Acoustic Lens Camera and Underwater Display Combine to Provide Efficient and Effective Hull and Berth Inspections

Edward O. Belcher
Applied Physics Laboratory
University of Washington, Seattle, WA

CWO2 Jeffery R. Barone
Shore Intermediate Maintenance Activity
Mayport, FL

Dennis G. Gallagher
Diving & Life Support Systems Division
NSWCDD-Coastal Systems Station, Panama City, FL

Ronald E. Honaker
Human Systems Integration & Engineering
NSWCDD-Coastal Systems Station, Panama City, FL

Abstract—With the advent of the War on Terrorism, and the formation of the Department of Homeland Security, security requirements for the nation's ports and harbors have increased exponentially. A grave threat to ports and harbors are mines or improvised explosive devices (IED) placed on ship hulls, piers, berths, and beds of harbors. Underwater detection is predominately carried out by divers. In dark, turbid water their searches require slow, tactile examinations. With the increasing demand for underwater security searches it is imperative that more efficient and effective methods are developed.

The Applied Physics Laboratory, University of Washington (APL-UW) developed acoustic cameras that use acoustic lenses and produce almost photographic quality images with sound—even in dark, turbid water where optical systems are ineffective. These acoustic cameras can be configured for operations with ROVs, AUVs, or divers. When used by divers, the camera system includes a high-resolution, head-mounted color display system developed by NSWCDD-Coastal Systems Station. This paper concentrates on the diver-held system.

Two versions of the acoustic cameras have been used by divers. The first is the Limpet Mine Imaging Sonar (LIMIS). The LIMIS operates at 2 MHz, has 64 beams, and has a field of view of 20 degrees. Its maximum effective range is 12 m. The second is the Dual-Frequency Identification Sonar (DIDSON). DIDSON operates at two frequencies—1.8 MHz and 1.1 MHz—with maximum effective ranges of 15 m and 35 m, respectively. DIDSON has 96 beams at 1.8 MHz and 48 beams at 1.1 MHz. In each case the field of view is 30 degrees.

In February 2003, two LIMIS systems were tested and evaluated by The Shore Intermediate Maintenance Activity (SIMA) and local law enforcement dive units at the Mayport Naval Station near Jacksonville, FL. The two LIMIS prototype units were used in underwater security sweeps at the Blount Island pier and docking area and under the aircraft carrier USS *Kennedy*.

The pier and dockside underwater security sweep typically is conducted by 2 divers and takes approximately 1 hour to complete (for the specified area). Using a LIMIS unit one diver completed the sweep in approximately 13 minutes, covering the same area with an increased confidence level of finding potential mines or IEDs. A diver team using two LIMIS systems completed a hull sweep of the aircraft carrier using 12.5% of the man-hours used in a normal sweep. They also reported a higher confidence level when using the LIMIS.

I. Introduction

Efficient and effective hull and berth sweeps became a higher priority after 9/11. Before 9/11 the U.S. Navy performed security swims on vessels throughout the fleet on a case-by-case basis. Now Navy divers are required to do regimented, routine security swims. In addition, the Coast Guard has additional mandates to provide more security for civilian ports and vessels. There is high interest in equipment that can both decrease the time needed to search an area and at the same time increase the probability that threats will be found. When divers operate in clear water with sufficient ambient light, optical systems such as cameras and their eyes are sufficient to detect and identify underwater threats. Unfortunately, much of their work occurs in dark or turbid water where optical systems are ineffective and divers resort to tactile means. Sonars operate in dark and turbid water, but the typical sonar does not have sufficient resolution and/or refresh rate to provide the needed detail in this application. This paper describes lens-based sonars that bridge the gap between conventional sonars and optical systems and discusses the head-mounted display that allows a diver to see the sonars' detailed images in zero visibility water. The last part of this paper reports on the results of using these sonars and display in tests and actual missions.

II. Lens-based Sonar

In 1992, the Naval Explosive Ordnance Disposal Technology Division with support from the Office of Naval Research teamed with the Applied Physics Laboratory, University of Washington, and Ultra-Acoustics, Inc. to investigate technologies that would allow divers to identify mines in turbid water without resorting to tactile examination. The technology would be diver-held and thus needed to be compact and consume minimal power. After considering a number of alternatives, the research resolved on very-high resolution lens-based sonars that operated at frequencies above 1 MHz and formed sub-degree beams. Acoustic lenses provided important advantages over conventional electronic beamforming. Lenses formed narrow beams both on transmit as well as receive. The resulting two-way beampatterns generated sharper images than the one-way patterns formed in conventional systems with a single transmit beam covering the entire field of view and beamforming only on receive. Acoustic lenses formed many beams in parallel, consumed no power, and operated at the speed of sound. The major disadvantage of lenses is that they take up volume in front of the transducer array. The following two lens-based sonars give the Navy and Coast Guard useful tools for efficient and accurate hull and berth sweeps.

A. Limpet Mine Imaging Sonar (LIMIS)

The LIMIS (shown in Fig. 1) was sponsored in 1997 by the Explosive Ordnance Disposal/ Low Intensity Conflict (EOD/LIC) Program Office [1]. The LIMIS measures 17.8-cm wide, 20-cm high, and 35-cm long, including a 10-cm handle. It weighs 7.7 kg in air and is 100 g buoyant in seawater. A set of acoustic lenses occupies the upper, rectangular region of the sonar, and electronics occupy the lower region. The lenses form acoustic images that are almost photographic in quality. The entire field of view updates between 5 and 12 frames/s depending on the maximum range displayed. This allows a clear display of dynamic scenes generated by moving the sonar and/or objects moving in the field of view.

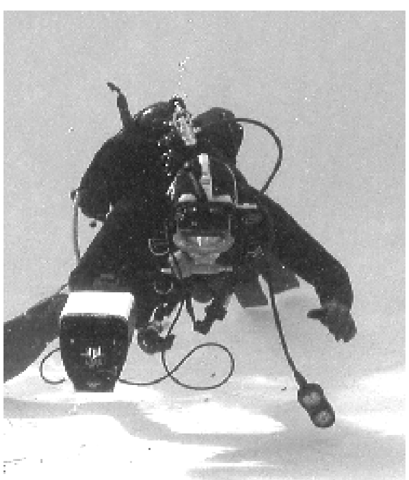

Fig. 1. The LIMIS held by a diver wearing the head-mounted display

Thumb switches on the handle allow the diver to change the range of the display, focus the image, and store digital images of interest (Fig. 2). The diver images the surface of interest by aiming the sonar as shown in Fig. 3. Each beam (0.3° horizontal by 7° vertical) hits the surface at a small grazing angle. Each of the 64 beams is responsible for one radial line in the display.

Fig. 2. Five thumb switches control the LIMIS. The four labeled F1–F4 control software commands. The fifth, between F1 and F3 controls focus. The COM port is an RS-232 link to download commands that duplicate F1–F4 controls and to upload stored digital images. The HUDDS port connects to the mask-mounted display.

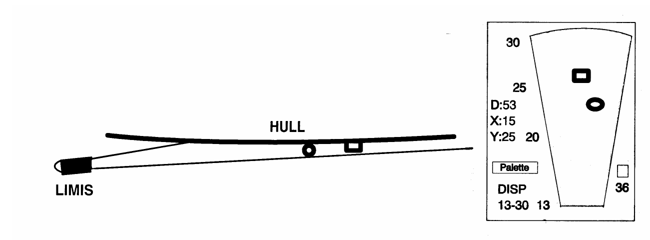

Fig. 3. The LIMIS is held near the hull to get a small grazing angle. Targets are displayed as if seen from below with a sound source illuminating the target from the side.

The sonar operates for 3.5 hours on its internal, rechargeable nickel metal hydride batteries. An auxiliary power pack approximately 2.5 cm by 8 cm by 15 cm attaches on the bottom of the unit to give 1.5 hours of additional operation. Alternatively, 15 VDC can be cabled to the unit from topside for indefinite operation. Fig. 4 is a LIMIS image showing a 50-gallon drum 20 feet from the sonar. Fig. 5 shows three LIMIS images. The left image shows a limpet mine on a hull. The center image shows a pair of hands. The right image shows a hull intake. These images were stored by the diver and later downloaded for analysis and display on a topside computer. The LIMIS allows divers to store up to 50 images.

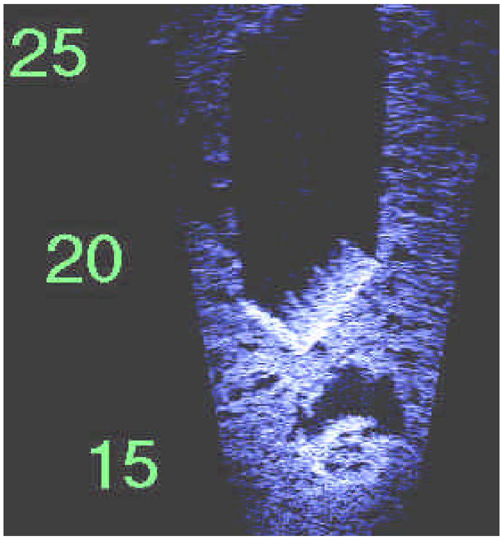

Fig. 4. A LIMIS image of a 50-gallon drum at 20 feet and an old tire at 15 feet.

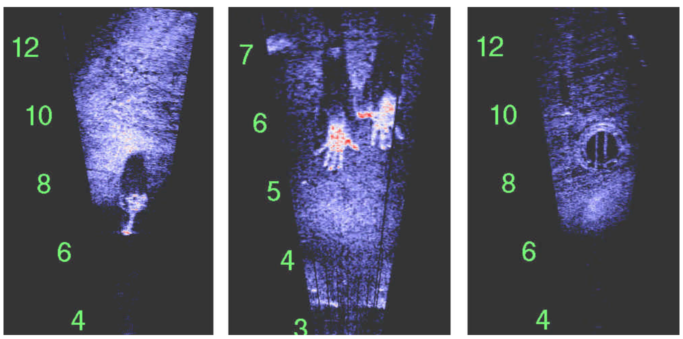

Fig. 5. Three sample images taken with the LIMIS. The left image shows a limpet mine on the hull of a ship 7 feet (2.1 m) from the sonar. The center image shows two hands. The right image shows an intake on the hull of a ship. The intake is approximately 46 cm in diameter and is 9 feet (2.7 m) from the sonar. The left and right images were taken in Chesapeake Bay in water with 15-cm visibility.

B. *Dual-Frequency Identification Sonar (DIDSON)*

The DIDSON's design was impacted by the successes and limitations of the LIMIS. DIDSON has the same resolution and image clarity as the LIMIS for ranges out to 15 m but has the additional capability to switch from 1.8 MHz to 1.1 MHz and extend its range out to 35 m (Fig. 6). The LIMIS has a manual focus. DIDSON has an auto-focus for ranges between 1 m and max range. DIDSON has a 30° field of view 1.5 times as wide as the LIMIS. Table 1 lists the DIDSON specifications.

Table 1. DIDSON Specifications

Detection Mode	
Operating Frequency	1.100 MHz
Beamwidth (two-way)	0.4° H by 12° V
Number of beams	48
Range settings	
window start	0.75 m to 23.25 m in 0.75-m intervals
window length	5 m, 10 m, 20 m, 40 m
Range bin size relative to window length	10 mm, 19 mm, 39 mm, 78 mm
Pulse length relative to window length	16µs, 32µs, 64µs, 128µs
Identification Mode	
Operating Frequency	1.8 MHz
Beamwidth (two-way)	0.3° H by 12 ° V
Number of beams	96
Range settings	
start range	0.38 m to 11.63 m in 0.38-m steps
window length	1.25 m, 2.50 m, 5.0 m, 10.0 m
Range bin size relative to window length	2.4 mm 4.9 mm, 10 mm, 19 mm
Pulse length relative to window length	4µs, 8µs, 16µs, 32µs
Both Modes	
Max frame rate (window length dependent)	4-18 frames/s
Field-of-view	29°
Remote Focus	1 m to max range
Power Consumption	30 Watts typical (24 VDC @ 1.25 A)
Weight in Air	7.0 kg (15.4 lb.)
Weight in Water	0.61 kg neg. (1.33 lb.)
Dimensions	30.7 cm by 20.6 cm by 17.1 cm
Depth rating	152 m (500 feet)
Control	Ethernet

Fig. 6. A handle and head-mounted display were added to the DIDSON for this exercise. A cable connected the sonar to topside for commands and data transfer. A monocular version of the display is on the diver's mask.

The Space and Naval Warfare Systems Center (SPAWARSYSCEN) sponsored DIDSON to develop technology to identify underwater intruders detected by a harbor surveillance system. Other groups use it for underwater inspection, identification of bottom mines, measuring fish abundance, and obstacle avoidance. Fig. 7 shows a DIDSON image of an anode on a metal hull. Fig. 8 shows the stern of a ship resting in 10 m of water. The numbers on the side of the images indicate range from the DIDSON in meters. The DIDSON operated at 1.8 MHz when imaging Fig. 7 and operated at 1.1 MHz for Fig. 8.

The image update rate varies from 18 frames/s to 5 frames/s depending on the operating frequency and the maximum range imaged. The 1.8 MHz mode builds an image with 96 0.3° beams spaced 0.3° apart. It builds this image with eight transmit/receive cycles, each using a different set of 12 beams. The 1.1 MHz mode builds an image with 48 0.5° beams spaced 0.6° apart. It builds this image with four transmit/receive cycles, each using a different set of 12 beams [2, 3]. Table 1 lists the DIDSON specifications.

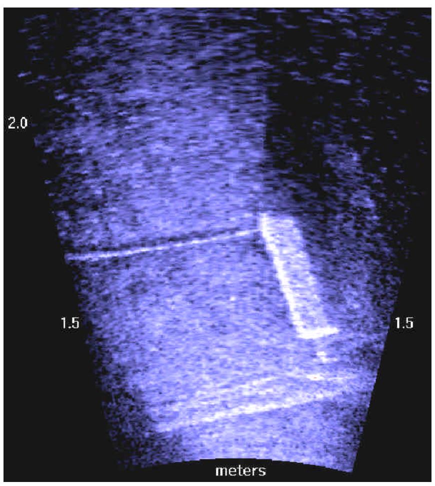

Fig. 7. A DIDSON image of an anode on a metal hull. This image was taken in the high-resolution mode. The range scale for DIDSON is in meters.

III. Miniature Diver Display System (MDSS)

A high-resolution diver-held imaging sonar requires a high-resolution display. When visibility is zero or just a few centimeters, the diver needs the display mounted near his eyes with lenses that provide a large virtual image at a comfortable viewing distance.

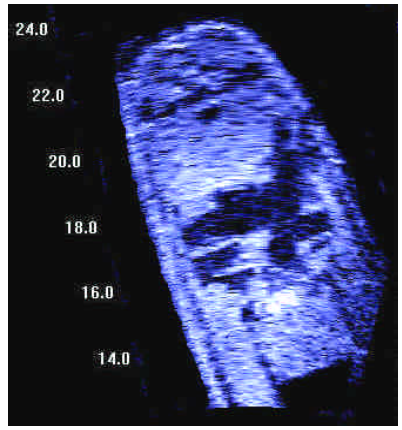

Fig. 8. A DIDSON image of the stern of vessel resting in 10 m of water. This image was taken in the low-resolution mode. The range scale is in meters.

The MDDS (Fig. 9) is such a system that uses a liquid crystal on-silicon (LCOS) microdisplay and a patented mirror-based optical system from i-O Display Systems, LLC (Sacramento, CA). The unit provides binocular viewing of a color, SVGA (800 by 600 pixel) display. The urethane housing has a 150-ft depth rating. A single 1/4-inch diameter, 6-FT cable connects the MDDS directly to the sonar via a standard 8-pin Impulse connector. Three control buttons are located on the top right-side of the MDDS that allow the diver to turn power on or off as well as adjust brightness, contrast, tint, and other viewing parameters. The MDDS is easily used with a number of dive masks, including the US Navy MK-20 full-face mask (Interspiro Divator MK-II) and a range of low-volume SCUBA masks. The MDDS can be flipped up out of the way when not in use, or flipped down into a normal viewing position. The MDDS requires a 7VDC – 18VDC voltage source, and draws 5 watts of power (maximum). It accepts a standard 640 x 480 VGA signal at 60 Hz, or 800 x 600 SVGA signal. Power and signal come directly from the sonar [4].

Fig. 9. Binocular version of the head-mounted display.

IV. Tests and Field Experience

A. DIDSON in Puget Sound

DIDSON was modified to be held by divers for a data collection in October 2002. A handle was bolted on the back and a second connector was wired to operate the MDDS. Topside operators continued to control the sonar and receive images from DIDSON as usual. The diver controlled the aim and position of the sonar and had voice communications with topside. A number of objects were placed in Puget Sound at a depth of 35 feet. The diver went to the bottom and used the low-frequency mode to find objects and swim to them. Fig. 10 shows a photograph and an acoustic image (high-frequency mode) respectively of one of the shapes. Sufficient details are shown in the acoustic image to provide a positive identification even in zero visibility water without having to resort to a tactile examination. The diver also swept the bottom of a metal pontoon on a 70-ft catamaran. Fig. 11 shows a "snapshot" of the bottom of the pontoon.

B. The LIMIS at Mayport, FL

Pier Sweep—On 10 February 2003, the Naval Shore Intermediate Maintenance Activity (SIMA) dive team, at the request of the U.S. Coast Guard, participated in a joint security swim operation with the Jacksonville Sheriff's Office (JSO) dive teams to clear the pier area at Jacksonville's Blount Island cargo terminal.

A typical search of the pier would involve a diver descending and searching each individual piling, by feel if necessary, in the turbid water.

Fig. 10. Photograph and a DIDSON image of a mine shape.

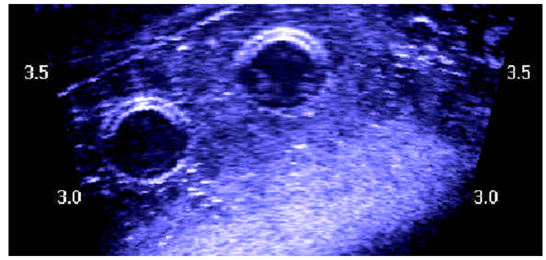

Fig. 11. A DIDSON image of the bottom of a metal pontoon showing instrumentation wells approximately 30 cm in diameter.

Shortly after entering the water with the LIMIS, both dive teams realized that they did not need to submerge to use the LIMIS to search the pier, undercut, and pilings. They simply floated on the surface and imaged the pier undercut by holding the LIMIS underwater while keeping the MDDS, and their heads, above the water. The divers moved quickly down the pier facing, using their free hands to move with the LIMIS set at maximum range of 25 feet to acoustically "see" the back of the undercut. As the diver moved down the pier, he was able to image each individual piling from the sides to see both the front and back of the piling. Without the LIMIS, it would take a team of two divers approximately one hour to search each 100 feet of pier length. With the LIMIS, it took a single diver 13 minutes to search 100 feet of pier. Moreover, the SIMA divers stated that using the LIMIS in this manner yielded a higher cleared validity (probability that all threats have been found).

The advantages in using the LIMIS in this type of operation are apparent. Use of the LIMIS in the pier sweep took less than 25% of the time it would normally take, and increased the cleared validity. Furthermore, diver safety was greatly increased in that: (1) the divers were not forced to submerge and dive underneath the pier to face possible entanglement and overhead hazards; and (2) divers did not have to search the pilings and pier by feel in the turbid water, minimizing the hazards of anti-removal devices found on mine types that were the target of the search.

Hull Sweep—On February 11, 2003, The SIMA dive team, assisted by the Naval Explosive Ordnance Disposal (EOD) dive team, gave the USS *John F. Kennedy* an underwater hull security sweep. The SIMA dive team swept the middle portion of the ship. The EOD team swept the forward bow and the aft running gear and hull. Sections of hull were designated "no go" areas because ship suctions (large intakes used for cooling) were in operation. Both teams began diving operations at approximately 09:00. By mid-afternoon, the teams had completed the full hull sweep of the *Kennedy*. The sweep in Mayport's 1-foot visibility water with two LIMIS systems took 12.5% of the man-hours needed without the LIMIS. In addition, the cleared validity was significantly higher when using the LIMIS. Also, on a normal hull sweep, the two "no-go" areas would go unchecked without turning off and tagging the suctions. With the LIMIS, however, the two dive teams used the 50-foot imaging range on the system and cleared the suctions and surrounding areas from a safe standoff distance [5].

C. STS-107 Columbia Recovery Operations

On 25 February 2003, the operational commander for the in-water recovery of debris from the STS-107 *Columbia*, contacted management at CSS and requested the deployment of the LIMIS to aid in *Columbia* recovery operations. The LIMIS was operated by a member of the SIMA dive team and was designated as the primary visual display sonar asset for searching small areas where larger sonar units could not be utilized - in ponds, rivers, and shallow-water areas around piers and seawalls [6].

D. Fleet Week SIMA Mayport Security Operations April 2003

The dive team at the Shore Intermediate Maintenance Activity (SIMA), Mayport Naval Station, was tasked with providing security swims for piers, bottom areas, and ships in support of the U.S. Navy's Ft. Lauderdale, Florida Fleet Week 2003 (part of Operation Liberty Shield/Neptune Shield).

The security swims using the LIMIS systems were conducted at the Fleet Week Port Lauderdale docks during the first four days of SIMA's operations. The security swims included:

1) Searching approximately 2500 feet of pier and bottom area in preparation for Navy and Coast Guard ships' arrival and berthing
2) Searching the bottoms of all tugs, pilot boats, and tenders used to escort and assist incoming Navy and Coast Guard ships
3) Searching all barges and ancillary structures placed for ships' berthing
4) Conducting daily random security swims of pier areas and ships hulls

Overall, the LIMIS-MDDS systems enabled the SIMA divers to quickly and effectively clear the pier areas, ships, and support boats involved in Fleet Week 2003. For the initial pier security swim, the divers cleared approximately 2500 feet of pier area in less than two hours of dive time. Operations officers in charge of pier security estimated that it would take the divers at least four to six hours to clear this amount of pier and bottom area. The area was cleared using one surface swimmer sweeping the pier facing and pilings with the LIMIS and a SCUBA diver underwater sweeping the bottom to approximately 75 feet out from the pier. During this initial security swim only three objects of interest were identified by the divers – the SCUBA diver sweeping the bottom detected three metal folding chairs using the LIMIS's 50-foot imaging range.

The LIMIS-MDDS systems were also used to clear the bottoms of all the berthing barges for the Navy and Coast Guard ships. Each barge was cleared by a surface swimmer, holding the LIMIS below the water and under the barge while keeping his head with the MDDS out of the water. An individual barge's bottom could be cleared in less than 5 minutes using this method, without the need to deploy SCUBA or surface-supplied diving units.

As the Navy and Coast Guard ships entered Port Lauderdale, each and every one of the tug boats, support boats, and pilot boats involved in the operations had its hull searched using the LIMIS. These searches occurred in the darkness of the early morning hours. The deployed SIMA diver was able to search each large tug boat in less than 10 minutes using SCUBA with no flashlights or ancillary lights under the night diving conditions. For the pilot boats, the 4-foot draft v-hulls were searched by a surface swimmer using the LIMIS.

Finally, throughout the four days of Feet Week deployment, divers used the LIMIS for searches of pier and bottom areas. Portions of the docked ships' hulls could also be searched from a stand-off distance using the LIMIS's 50-foot imaging range.

Overall, users provided positive comments from using the LIMIS-MDDS systems. The LIMIS enabled the SIMA divers to markedly reduce the time and resources required to conduct the security swim operations. The divers also felt that they had a greater confidence that an area was clear of hazards after "seeing" it with the LIMIS-MDDS system. For several of the operations, using the LIMIS enabled the divers to clear an area without the need to set up SCUBA or surface-supplied diving equipment – i.e., the security swim was conducted by a surface swimmer holding the LIMIS unit underwater and keeping his head out of the water while using the MDDS.
Users felt that the system was easy to use and met the operational needs for the port security diver searching for mines or hazards on ship hulls, piers, and bottom areas [7].

Acknowledgments

The Space and Naval Warfare Systems Center Bayside, San Diego, (Brian Matsuyama, Code D374) sponsored the development of DIDSON at the Applied Physics Laboratory, University of Washington. Earlier lens-based sonars were funded by the Office of Naval Research (Tom Swean), the Naval Explosive Ordnance Disposal Technology Division (Bruce Johnson), Coastal Systems Station (Jody Wood-Putnam), and the EOD/LIC Program Office (Larry Tierney). The MDDS was developed at the NSWCDD- Coastal Systems Station, Panama City, FL under the sponsorship of the EOD/LIC Program Office (Larry Tierney).

References

[1] E.O. Belcher, "Limpet mine imaging sonar," Proceedings of SPIE, Vol. 3711, 13th Annual International Symposium on AreoSense, Orlando, FL, April 1999, pp. 2-10.

[2] E.O. Belcher, B. Matsuyama, and G.M. Trimble, "Object Identification with Acoustic Lenses," Conference Proceedings MTS/IEEE Oceans 2001, Volume 1, Session 1, Honolulu, Hawaii, November 5-8, 2001, pp. 6-11.

[3] E. Belcher, W. Hanot, and J. Burch, "Dual-Frequency Identification Sonar," Proceedings of the 2002 International Symposium on Underwater Technology, Tokyo, Japan. April 16-19, 2002, pp 187-192.

[4] D.G. Gallagher, "Development of Miniature, Head-Mounted, Virtual Image Displays for Navy Divers," Proceedings of OMAE99 18th International Conference on Offshore Mechanics and Arctic Engineering, St. John's Newfoundland, Canada, July 11-16, 1999.

[5] R. Honaker, "Trip Report: SIMA Mayport Demo and Security Operations Utilizing the Limpet Mine Imaging Sonar (LIMIS) 5-11 February 2003," NSWC-DD Coastal Systems Station (CSS), Panama City, FL 32407

[6] R. Honaker and W. Olstad, "Trip Report: STS-107 Columbia Recovery Operations Utilizing the Limpet Mine Imaging Sonar (LIMIS) 26 Februray – 04 March 2003," NSWC_DD Coastal Systems Station (CSS), Panama City, FL 32407

[7] R. Honaker, "Trip Report: Fleet Week SIMA Mayport Security Operations Utilizing the Limpet Mine Imaging Sonar (LIMIS) 27-30 April, 2003," NSWC-DD Coastal Systems Station