ELECTRO-OPTIC IDENTIFICATION RESEARCH PROGRAM

James S. Taylor, Jr.[1] and Mary C. Hulgan[2]

Abstract-- Electro-optic identification (EOID) sensors provide photographic quality images that can be used to identify mine-like contacts provided by long-range sensors, such as sonar systems. To help support the transition of these sensors to the Fleet as well as to aid in the development of future EOID sensors, the Office of Naval Research (322-OP) has funded a five-year research program to investigate the performance properties of existing EOID sensors as a function of ocean environment. This paper describes the EOID research program and its objectives along with a brief discussion of supporting tasks such as validating existing electro-optic models, development of performance metrics, and development of computer aided identification and automatic target recognition algorithms. In addition, data from the recent field test will be presented.

***Index Terms*—Modeling, EOID, Performance Prediction, Laser Line Scan, Streak Tube Imaging Lidar, Computer Aided Identification, Automatic Target Recognition, Image Database**

I. INTRODUCTION

Identification of mine-like objects (MLOs) is a pressing Fleet need. During mine countermeasures (MCM) operations, sonar contacts are detected and classified as mine-like if their signatures are sufficiently similar to known signatures of mines. For littoral regions, tens or even hundreds of MLOs must be identified for safe passage of the Fleet. Currently, this time-consuming identification process is performed manually by Explosive Ordnance Disposal (EOD) divers or Remotely Operated Vehicles (ROVs). Rapid visual identification of MLOs using electro-optic identification sensors will dramatically improve MCM operations.

To support rapid visual identification, two electro-optic identification (EOID) sensors are currently under investigation by the Navy. These are the Streak Tube Imaging Lidar (STIL), an addition to the AN/AQS-20/X and the AN/WLD-1 (Remote Mine-hunting System) programs, and the Laser Line Scan (LLS), which will be part of the AN/AQS-14A(V1) program. Through these programs, EOID will be a key element in implementation of Fleet plans for a robust organic MCM capability.

With these systems, the Fleet will have their first experience with high-resolution underwater electro-optical imagery. It is anticipated that there will be evolutions in tactics and opportunities for unexpected missions for EOID as the Fleet gains experience and confidence with the capabilities of these systems. Accordingly, the Office of Naval Research (ONR) has initiated a science and technology (S&T) program to address issues that impact the success of these transitions, as well as the development of future EOID sensors that may be candidates for new organic platforms, especially small unmanned underwater vehicles (UUVs) and unmanned surface vehicles (USVs).

II. EOID RESEARCH PROGRAM

The primary objectives of the program are the validation of existing electro-optic models and the development and testing of Computer-Aided Identification (CAI) and Automatic Target Recognition (ATR) algorithms. Other objectives include the development of post-mission analysis tools, the development of an operator performance prediction model (Target Acquisition Model), and the quantification of environmental performance envelopes for EOID sensors.

Electro-optic models have been developed[3] to predict the performance of EOID sensors under varying conditions and parameters. Each model, however, has been lacking a sufficient data set for validation. Therefore, a field test was conducted in August 2001 to collect data specifically for model validation and, secondarily, for development of Automatic Target Recognition (ATR) algorithms. To maximize the application of the data to the models and for algorithm development, three different Electro-Optic Identification (EOID) sensors were incorporated into a single Towed Body (TB) along with a suite of environmental sensors. Data was collected simultaneously from each of the EOID and environmental sensors at the same altitude in the same instant of time to develop the body of data for use in optimizing system performance and model validation.

In addition to the environmental sensors on the towed body, an environmental team was present around the target field to collect supplementary environmental information via hand-held and stationary instruments to profile the Inherent Optical Properties (IOP) and Apparent Optical Properties (AOP). This supplementary data, along with the environmental data from the towed body, has been cross-correlated with the sensor data to determine as closely as possible the local environmental conditions under which the imaging took place. With this information, the models'

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[3] Electro-optic models have been developed by Areté Associates, Metron, and NSWCCSS

performance predictions will be compared against the actual performance. This environmental data set will also be used to quantify the environmental limits of the sensors.

III. EOID SENSORS

To support this program, the three EOID sensors were housed in a single underwater towed body that is capable of maintaining operator-selected fixed depths below the sea surface or fixed heights above the sea bottom. The three laser identification systems used are the Areté Associates Streak Tube Imaging LIDAR (STIL) system, the Northrop Grumman Laser Line Scan (LLS) system, and the Raytheon LLS system

A. *Laser Line Scan Technology*

The EOID laser line scan technology uses a diode-pumped Nd: YAG laser that provides 500 mW of power for the Raytheon system and 160 mW for the Northrop Grumman system, both operating at 532 nm wavelength. The Raytheon system was a research and development sensor maintained and operated by CSS while the Northrop Grumman system was sized to fit into the AN/AQS-14A(V1) towed body.

The laser illuminates a small spot, which is synchronously scanned by a photomultiplier receiver to build up a raster-scanned image. The laser scans downward through a 70-degree field-of-view (FOV). Figure 1 represents the EOID scanning scheme for target identification.

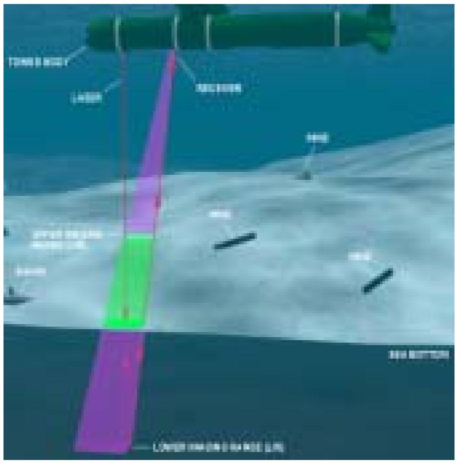

Figure 1. EOID Scanning Scheme for Target Identification

B. *Streak Tube Imaging LIDAR*

Areté Associates developed the patented[1] STIL technology specifically for high-resolution three-dimensional imaging of underwater objects. The attributes of a scannerless design allow implementation of the hardware into a compact and rugged configuration. The STIL system is an active imaging system using a pulsed laser transmitter and a streak tube receiver to time resolve the returned light. The laser beam is diverged in one dimension using a cylindrical lens to form a fan beam. The returned light is imaged onto a slit in front of the streak tube photocathode by a conventional lens, and is time (range) resolved by electrostatic sweep within the streak tube, generating a 2-D range-azimuth image on each laser pulse. By orienting the fan beam perpendicular to the vehicle track, the in-track dimension is sampled by adjusting the Pulse Repetition Frequency (PRF) of the laser to the forward speed of the vehicle, thus sweeping out the three-dimensional ocean volume in a push broom fashion (Figure 2).

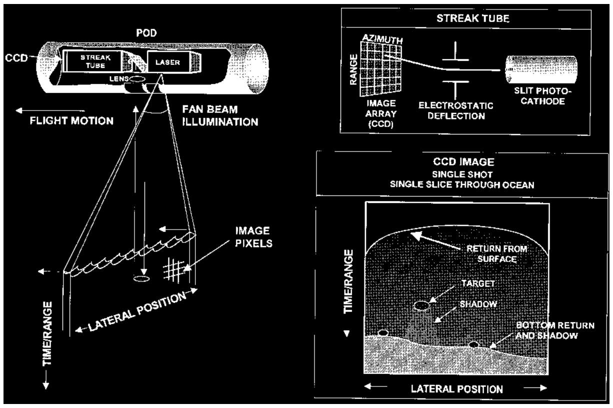

Figure 2. STIL Technology Overview

The Areté STIL system is illustrated in Figure 3. Figure 4 shows a single shot range-azimuth image from the STIL illustrating the exponential decay of the water backscatter and the return from the bottom. This image illustrates how the water backscatter is temporally separated from the bottom return, providing outstanding backscatter rejection. This precise temporal sampling also makes the sensor entirely immune to ambient sunlight. The bottom return includes both time of flight information, which provides a quantitative measure of the height of the object above the bottom and the radiometric level that is proportional to the reflectivity of the bottom object. Each laser shot thus provides range to and contrast of the bottom for each cross-track pixel.

Figure 3. Areté STIL system

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[1] US Patent 5,467,122

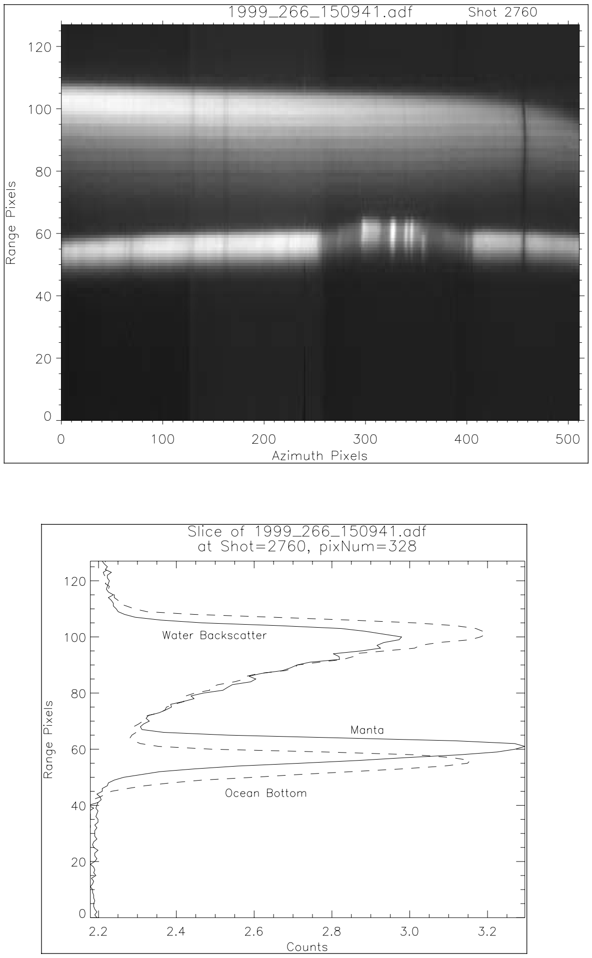

Figure 4. Single Shot Range-Azimuth Image (Top) and Water Backscatter Decay

IV. EOID FIELD TEST

A. *Targets and Target Field Setup*

Targets used in the data collection exercise were a selection of mine-like objects, technical (analytic) targets with specified reflectance, and assorted items that might be found on the sea floor with characteristics resembling mines. The technical targets will be used to quantify various physical phenomena found in the laser systems and the medium while the other targets were used primarily to provide a baseline for ATR algorithm development.

1) *Technical Targets*

Technical targets were designed and fabricated to support model validation. There were a total of 25 technical targets, using 1/8-inch thick aluminum, that included eighteen 4‘ x 4‘ panels, two 1’ x 2’ panels, and three 4’ diameter flat panels. Each panel was painted with specifically designed patterns using paint with specified optical properties. In addition to the painted panels, one three-dimensional step target and one 16’ long x 21” diameter fiberglass cylinder, fitted with assorted bolts and lifting eyes, were also deployed. The step target was used to quantify range accuracy for the STIL and the 16’ cylinder target was designed to aid in the development of performance metrics for identification.

2) *Mine Shapes*

This category of targets included inert U.S. mine and bomb casings, and facsimiles of two foreign mines. These included two bomb casings, two types of bottom cylindrical mines (two for each type), two truncated cone shapes, and four facsimiles of another oddly shaped mine.

3) *Clutter*

This category of targets included items that could typically be found in offshore waters, including a tire, a crab/fish trap, a concrete pipe, and a 55-gallon drum.

4) *Miscellaneous*

There was only one target in this category; a 12-foot stepladder that was installed upright on the bottom. This target was only present for the first three days of data collection and was intended to help measure the depth of field.

Examples of the technical target panels used during testing are shown in Figure 5, examples of the mine shapes are shown in Figure 6, clutter examples are shown in Figure 7, while the ladder is shown in Figure 8.

Figure 5. Technical Target Panels

Figure 6. Mine Shape Targets

Figure 7. Clutter Targets

Figure 8. Ladder

5) *Target Field Set-up*

The target field was made up of the technical targets, mine shapes, and clutter placed along a 500-foot length transect of _-inch wire rope, stretched between two 1600-pound concrete clumps in 60 feet of water. For navigational guidance, four marker buoys were placed 150 feet perpendicular to the centerline at each clump and a reference buoy was placed 120 feet off the center. The result was a 500' x 300' box with the mines and clutter placed along its centerline.

The technical target panels were deployed by attaching them to the _-inch wire rope with brass clips at pre-determined points along the wire rope. This placed the centerline of the panels 2 feet to one side of the wire rope. The panels were spaced 2 feet apart – enough distance to avoid interference effects between panels during imaging, but close enough to minimize the target field length. The "EMNIIRS Real Object – 3D" (Target 27) target was placed with its centerline aligned with the centerline of the panels 22 feet from the end of the last panel (Target 24) and 22 feet before the first mine shape (Target 28). The mine shapes and clutter (Targets 28–43) were placed with their centers 5 feet from either side of the panel centerline (3 and 7 feet on either side of the wire rope). The result was a line of targets 320 feet long. Two environmental sensor packages were placed along the centerline, one at either end of the technical targets. A detailed layout of the target field is shown graphically in Figure 9.

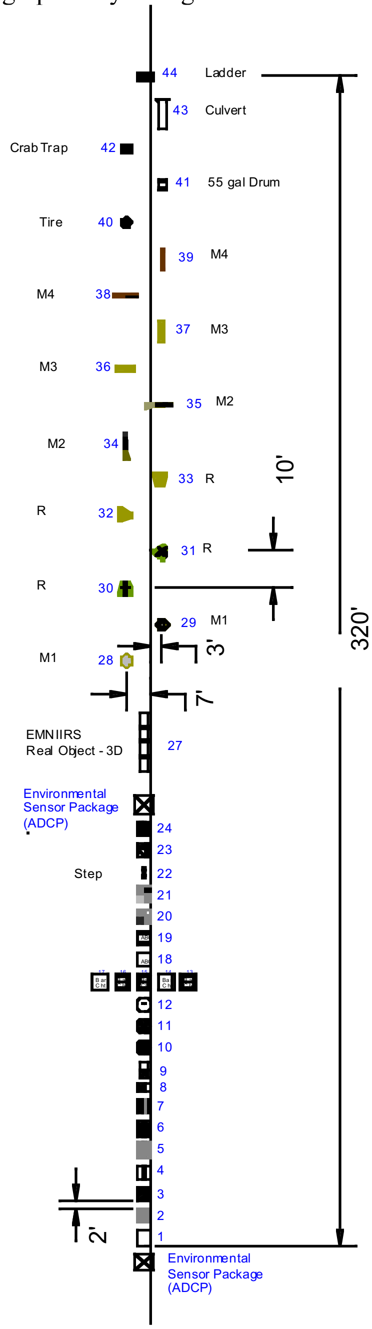

Figure 9. Target Field Layout

B. *Environmental Support*

The environmental data collection team operated from the *R/V Edwin Link* and was supported by three contractors: Bigelow Laboratories, Physical Sciences, Inc., and the University of Miami.

The primary task of Physical Sciences, Inc. was to collect in-situ reflectance measurements on the targets and surrounding sediment. Other tasks included reflectance measurements of non-target objects on the seafloor, photographic and video documentation of the site, and collection of sediment samples for grain size analysis. All these measurements were accomplished using portable sensors carried by divers.

Bigelow Laboratories' primary task was to characterize the physical, biological, and optical fields present in the target area during the test. This was accomplished with sensor packages deployed on the seafloor, attached to the ship, and lowered through the water column, as well as through satellite imagery. Locations of the two sea floor sensor packages are shown in the target field layout depicted in Figure 9.

The University of Miami's primary task was to collect water column optical properties and benthic Bi-directional Reflectance Distribution Function (BRDF) measurements in the target area. This was accomplished using General Angle Scattering Meter (GASM), Point Spread Function (PSF), and BRDF instruments.

Table 1 shows the variety of environmental data collected.

Table 1. Variety of Environmental Data Collected

Environmental Data Products	Details
K_{532}	surface
K_d and K_u	depth binned profile (412,443,490,510,532,555,665 nm)
a	depth binned profile (412,443,488,510,532,555,665, 676, 715 nm)
a_{532}	surface and near bottom
C	depth binned profile (412,443,488,510,532,555,665, 676, 715 nm)
c_{532}	Surface and near bottom
b_{b532}	Surface and near bottom
B	depth binned profile (412,443,488,510,532,555,665, 676, 715 nm)
b_{532}	Surface and near bottom
Point Spread Function_{500}	500 nm
$\beta_{\_}$	(VSF at near backward to 170º)
β_{100}, β_{125}, and β_{150}	Depth binned profile (450, 530, 650 nm)
β_{140}	Surface and near bottom at 532 nm
Upwelling Radiance and downwelling Irradiance	
Surface downwelling irradiance	
Reflectance of Bottom	Near vertical
BRDF	Targets and bottom
Target reflectance	In-situ
Cloud cover and Air temp	
Chlorophyll concentration	Surface and near bottom
Conductivity	Surface, near bottom, and binned profile
Salinity	Surface, near bottom, and binned profile
Water temperature	Surface, near bottom, and binned profile
Water density	Surface, near bottom, and binned profile
Current Velocities	Binned profile
Depth	

C. Field Test Results

This program has collected a dataset that is unlike any other to date. The results from this test include an extensive EOID sensor image database with accompanying environmental ground truth. Table 2 summarizes the sensor data.

Table 2. STIL, NG, and Raytheon Run Summaries

TEST	SENSOR	# of RUNS	# of ALTITUDES
8/14/01	STIL	10	5
	NG	13	5
	Raytheon	14	5
8/15/01	STIL	3	5
	NG	14	5
	Raytheon	18	5
8/16/01	STIL	0	5
	NG	12	5
	Raytheon	10	5
8/17/01	STIL	0	5
	NG	1	5
	Raytheon	1	5
8/21/01	STIL	5	5
	NG	8	5
	Raytheon	7	5
8/22/01	STIL	4	5
	NG	13	5
	Raytheon	14	5
8/23/01	STIL	2	5
	NG	2	5
	Raytheon	2	5

During the course of the field test, a broad range of environmental conditions was experienced. Water clarities ranged from very good to very bad, with a suspension layer hovering as much as 10 feet above the bottom.

Both environmental and sensor data were collected primarily during daylight hours with some collected at night to serve as a control on the measure of ambient light impact.

The TB and sensor packages were operated for a total of seven days and nights of testing. These runs consisted of 76 runs over the primary target field and 23 runs over "targets of opportunity". Altitudes of the data runs were varied over a prescribed range so that the quality of the data varied from poor to very good. Every attempt was made to obtain imagery on both ends of the performance envelope as well as points in between (*i.e.,* from approximately 2.5 beam attenuation lengths to greater than 5 beam attenuation lengths). Figure 10 shows the environmental boundaries as given by three curves of the beam attenuation at 532 nm.

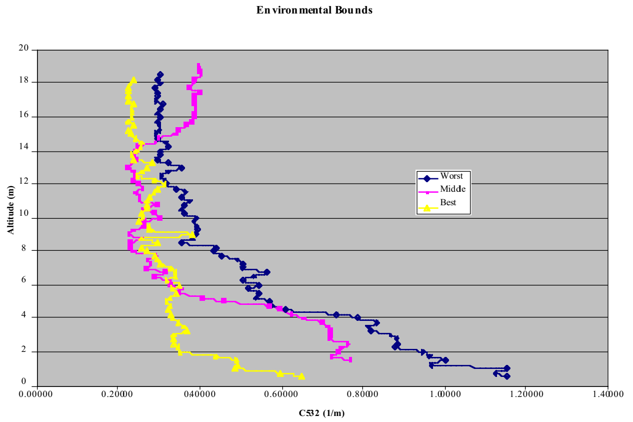

Figure 10. Representative Environmental Boundary

The imagery shown in this section is representative of the type of imagery that was obtained from the field test. All of the imagery shown here has been processed (rendered and enhanced) using a NSWCCSS developed automated routine. This imagery is only shown to represent the data product from the test and is not intended for comparison of sensors, thus altitudes, run numbers, and environmental data are not presented with each image.

The full target field included the long line of technical targets present for model validation. Figure 11 shows the full field images as taken from the Northrop Grumman LLS. Seams or transitions appear because the image has been stitched together from individual files. Figure 12 is the STIL contrast image of the full field. Since very few of the technical targets were 3D, there is little range information in the technical portion of the field.

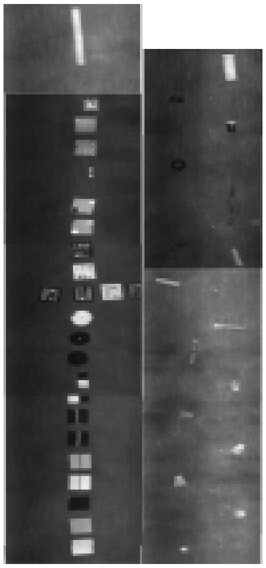

Figure 11. Northrop Grumman LLS Image of the full Target Field

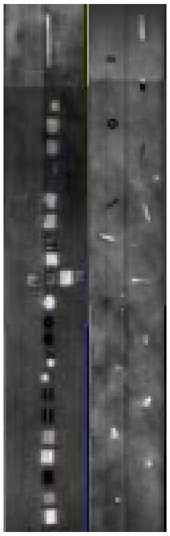

Figure 12. STIL Contrast Image of the Full Target Field

Figures 13-15 show the contrast image of one of the 3D Shape targets (Target 23). The images shown are from altitudes corresponding to low, medium, and high, respectively. Figure 16 is a corresponding digital photo of the panel taken in-air.

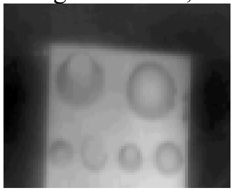

Figure 13. Target 23 at Low Altitude

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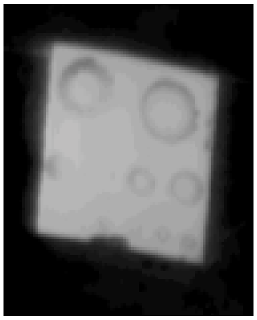

Figure 14. Target 23 at Medium Altitude

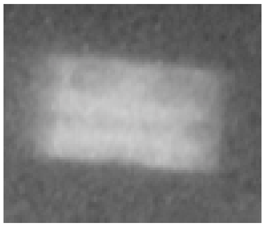

Figure 15. Target 23 at High Altitude

Figure 16. Digital Photo of Target 23

Figures 17-19 show the contrast imagery from a technical target (Target 19) panel at low, medium, and high altitudes, respectively. Figure 20 shows a corresponding digital photo of the target taken in-air.

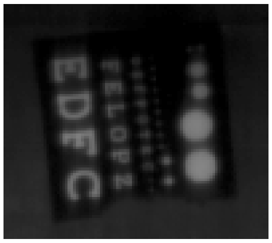

Figure 17. Target 19 at Low Altitude

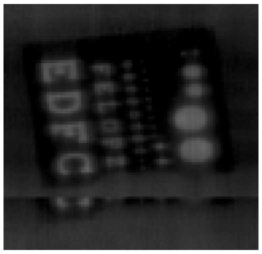

Figure 18. Target 19 at Medium Altitude

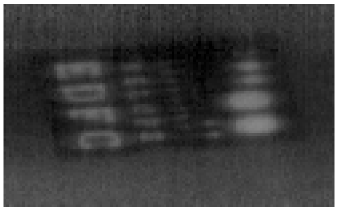

Figure 19. Target 19 at High Altitude

Figure 20. Digital Photo of Target 19

Figures 21 and 22 show contrast imagery of Target 34 taken from low and medium altitudes. Figure 23 shows a corresponding digital photo of the target taken in air.

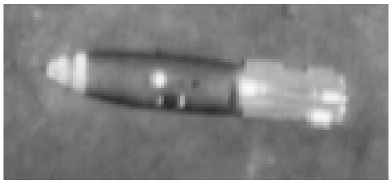

Figure 21. Target 34 at Low Altitude

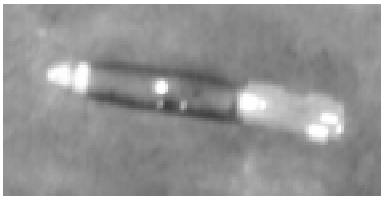

Figure 22. Target 34 at Medium Altitude

Figure 23. Digital Photo of Target 34

In addition to these contrast images, the STIL system also produced range imagery. Some examples are shown in Figures 24 and 25.

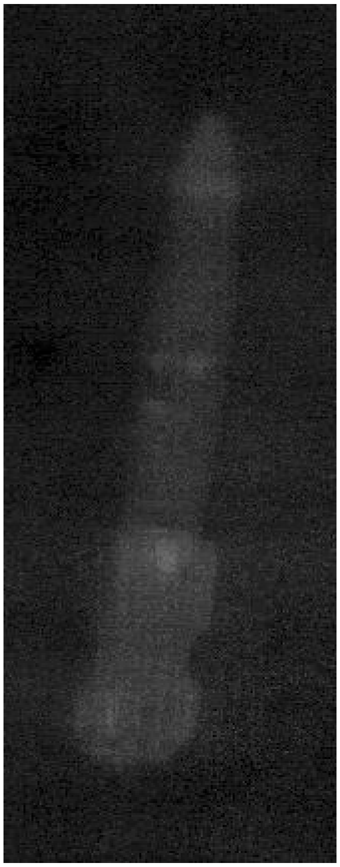

Figure 24. STIL System Range Image of Target 25 at medium altitude

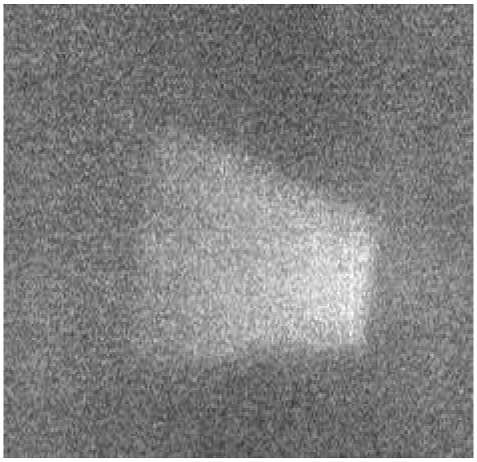

Figure 25. STIL System Range Imagery (Target 33 at Medium Altitude)

As shown by these examples, this program has provided a large database of imagery and environmental data that can now be used by the community at-large for the validation of the underwater electro-optical sensor models. In addition to model validation, the data can be used as a starting point for Automatic Target Recognition (ATR) algorithm development. Moreover, this data has provided insight into the performance envelope of these sensors, and has provided some immediate, near-term benefits for the Fleet transitioning systems. The lessons learned from this exercise will prove to be invaluable in the fielding of these sensors under operational conditions.

V. EOID APPLICATION

A. Fleet Deployment

The two Measures of Effectiveness (MOE) for MCM operations are time and residual risk. A given area will be declared clear of mines to a certain confidence level based on the search effort and the search results. A more confident declaration of a cleared area requires that more time and assets be applied in the operation. To calculate the MOE, Measures of Performance (MOP) must be established to quantify the individual system contribution. All MOPs must be defined in order to calculate the MOE of time and residual risk.

In real world operations, the overall MCM MOE should be improved with the addition of EOID. Search systems provide large lists of mine-like contacts that will form the basis of prosecution lists for identification assets. Objects positively identified as mines can either change the ship operations area or call for neutralization assets to clear the mined area. As currently executed, the time required to identify the objects can be significant.

Both EOID systems will use sonar systems to help reacquire the contact, increasing the Probability of Reacquisition (P_{reacq}). The EOID systems will then be towed over the target for high resolution imaging of the object. The Probability of Identification (P_{id}) and Probability of False Identification (P_{fid}) are functions of water clarity and the altitude of the sensor over the target. Along with T_{id}, the time to identification against a single object, an analyst can calculate the time to perform the identification mission and the numbers of correctly and incorrectly identified mines. The MCM analysts would then have an estimate of the time and the residual risk to ships transiting in that area. Of even greater significance, MCM Commanders would have the ability to deploy only those neutralization assets required for the immediate future saving considerable time.

Both STIL and LLS systems have target cueing and snippet generation of EOID objects, but do not yet have Computer Aided Identification in either the airborne console or the Post Mission Analysis computers. Target cueing is basically a Region of Interest (ROI) matched filter algorithm that highlights certain areas of the image for the operator. Image snippets are generated either automatically by the ROI algorithm or manually by the system operator.

Performance models are being developed so operations can be planned using water clarity measurements from historical oceanographic databases. The best water clarity data, however, comes from sensors in the operation area during the mission. The STIL system is using a water clarity measurement to suggest an operational altitude during the sortie. Models have also been suggested to show reference targets as they would be seen through the expected water conditions.

These types of systems will be entering service within the next few years after a series of developmental and operational tests. ATR and Model upgrades can be provided to the Fleet immediately following introduction as either a software modification or as part of a larger Pre-Planned Product Improvement (P^3I) effort.

VI. CONCLUSION

All three EOID systems performed very well and captured needed data. All experienced challenges with both hardware and software, as can be expected in non-production systems. Nevertheless, each system gained very valuable experience on their system and found a number of issues for improvement or correction within the scope of their development programs. In particular, each had the opportunity to test their system under very stressing environmental conditions.

In summary, it was agreed by all program participants that the data collected was sufficient for validation of the models. In fact, more data was collected than had been anticipated, relieving the group of the need for an additional data set for modeling in the next fiscal year.

ACKNOWLEDGMENTS

The authors would like to acknowledge the joint efforts of the individual sensor vendors (Areté, NG, and Raytheon), supporting industry contractors (Metron, Bigelow Laboratory, University of Miami, PSI Corporation, and ARINC), and the many NSWCCSS codes supporting the execution and documentation of the field test.

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