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Range imaging for underwater vision enhancement

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ABSTRACT

This paper presents results from a series of preliminary tests to evaluate a scannerless range-imaging device as a potential sensory enhancement tool for divers and as a potential identification sensor for deployment on small unmanned underwater vehicles. The device, developed by Sandia National Laboratories, forms an image on the basis of point-to-point range to the target rather than an intensity map. The range image is constructed through a classical continuous wave phase detection technique in which the light source is amplitude modulated at radio frequencies. The receiver incorporates a gain-modulated image intensifier, and range information is calculated on the basis of the phase difference between the transmitted and reflected signal. The initial feasibility test at the Coastal Systems Station showed the device to be effective at imaging low-contrast underwater targets such as concertina wire. It also demonstrated success at imaging a 21-inch sphere at a depth of 10 feet in the water column through a wavy air-water interface.

Key Words: range-image, underwater imaging, sensor, mine reconnaissance, diver

1. INTRODUCTION

Near-shore hydrographic reconnaissance and very shallow water (VSW) mine countermeasure (MCM) operations are functions currently performed by teams of divers and/or divers and marine mammals. The MCM mission involves the detection and identification of both mines and mine-like targets. It also involves the subsequent reacquisition and neutralization of any mines found during the search. In hostile areas, the operator can expect to encounter various moored contact mines, bottom influence mines, and anti-invasion mines. Some of the newer bottom influence mines have plastic or composite outer cases with case profiles that are very effective at blending into the bottom. Marine growth can make these weapons difficult to detect, and because of the influence triggering mechanisms, they are a threat to military divers as well as landing craft. Mine and obstacle populations become even denser in the surf zone (SZ). Here, the mine threat includes all of the numerous pressure-plate and tilt-rod mine variants available on the international market, as well as obstacles such as hedgehogs, concrete blocks, stake jacks, steel tetrahedrons, and both single- and triple-stranded concertina wire.

Regardless of the objective, coastal environments can be a challenging place for the military diver to conduct any type of underwater operation. Nearshore waters are often optically turbid with overall clarity depending on variables such as bottom type, proximity to rivers, bays, and inlets, rainfall history, proximity to civilization, and time of year. Due to the nature of the missions, the effects of low visibility, currents, rip tides, and wave surge in combination with the existence of underwater hazards create stressful conditions for the military diver. For clandestine activities, planning thresholds preclude operations in waters where shore-based personnel might be able to observe either vehicles or swimmers at depths in excess of 10 feet,[1] so water clarity becomes a factor in determining when and where these activities will occur.

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DISCLAIMER

Divers clearly need the ability to locate obstacles and hazards in low-visibility conditions and to identify dangerous targets at a safe stand-off distance. The Coastal Systems Station has hands-on experience with two diver-specific range-gated imaging systems; the SeeRay, which operates at 532 nm and the Clandestine Diver System (CDS) which was developed specifically for military applications. The SeeRay was developed by Sparta, Inc., Laser Systems Laboratory, since acquired by Xybion Corporation, and the CDS, which is still a prototype, was developed by Xybion for the Navy. Range-gated imaging systems generally give an operator the capability to see targets at much longer distances in scattering media than possible with other types of active systems or with the unaided eye. However, any system depending on image contrast for target recognition will have limited effectiveness in viewing targets with geometry and surface coloration/texture that closely matches that of the background. Spectral contrast is lost due to varying rates of color attenuation and the use of a monochromatic source. Low signal-to-noise ratio is an issue when concerned about small form-factor hazards such as concertina wire in the water volume. Non-diving applications, such as imaging mines in the water volume through a wavy air-water interface, also present problems that have required complex solutions with conventional gated imaging systems.

A less-conventional imaging alternative is to use a system that forms a three-dimensional image on the basis of range rather than a two-dimensional image based on reflected energy. Formation of the "range-image" is a function of the ability to unambiguously determine the distance between each element of the detector and the points on the target that are in that particular element's instantaneous field of view. Thus, image contrast associated with a given target is more a function of its 3-D geometry and position relative to the background than of reflectivity and surface texture. This concept is embodied in a scannerless range imaging system (SRI) developed at Sandia National Laboratory (SNL),[2] under joint sponsorship by the Department of Energy and the Office of Munitions, within the Department of Defense. The system constructs a three-dimensional image on the basis of time-of-flight and phase information. The original intent of the system was to identify terrestrial 3-D targets that tended to blend into the background in a normal 2-D image taken at moderate to long range. However, there are a number of underwater applications to which such a system may be well suited, including bathymetry and underwater object location.

The Coastal Systems Station became interested in the SRI technology for underwater imaging applications after it was postulated that the phase information used to construct a 3-D range image would be preserved under conditions that would render target recognition impossible in a 2-D reflectance image. Thus, the range imager might be able to produce recognizable shapes for 3-D targets within its detection range that might otherwise blend into the background or become lost in the backscatter with a normal imaging system. This potential was recognized relatively early by principle investigators at Sandia National Laboratory, but the opportunity to actually test the concept didn't occur until the spring of 1998 when a series of discussions led to a joint effort between SNL, Nichols Research Corporation, and the Coastal Systems Station (CSS) to perform a short sequence of feasibility experiments in the swimmer delivery vehicle (SDV) test tank at CSS. Those experiments took place over the three-day periodof April 22 – April 24, 1998. Images were gathered at several different turbidity levels, and it was found that 3-D volume targets in the range images were often recognizable beyond the point where there was sufficient image contrast to recognize the target in the standard 2-D image. The system, while range-gated, had a gate width too wide for the short ranges available in the test tank, so the results from the experiments are not representative of the performance of a properly designed system. The results do, however, indicate some of the advantages and disadvantages that would be embodied in range imaging systems for both diving and other types of applications. The purpose of this paper is to present the results of the feasibility experiments and to briefly discuss their implications with respect to future imaging systems for the diver.

2. SCANNERLESS RANGE IMAGER

The scannerless range imaging device used in the underwater feasibility tests is basically an imaginglidar that forms a range image through a unique series of hardware modifications and processing techniques that eliminate using either mechanical or electrical beam steerage processes. It was originally developed at Sandia National Laboratory, and the technology was patented in 1990 by the Department of Energy.[3] The basic system elements consist of a light source and a receiver that utilizes an image intensified CCD (ICCD) array as the detector. The source can be either continuous wave (CW) or pulsed, but operates in floodlight mode in either case to ensure operation as a total field of view system. Range information is generated through a sequence of processes that starts with the synchronous modulation of both the light source and intensifier gain at RF frequencies. Energy reflected from the target (or within the volume) is collected by the receiver, and the phase information captured through the mixing of the return signal with the modulated intensifier gain prior to being recorded by the CCD array on a pixel-by-pixel basis. Thus, phase information is captured simultaneously for each pixel in the array. An on-board digital signal processor is used to compare two or more frames of reflectance data generated with different modulation schemes and extract the range information for each pixel. The images are then output as a standard video signal. Reflectance imagery is thus available at normal video rates, and the range imagery available at near normal video rates. The latest camera/DSP combination makes the system capable of one to three- inch range resolution and a high range-image pixelrate.[2] The use of a Gen II or Gen III image intensifier also enables the implementation of conventional range gating techniques to minimize the effects of backscatter and enhance the signal to noise ratio for targets located within the gated volume.

3. UNDERWATER TEST SETUP AND OBJECTIVES

The range imager used in the underwater feasibility experiments was a breadboard configuration assembled from available components by Sandia National Laboratory. Basic components were the receiver, the source, power supplies and control electronics, and a desk-top computer. The receiver consisted of a Kodak digital camera with 1534 by 1024 pixel CCD array coupled to a slow response image intensifier with a 50ns rise time for the gate and a minimum 100 ns gate width. Standard 25 mm and 50 mm photographic quality lenses were used to collect and focus the return signal. The source was a frequency-doubled Nd:YAG laser operating at 532 nm and coupled to a diverging lens and a diffuser element. Five targets were selected for use in the experiments; contrast and spatial resolution panels, a range resolution panel, a PDM-1 mine simulant (tilt-rod SZ bottom mine), a painted 21-inch diameter aluminum sphere to simulate volume mines, and a 20 foot length of triple stranded concertina wire.
All experiments were performed in the SDV test tank located within building 319 at the Coastal Systems Station. The SDV test tank is a rectangular fresh-water vehicle test facility 16 feet wide, 40 feet long, and twenty feet deep equipped with cranes and observation/working platforms that were ideal for the planned series of tests. The facility also has a good set of pumps and filters that make it possible to quickly change turbidity levels by the adding and removing Maalox®. A Wetlabs AC-9 dual path absorption and beam attenuation instrument was used to monitor the turbidity levels throughout the testing period.

The test objectives were to assess the ability of the range imager to see underwater targets under two different imaging situations. First, it was desired to test the range imager as an underwater imaging system with source and receiver operating underwater as would be the case for a diver-portable system, and subsequently, to determine if there were any obvious advantages to be gained by using the SRI to view volume targets through the air-water interface.

4. RESULTS AND DISCUSSION

4.1 Underwater Tests

In order to conduct the underwater experiments, it was necessary to devise a way to use existing system components to collect underwater images. The Sandia group accomplished this by affixing and sealing transparent end-caps to two lengths of PVC pipe and building a frame to mount the pipe sections on the side of the test tank. The receiver and source were then placed within the PVC sections which were positioned so that the source and receiver apertures were physically located below the water surface. The basic setup can be seen in Fig. 1, which shows both sections of PVC pipe with the portals immersed in water. Source-receiver separation was on the order of two feet. The various targets were positioned in the test tank relative to the source and receiver as diagrammatically illustrated in Fig. 2. Targets were located by performing an initial visual alignment and then adjusting the mounting brackets until the targets appeared within the SRI field of view. In-air photos of the 21-inch sphere, the PDM-1 mine simulant, and the bundled concertina wire are shown in Fig. 3.

Data gathered during the course of the tests were ported to a desk-top computer where the results were displayed and the digital image information stored for both immediate post processing and subsequent detailed analysis. The 2-D reflectance and 3-D range images were collected and displayed simultaneously making it possible to do side-by-side comparisons during the course of the tests. Sandia's visualization software produces plots of relative pixel intensity for a cross-section of each image that are useful in assessing image quality. These plots can be interpreted in terms and of relative surface geometry for each range image

A side-by-side comparison of the initial range and reflectance images made of the spatial resolution panel, as shown in Fig. 4, is useful for illustrating some of the differences between the two types of images. These images were made in relatively clear water with measured absorption and beam attenuation coefficients of $a = 0.001\ m^{-1}$ and $c = 0.085\ m^{-1}$ respectively. The resolution panels were suspended from a rail to a depth of approximately ten feet inside the test tank. Distance from the imager could be adjusted by simply sliding the rail along the top of the tank. Overall range to the targets was measured by hand with a stiff length of PVC pipe, and the distance in this case was 14 feet. Fundamental differences in the two types of images are immediately obvious. The white stripes painted on the black background of the spatial resolution panel are the only features that show up on the reflectance image, and the edges of the panel are not visible at all. Spatial changes in reflected intensity are clearly evident in the 1-D intensity plot accompanying the image. On the other hand, the edges of the resolution panel are the only thing visible in the range image, and the surface profile plot indicates that the surface of the panel is flat. There is no evidence of surface markings as would be expected from an image where contrast is a function of geometry.

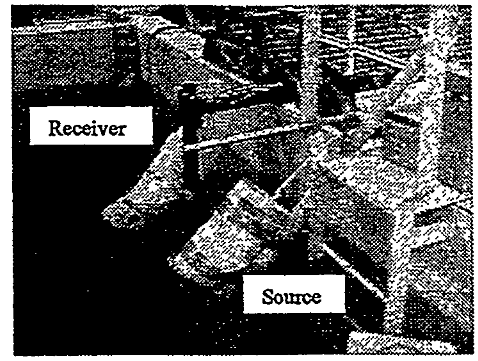
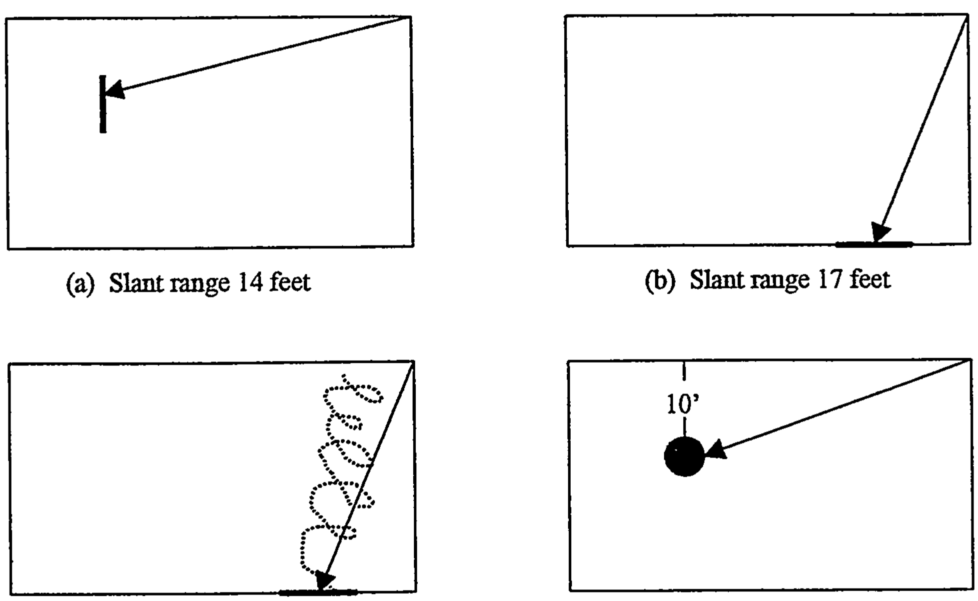


Figure 1. Source and receiver mounted to the side of the SDV test tank.



(a) Slant range 14 feet

(b) Slant range 17 feet

(c) Slant range 17 feet

(d) Slant ranges of 17-33 feet

Figure 2. Position of targets relative to the source and receiver for the underwater tests. Targets are (a) resolution panels, (b) PDM-1 mine simulant, (c) PDM-1 and concertina wire, and (d) 21-inch painted aluminum sphere.

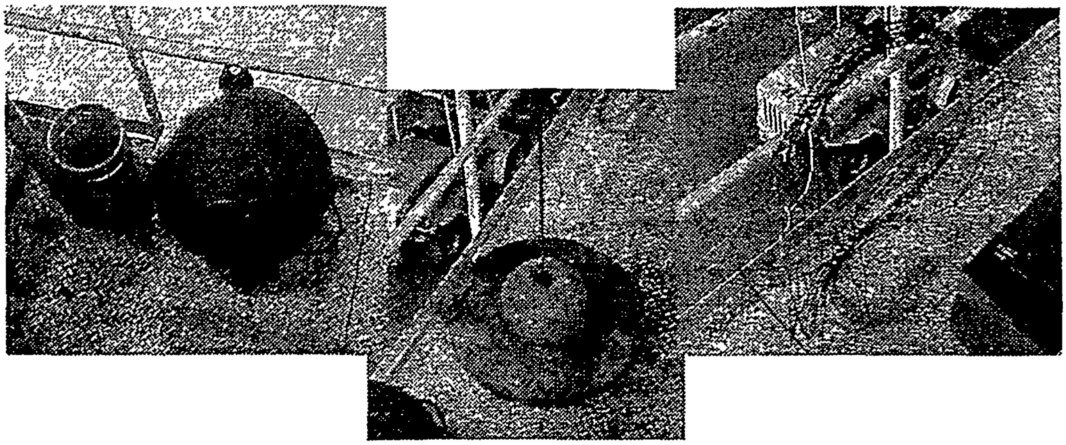


Figure 3. In-air photos of the primary targets used in the tests; 21-inch sphere (left), PDM-1simulant (center), and concertina wire (right).

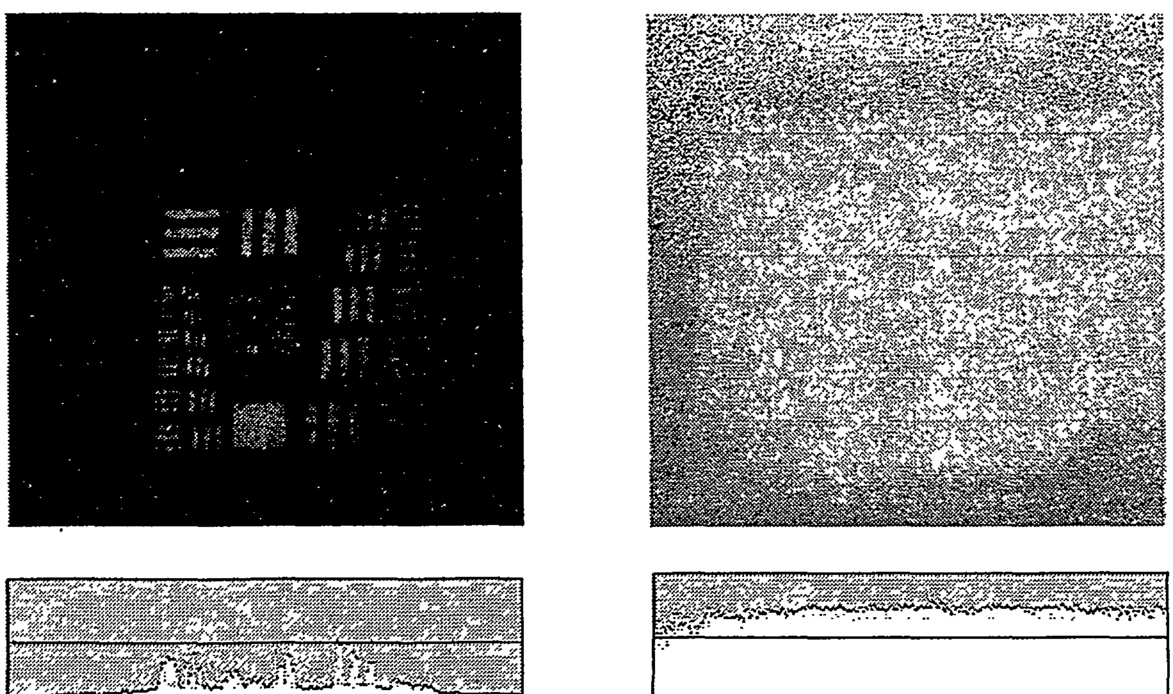


Figure 4. Side-by-side comparison of reflectance image (left) and range image (right) for spatial resolution panel at a distance of 14 feet in clear water ($a = 0.001\ m^{-1}$ and $c = 0.085\ m^{-1}$). The associated plots of pixel intensity and surface geometry are shown below the respective images.

Data collected on the three dimensional targets begin to illustrate the real possibilities of the SRI for underwater imaging applications. The next several images were taken of the 3-D targets cited earlier under different imaging circumstances and visibility conditions. Figure 5 is a side-by side comparison of the reflectance and range images in clear water for the PDM-1 mine simulant resting on the bottom 17 feet away from the receiver. Measured

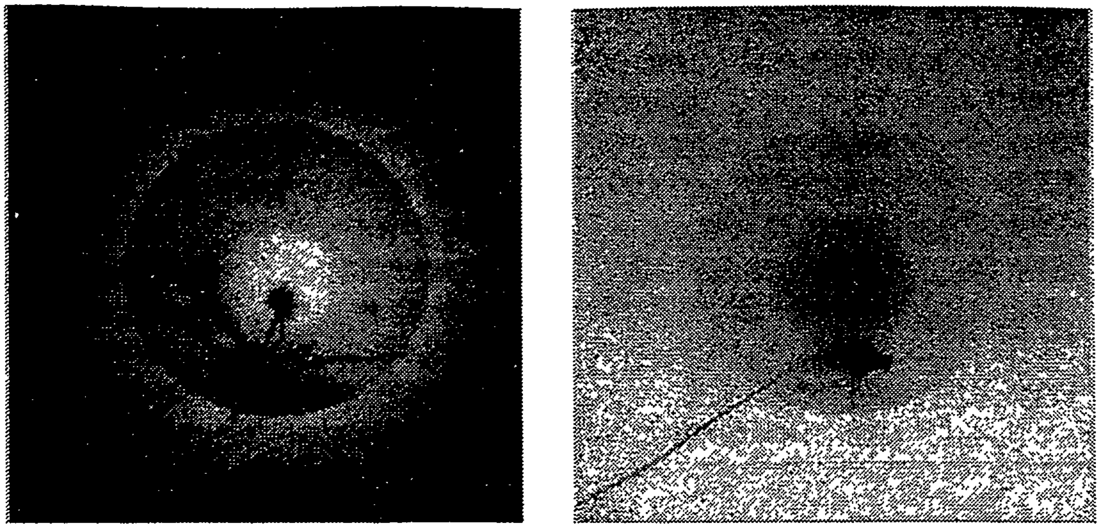


Figure 5. Reflectance image (left) and range image (right) for PDM-1 simulant sitting on the bottom of the SDV test tank at a range of 17 feet from the receiver. Water was clear with a = 0.001 m^{-1} and c = 0.085 m^{-1}.

absorption and beam attenuation coefficients were the same as in the previous case. The intensity map on the left side of the figure is clearly recognizable as the mine simulant, because shadows and differences in reflectivity from some of the targets features produce a high degree of contrast. However, note the lack of contrast between the housing and the base-plate between 11 o'clock and 5 o'clock. In the range image, it can be seen that the base-plate, which is only a fraction of an inch thick, is just distinguishable from the flat bottom background, since it is very nearly a 2-D feature. This highlights one disadvantage of the SRI, i.e., that geometric features that closely match the background geometry will be harder to see. The hemispherical housing and tilt-rod stand out, with cleanly defined edges as would be expected. Another feature that stands out very cleanly is the cable attached to the vertical tilt-rod to facilitate target removal at the end of the tests. This is because the phase information contained in the energy reflected from the cable produces a high degree of contrast relative to the water volume; whereas, that contrast may be lost when looking at just the intensity level of the reflected energy.

Imaging performance under low visibility conditions is important in underwater applications because the combined effects of attenuation and backscatter are difficult to overcome. Although the breadboard imager used in the feasibility tests was less than optimal for turbid water operations, an effort was made to qualitatively examine the performance of the range imager in low-visibility conditions. Turbidity was increased by adding Maalox to the test tank and making sure that it was well-mixed before proceeding to gather data.

Figure 6 shows image data taken of the PDM-1 simulant with a coil of concertina wire suspended from the surface and making contact with the top of the target underneath. Water conditions were turbid water with a = 0.11 m^{-1} and c = 0.65 m^{-1}. A close look at the images reveals that the outline of the bottom target can just barely be seen in each one, and the target would probably not be recognizable under field operating conditions. However, the concertina wire, which is just discernable in the intensity image, is clearly identifiable in the range image. This characteristic of the SRI would be valuable to divers, since nets, cables, and similar clutter in the water volume are entanglement hazards that divers avoid if possible. As a matter of fact, the SRI proved to be very effective at imaging volume targets in general, because the inclusion of the extra dimension of the 3-D targets provided a means of increasing the effective signal to noise ratio in the presence of backscatter. Evidence of the ability to discriminate targets in the range image at distances beyond which this was possible in the intensity image is presented in Figure 7. Figure 7 contains two image pairs taken of the 21-inch diameter sphere at different distances in moderately turbid water with a = 0.07 m^{-1} and c = 0.26 m^{-1}. The sphere was suspended 10 feet below

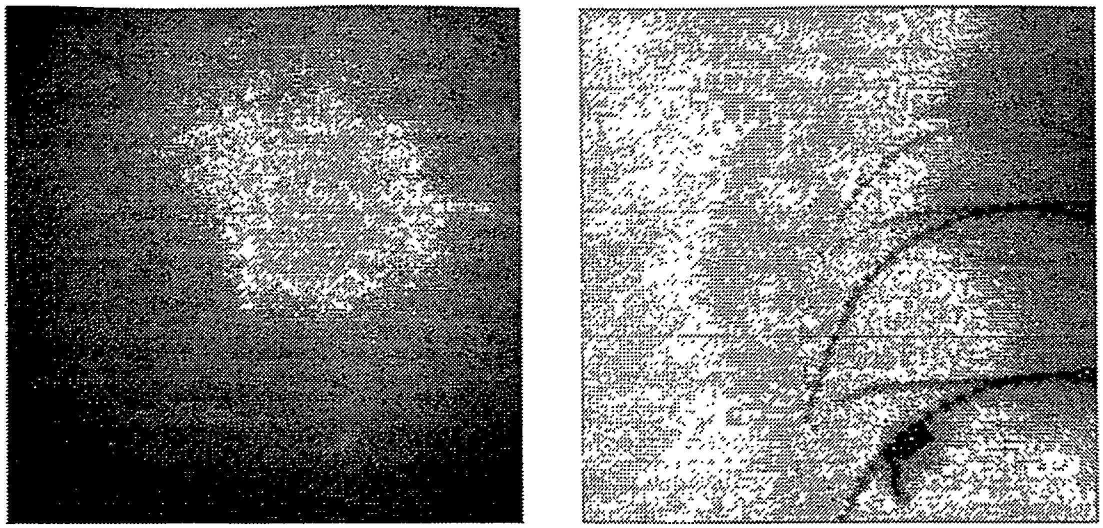


Figure 6. Reflectance image (left) and range image (right) of PDM-1 simulant and suspended concertina wire in turbid water with $a = 0.11\ m^{-1}$ and $c = 0.65\ m^{-1}$.

the water surface for each pair of images. The upper image pair was taken with the sphere a distance of 17 feet from the receiver while the lower image pair was taken with the sphere a distance of 33 feet from the receiver. A different source receiver geometry was used in making these images in which the laser source was directed through a window located directly below the receiver, but near the bottom of the test tank. The target is clearly identifiable in both images from the 17-foot data; however, there is more contrast in the range image than the intensity image. Cables are also clearly visible in the range image, but cannot be seen in the intensity image. The biggest difference is observed in the 33-foot data in the lower image pair. Here, the laser power had to be boosted, and the intensity image washed out in the volume backscatter. However, the target in the range image was still recognizable as a moored target with cables attached to the bottom.

4.2 Imaging through the air-water interface

A second series of tests were performed to see if the range imager offered any potential advantages for imaging volume targets through the air-water interface such as would be the case for some types of operations conducted from an airborne platform. In order to do this, both source and receiver were co-located on a single optical base attached to a tripod. The tripod was locked onto a large flat platform that was raised by a crane until the source/receiver apertures achieved a height of approximately 16 feet above the water surface in the test tank. The same 21-inch diameter sphere used in the previous tests was used as a target. Depth of the sphere was maintained at 10 feet below the water surface, and range from the SRI to the sphere was measured as 39 feet. The water in the test tank was filtered overnight to remove as much of the Maalox as possible, and the resulting absorption and beam attenuation coefficients matched those of the first series of tests, i.e., $a = 0.001\ m^{-1}$ and $c = 0.085\ m^{-1}$. The objective was to compare the results obtained between images taken with and without surface waves. The results are presented in Figure 8.

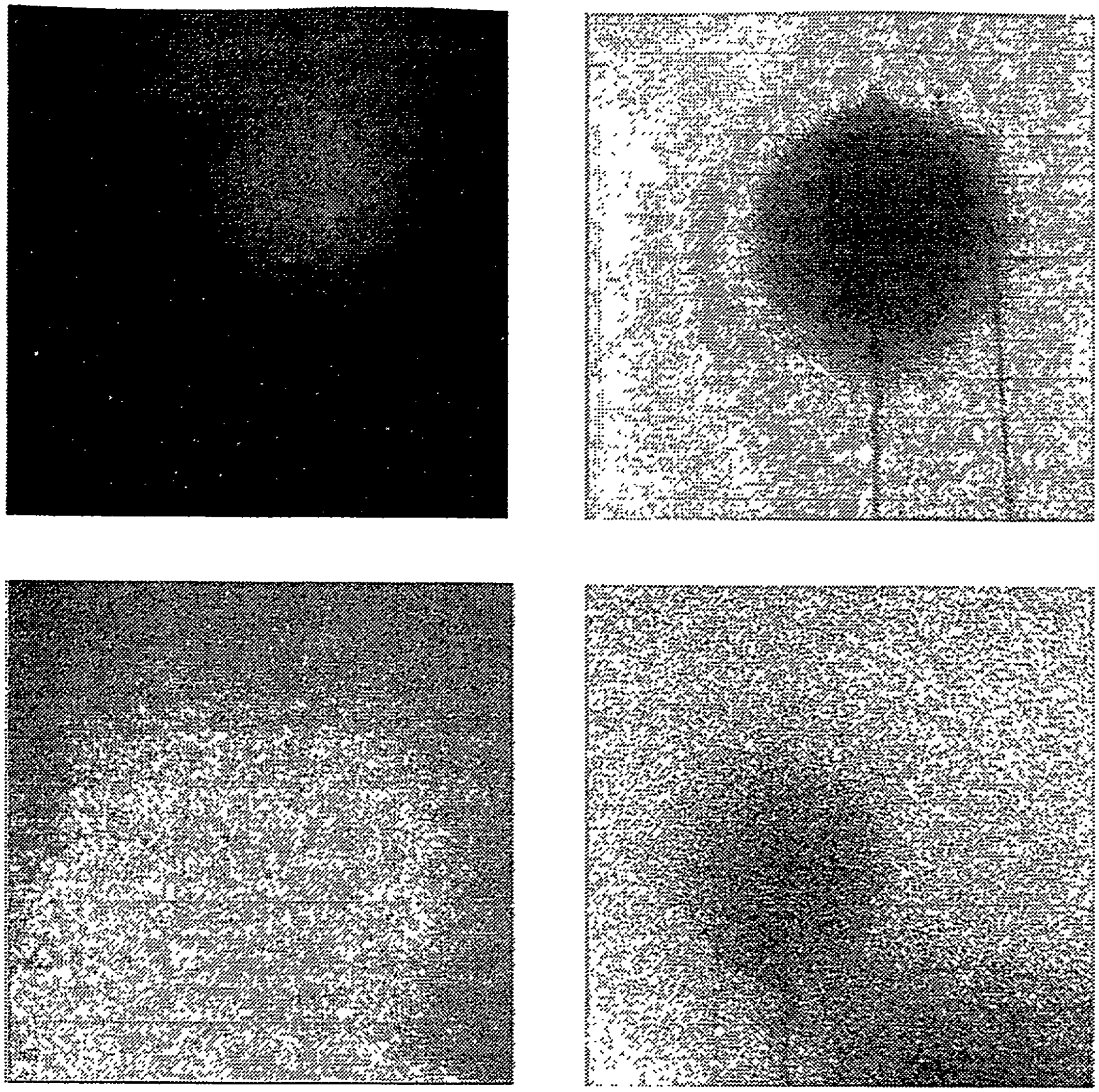


Figure 7. Image pairs with reflectance image on the left and range image on the right for 21-inch sphere at distances of 17 feet from the receiver (top) and 33 feet from the receiver (bottom). The sphere was suspended 10 feet below the water surface in each case. Water was moderately turbid with $a = 0.07\ m^{-1}$ and $c = 0.26\ m^{-1}$.

The upper image set in Figure 8 was taken with a smooth surface, and the primary observation is very similar to those made in the previous discussions. The underwater target is clearly identifiable in both the range image and the intensity image, but the range image offers a higher degree of contrast. As before, the mooring cables are highly visible in the range image; thus, providing additional information that can be used by an operator to help identify the nature of an underwater target. The lower pair of images was generated to get an idea of what would happen in a real environment. A pair of trolling motors were employed to generate the small surface waves with wavelengths on the order of a few centimeters that are so troublesome to viewing objects across the air-water interface. When the wave action was initiated, the intensity image immediately became just a bright spot on the surface. The range image still clearly indicates the existence of something beneath the surface, and there is even a slight visual hint that there might be cables attached.

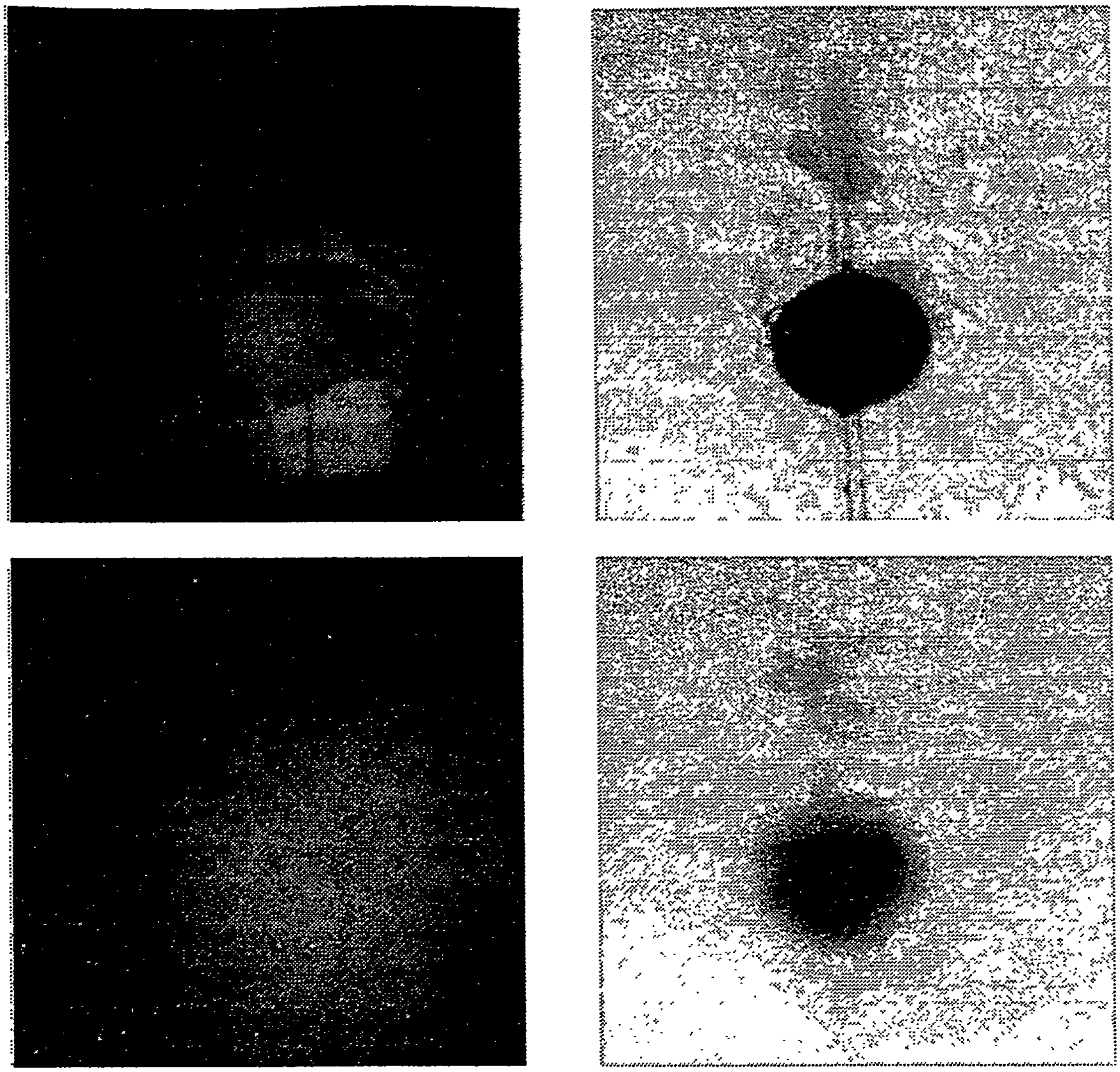


Figure 8. Image pairs taken through the air-water interface with intensity image on the left and the range image on the right. Upper pair of images was taken with smooth water surface. Lower pair of images was taken in the presence of small surface waves.

5. CONCLUSIONS

The quick-look feasibility tests to assess the SRI's potential as an underwater imaging tool indicate that substantial benefit might be gained by adapting this technology to operate in the underwater environment. A qualitative assessment of imaging performance against 3-D targets seems to indicate that, all other things being equal, the range image provides a substantial signal to noise advantage over a reflectance image in turbid environments or when looking through a modulated surface. One characteristic that presents a potential advantage to the diver is the high level of contrast observed when imaging normally low contrast objects such as wire or cable in the water column. Since the technique can be used with a continuous source, it offers the potential to design small, low-cost systems that might perform adequately under some conditions and circumstances, and which, would offer and size and weight benefits over range-gated imagers.

The results presented here are strictly qualitative in nature. Future work is planned, in order to better assess how well the SRI would perform in an optimized system configuration. The system employed during the tests had a gate width much too long to be useful at the ranges for which the data was taken, while a shorter gate width might be expected to improve performance considerably. The ability to generate both a range and reflectance image in a near simultaneous fashion makes it possible to fuse the two complementary images or to display them in a side-by-side fashion. Combining these capabilities with embedded processing and appropriate target recognition algorithms should provide a powerful low-cost tool for locating and identifying underwater targets.

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