaching the ACS to the barge. One was with a magnetic attachment, which worked sucessfully. The other was with a suction device known as a ''limpet,'' which uses water-generated suction to attach to the hull of the barge; this attachment method proved unsuccessful.

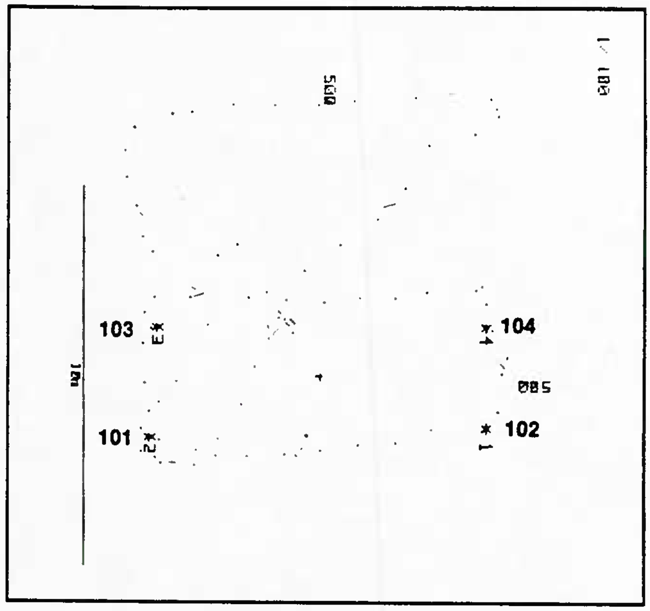

Figure 7. Plot of diver's track in pool.

The second Acoustic Calibration Sensor was secured to the hull by a line passed around the barge.

The Diver-Mounted Sensor Package was moved along the outer edge of the barge and stopped at the locations marked by the lines. The comparison of data is shown in Table 2. It should be noted that changing the Diver-Mounted Sensor Package depth did not affect the range accuracy much, but did increase the spread in the data. A large part of the error in position measurements was because the barge could move about 1 m while moored in the lock.

The Diver-Mounted Sensor Package was then attached to the diver, and the diver was tracked under the barge. The first tracks were completed by instructing the diver to follow known paths under the barge. Again, as in the pool, several tracks were completed trying to find the optimum filter setting. Several of the first diver tracks indicated that the diver was located in the wall of the lock instead of in the water. An additional problem in the first attempts to track a diver was using an incorrect water depth; with the incorrect depth, the system had problems calibrating itself. After adjusting the filter several times and using the correct water depth, very good diver tracks were achieved. A sample of one of these tracks is shown in Figure 9. An attempt was also made to vector the diver to specific locations, but this was not successful because of inadequate diver-to-supervisor communications. Communications via a hardwired system were attempted; however, the diver helmet did not fit the diver well, and the attempts to use the communication system were aborted.

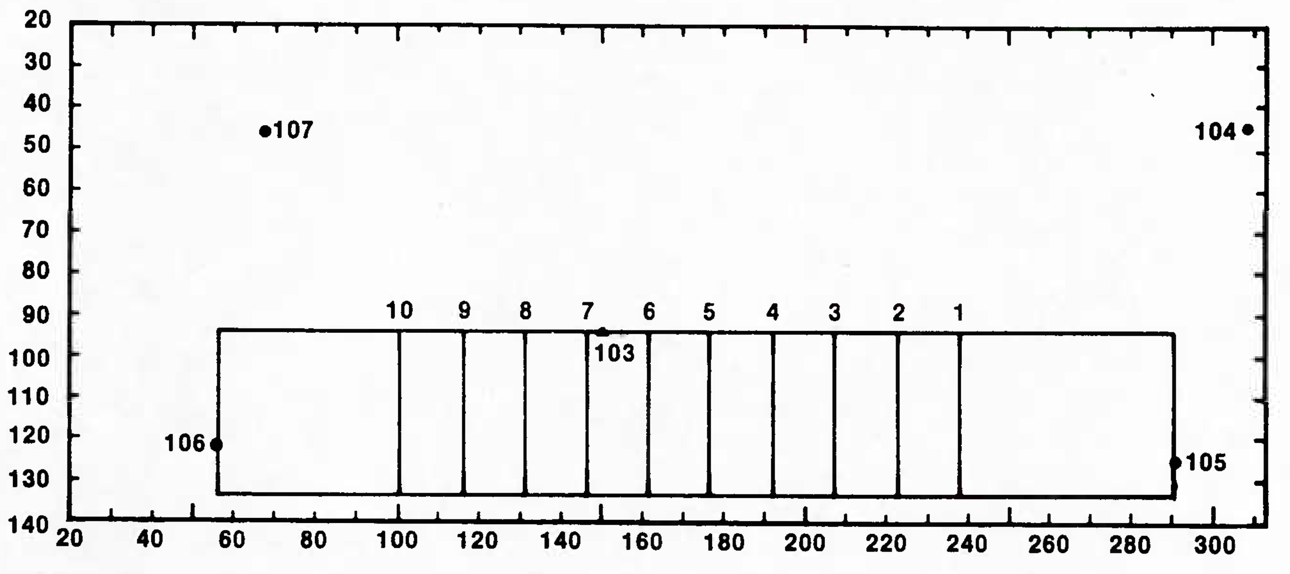

Figure 8. Sonardyne lock test.

Table 2. Sonardyne lock test.

Position Name	Measured by tape (m)		Diver-Mounted Sensor Package 1.82 m deep: Measured by System (m)		Error (m)	Diver-Mounted Sensor Package 1.22 m deep: Measured by System (m)		Error (m)
	X	Y	X	Y	R	X	Y	R
D-10	28.53	30.63	29.39	30.36	0.90	29.18	31.30	0.93
D-9	28.53	35.36	28.34	35.50	0.24	27.38	35.34	1.15
D-8	28.53	39.93	25.46	39.50	3.10	29.27	40.08	0.76
D-7	28.53	44.50	27.08	45.92	2.03	30.28	44.86	1.79
D-6	28.53	49.07	27.83	50.10	1.25	27.71	48.79	0.87
D-5	28.53	53.80	28.20	54.69	0.95	28.65	53.72	0.14
D-4	28.53	58.52	27.80	59.54	1.25	28.65	58.48	0.13
D-3	28.53	63.09	27.16	63.25	1.38	28.03	61.50	1.67
D-2	28.53	67.82	27.23	67.91	1.30	27.86	67.44	0.77
D-1	28.53	72.42	27.14	72.37	1.39	27.73	72.22	0.82
Z-1	40.72	72.42				40.85	72.26	0.21
Z-2	40.72	67.82	41.29	67.70	0.58	40.98	67.80	0.26
Z-3	40.72	63.09	41.92	63.69	1.34	41.69	63.66	1.13
Z-4	40.72	58.52						
Z-5	40.72	53.80	41.48	54.82	1.27	41.82	54.53	1.32
Z-6	40.72	49.07	41.32	49.50	0.74	42.76	50.18	2.32
Z-7	40.72	44.50	41.59	44.74	0.90	40.46	45.01	0.57
Z-8	40.72	39.93	42.07	39.49	1.42	45.15	39.81	4.43
Z-9	40.72	35.36				41.75	35.22	1.04
Z-10	40.72	30.63				41.58	30.83	0.88
			Statics for Test n = 16 R = 1.25 σ = 0.62			Statics for Test n = 19 R = 1.11 σ = 0.96		

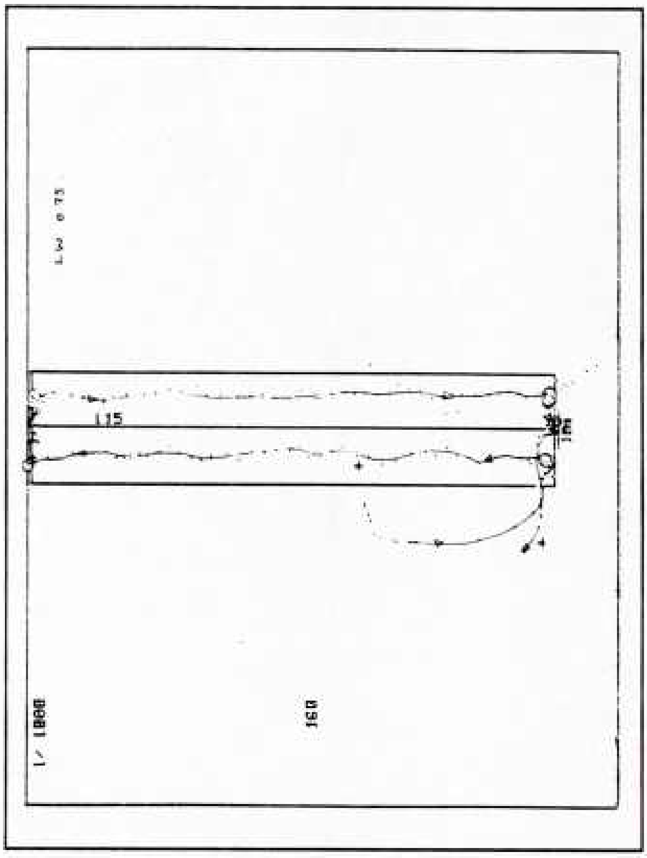

Figure 9. Diver tracks in lock under barge.

5.1.3 Sonardyne dockside tests

The dockside tests, described in paragraph 3.3, were completed 22–23 November. Four Acoustic Tracking Units were suspended from the sides of the ''Pearl River'' and two Acoustic Tracking Units were placed outboard in the channel by a small boat (recall that Acoustic Tracking Units and Acoustic Calibration Sensors are interchangeable with this system). The system was then calibrated. The first test was conducted by moving the Diver-Mounted Sensor Package along the edge of the ''Pearl River'' much as was done on the barge. The comparison of data is shown in Table 3. Figure 10 shows the near-real-time plot of the Diver-Mounted Sensor Package as it was moved along the edge of the ''Pearl River.'' After completing the tow-around tests, several diver vector tests were performed. The communication with the diver via the hardwired system worked very well after adjustments to the diver helmet. The diver would attach a marking magnet to the hull of the ship, then depart the area. The diving supervisor would then vector the diver back to the marked position. An attempt to vector the diver to compatt 4 (Fig. 11) was unsuccessful because the umbilical snagged and the vector to compatt 4 was aborted. The diver was then successfully vectored to compatt 3.

5.2 Datasonics

The results of the Datasonics tests are broken down into the results at each location: pool, lock, and dockside.

5.2.1 Datasonics pool tests

The pool tests, described in paragraph 3.1, were completed on 22 November 1985. Four Acoustic Tracking Units were placed at the locations shown in Figure 12.

Table 3. Sonardyne dockside test.

Position Name	Measured by tape (m)		Measured by system (m)		Error (m)
	X	Y	X	Y	R
P-0	0.0	0.0	−0.28	0.13	0.31
P-15	0.0	4.57	−0.15	5.04	0.41
P-30	0.0	9.14	−0.23	9.28	0.25
P-45	0.0	13.72	−0.19	13.43	0.35
P-60	0.0	18.29	−0.22	18.38	0.24
P-75	0.0	22.86	−0.17	22.95	0.19
P-90	0.0	27.43	−0.12	27.78	0.37
P-105	0.0	32.00	−0.14	32.35	0.38
P-120	0.0	36.58	−0.59	37.05	0.75
P-135	0.0	41.15	−0.10	41.50	0.36
P-150	0.0	45.72	0.25	46.35	0.68
P-165	0.0	50.29	0.09	51.17	0.88
P-180	0.0	54.87	0.48	55.90	1.13
P-195	0.0	59.44	0.14	60.30	0.87
P-210	0.0	64.00	0.56	64.87	1.03
S-210	14.63	64.00	14.93	64.46	0.55
S-195	14.63	59.44	15.29	59.42	0.66
S-180	14.63	54.87	15.30	54.78	0.68
S-165	14.63	50.29	15.43	50.26	0.80
S-150	14.63	45.72	15.78	45.63	1.15
S-135	14.63	41.15	15.51	41.07	0.88
S-120	14.63	36.58	15.45	36.48	0.83
S-105	14.63	32.00	15.23	31.60	0.72
S-90	14.63	27.43	15.08	26.91	0.69
S-75	14.63	22.86	14.76	22.13	0.74
S-60	14.63	18.29	14.96	17.92	0.50
S-45	14.63	13.72	15.82	13.67	1.19
S-30	14.63	9.14	14.72	9.23	0.12
S-15	14.63	4.57	14.72	4.73	0.18
S-0	14.63	0.0	15.35	0.67	0.98
B	4.41	−1.22	4.71	−1.60	0.48
A	10.03	−1.22	10.48	−1.90	0.82

Statics for Test
$n = 32$
$R = 0.63$
$\sigma = 0.30$

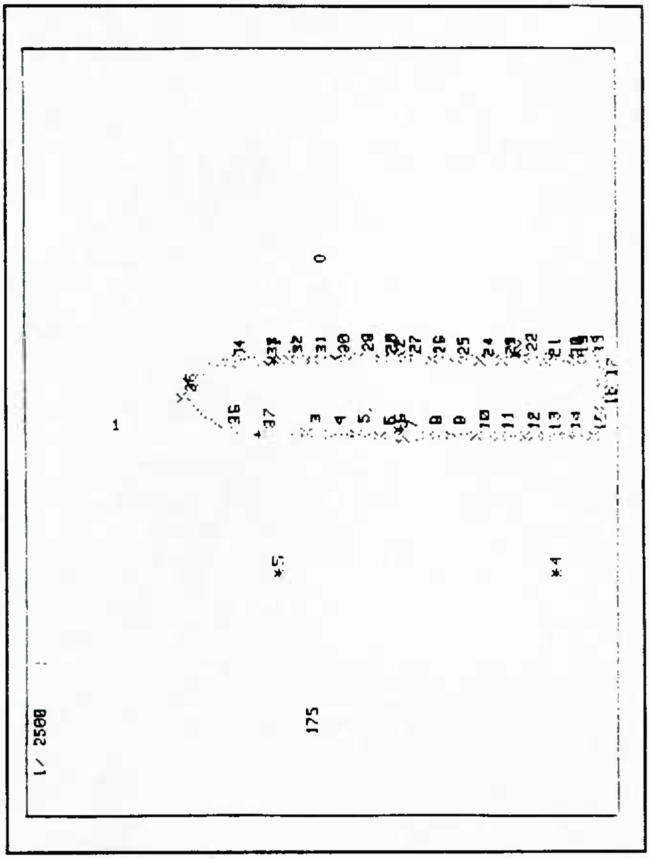

Figure 10. Plot of Diver-Mounted Sensor Package as unit is moved along "Pearl River."

Figure 11. Diver vector dockside.

They were suspended from the sides of the pool by wooden standoffs and the system was then calibrated. Because the Acoustic Tracking Units are small, this system was extremely easy to install. Initally, the system seemed to be very noisy, but after examination, a ground wire was found to be the problem. With the ground repaired the system operated normally. The Diver-Mounted Sensor Package was tied to a float and positioned in several known locations about the pool. A comparison of the data is shown in Table 4. The final phase of the tests consisted of moving the Diver-Mounted Sensor Package around the pool to determine if the system could track a diver. The system successfully tracked the Diver-Mounted Sensor Package in the shallow end of the pool. Few dropouts were noted while tracking the Diver-Mounted Sensor Package. This system did not have the capability of transferring the track to hardcopy, which made it difficult to quickly get a "feel" for the spread in the data of more than one track. The pool tests were considered extremely successful.

5.2.2 Datasonics lock tests

The lock tests, described in paragraph 3.2, were conducted 23–24 November 1985. Four Acoustic Tracking Units were suspended from the sides of the barge. The tracking network was then calibrated. The Diver-Mounted Sensor Package was moved along the edge of the barge and data were collected at each of the marked locations. Two of the Acoustic Tracking Units were then moved across the lock as shown in Figure 13, and the Diver-Mounted Sensor Package was again moved around the barge, stopping at the known locations. The comparison of data is shown in Table 5. The problem with the moving barge was solved during these tests by using standoffs to keep the barge away from the edge of the lock. This also allowed some separation between the lock wall and the Acoustic Tracking Units that were attached to the barge. As is obvious from the data in Table 5, this system is very sensitive to the Acoustic Tracking Unit's geometry. The ranges that give the best circle intersections give the

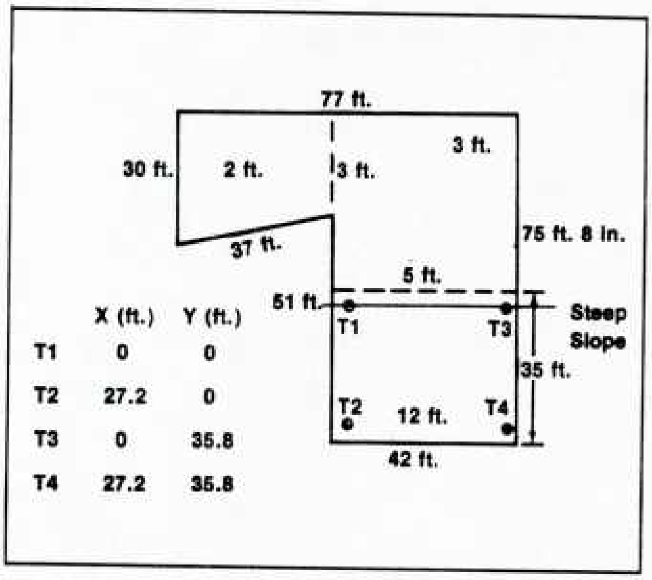

Figure 12. Datasonics pool test, Picayune, Mississippi.

best fixes. With the Acoustic Tracking Units on the barge the x coordinate was much more accurate than the y coordinate. By moving the two Acoustic Tracking Units across the lock, the y coordinates measurements were improved, thereby improving the system accuracy. The Diver-Mounted Sensor Package was then attached to a diver and the diver swam known tracks under the barge. The track data was displayed on the IBM-PC display, but there was no capability to obtain a hardcopy of the track. A hardwired diver communication system was not available in the lock. Therefore, control diver vectors were not attempted. This system software also had a range window that could be adjusted. Again with this system some experience was required to adjust the window to an optimum. If the range window were too high, the diver position would wander around; however, if the range window were too low, many positions would be rejected and the diver could not be tracked. Even after adjustment it was extremely difficult to follow the diver as he tracked down line C, then back up line B. His track down line B would appear to merge with the track of line C. It should be recalled that line C and line B are 7 feet apart.

Table 4. Datasonics pool test.

Measured by Tape (m)		Measured by System (m)		Error (m)
X	Y	X	Y	R
8.23	1.22	7.8	1.4	0.47
6.71	5.18	6.0	4.7	0.86
1.22	2.74	1.6	3.8	1.13
3.66	9.14	3.4	8.5	0.69
7.92	7.47	7.5	6.5	1.06

Statics for Test
n = 5
R = 0.84
σ = 0.24

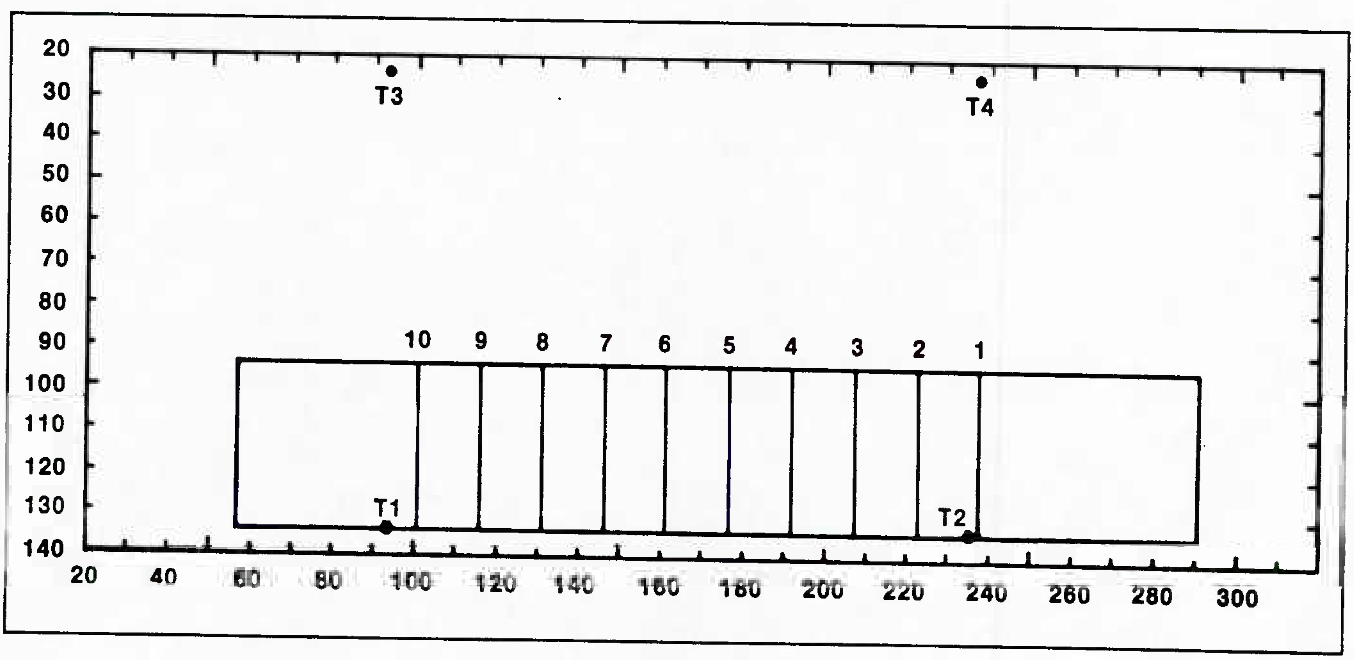

Figure 13. Datasonics at lock.

Table 5. Datasonics lock test.

Position Name	Measured by tape (m)		4 Acoustic Tracking Units on the Barge: Measured by System (m)		Error (m)	2 Acoustic Tracking Units on the Barge and 2 across the Lock: Measured by System (m)		Error (m)
	X	Y	X	Y	R	X	Y	R
D-10	2.13	12.19				2.3	14.3	2.12
D-9	6.79	12.19				7.0	14.4	2.22
D-8	11.38	12.19	11.7	15.7	3.52	11.5	13.6	1.42
D-7	15.95	12.19	15.8	13.3	1.12	16.2	13.9	1.73
D-6	20.45	12.19	20.4	13.6	1.41	20.9	14.3	2.16
D-5	25.06	12.19	24.7	9.8	2.42	25.2	14.2	2.01
D-4	29.71	12.19	29.3	9.4	2.82	28.1	11.7	1.68
D-3	34.29	12.19	33.8	9.2	3.03	32.9	12.0	1.40
D-2	38.87	12.19	38.4	9.6	2.63	37.5	11.5	1.53
D-1	43.45	12.19	43.1	9.3	2.91	42.6	11.4	1.16
Bow-C	60.19	8.23	59.2	5.4	3.00	58.6	7.4	1.79
Bow-B	60.19	6.10	59.3	1.0	5.18	58.9	5.0	1.69
Bow-A	60.19	3.96	58.5	−2.5	6.68	58.5	3.0	1.94
Z-1	43.45	0.0	43.6	6.1	6.10	43.1	0.2	0.40
Z-2	38.87	0.0	37.0	−3.2	3.71	37.3	0.2	1.58
Z-3	34.29	0.0	33.9	−3.2	3.22	33.3	0.8	1.27
Z-4	29.71	0.0	27.7	−3.5	4.04	29.4	0.7	0.77
Z-5	25.06	0.0	23.8	−3.1	3.35	25.5	2.0	2.05
Z-6	20.45	0.0	19.7	0.3	0.81	20.0	1.4	1.47
Z-7	15.95	0.0	15.4	0.6	0.81	15.9	1.7	1.70
Z-8	11.38	0.0	11.3	0.9	0.91	12.1	2.0	2.12
Z-9	6.79	0.0	6.1	0.3	0.75	6.5	3.1	3.11
Z-10	2.13	0.0	1.4	2.8	2.89	1.7	3.3	3.33
ST-A	−11.35	3.96	−12.3	4.8	1.27	−11.6	3.8	0.30
ST-B	−11.35	6.10	−12.0	6.8	0.96	−11.5	7.0	0.91
ST-C	−11.35	8.23	−12.3	5.1	3.27	−11.6	10.0	1.79
			Statics for Test n = 24 R = 2.78 σ = 1.60			Statics for Test n = 26 R = 1.68 σ = 0.67		

5.2.3 Datasonics dockside tests

The Dockside tests, as described in paragraph 3.3, were completed 25 November 1985. For these tests two Acoustic Tracking Units were suspended from the dock, and two Acoustic Tracking Units were suspended from the "Pearl River." Figure 14 shows the relative locations of the Acoustic Tracking Units and the "Pearl River." Table 6 shows a comparison of data taken by moving the Diver-Mounted Sensor Package along the edge of the "Pearl River" and stopping at the known locations. As can be seen this data indicated that the system performed better in the second test conducted in the lock than dockside. Recall that this system is very dependent on the geometry of the Acoustic Tracking Units because the system uses only the two longest ranges to calculate positions. This method of determining positions means that one coordinate is accurate at the expense of the other coordinate. In this case the x coordinate is more accurate than the y coordinate.

Also, there is no way to check the likelihood of multipath error using redundant range measurements. This data was taken after the system had been calibrated. Diver vectors were attempted under the "Pearl River" but were not very successful. First, the diver communication unit interfered with the navigation system and could be used only between range "pings." This interference created problems in getting instructions to the diver in time to correct his path. Also, the diver was forced to operate in a listen-only mode to avoid interference with the acoustic

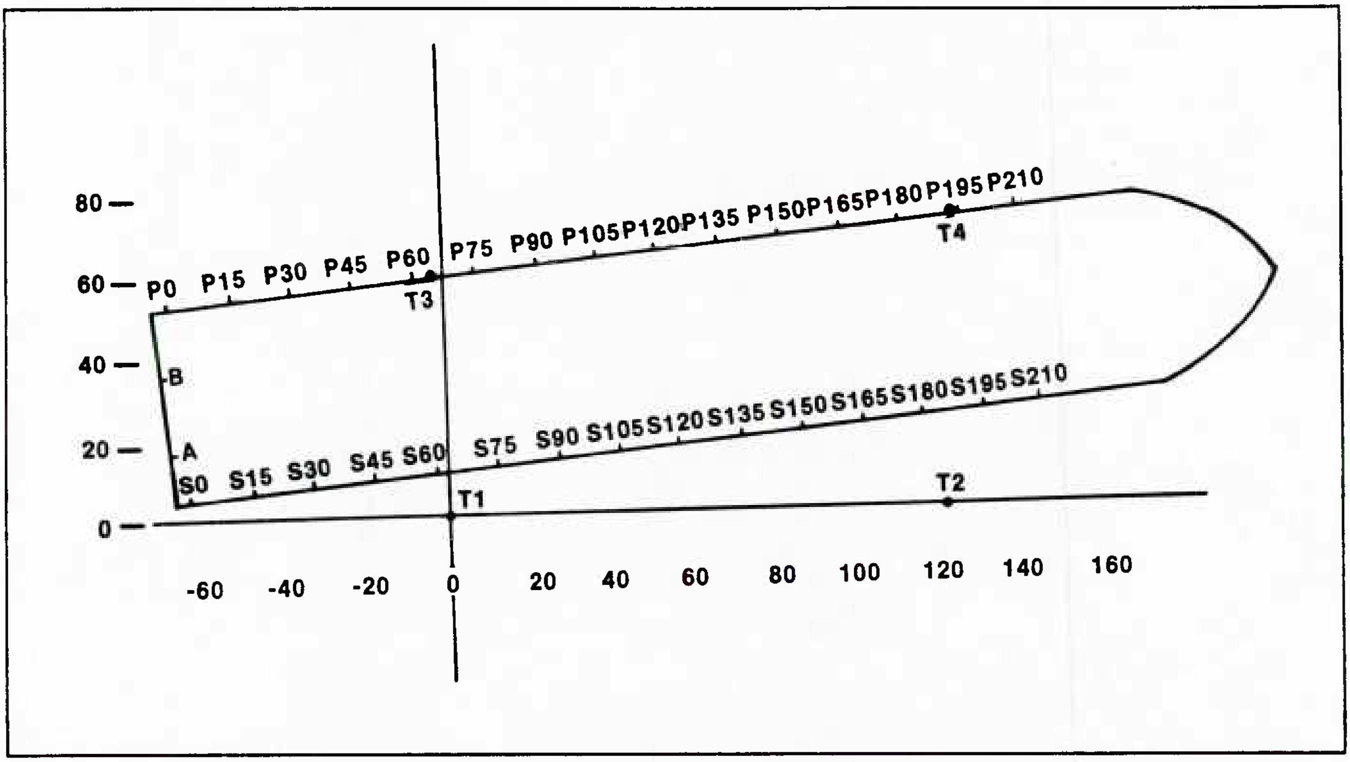

Figure 14. Datasonics dockside.

navigation transponders. These communication problems should in no way be a factor in the accuracy of either of the demonstrated systems. However, poor diver-to-supervisor communications created quite an obstacle to overcome to obtain a successful demonstration of diver vectoring. Toward the end of these tests the IBM-PC failed to operate and the tests were terminated.

6.0 Conclusion

6.1 System accuracy

Both the systems demonstrated can track a diver under the hull of a ship, the accuracy with which they can track the diver and the maturity of the software to present the results are the major differences. Accuracies given in the tables are referred to tape measurements, which could be in error by several inches; however, both systems were measured at the same locations. The poolside test results indicate that the Sonardyne system could meet the 0.45 m (1.5 feet) required by the specification, but only two positions were recorded. In the lock and dockside tests neither system met the 0.45-m requirement. However, with inaccuracies in tape measurements it is felt that the Sonardyne system could meet the 0.45-m specification. The errors in measurements in the lock could also be attributed to the fact that the barge was able to move about 1 m while moored. This movement could explain why the errors in the lock exceeded the dockside errors. The dockside environment was also acoustically better; that is, there were not as many potential multipaths. The inaccuracies in ranges with the Datasonics system are attributed to their inaccuracies in calibrating the system and to using only two sensors for fixing. This system performed better in the lock than dockside, primarily due to the better geometry of Acoustic Tracking Units in the lock.

6.2 System calibration

The capability of self-calibration provided by the Sonardyne system is considered a requirement (paragraph 5.2 of specification). For calibration each compatt would obtain 10 good ranges from each of the other compatts, and relay this information to the computer. The computer would then fix the network. The Datasonics system did not provide for detecting range measurement errors by testing all geometric calculations for closure as required in paragraph 5.2 of the specification. To calibrate the Datasonics system it was necessary to lower a transducer beside each receiver unit and range on the remaining Acoustic Tracking Units. When all Acoustic Tracking

Units were on the barge (or ship), this procedure was difficult, but when the Acoustic Tracking Units were placed outboard of the ship it was impossible. In these cases the system could be calibrated only by placing the transponder beside the Acoustic Tracking Units on the ship and using range circles to determine the position of the Acoustic Tracking Units placed on the floor of the harbor or lock. In these cases the accuracy of the system calibration suffered.

6.3 System software

Sonardyne's software package is much more mature than Datasonics. It accepted ranges from six Acoustic Tracking Units, and did a "least-squares" fit to fix the position of the Diver-Mounted Sensor Package. By this process it could reject several ranges from Acoustic Tracking Units as being outside a certain range window, and then use the remaining good ranges for the least-squares fit. The Datasonics software used only two Acoustic Tracking Unit ranges for a fix. It used the two largest ranges independent of physical geometry. The Datasonics software used a third range to determine ambiguity only. The Sonardyne software used for the limited capability system had been adapted from one of the company's long-range base navigation systems and included several functions that were not required for the UHDLS. Eliminating these functions would simplify the UHDLS software. Modification would be required to provide a menu-driven software for the diving supervisor.

6.4 Temperature/Depth/Sound Velocity Sensor Package

The Temperature/Depth/Sound Velocity Sensor Package required by the specification could be incorporated into either system and thereby simplify the system. The Temperature/Depth/Sound Velocity Sensor Package could use temperature and depth derived from the Acoustic Tracking Unit and the Diver-Mounted Sensor Package to determine the sound velocity. The Acoustic Tracking Units built by Sonardyne are capable of including environmental information in their data transmission.

6.5 Diver Supervisor Display Unit

One system uses a general-purpose computer, the other a personal computer, for the Diver Supervisor Display Unit. A Diver Supervisor Display Unit should be capable of withstanding the weather conditions that would be encountered aboard a moored or anchored ship. A weather-resistant, sealed unit would have to be developed for a Diver Supervisor Display Unit for UHDLS to be successfully used aboard ship.

Table 6. Datasonics dockside test.

Position Name	Measured by tape (m)		Measured by system (m)		Error (m)
	X	Y	X	Y	R
P-0	−20.42	15.85	−18.8	14.5	2.11
P-15	−15.85	16.46	−14.2	14.7	2.43
P-30	−11.43	17.07	−10.0	16.4	1.58
P-45	−6.86	17.37	−5.3	15.9	2.14
P-60	−2.19	17.98	−0.9	16.4	2.04
P-75	2.29	18.44	3.6	16.7	2.18
P-90	6.86	18.90	8.1	17.2	2.10
P-105	11.86	19.35	12.6	18.4	1.20
P-120	15.85	19.81	15.6	16.2	3.61
P-135	20.42	20.12	20.0	16.7	3.44
P-150	24.99	20.73	24.8	16.3	4.43
P-165	29.57	21.18	29.3	16.7	4.49
P-180	34.14	21.64	33.9	16.7	4.95
P-195	38.10	21.95	38.5	16.8	5.17
P-208	42.98	22.37	42.5	16.9	5.49
S-208	44.20	8.02	42.8	4.5	3.79
S-195	40.08	7.62	38.5	3.9	4.04
S-180	35.51	7.16	34.0	3.8	3.68
S-165	30.94	6.71	29.5	3.6	3.43
S-150	26.37	6.10	24.9	3.4	3.07
S-135	21.88	5.64	22.5	7.0	1.49
S-120	17.22	5.18	18.1	6.3	1.42
S-105	12.80	4.72	14.3	4.9	1.51
S-90	8.23	4.27	9.8	4.6	1.60
S-75	3.66	3.81	4.9	4.4	1.38
S-60	−0.91	3.35	0.4	4.0	1.46
S-45	−5.49	2.74	−4.3	3.3	1.32
S-30	−10.06	2.29	−8.6	2.2	1.46
S-15	−14.48	1.82	−13.0	2.4	1.59
S-0	−19.05	1.22	−17.6	2.4	1.87
B	−20.73	5.49	−19.5	5.9	1.30
A	−21.34	11.43	−20.0	9.3	2.52

Statics for Test
$n = 32$
$R = 2.63$
$\sigma = 1.28$

6.6 Summary

The system accuracy, self-calibration, and software of the Sonardyne system met the minimum requirements of Reference 3; the Datasonics system did not. The Sonardyne system will require the development of a Diver Supervisor Display Unit and the incorporation of a temperature/depth/sound velocity package. The results of these tests demonstrated that commercially produced, field-proven, acoustic tracking equipment can be incorporated into a UHDLS. Procurement of the limited capability Sonardyne system is recommended.

7.0 Recommendations

- Select option 3 (adaptation of underwater tracking equipment to a limited capability UHDLS in accordance with Reference 3) of the demonstration contract to procure the Sonardyne equipment. This action will effectively procure the development of the Diver Supervisor Display Unit with menu-driven software for the unit.

8.0 References

1. G. J. Moss, C. R. Holland, and R. A. Brown, *Under-the-Hull Diver Location System, System Definition Study*, Naval Ocean Research and Development Activity, NSTL, Mississippi, NORDA Technical Note 304, September 1984.

2. C. R. Holland, *Under-the-Hull Diver Location System (UHDLS) Field Test Plan*, 3 October 1985.

3. Specification for Qualification of Components and Optional Purchase of Components, and/or an Under-the-Hull Diver Location System (UHDLS), SC-85-0180.