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Wide Area Detection and Identification of Underwater UXO Using Structural Acoustic Sensors

J. A. Bucaro (PI)
B. H. Houston
M. Saniga

Physical Acoustics Branch
Acoustics Division

H. Nelson

Chemical Dynamics and Diagnostics Branch
Chemistry Division

T. Yoder
L. Kraus

SFA, Inc.
Crofton, MD

L. Carin

Duke University
Durham, NC

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J.A. Bucaro, B.H. Houston, M. Saniga, H. Nelson, T. Yoder,* L. Kraus,* and L. Carin†

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*SFA, Inc., Crofton, MD 21114 †Duke University, Durham, NC 27708

14. ABSTRACT

This new project is exploring the potential for developing a structural acoustics (SA) based sonar methodology for wide area search and identification of underwater unexploded ordnance (UXO). This new approach may have significant advantages over more conventional acoustic approaches, which rely on the formation of high resolution images. These advantages include: diverse set of "fingerprints" leading to low false alarm rates; longer range operation leading to wide area coverage; and low frequency sediment penetration leading to buried target prosecution. A core element of the current project is a comprehensive examination of the scattering levels and features exhibited by typical UXO targets in the SA regime using NRL's state-of-the-art underwater scattering facilities, both laboratory-based and at-sea. We have recently completed the first phase of this data collection using the laboratory-based facility, and these results are reported here.

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Wide Area Detection and Identification of Underwater UXO Using Structural Acoustic Sensors

INTRODUCTION

This document represents the first annual report for the new SERDP sponsored scientific effort at the Naval Research Laboratory involving structural acoustic-based detection and identification of underwater unexploded ordnance (UXO). The report covers work performed during the period December 1, 2005 through December 1, 2006.

PROJECT BACKGROUND

Many active and former military installations have ordnance ranges and training areas with adjacent water environments in which unexploded ordnance (UXO) now exists due to wartime activities, dumping, and accidents. These contaminated areas include coastal and inland waters both in the United States and abroad. SERDP goals require the development of innovative technologies able to separate UXO from false targets and to discriminate amongst individual UXO targets themselves. Over time, such geographic areas are becoming less and less remote as the adjacent lands become further developed, and the potential hazard to the public from encounters with such UXO has begun to rise. Presently there exists no sufficiently effective capability to survey such underwater areas and map UXO locations.

This new project (SERDP Project MM-1513) is exploring the potential for developing a structural acoustics (SA) based sonar methodology for wide area search and identification of underwater unexploded ordnance (UXO). This new approach may have significant advantages over more conventional acoustic approaches which rely on the formation of high resolution images.

Conventional sonar approaches which form images (see Fig. 1 in Project Accomplishments Section) must operate at relatively high frequencies since the image resolution is directly proportional to the acoustic wavelength. In this regime, acoustic wavelengths are short compared to the target dimensions and the waves are scattered for the most part from the external boundary of the target (specular scattering). In contrast, in the structural acoustic regime, acoustic wavelengths are comparable to, or longer than, the target dimensions. Sound readily penetrates the target, and the acoustic scattering is now related to the vibrational dynamics of the object, both whole-body and internal structure. The time-frequency features in the scattered echoes can then be used to “fingerprint” the target without the need to form an image.

The inherent advantages of the SA approach include: diverse set of “fingerprints” leading to low false alarm rates; longer range operation leading to wide area coverage; and low frequency sediment penetration leading to buried target prosecution.

Manuscript approved December 4, 2006.

OBJECTIVE

Our objective is to address the technical issues necessary to implement an innovative structural–acoustics (non–imaging) sonar system for wide search area identification using structural acoustic features from proud and buried UXO objects. In addition to providing wide–area capability, the structural–acoustic features may be integrated with other SERDP near–range sensors, including magnetometer, induction, and acoustic–imaging devices to increase identification performance. In contrast to imaging, the structural–acoustic technique exploits both non–specular and specular scattering features. This represents a new approach to acoustic identification of UXO; and we believe a number of exploitable structural–acoustic mechanisms exist for the in–water UXO problem and that the features derived there–from will be sufficiently separable from individual classes of UXO and from those associated with clutter. Further, some of the features should manifest themselves at frequencies where significant bottom penetration persists, allowing detection and identification of buried UXO even at long ranges due to evanescent wave penetration.

The broad objective stated above can be broken into three objectives. The first is to understand the UXO target and clutter structural acoustic scattering signature phenomenology and the environmental impact on those signatures by performing controlled, high fidelity acoustic scattering and propagation measurements in the laboratory and at sea. Understanding the scattering phenomenology and the environmental impact on the signatures is the key to generating features that provide robust target identification. The first part of this objective will be met in the first year of the program through laboratory measurements on target set 1 and extended to target set 2 in the second year, while the second environmentally-related goal will be achieved in the third year. The second objective is to extract structural–acoustic features from scattered echoes collected both in the laboratory and at sea and to demonstrate that UXO and clutter can be separated via kernel–based identification algorithms exploiting these features. This objective will be met in the second year as it relates to laboratory data and in the third year regarding at-sea data. The third objective is to apply site–specific active–learning paradigms developed under previous SERDP support and determine the bounds on performance of system concepts based on structural acoustic ID. This final objective will be achieved in the third year.

TECHNICAL APPROACH

The tasks described below answer three fundamental questions about UXO structural acoustic scattering phenomenology in a marine environment. 1) Does enough acoustic energy reach proud/buried UXO to produce a detectable and exploitable scattered signal? 2) Are the structural-acoustics signatures from underwater UXO and clutter sufficiently separable in a marine environment? 3) Can we structure identification algorithms so as to be robust with respect to the environmental and historical circumstances? We believe successful prosecution of the program tasks will answer these questions in the affirmative and provide the foundation for a new structural acoustics-based approach for identifying proud and buried UXO objects. The three main tasks include: 1) experimental measurements of the structural acoustic UXO and false target responses; 2) demonstration of the separability of UXO and false targets using structural acoustic features; and 3) the development and demonstration of a robust, site-specific active learning identification algorithm which could exploit the structural acoustic features regardless of the environment or historical conditions.

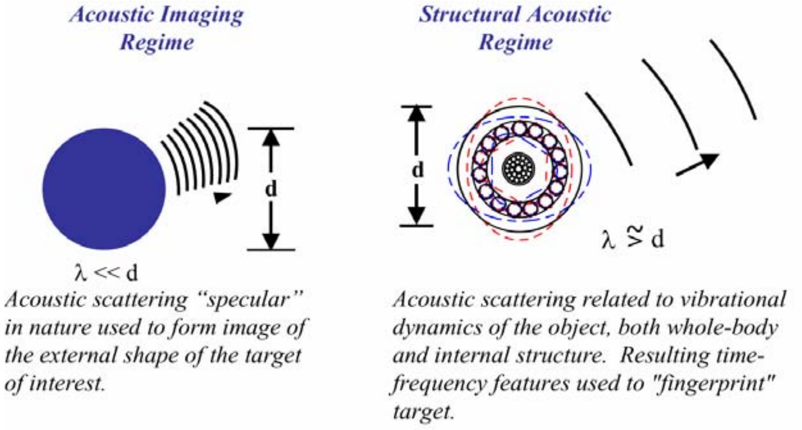
In the first year, the first of two representative sets of inert UXO devices will be acquired and filled with the appropriate materials which simulate the elastic properties and density of a generic explosive. Systematic acoustic scattering measurements will be carried out in the NRL Laboratory for Structural Acoustics Facility yielding full 360 degree broadband (1kHz - 140 kHz) data bases. These measurements made in the free-field will be augmented by those made in the proud, partially buried, and fully buried conditions using a companion sediment scattering facility and an at-sea rail-based system. The data bases will be processed using kernel–based algorithms such as Relevance Vector Machines (RVM) and Kernal Matching Pursuits (KMP) which use the structural acoustic features for identification, and this will lead to the first critical "go-no go" decision point in the first quarter of the second year. At this point the ability to separate UXO and false targets based on their structural acoustic features will have been determined using the data collected in the laboratory facilities. Also in the second year, another UXO target set will be acquired, filled with explosive simulant, and measured in the laboratory facilities. Similar processing with the RVM and KMP algorithms will provide further confirmation regarding the general applicability of the structural acoustic identification approach to UXO. In the third year, the targets will be seeded in a maritime environment off the coast of Panama City, and acoustic scattering data will be collected using a rail-based system already developed and used at that site. The ability to identify the targets based on their structural acoustic features will again be tested using the RVM and KMP algorithms. Finally, in order to allow the structural acoustic identification algorithms to adapt to new site-specific details such as target type/orientation and environmental conditions, an active learning identification algorithm suitable for UXO will be developed beginning in the third quarter of the second year. Both its feasibility and performance will be demonstrated off-line using all the data collected in the previous tasks. The program will be carried out by NRL using its scientists and engineers and those of its long time on-site contractor SFA, Inc. In addition, the Department of Electrical and Computer Engineering of Duke University will develop the advanced feature extraction and identification algorithms and participate in the application of those algorithms to the experimental data bases.

PROJECT ACCOMPLISHMENTS

INTRODUCTION

This new project is exploring the potential for developing a structural acoustics (SA) based sonar methodology[1] for wide area search and identification of underwater unexploded ordnance (UXO). This new approach may have significant advantages over more conventional acoustic approaches which rely on the formation of high resolution images. These advantages include: diverse set of "fingerprints" leading to low false alarm rates; longer range operation leading to wide area coverage; and low frequency sediment penetration leading to buried target prosecution[2].

Conventional sonar approaches (see Fig. 1) which form images must operate at relatively high frequencies since the image resolution is directly proportional to the acoustic wavelength. In this regime, acoustic wavelengths are short compared to the target dimensions and the waves are scattered for the most part from the external boundary of the target (specular scattering). In contrast, in the structural acoustic regime, acoustic wavelengths are comparable to, or longer than, the target dimensions. Sound readily penetrates the target, and the acoustic scattering is now related to the vibrational dynamics of the object, both whole-body and internal structure. The time-frequency features[3,4] in the scattered echoes can then be used to "fingerprint" the target without the need to form an image.



Acoustic scattering "specular" in nature used to form image of the external shape of the target of interest.

Acoustic scattering related to vibrational dynamics of the object, both whole-body and internal structure. Resulting time-frequency features used to "fingerprint" target.

Fig. 1 **– Structural Acoustic ID vs. Imaging**

A core element of the current project is a comprehensive examination of the scattering levels and features exhibited by typical UXO targets in the SA regime using NRL's state-of-the-art under-water scattering facilities, both laboratory-based[5] and at-sea[6]. We have recently completed the first phase of this data collection using the laboratory based facility, and these results are reported here.

EXPERIMENTAL DETAILS

An initial, representative UXO target set was identified, and the specific targets obtained from the Aberdeen Proving Grounds. This four target set included a 155 mm artillery shell, a 5 inch rocket warhead, an 80 mm mortar round, and a

120 mm mortar round. Each target was then filled with a material system designed by NRL to roughly approximate the elastic moduli and density of a generic explosive.

The acoustic scattering measurements were carried out at the Laboratory for Structural Acoustics (LSA)[5] at NRL (see Fig. 2) which is a state-of-the-art underwater acoustic research laboratory unique in the world. The LSA infrastructure includes a large cylindrical one million gallon (17 m diameter x 15 m deep) de-ionized water tank located in Building 5. This tank is vibration isolated, temperature controlled, and heavily instrumented with in-water precision robots for nearfield acoustic holography (NAH), laser Doppler vibrometry (LDV), and compact range measurements.

Fig. 2 **– NRL Laboratory for Structural Acoustics**

One million gallon pool facility with adiabatic walls and acoustic coatings, vibration isolation system, and complex acoustic scanners, sources, and processing algorithms.

The measurements reported here were conducted with the facility in its compact scattering range mode as shown in Fig. 3. Each UXO target was suspended at mid-depth in the tank together with the source and receiver. Two sources were used for these experiments. The first source is a 3 meter long nearfield line array mounted horizontally. The array elements are shaded in such a was as to produce a plane-wave sound field in its nearfield throughout a limited volume centered at the target position. The line array generates a broadband pulse approximately 1 ms in duration and covers the band from 1 – 25 kHz. The receiver used in these experiments is a vertical line array that was also suspended at the mid-depth of the tank. A second piston-like source was used to collect data in the band from 8kHz – 140 kHz. The measurement system is designed for collection of both monostatic and bistatic scattering data. However, for the measurements reported here, only the monostatic configuration was used, i.e. the source and receiver fall along the same bisector to the target center. The scattered echo response was measured 2.7 meters from the target in 1 degree increments over 360 degrees. The data was processed to recover full complex scattering cross-sections expressible as target strength referenced to 1 meter. In this method, the time domain scattered data from the target at a given aspect angle is cleaned to remove unwanted reflections not associated with a target return, Fourier transformed, and then normalized by a reference measurement.

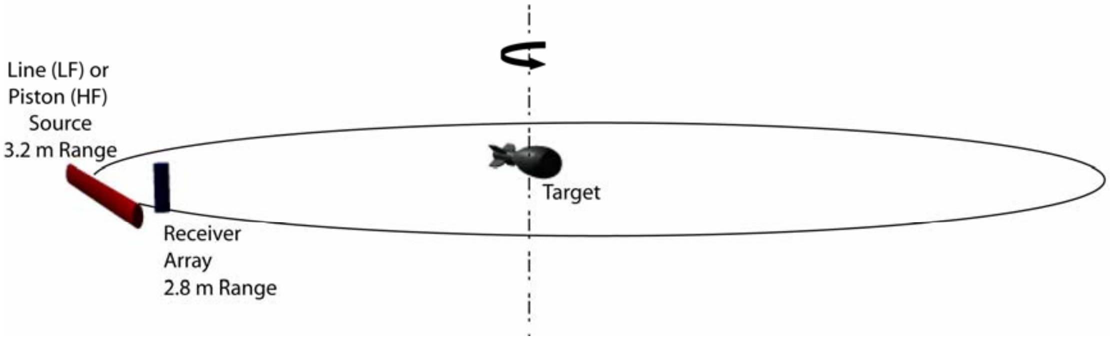


Fig. 3 **– Experimental Measurement Geometry**

The target is placed in the plane-wave region of (1) a near-field cylindrical source at low frequency (LF) or (2) a farfield piston source at high frequency (HF) with a nearly co-located broadband short vertical receiver array. The target (which is ~ 2.8 m from the receiver) is rotated over a full 360 degrees in increments of 1 degree.

We also made similar measurements over the lower part of this frequency band for two non-UXO targets including a large rock and a cinder block and for two concrete-filled metal pipes. The former will be used as “false targets” in our studies to determine ID algorithm performance and false alarm rates. The latter are “overlap targets” whose scattering will also be measured by CSS Panama City thus allowing a controlled comparison between the findings of the two groups.

The basic data acquisition parameters are summarized as follows: overall bandwidth 1 kHz – 140 kHz; sample rate (per chan.) 500 kHz (min.); record length (per chan.) ~32 k; record length (time) 16 ms; ensemble number ~16; dynamic range ~ 80 dB; and typical measurement duration ~1 week.

In some cases, structural acoustic features could be integrated with responses from SERDP near-range sensors such as induction detectors in order to further increase identification performance. To permit evaluation of this possibility at a later time, inductive measurements were also carried out using a Geonics Limited EM61-MK2 submersible sensor system, a high powered time domain pulsed-induction device suitable for detecting both ferrous and non-ferrous metals. Metallic objects interact with the transmitted field inducing secondary fields which are subsequently detected by coils co-located with the transmitter. The data was collected on a battery operated data acquisition system which was also provided by Geonics and down-loaded to a PC. In these measurements, the 155mm artillery shell target filled with the explosive simulant was hung with Kevlar fishing line (non-magnetic) in the NRL pool facility. The measurements, taken as ensemble data to be averaged off line, were monostatic covering angular aspects from 0 to 360 in increments of 15 degrees with a source/receiver to target center distance of 1.27m. The completed data base will be used at a future time to evaluate the merits associated with combining structural acoustic ID with this additional sensor modality.

MEASURED SCATTERING DATA

The measured data over the composite band from 1 – 140 kHz are displayed in Figs 4-11 as a function of frequency and target aspect for the four UXO targets, the two “false targets”, and the concrete-filled pipes with the color scale mapping actual target strength levels.

As can be seen, the highest target strength level observed for each target ranges from -15dB for the smallest target (80 mm mortar round) to 0 dB for the largest (155 mm artillery shell). Taken as a set, we can readily observe scattering features with levels anywhere from 0 dB down to – 25 dB. Based upon our experience in at-sea measurements in related programs involving target detection and identification, these levels should provide sufficient signal to noise for successful operation of the ID algorithms we expect to employ.

The scattering data of the four UXO targets can be seen to have both expected common features as well as those that are more target specific. The former include strong, narrow aspect, broadband signatures from the broadside (90 degrees) of the target associated with specular reflection. Two of the targets also have similar strong returns from their backsides which present a nearly flat surface. This return is greatly diminished from the other two targets because of their more fin-like stern construction. All but the 120 mm mortar round also present large specular returns from their more or less flat bow while the nearly tapered front of the latter precludes this effect. In addition to these specular highlights, other structure unique to each target can also be observed at various frequency-aspect locations. Examples here include the strong responses of the 155 mm artillery shell localized around 8 kHz and 145 degrees; a number of weaker localized responses from the 80 mm mortar round between 20 kHz and 40 kHz and for aspects from 145 degrees and 215 degrees; and a strong response from the 5 inch rocket warhead near 20 kHz and 35 degrees. We believe these responses are related to elastic wave phenomena within the interior of the targets. The returns from the more cylindrical targets (the 155 mm mortar round and the 5 inch rocket warhead) also exhibit the well known ring resonance structure at beam aspect (resulting from the interference of specular reflection and elastic circumferential wave re-radiation) an effect readily predicted for elastic cylinders.

Regarding the measured scattering data from the “false targets”, for the cinder block (presently collected only over the lower portion of the frequency band), the very strong specular returns from each of its four sides are to be expected from these large planar reflectors. (Note that in the measurements the block was placed horizontally.) The low frequency scattering levels for the large rock are asymmetric with respect to aspect as expected given its irregular shape.

Finally, the low frequency responses for the two concrete-filled pipes can be seen to have noticeable differences from the UXO targets in part owing to the significant differences between their filler materials and to their regular cylindrical shape.

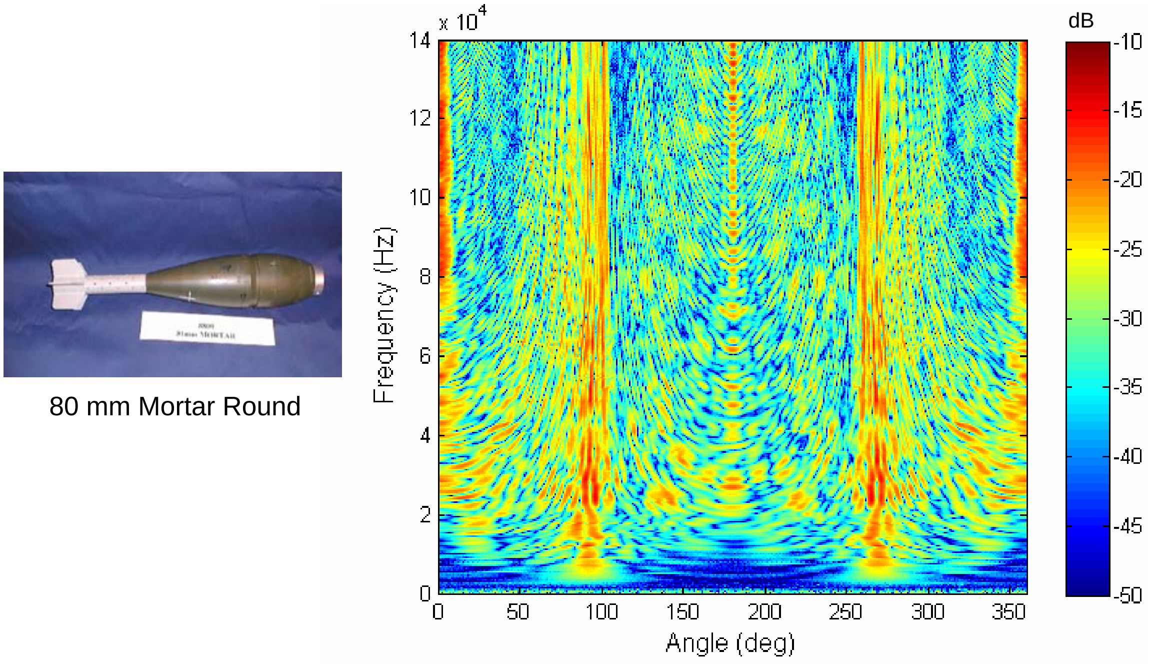

80 mm Mortar Round

Fig. 4 **– Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the 80 mm mortar round.

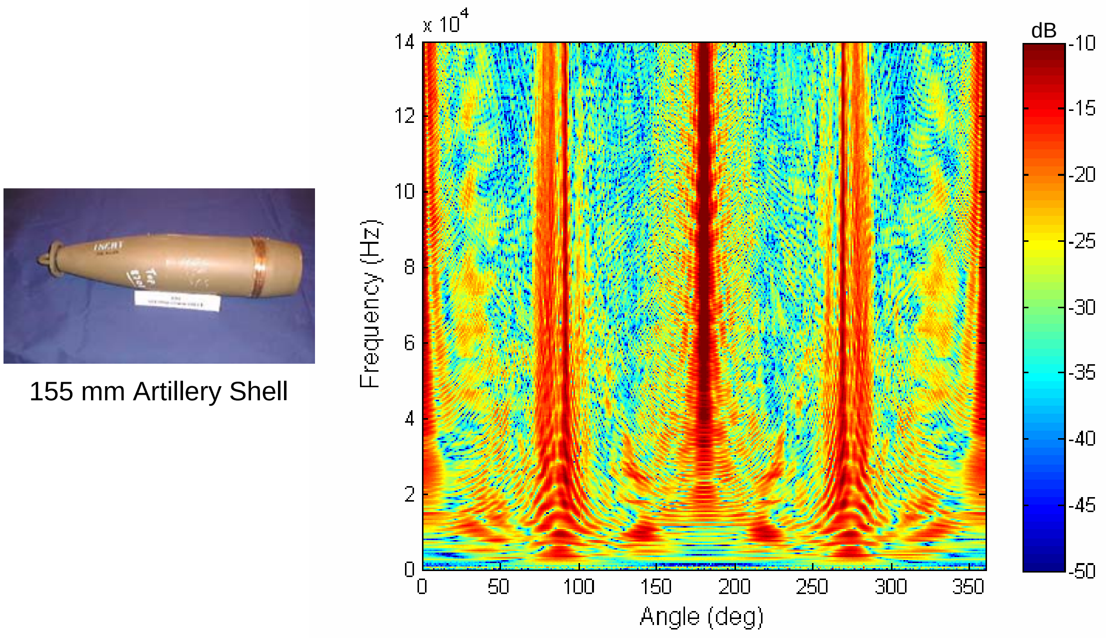

155 mm Artillery Shell

Fig. 5 **– Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the 155 mm artilleryshell.

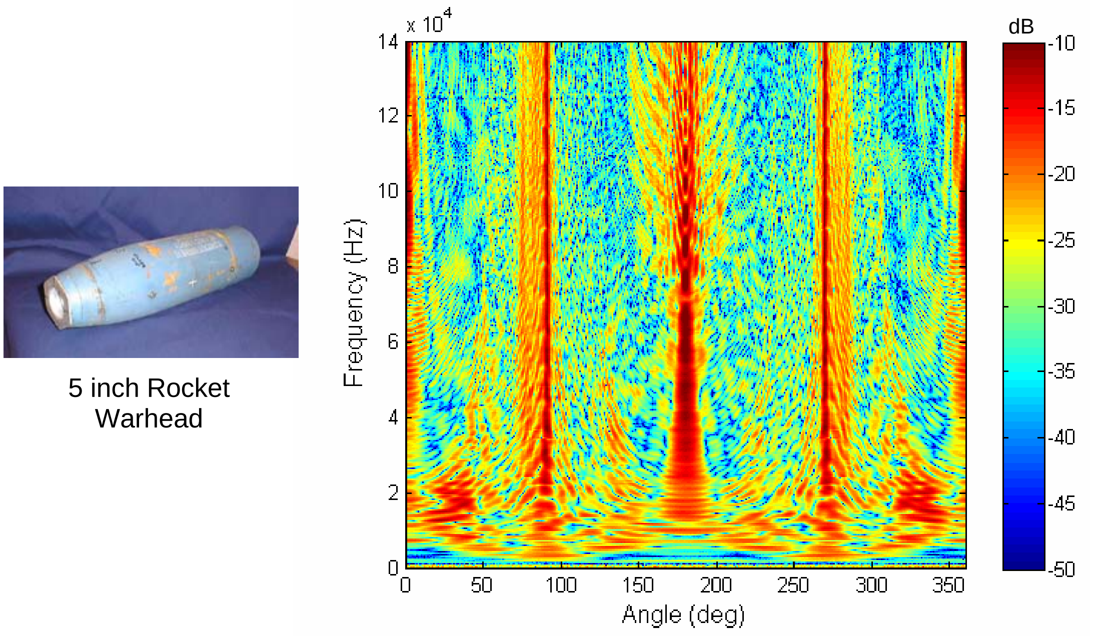


***Fig. 6* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the 5 inch rocket warhead.

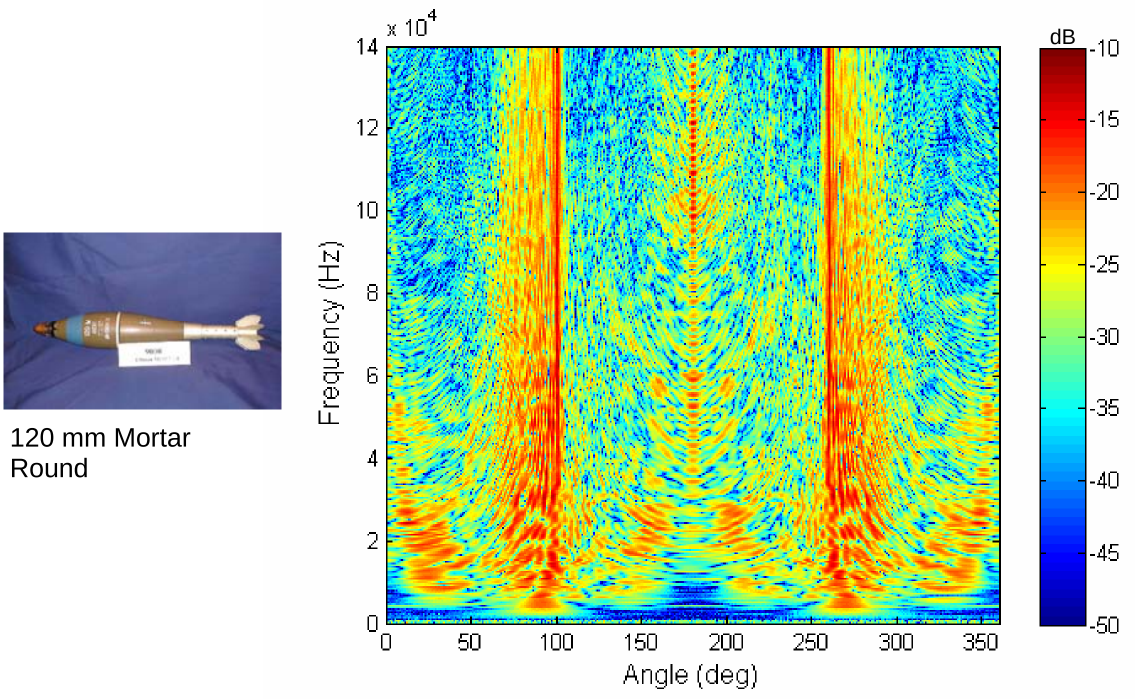


***Fig. 7* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the 120 mm mortar round.

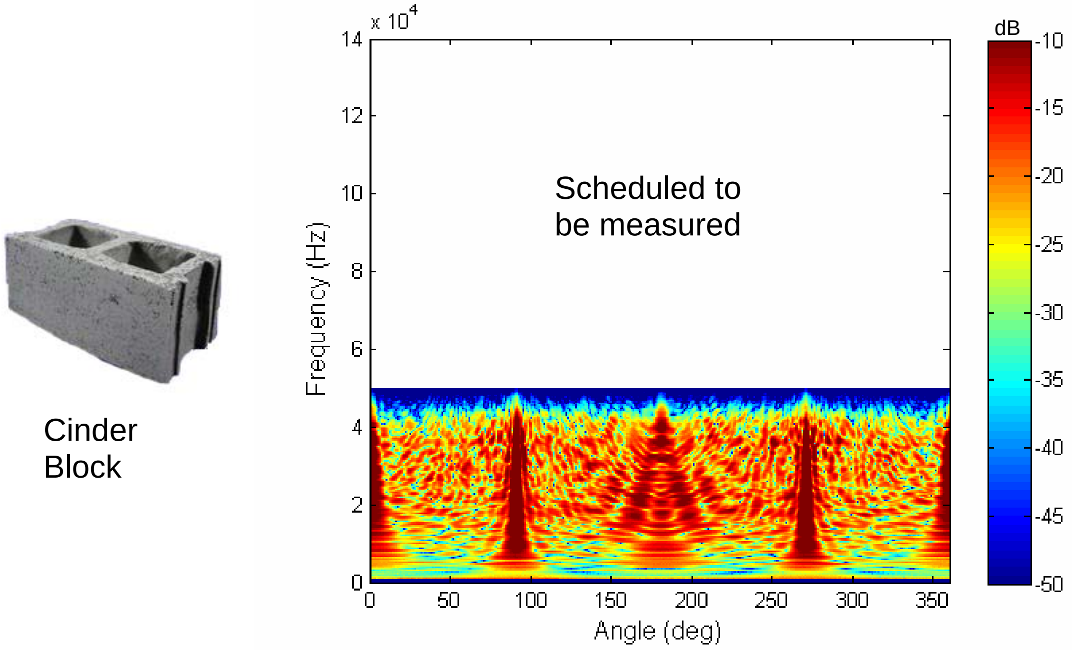


***Fig. 8* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the cinder block oriented in its normal construction orientation.

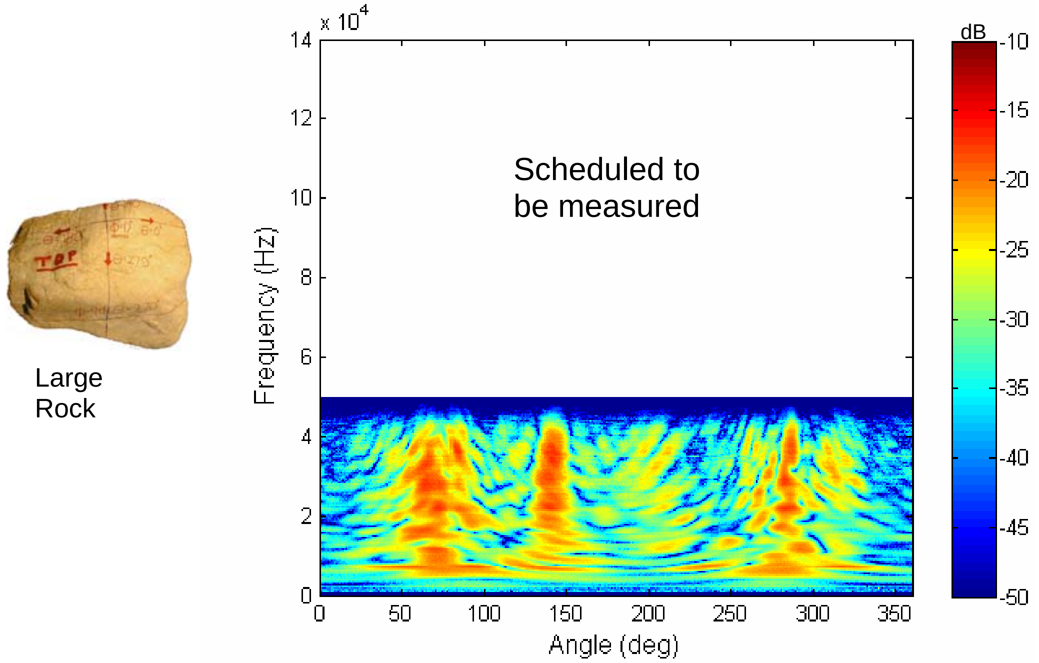


***Fig. 9* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the large rock.

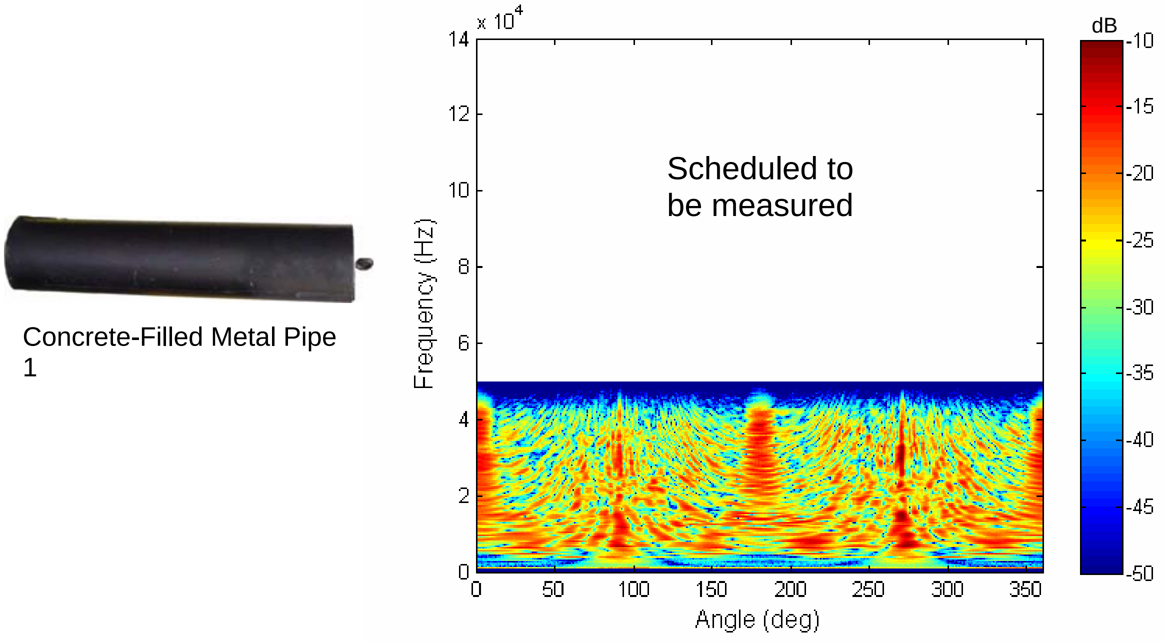


***Fig. 10* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the concrete-filled metal pipe #1.

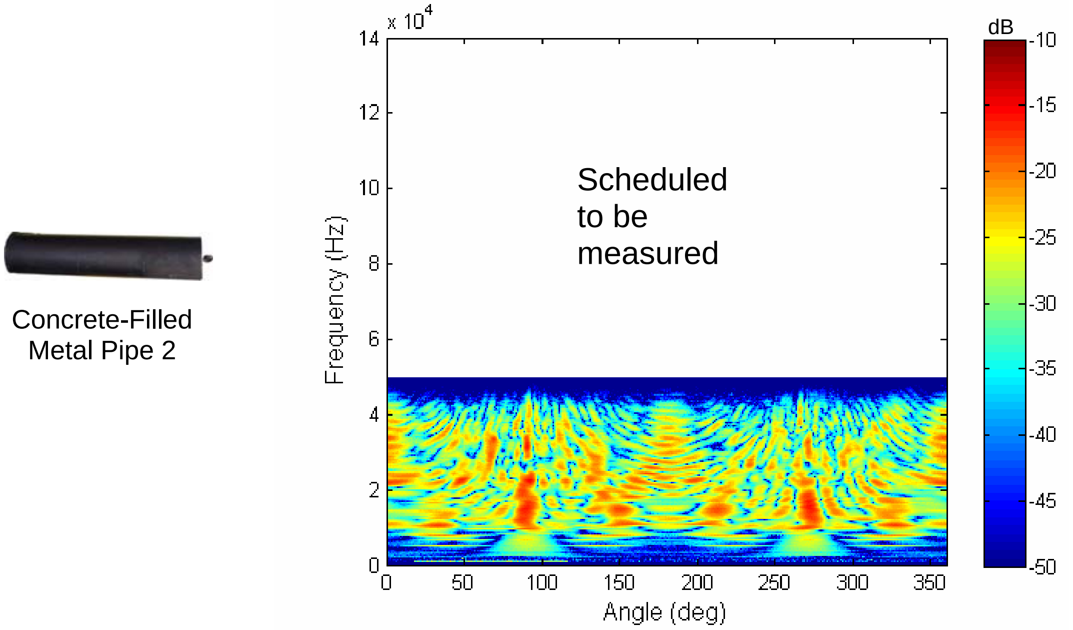


***Fig. 11* – Measured Target Strength & Target Photo**

Magnitude of the target strength coded in color map versus frequency and target aspect for the concrete-filled metal pipe #2.

PRELIMINARY TARGET IDENTIFICATION RESULTS

The next step in the project (and work now underway) involves post processing of the measured data bases to extract the structural acoustic features around which the identification algorithms will be designed, trained, and tested. The post processing algorithms have already been developed in our work on mine identification and include feature extractors such as Matching Pursuits[4,7] and identification algorithms such as Relevance Vector Machines (RVM)[8], Hidden Markov Models (HMM)[4,9], and Kernal Matching Pursuits (KMP)[10]. In the preliminary example results shown in Fig. 12, we processed the scattering data associated with the four UXO targets and the two false targets in the band 7 to 35 kHz in order to evaluate to what extent these targets were separable based on a simple set of scattering features. These features were taken to be the energy in each of thirty equally-spaced sub-bands. We randomly added additional noise to each data set until ten different realizations were obtained for each target. At this point the total data base consisted of 2.17×10^4 noise-corrupted scattering realizations (6 objects with 361 target orientations and 10 noise realizations per object). The SNR is 3 dB and is defined as the ratio of the average energy in the UXO and clutter returns and the average energy in the added noise signal. A KMP[10] ID algorithm was then trained using 30% of these noise-corrupted realizations and all target aspects. The ability of the trained algorithm to correctly identify whether or not the object was a UXO was then tested on the remaining 70% as a function of angular aperture, and the results averaged over the full 360 degrees. Since a single aspect feature is being evaluated in this example, the performance as a function of angular aperture is determined by combining in an incoherent manner the log likelihood values for all target aspects within the aperture. As can be seen in the upper ROC curves, even this simple feature set is effective in distinguishing between UXO and false targets. In fact, with an angular aperture of ± 90 degrees the KMP is able to achieve ~ 80% probability of detection (P_d) and 20% probability of false alarm (P_f) while an aperture of ± 170 degrees results in ~ 99% probability of detection (P_d) and only 1% probability of false alarm (P_f). The features, chosen here for convenience, are by no means the optimal feature set so that the overall performance is expected to improve significantly as we choose more sophisticated sets.

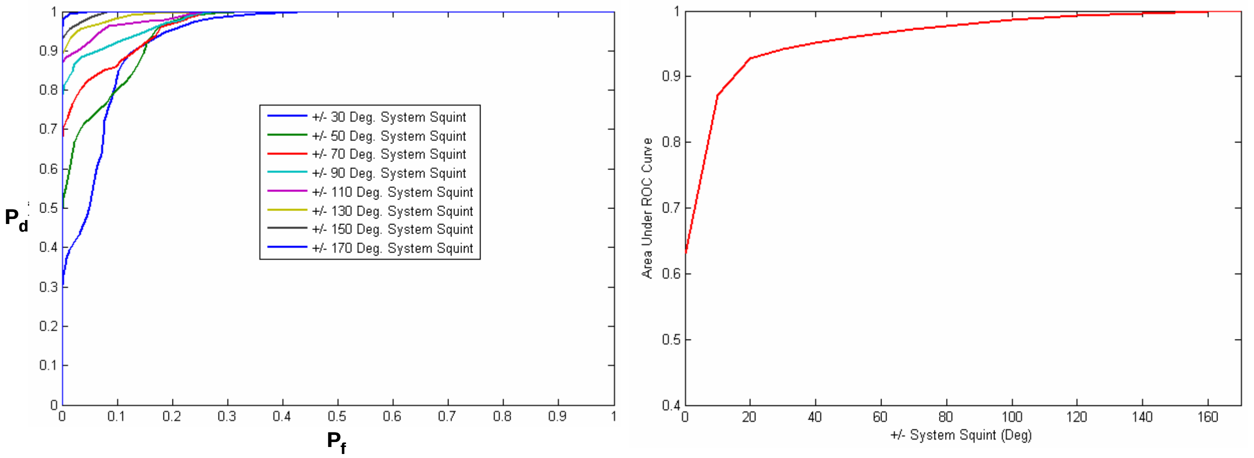


***Fig 12* – Identification Performance Curves**

(Left) ROC curves showing probability of (correct) detection versus probability of false alarm. (Right) Area under the ROC curves.

CONCLUDING REMARKS

We have completed the first phase of comprehensive broadband acoustic scattering measurements on UXO target set 1. This four target set included a 81mm mortar round, a 120mm mortar round, a 155mm artillery shell, and a 5 inch rocket warhead, each filled with explosive simulant. These measurements were carried out in the NRL Laboratory for Structural Acoustics pool facility and covered the frequency band from 1 kHz to 140 kHz. Monostatic measurements (co-located source and receiver) were made in the free-field over a full 360 degrees and at 1 degree angle increments. To our knowledge, these data sets represent the first of their kind for actual UXO targets. Several important conclusions can already be drawn upon observation of the data. (1) In general, there are a number of aspects that provide relatively high target strength levels (~ 0 to -15 dB). Based upon our experience, this implies that these targets, even though relatively small, are detectable in this structural acoustics band out to long ranges (> 100 meters) in most acoustic environments. (2) The associated features appear to be exploitable for target identification. For example, the scattering features are clearly separable from those we have seen from non-man-made targets such as rocks. Our preliminary results do indicate that the data will be able to support feature – based separation of various classes of UXO. The various structural acoustic features that are observed include for example whole body and interior structure resonances, ring resonances, and a number of specular highlights. (3) As expected, the measured scattering patterns from all four targets have almost perfect right/left symmetry, and we believe this can also be exploited for separating such UXO from most natural irregularly shaped objects.

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APPENDIX

Abstract # 591 of The Partners in Environmental Technology Technical Symposium & Workshop, Washington, D.C., November 28 - 30, 2006: "Broadband, Multi-Aspect Scattering Measurements from Shells and Rockets in the Structural Acoustics Domain."

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