Signal Processing Applied to the Dolphin-Based Sonar System

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***Abstract -* The bottlenose dolphin has evolved a unique system of biosonar, or echolocation, that allows it to exploit a visually limited littoral niche. The effectiveness of dolphin echolocation at finding and identifying submerged objects is unsurpassed by man-made hardware systems built for similar tasks. It has become a model system from which to draw hardware and signal processing design concepts and is the basis for the development of biomimetic mine-hunting systems of the shallow water (SW) and very shallow water (VSW) zones. The Dolphin Based Sonar (DBS) system is a proof-of-concept sonar system designed for operations in the SW/VSW environments that incorporates characteristics of dolphin sonar transmission and structural elements of dolphin auditory anatomy. Specifically, the system is designed to reproduce dolphin signal types and source levels and to match the animal's transmission and reception beam patterns, directivity indices, receive sensitivity, and auditory filtering capabilities.**

The DBS, built as part of a cooperative agreement with SPAWARSYSCEN – San Diego (SSC-SD) and Applied Research Laboratories, University of Texas (ARL-UT), consists of a topside unit (dry-end computer) and wet-end unit (sonar head and connections). The wet-end unit, constructed by ARL-UT, is integrated around the Analog Devices SP 21061 SHARC processor architecture. Both the projector and receiver array were made from 1-3 piezocomposite transducer material. The projector has a 12 degree beam width at 110 kHz with sidelobes on the order of ~17 dB. It is capable of delivering echolocation click-like synthetic waveforms and FM chirps and sweeps with source levels up to 206 dB re: 1 uPa @ 120 kHz. Signals can be transmitted at a frequency range of 30 to 120 kHz and with an 80 kHz 10-dB bandwidth. Correlation coefficients between "real" and "synthetic" wideband and low-frequency unimodal echolocation clicks were 0.95 on the maximum response axis (MRA). The receiver employs two directional hydrophones with beam widths of 20-degrees at 80 kHz. The matched receivers are separated ~ 12.5 cm, the approximate distance between the ears of the bottlenose dolphin. The projector and receivers are attached to a pan-and-tilt unit that permits +/- 170 degrees of pan and +/- 170 degrees of tilt.

The DBS has been tested on the placement of known targets across a bay silt and mud bottom (categorized as a B2 type bottom) as well as on the detection of a human diver in the water column. Testing was done from a fixed-position on a stationary piling and from a variable-position, the latter providing multi-aspect data via movement along a 100 m trolley system (long-line). Fixed piling testing included the placement of 4 proud mine-shapes and 3 non-mine bottom objects (NOMBOS). Long-line testing included the placement of 8 proud mine-shapes, 4 PVC markers, and naturally accumulated man-made clutter. A matched filter detector was used for initial detection of targets in acoustic returns and has been combined with a spectral detector to reduce the false alarm rate. Cross-correlation beam forming (CCBF) and the Chirp Corporation's adaptive beam former (ABF) were evaluated to assess beam-forming processing of the two receivers. A "snippet" algorithm was developed for isolation of regions of interest existing within a Cartesian coordinate map created from successive sonar returns. Visualization of the map was increased to a 5 cm resolution and further refined via additional energy thresholding by application of a Cartesian binary mask. The mask was created by replacing Cartesian cell values with a 1 or 0, depending upon a minimum number of returns per total number of scans, and multiplying the binary mask by the original Cartesian map. Approximately 40 target features have been identified for potential use in target classification. Classification testing is currently limited to using 8 – 10 of the most useful features identified to date.

Results to date for the DBS system show the system is capable of detecting all targets (including one, which was fully buried). Simple classification results are obtained by thresholding on two features: a) the ratio of the number of detection's divided by the number of detection opportunities, and b) the integrated energy value of the multiple detection's. Results at the knee in the receiver operating characteristics (ROC) curve show correct classification of 7 of the 8 mine shapes (as mine shapes) while only false alarming on 4 of the clutter objects. This multiple aspect detection and classification processing is believed to provide a significant improvement over standard sonar processing. Further development is being pursued.

I. INTRODUCTION

The ability of the bottlenose dolphin (*Tursiops truncatus*) to detect and identify underwater objects is unsurpassed when compared to man-made systems built for the same purpose. This is particularly true in shallow water (SW, 40 – 200 ft water depth) and very shallow water (VSW, 10 – 40 ft water depth) systems. Such systems, which are often inhabited by dolphins, are frequently highly cluttered, visually limiting and acoustically rich. These environmental characteristics had important consequences for dolphin evolution. They created selective pressures that favored sound-based sensory systems that allowed the location and identification of conspecifics, navigation, avoidance of predators, and capture of resident prey. The evolutionary culmination of these selective pressures is reflected in dolphin echolocation, a form of biological sonar that permits the exploitation of near shore environments.

The United States Navy has long been interested in dolphin echolocation. Decades of navy-supported research has demonstrated that dolphins are capable of forming generalized classes of targets, detecting differences in object composition [1], detecting variations in the wall thickness of similarly constructed targets [2], detecting small metal spheres (< 3 inches in diameter) at ranges exceeding 100 m [3],

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discriminating small variations in target range, and detecting buried targets [4]. The navy capitalizes on these capabilities through the use of Marine Mammal Systems (MMS); groups of dolphins tasked with the detection of mines (Mk 4, Mk 7 and Mk 8) or water-borne intruders (Mk 6).

Man-made sonar systems built for similar purposes as the MMSs demonstrate reduced performance in target detection and search time when compared to dolphin systems [5]. As a result, MMS dolphins will remain part of the navy operational capability for the near future. However, it is logistically difficult to deploy MMSs to remote regions and there is considerable cost in the maintenance of MMS dolphins over time. Improvement in man-made systems adapted to UUV/AUV target hunting operations will eventually obviate the need for some MMSs, provided the search and detection metrics are comparable. One approach to achieving this is through a biomimetic development program. This approach explores mechanisms of sound production, reception and signal processing in echolocating dolphins in order to guide hardware and algorithm development of man-made sonar systems.

The Biosonar Program at the Space and Naval Warfare Systems Center in San Diego (SSC-SD), California, is engaged in the design of a SW/VSW-deployable sonar system for the detection of submerged objects and water-borne targets. The system is biomimetic in that it contains hardware architectures and signal processing approaches that are inspired by the anatomy of the dolphin auditory and sound generation systems as well as dolphin hearing and signal processing ability. The program has two fundamental components – the study of dolphin echolocation behavior in a freely swimming dolphin, and the development of a hardware system and signal processing suite based upon prior and actively gained knowledge regarding dolphin echolocation. The focus of this paper is on the hardware development and signal processing approaches used in the development of the Dolphin-based Sonar (DBS).

II. BIO-INSIPRED HARDWARE DESIGN

A. General Architecture

The DBS system consists of a wet-end (i.e. sonar head) and a dry-end (i.e. top-side controller, storage and displays). The Applied Research Laboratory, University of Texas (ARL-UT), in a cooperative agreement with SSC-SD, created the wet-end system. The system is integrated around the Analog Devices 21061 SHARC DSP processor architecture. The dry-end was created at SSC-SD and is personal computer-based with a SHARC-based DSP card. Synchronous serial communications via the SHARC high-speed serial ports transfers data between the units.

B. Transmit System

The signals transmitted by the bottlenose dolphin during echolocation, commonly called "clicks," are short duration pulses (30 – 100 μs). Clicks may be very broadband, with –3 dB bandwidths exceeding 85 kHz [6], and with peak energy existing between 30 and 120 kHz. Source levels of the clicks have been measured in excess of 225 dB re: 1 μPa [7]. The clicks are emitted in rapid succession and projected through a lipid filled structure within the forehead of the animal known as the melon. The melon serves to collimate the outgoing signal. The transmitted sound beam is directional and has a 3 dB beam width (at 120 kHz) of approximately 10^0 in both the horizontal and vertical planes [8].

The DBS projector (Fig.1) is made from 1-3 piezocomposite transducer material. The transmit beam off the projector approximated that of the dolphin with a 12 degree beam width at 110 kHz with side-lobe levels approximately ~17 dB down from the maximum. Arbitrary signal transmission was achieved across a frequency range of 30 to 120 kHz and with an 80 kHz 10-dB bandwidth. The projector is capable of transmitting dolphin-like pulses as well as FM chirps and sweeps (140 – 80 kHz and 110 – 40 kHz). Mimetic pulse types, which were based upon "real" dolphin clicks, included wideband clicks, high frequency unimodal clicks, low frequency unimodal clicks and bimodal clicks [6]. The correlation coefficient between "real" and "synthetic" wideband and low frequency unimodal clicks is 0.95 when measured on the maximum response axis of the echolocation beam. Source levels of "synthetic" clicks and FM chirps and sweeps reached 206 dB re: 1 μPa.

C. Receive System

Dolphins receive sound energy returning from ensonified targets primarily through the lower jaw [9]. The lower jaw is hollow and filled with specialized lipids that transmit the received sound energy to the ear. In contrast to terrestrial mammals, each ear is free from the skull and is suspended in an air cavity by soft, fibrous tissue connections [10]. The spacing between the ears is approximately 12.5 cm. Although the ears are mammalian in design, they contain specialized support structures and have a greater density of hair cells within the cochlea than is observed in humans. These adaptations presumably contribute to the dolphin's keen echolocation ability.

The echoes received by a dolphin may be complex with variable modulation effects and temporal durations. The information that is extracted from these echoes in making target detections and identifications, and the manner in which it is extracted, are not exactly understood. However, dolphins demonstrate an acute hearing sensitivity and have an extended auditory range that matches and exceeds the frequency range across which they echolocate (~ 20 – 120 kHz;) [11, 12].

The DBS utilizes two matched receivers to capture returning echoes. These receivers, made of 1-3 piezocomposite transducer material, are located to each side of the transmitter (Fig.1) at a spacing of ~ 12.5 cm between their acoustic centers, the approximate distance between the ears of the bottlenose dolphin. The DBS projector and receivers are attached to a COTS pan-and-tilt unit that permits +/- 170^0 of pan and +/- 170^0 of tilt. Thus, the unit can emulate head scanning used by dolphins to presumably capitalize on slight variations in target aspect. The data acquisition electronics acquire the two receive channels with a –3 dB receive bandwidth of 130 KHz, thus encompassing the frequency range of audibility used by the dolphin. The receivers use two independent 16-bit Sigma-delta A/D converters with sample rates of 330 KHz operating in 32x over sample mode (non-comb filter mode) to digitize the analog signals. The system is capable of streaming receiver data to the topside unit continuously, but a maximum listen interval equivalent to a 125 m range was used in testing.

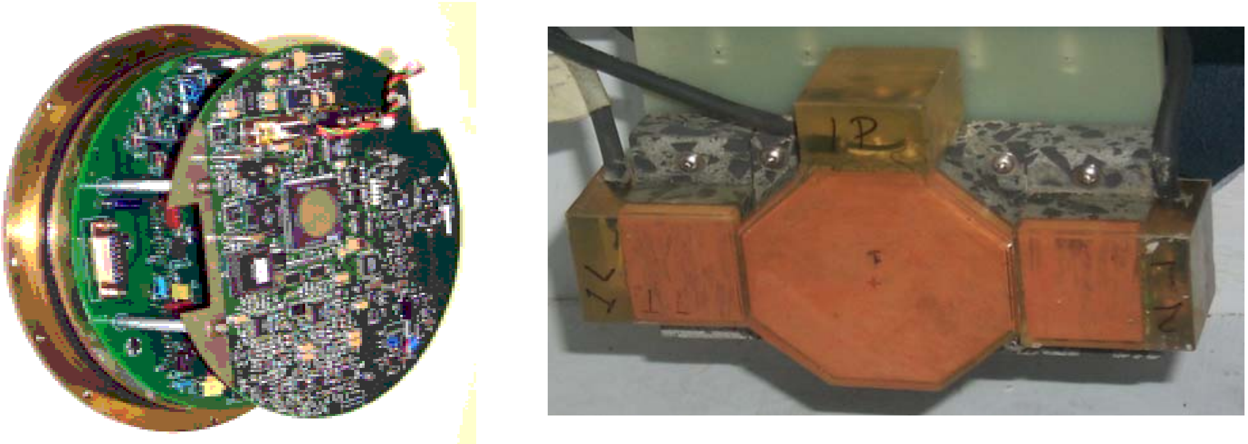

Fig. 1 The DBS sonar (left) and the biomimetic array (left)

D. System Testing

The DBS system was tested for object detection capability in San Diego Bay in both a stationary piling-mounted test and in a long-line test where the unit was moved through a known field previously seeded with targets. A third test was also run to determine the ability of the system to detect a diver. All testing occurred at the SSC-SD F122 facility within San Diego Bay. The bottom in this region is an irregular mixture of clay, silt and sand and contains a substantial amount of clutter. The area is classified as having a B2 bottom type.

1) stationary piling test

The DBS was attached to a fixed piling, approximately 5' above the sea floor, near the F122 facility. A total of 4 mine shapes were used for the collection of sonar data. Prior to collection on mine shapes a no-target test was run. As a result of this test, 4 non-mine objects (NOMBOS) were detected. A dive team later identified three of the NOMBOS; no bottom object was detected to which the fourth detection could be attributed. Identified NOMBOS included a 2" diameter bent steel pipe (partially buried), a 2' x 2' steel box (proud), and a 4' x 6' partially buried steel plate. Data was collected with multiple pan and aspect angles from a fixed position on the piling. All mine shapes, in addition to NOMBOS, were detected via a combined whitened matched filter (WMF) and spectral detector (*see below*; Fig.2).

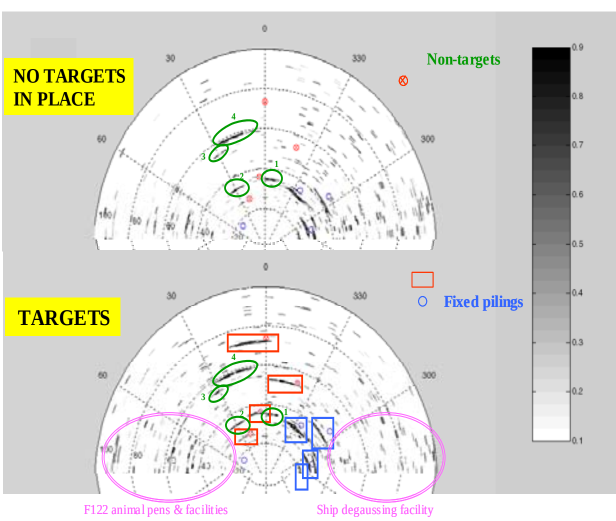

Fig. 2 Colorized plot of energy from the F122 ensonified target field after WMF processing. Top panel is the no-target present condition while the bottom panel has the targets in place. Mine shapes are shown in red. Non-mine shapes are in green. Pink ovals indicate animal holding pens (left) and a ship degaussing facility (right).

2) long-line test

The DBS was attached to a motorized trolley system and suspended from a line that was tensioned in a north to south orientation between two cement pilings. The line was ~100 m in length and was placed so the sonar head was approximately 4' above the seafloor. To one side of the trolley line (shoreward) were dolphin pens and pilings associated with the F122 facility, while to the other (bayside) there existed a nominally empty region where targets could be placed. Prior to testing on a target field, the DBS and trolley system were used to characterize the field in a "target absent" trial. The trolley system moved the DBS at ~1 m increments across the length of the suspension line. At each increment the DBS scanned across a pan range from +/- 160^0 while the pitch angle was between zero degrees horizontal and –3 degrees down pointed. Data were received out to a maximum range of 125 m. Thus, the entire field based upon scan distance was ~ 250 x 350 m. Increments in the pan angle were 3 degrees per collection with 9 waveforms transmitted at each increment, 2 FM sweeps and 3 "synthetic" dolphin clicks. The FM sweeps ranged from 110 – 40 kHz and 140 – 80 kHz. The "synthetic" clicks were of the broadband, low frequency unimodal, and bimodal types. All signals were transmitted as compensated and uncompensated forms, except for the bimodal, which was transmitted only in an uncompensated form.

A series of 8 mine shapes within 3 mine-type categories and four PVC markers were placed along the suspension line for the "target present" trial. Targets were placed up to 100 m away from the suspension line. For the target present trial, the trolley moved the DBS at 0.5 m increments across the length of the line. Scan rates and angle increments were the

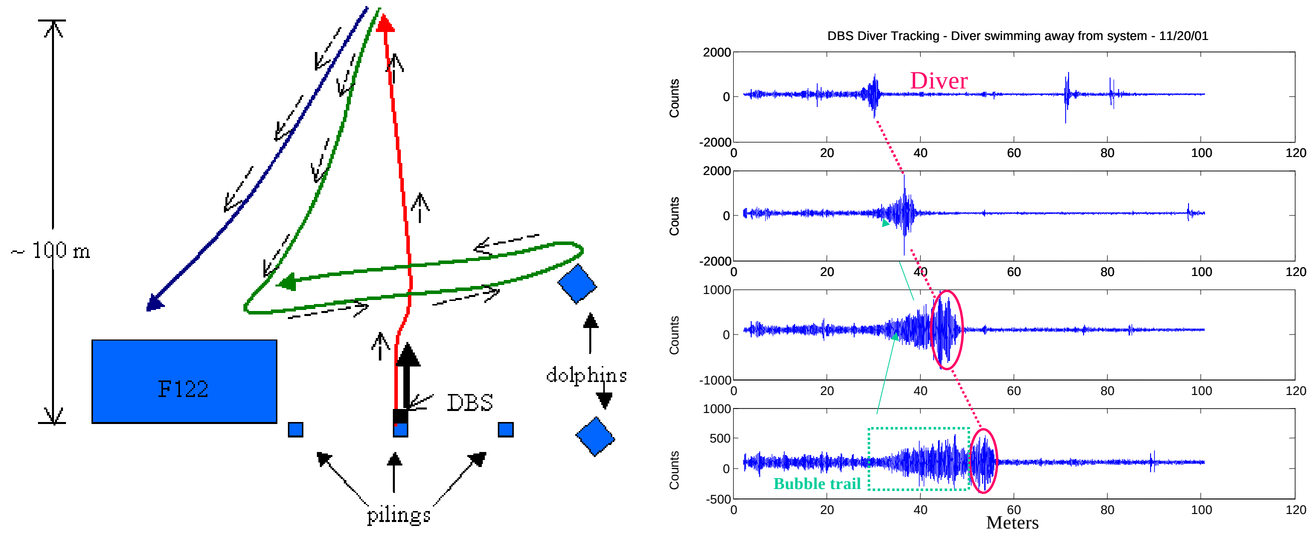

Fig.3 Diver swim path and resultant DBS backscatter from diver detection test.

same as that used in the "target absent" trial. The total number of pings generated over the two trials was ~150,000.

All targets were detected through the use of a dual-criteria detection method implementing both a WMF and spectral detector (*see below*).

3) swimmer detection

The ability of the DBS to detect a swimmer and track the swimmer was tested from a fixed position piling. After mounting, the DBS ensonified a 30-degree swath as a SCUBA-equipped diver swam through the area. Several paths were taken to, from and across the path of the sonar out to a range of 100 m. Bubble trails left by the diver and echoes off of the SCUBA tank were easily identified in the data stream (Fig.3). The diver track was recreated during the post-processing stage.

III. SIGNAL PROCESSING

Target detection was achieved through the combined use of a WMF detector and a spectral-based detector. The WMF detector was implemented by convolving the received signal with the time-reversed transmit replica. The output was half-rectified and put through a Hanning Window filter. Signal power was calculated on a 32 sample frame, slipped 50%, as 10 log of the variance and compared to an adaptive noise power estimator. When this signal power exceeded the threshold value representing a desired signal-to-noise ratio, the peak power values were output as detections to an "energy-detection vector."

The spectral-based detector uses a 32-sample FFT on the receiver samples. FFT slip was set to 50%. The FFT magnitude was summed across all spectral bins and across a frequency range closely approximating the transmit signal bandwidth to produce total and in-band spectral power estimates. The in-band power was compared with a threshold. If this threshold was exceeded, the ratio of the in-band power divided by the total power was calculated. This ratio was used to differentiate random, snapping shrimp-type broadband signals from signals generated by the DBS projector. Detections were declared when the in-band power threshold and the ratio of spectral energy threshold were exceeded. A second "spectral-detection vector" was created from the output.

DBS system-level detections were based upon a combination of the two above detectors. System level detections were coupled with sonar location and pan and tilt information from the sonar head to provide a first-pass estimate of the number of detections and a crude estimate of target location. Minimization of errors in echo placement was corrected via triangulation methods and acoustic positioning relative to known targets. Maps were created of the test fields by integrating sonar positions and echo positions with GPS locations of known stationary targets (including the cement pilings used for trolley line attachment (long-line test) and sonar mounting (fixed-piling test)). Combined, landmark information and echo position data were used to create maps of high-energy return regions in Cartesian coordinate space. For ease of visual localization of targets, the map of the target field was put through a total number of system-level detections to form a binary mask through which the map was filtered. Typically, at least 4 system level detections were required to generate good detection maps (fig. 4). Resolution of the field view was initially set at 0.254 x 0.254 m. Subsequently, the resolution of regions of interest (i.e. regions with high energy content) was "zoomed in" by reprocessing these regions at 5 x 5 cm. (The resolution limit was determined as a tradeoff between resolution of the grid dimension and the computational time required to process data at that resolution.)

A target "snippet" database was extracted from the detection maps for each independent look at specific regions on the bottom. The snippet database is used for classification processing to identify the mine shape targets of interest. Snippets were also submitted to biologically inspired synthetic aperture sonar (BioSAS) processing (©Chirp Corporation), an image generation approach that is more robust in its tolerance of motion errors but less computationally intensive than either traditional SAS or Algebraic Reconstruction (ART) algorithms.

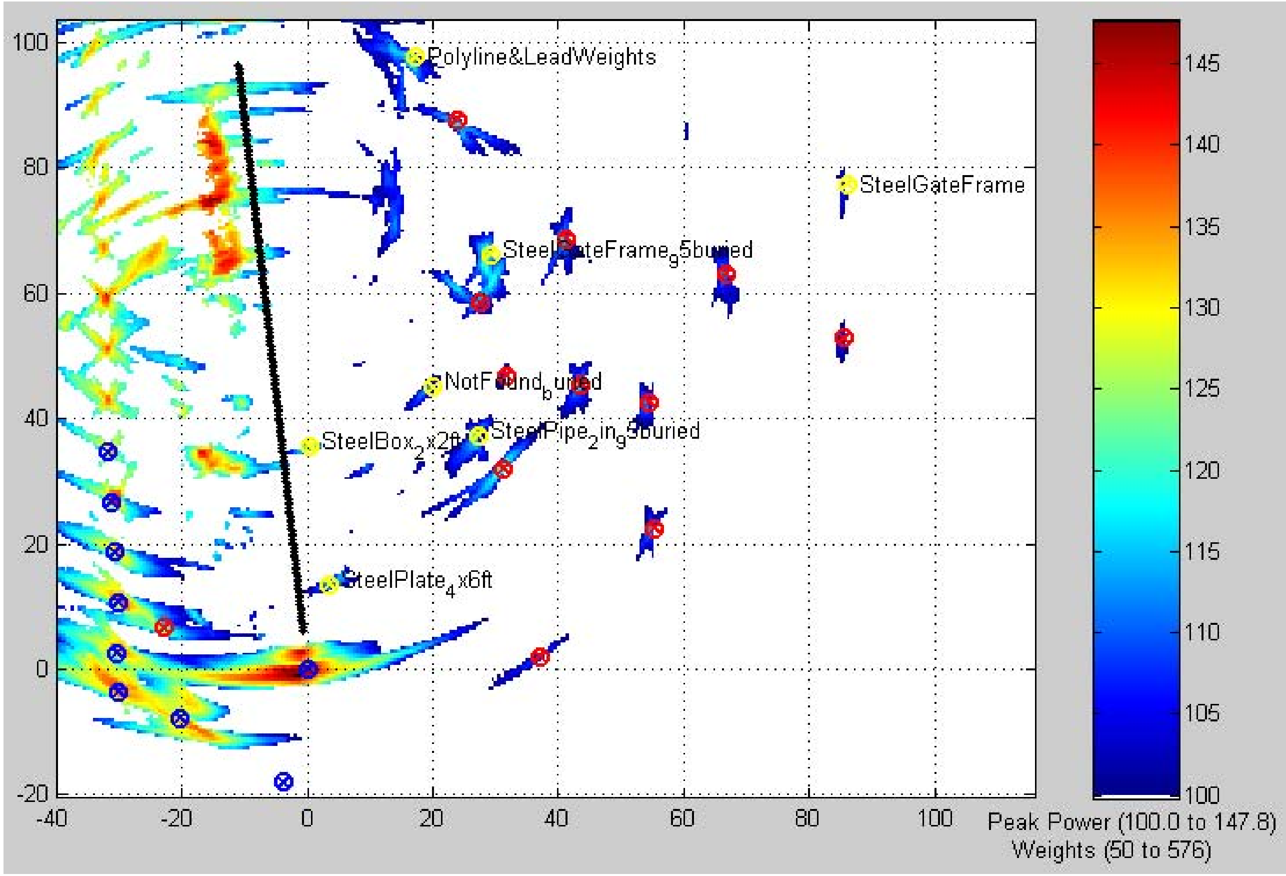

Fig. 4 Detection map created from the combined use of cumulative energy and a minimum number of detections.

A set of snippets from 39 hand-selected detection regions from the target placement area of the long-line test were chosen for initial target classification efforts. These detections were based upon the multiple aspect system level detection map generated with at least 4 detections in a region and over 80 dB cumulative energy. Fig. 4 demonstrates the detection map with a 100 dB cumulative energy and a binary mask (filter) with a 50 out of 576 scan minimum acceptance criterion. All snippets from these regions were collected and analyzed with a simple M-of-N classifier on the number of system level detections made. In this case, N is 199, as the sonar was stopped at 199 points along the long line and azimuthally scanned. For each scan position, the closed angle to the region of interest, ping cycle was employed to extract signals corresponding to the range of the region of interest. If a system-level detection was declared on the scan position range area, M was incremented. Thus, M represents the number of system-level detections made on the system-level detection map regions of interest. If the region has an aspect dependent object, many M opportunities can be obtained where no system level detections are made due to the low target strength of the target at unfavorable aspects.

A receiver operating characteristic curve can be generated for this hand-selected set of return areas on the seafloor (Fig. 5). Here the number of mine shapes correctly classified (Pcc – probability of correct classification) is presented against the number of NOMBOs. The line graph demonstrates the performance of the system as the M-of-N ratio is decreased from 1 to zero. The knee in the curve is for a M-of-N ratio of 0.35, which is optimal for this single feature classifier.

Given that the receiver employs two directional elements, some beamforming is possible. A simple cross correlation of the left and right receiver elements can be done for steering directions over a +/-90 degree sector (zero being directly in front of the receiver). While this often provides an echo azimuth angle relative to the maximum response angle, which is believable, it is only accurate to within several degrees. It is also not robust to interfering signals such as snapping shrimp. Chirp Corp constructed a more robust bearing estimator that interpolates the signals up by a factor of 32, providing angular estimates for echoes down to a degree and lower. The interpolation technique employed also proved to be more robust against interfering signals. Utilizing finer angular estimates could be of great value for real world application on UUVs. This would allow fine angular estimates for detections, in addition to the fine range resolution of the broadband sonar. Given the potential for finer accuracies in the generation of multi-aspect detection maps, this area has been identified for additional development applicable to UUV system performance enhancement.

IV. RESULTS AND DISCUSSION

All mine shapes and a number of NOMBOS were found during the fixed piling test. Similarly, all of the mine shapes and PVC markers were found during the long-line test. One of the mine targets was partially buried by sediment action prior to the long-line test. Detections were made out to a range of over 90 m. Thus, the DBS demonstrated an ability to effectively detect both NOMBOS and mine shapes at extended ranges and under proud, buried and partially buried conditions. The ability to detect a water-borne intruder was also demonstrated and highlights the flexibility of the system with respect to potential application. Further characterization of the system's capability in regard to diver and swimmer detection is required.

Whereas the fixed-piling and diver detection tests were proof-of-concept, the long-line test was meant to more thoroughly test the capability of the DBS and provide data to simulate it's operation on a small unmanned underwater vehicle (i.e. a down-sampling of echoic returns and aspect looks). The simulation results are not reported here, but were deemed effective at producing similar detections maps to those obtained with a full complement of N looks.

The ROC plot was based upon the energy threshold and number of hits detection map, and employs only one additional feature, M-of-N detections. Both WMF and spectral detection measures were used. A M-of-N threshold of approximately 0.35 provided the best trade-off between target detection and false alarm rate. At this threshold all mines but the buried DST were correctly classified as a mine and only 4 NOMBOS were misclassified as mines. Divers were sent to investigate several of the NOMBOS following the test. NOMBOS found by divers included; a spool of ¼" line, both proud and fully buried gate frames, a buried 2' length of metal pipe, a 2' x 2' steel box and a 4' x 6' steel plate. The NOMBOS incorrectly classified were: the clump of poly-line with lead weights at spaced intervals, a 95% buried 4' x 4' steel gate frame, and a 95% buried 2" diameter steel pipe (approximately 2' long and slightly bent). The fourth NOMBO was not identified and may be fully buried.

The DBS has demonstrated an ability to effectively detect targets of interest at distance, within clutter, and under partially buried and fully buried conditions. However, it requires refinement of target classification for a more robust set of features than the simple M-of-N criteria reported here. A set of 40 features based upon energy characteristics of mine shapes has been created to further improve the mine-like classification while reducing the number of false alarms. The feature set is currently under evaluation. Eight of the 40 features have demonstrated value in helping to improve classification, but further exploration of features and their implementation into classification algorithms remains to be completed. In addition to the use of the feature set, generation of BioSAS images from target "snippets" may augment the classification process. First-pass images using BioSAS processing are currently being created.

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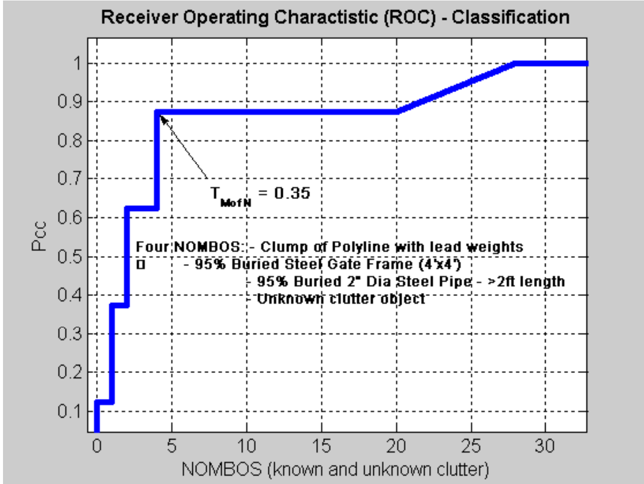

Fig. 5 The approximation of an ROC as determined from the M-of-N "detections" to "looks" ratio. The optimal ratio was approximately 0.35.

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