Modeling for Sensor Evaluation in Underwater UXO Test Beds: Final Report

SERDP PROJECT UXO-1329

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14. ABSTRACT
This report summarizes an effort carried out at the Naval Surface Warfare Center – Panama City (NSWCPC) under SERDP funding to develop a performance prediction capability for sonar against UXO. This development built upon existing sonar performance prediction software (PCSWAT) developed to aid sonar design for underwater mine-countermeasure purposes at NSWCPC. The wide variety and distribution of UXO required a number of scientific issues to be resolved in order to update PCSWAT appropriately. UXO are expected to be completely buried, sometimes quite deeply. Thus, the sonar response of buried targets needed to be investigated and new target scattering algorithms used to account for burial effects formulated, checked through controlled measurements, and incorporated into PCSWAT. Among the issues that were explored to accomplish this are: what environmental parameters are most important in modeling the response of buried targets, how do we accurately measure these inputs, can the target models currently built into PCSWAT be extended to the shapes and sizes encountered with UXO, and what environmental factors affect acoustic detection of buried targets the most. Both modeling and experimental measurements were carried out to answer these questions to the degree possible and these and their results will be discussed in this report.

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Underwater UXO, buried target detection, target scattering, simulation, sonar performance prediction, PCSWAT

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Acronyms

APL-UW – Applied Physics Laboratory at the University of Washington
AUV – Autonomous Underwater Vehicle
BBSAS – Broad-Band SAS
BOSS – Buried Object Scanning Sonar
BU – Boston University
FAU – Florida Atlantic University
GTD – Geometric Theory of Diffraction
IMP2 - In-situ Measurement of Porosity 2
LFSAS – Low-Frequency SAS
LFM – Linear Frequency Modulated
MCM – Mine CounterMeasures
NSWCPC – Naval Surface Warfare Center Panama City
ONR - Office of Navy Research
PCSWAT - Personal Computer Shallow Water Acoustic Toolset
REMUS – Remote Environmental Monitoring Units
SAS – Synthetic Aperture Sonar
SAX99 – Sediment Acoustics experiment - 1999
SAX04 – Sediment Acoustics experiment - 2004
SERDP – Strategic Environmental Research and Development Program
SNR – Signal-to-Noise Ratio
USACE – US Army Corp of Engineers
UXO – UneXploded Ordnance
WHOI – Woods Hole Oceanographic Institute

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Acknowledgements

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Executive Summary

Unexploded ordnance (UXO) in coastal areas remains an unwanted barrier to safe passage of commercial sea traffic during peacetime in many parts of the world. Clearing these areas requires sophisticated underwater sensor systems that can detect and identify UXO for subsequent marking and removal. Test and evaluation of these sensor systems is expensive and would benefit from design tools that help to identify potential problems via simulation of sensor concepts. For sensors based on acoustic technologies (sonar), a natural test bed representative of the many environments possible with UXO and with characteristics that can be controlled well enough for sensor testing and comparison is difficult to find. Bottom characteristics, water depth, and water turbidity can be quite variable between tests and even over the duration of a given test. Test targets can also experience varying levels of burial.

Under these conditions, assessing a given sensor's performance against another's or assessing a given sensor's performance over the range of environmental conditions likely to be encountered can be problematic without extensive field measurements. Given the expense of underwater tests, sensor performance modeling makes a great deal of sense for mitigating the need for extensive field testing and helping to identify potential difficulties. Where sensors have not been tested under common conditions, sensor modeling can be used to extend a sensor's performance curve past the test conditions; thus, making consistent comparisons and assessments possible.

This report summarizes an effort carried out at the Naval Surface Warfare Center – Panama City (NSWCPC) under SERDP funding to develop a performance prediction capability for sonar against UXO. This development built upon existing sonar performance prediction software (PCSWAT) developed to aid sonar design for underwater mine-countermeasure purposes at NSWCPC. The wide variety and distribution of UXO required a number of scientific issues to be resolved in order to update PCSWAT appropriately. UXO are expected to be completely buried, sometimes quite deeply. Thus, the sonar response of buried targets needed to be investigated and new target scattering algorithms used to account for burial effects formulated, checked through controlled measurements, and incorporated into PCSWAT. Among the issues that were explored to accomplish this are: what environmental parameters are most important in modeling the response of buried targets, how do we accurately measure these inputs, can the target models currently built into PCSWAT be extended to the shapes and sizes encountered with UXO, and what environmental factors affect acoustic detection of buried targets the most. Both modeling and experimental measurements were carried out to answer these questions to the degree possible and these and their results will be discussed in this report.

As a result of the work carried out, the latest version of PCSWAT (v. 9) now has sonar simulation capability for buried UXO targets with some validation in sandy underwater environments. Five UXO shapes spanning the range of UXO sizes have been built in as representative targets for use in simulations. Algorithms to account for surface roughness effects, which have been shown to significantly enhance shallow-grazing-angle detection of buried targets, have been included. Some concerns remain to be resolved in validation of the buried target predictions with measurements at shallow sonar grazing angles, but the current version of PCSWAT is expected to provide realistic simulations of sonar imagery for sonar operated above the critical grazing angle on targets lying above or buried in sandy sediments.

For shallow grazing angles, performance prediction is expected to be good for targets lying above or buried under flat surfaces and to provide acceptable trends at least for targets buried under rough, rippled sand surfaces. While ongoing research will work toward improving the fidelity of predictions and extending validation to more diverse environments, the current version of PCSWAT should provide a useful tool for getting at least a first-order assessment of existing sonar against unburied and buried UXO.

Objective

The objective of the work funded by SERDP was to adapt and use the sonar performance prediction capability developed at NSWCPC to support testing and evaluation of sonar/environment configurations that are being proposed to solve the underwater UXO problem. Initially, this would focus on adapting and/or extending our current acoustic models to predict the performance of systems deployable by NSWCPC in future UXO test beds. However, as these models are validated, enough flexibility will be included in their software configuration so they will also be adaptable to sonars being proposed by others. Our ultimate goal will be to adapt our models well enough to be used as a numerical test bed for assessing future UXO sonar concepts.

The major issues for adapting NSWCPC's sonar prediction software (PCSWAT) were associated with modeling the acoustic response of buried targets; thus, efficient algorithms had to be formulated for modeling scattering by elongated targets in stratified environments over a broad frequency band. The sonar response of a buried target is complicated by greater influence of bottom properties. Thus, an accurate model for the sonar response must account for variations in these properties and these properties must be measurable as inputs for the model. Furthermore, the presence of the interface between the sonar and the target can change sound transmission to and from the target in unexpected ways. As such, several tasks to account for these effects were planned over the course of the project to augment, verify, and validate PCSWAT for predictions on UXO targets. A method to measure bottom wave speed and attenuation levels had to be developed for lower frequency bands to complement the frequency range accessible to high-frequency time-of-flight measurements. Quantitative models to account for the effect of bottom surface roughness on the scattering level of a buried target had to be developed and tested. Based on previous observations from field tests, bottom surface roughness, especially bottom ripple, was suspected to be a major contributor to enhanced backscatter levels by buried targets detected with shallow-grazing-angle sonar. Experimental validation of these models with controlled measurements was a concurrent goal. Furthermore, explicit target shapes to represent UXO had to be chosen and implemented into the high frequency scattering algorithms in PCSWAT. These algorithms, in turn, needed to be updated to work with buried targets. Complementing the high frequency algorithms, new scattering algorithms to account for these shapes at low to moderate frequencies were needed for implementation in PCSWAT. Free-field measurements to check the scattering predictions of these algorithms were needed and planned. Finally, sonar field data with buried UXO targets to be used in comparisons with PCSWAT updates were needed and planned through leveraging of on-going tests of sonar funded through ONR.

Background

Systems currently under development at Naval Surface Warfare Center Panama City (NSWCPC) include a wide variety of acoustic, magnetic, electromagnetic, and optical sensors on both towed and autonomous platforms. Prototypes of most of these systems have undergone numerous tests in the waters of St. Andrews Bay, FL, which provides an ideal environment for these tests due to its easy access and the diversity of bottom types available.

The development of these sensors greatly benefited from performance modeling. Although the complexity of shallow-water environments limits the fidelity of available models, they are at least semi-quantitative and allow one to develop a great deal of insight into expected trends in detection and classification capability with variations in sensor design parameters. Exercising such models has been found to be invaluable to optimizing design requirements. The modeling capability available for sonar can be summarized as follows.

The Personal Computer Shallow-Water Acoustic Toolset (PCSWAT), developed by Dr. G. Sammelmann (NSWCPC Code HS11) [1], is a collection of acoustic propagation and scattering codes combined to provide a complete end-to-end simulation of a sonar signal in complex shallow water environments, especially those typical of littoral operational and test areas. In an “end-to-end” simulation, the user can specify sonar, environment, and target parameters for a simulated field measurement and PCSWAT can compute and output a simulated image of the target embedded in the specified environment. A Gaussian ray bundle algorithm [2] makes possible propagation of user configured source beam profiles into nonuniform, layered ocean environments. Effects that modify the ray propagation due to sensor degrees-of-freedom or environmentally induced processes (e.g., 3-D multipath reflections, small-scale random bottom roughness, bubble clouds created in surf zones, Doppler shifts of signals caused by sensor motion, etc.) are accounted for by several physics-based corrections. Scattering by generally shaped 3-D targets embedded in the environment is simulated using the Kirchhoff approximation on a faceted representation of the target and using Geometric Theory of Diffraction (GTD) corrections for edges [3]. The final image is a result of processing the simulated field at the detector using canonical image processing algorithms.

In its current configuration, PCSWAT has been found to produce simulated images of excellent quality at sonar frequencies of tens of kHz and higher. Four examples of simulated acoustic images are shown in Fig. 1 below for a 0.5m-long, 0.15m-diameter cylinder lying on a sandy bottom and illuminated by a 400kHz sonar. The sonar is configured to allow scanning in the horizontal plane from forward of the sonar to 120^{o} to the side with 2^{o} beams. The four images correspond to 4 looks at the cylinder obtained by beamforming the simulated data in 4 directions as the sonar moves past the cylinder.

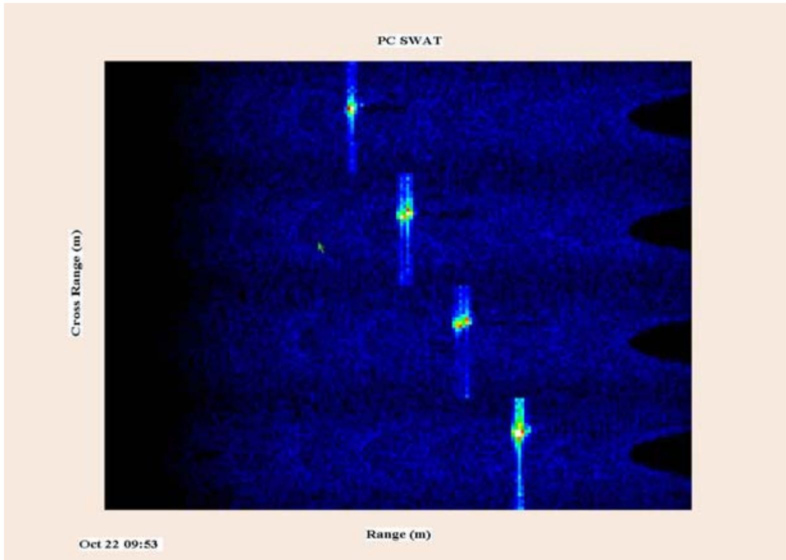


Figure 1. Simulated acoustic images for a 0.5m-long, 0.15m-diameter cylinder lying on a sandy bottom and illuminated by a 400kHz sonar.

Lambert scattering was added to the target to model the effect of biological growth, which tends to appear when a target has been under water for long periods.

Until recently, PCSWAT was maintained and developed in 2 versions: a high-fidelity version called Imaging SWAT that computes a fully coherent representation of the field propagated from the source to the environment and target and back to the receiver and a lower-fidelity version called PCSWAT that computes target signal-to-noise levels for the detected field. Both versions were merged into one program in PCSWAT 7.0. It is menu driven with a user-friendly interface that can run on Windows-based personal computers. Upgrades to this version of PCSWAT have been periodically implemented as algorithms to improve the fidelity of the models were formulated and data for testing the new algorithms became available. Technical improvements (vice convenience features) are generally formulated and tested in collaboration with university and industry research partners and then the software is developed in modular form at NSWCPC to facilitate implementation. The current release of PCSWAT is v. 9.0, which recently completed beta testing.

Materials and Methods

Existing models had to be extended to satisfactorily include the range of environments where UXO are found. Extensions were pursued where the overlap with UXO applications exhibited capability gaps. For the acoustic modeling component of this effort, gaps needing attention were illuminated by supporting UXO test efforts using sonar to collect data for comparison with simulations. The simulations used were based on our existing models and information available on targets of interest, environmental parameters, and sonar parameters. Performance curves in terms of expected signal-to-noise, as a function of various operational parameters for specific available sonar, were predicted for a set of UXO targets in a few typical environments. Sonar considered include NSWCPC's low-frequency and broad-band synthetic aperture sonar (LFSAS, BBSAS), NSWCPC's acoustic lens sonar, and Florida Atlantic University's Bottom Object Search Sonar (BOSS). This modeling effort collaborated closely with participants of planned tests.

UXO shapes spanning the range of available sizes were considered and typical ones built into the PCSWAT target database to be used in imaging simulations. Because UXO are so varied, free-field tank measurements of available UXO shapes were needed to ensure the Kirchhoff/GTD routines embedded in PCSWAT remained accurate for these targets. Five UXO shapes were obtained for this purpose: a general purpose, 2.2 m long, 500-lb bomb; a modified version of the previous bomb; 203 mm Howitzer shell; 100 mm shell; and a mortar. The measurements were carried out in NSWCPC's Acoustic Test Facilities, which includes a lined, 30ft-deep, freshwater pool supported by pier pilings. This facility contains a powered winch to simplify deployment of large targets and a rotator to enable data collection from targets at any aspect angle relative to the source. Backscatter data were collected at several frequencies between 20 and 80kHz and the observed intensities compared with predictions of PCSWAT as a function of aspect angle.

UXO acoustic simulations must anticipate a high incidence of completely buried targets. To augment the UXO capabilities of PCSWAT, scattering and imaging algorithms were developed to account for complete burial. For high frequencies (>50 kHz), this was done by extending the existing propagation and scattering algorithms used to account for surface targets based on ray theory and Kirchhoff scattering. These extensions enable an imaging capability that is useful for the UXO problem when buried UXO are illuminated from high sonar grazing angles.

Low frequency to mid-frequency (1-50 kHz) sonar systems could also benefit the UXO problem. These systems would have less range/detection limitations and could rely on elastic reradiation from a target for classification and perhaps identification. However, the high-frequency extensions to PCSWAT discussed above are insufficient to represent acoustic responses of buried targets in this frequency range. Previous tests had shown an anomalous enhancement in bottom transmission and detection for sonar operated in sandy areas in this frequency range at below the critical grazing angle [4,5], which necessitated development of new models to resolve the enhancements and measurements to test them. Toward this end, we formulated and encoded analytic transition matrix methods [6] to simulate the low-to-mid frequency response of UXO targets buried in layered environments. Complex environmental features such as surface roughness were treated using perturbation theory. The types of target shapes that can be represented via transition matrix methods are typically simple, smooth, axisymmetric targets (e.g., spheres, spheroids, superspheroids). However, because transition matrix scattering solutions are full wave solutions to the Helmholtz equation, these could be used to investigate burial effects with minimal approximations. By comparing their predictions with controlled measurements, the validity of physical mechanisms leading to suspected scattering phenomena could be tested unambiguously before building them into PCSWAT using faster, approximate methods. These algorithms also formed benchmarks for verifying PCSWAT algorithms for simple targets. This enabled a careful study of burial effects at shallow grazing angles, which was previously missing in existing versions of PCSWAT.

During the first year of funding, environmental samples were collected from candidate UXO test areas around NSWCPC and analyzed through collaboration with Dr. Ron Roy at Boston University (BU). Impedance tube measurements were performed on bottom samples collected and used to deduce relevant bottom acoustic parameters such as sound speed, attenuation, density, gas content, etc. This approach for measuring bottom properties accesses a lower frequency band than is practical with buried hydrophone arrays used to carry out time-of-flight measurements. When used in conjunction with time-of-flight measurements, it was possible to extend dispersion curves for bottom sound speeds and attenuation below 20kHz so that these inputs would be available for PCSWAT simulations. On-going research at BU continues to explore advantages for using an impedance tube to measure acoustic parameters in gassy fluid sediments.

From an environmental point of view, PCSWAT is meant to accommodate a wide range of environments, including waters of 15ft or less depth with muddy bottoms, which is understood to be typical of UXO test sites. These types of environments were expected to be difficult to model accurately due to their high variability. Temperature and salinity gradients can be pronounced, and the bottom can be more dynamic than in deeper water. The shallow water depth will make acoustic reverberation more prominent, both due to the proximity of the top and bottom surfaces and the greater likelihood for suspended scatterers such as bubbles. Shallow, muddy areas are also likely to have a significant amount of entrained gas in the mud due to organic activity. It is currently unknown how well assumptions made in the models included in PCSWAT will account for all these processes. To help clarify environmental issues such as these so that future simulations can be improved as well as test new algorithms built into PCSWAT, we collected data by leveraging measurement efforts funded by ONR to the degree possible. This generally involved seeding the test areas with UXO or UXO surrogates to obtain data. Although measurement of environmental parameters in UXO test areas simultaneous with UXO sensor tests is often lacking in these measurement efforts, knowledge of the bottom type (sand, mud, etc.) and water temperature can help bound the required parameters enough to make comparisons that reveal significant discrepancies.

As mentioned above, data for validating the models to be built into PCSWAT were obtained by leveraging on-going field and laboratory tests. Some of the tests leveraged were as follows. During FY03-06, ONR funded a controlled study of bottom roughness effects on detection of buried targets in a large fresh-water pond on-board NSWCPC. This facility allowed targets to be set up in a clean, well-characterized, sand bottom that remained undisturbed by currents or sea life. Data could be collected with sonar operated from precise positions along a rail system and the surface of the sand above buried targets could be profiled with contoured, mechanical scrappers. SERDP funds leveraged this data collection and the associated analysis for simple buried targets (e.g., spheres and cylinders) insonified at low grazing angles to assess the scattering models under consideration for explaining target detection enhancements previously observed in field tests. The set-up for the measurements was also augmented to allow data collection from proud and buried inert UXO at high grazing angles.

In on-going field tests, NSWCPC deployed a new 8-55 kHz synthetic aperture sonar (SAS) on an unmanned underwater vehicle (Bluefin Robotics) in the waters off Panama City. Sonar data of UXO-like targets in 25-ft water depths was collected. This data was useful for comparison with buried target models incorporated into PCSWAT for UXO sonar simulation. We processed this data for that purpose. The US Army Corp. of Engineers (POC: Roger Young) provided some funds to deploy extra UXO-sized targets in two sites off Panama City in about 10-ft water depth. In FY04, data from these sites were collected using a platform combining Florida Atlantic University's Bottom Object Search Sonar (BOSS) and the Real-time Tracking Gradiometer (RTG) developed by Quantum Magnetics.

During FY05, two other ONR funded field tests were leveraged. ONR funded the Sediment Acoustics Experiment – 2004 (SAX04) field measurement off Fort Walton Beach, FL to better understand the acoustic detection at low grazing angles of objects buried in sandy marine sediments. One component of the SAX04 work was designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. Buried cylindrical UXO-sized targets were added to this measurement to obtain model and PCSWAT validation data for the SERDP related work. In a second sonar test off Panama City, a 12.75 in-diameter AUV (WHOI REMUS 600) carrying a 120 kHz high-frequency and a 8-55 kHz broadband sonar was run against a series of targets including cylindrical UXO-sized targets in three states of burial: unburied on the surface, half-buried, and completely buried flush with the surface. This test was meant to assess the viability of the WHOI AUV platform for stable SAS operation in a fairly dynamic environment, where currents could throw the vehicle off course and make motion compensation processing a challenge.

Much of the UXO modeling described above also leveraged modeling efforts funded through ONR. The UXO modeling effort worked jointly with those efforts to produce the simulation capability for buried objects.

Results and Accomplishments

In this section we will summarize the major accomplishments of our SERDP project over the past 3 years in several tasks, which were performed to provide the techniques, models, and data needed to develop, test, and validate UXO-based enhancements to PCSWAT. These tasks included: a study of a promising environmental characterization technique, theoretical model developments for buried targets, controlled sonar tests of model predictions, free-field tests of UXO targets, UXO enhancements in PCSWAT and controlled tests of image simulations, and field test data collection and analysis.

1) ***Environmental characterization technique***. Boston University (BU) was funded to do a study assessing the feasibility of using a new water-filled impedance tube [7] for determining the acoustic properties of marine sediments encountered in validation tests of new models of target/bottom physics as well as PCSWAT extensions. The instrument, originally designed for use with bubbly liquids, was modified for this purpose and was used at the NSWCPC to measure the acoustic impedance of a sandy sediment collected from the Facility 383 Test Pond. Measurements were made from 500 Hz to 32 kHz, but the impedance measurements were found to be useful only from 4-10 kHz. Sediment sound speed and attenuation were inferred from the measured impedance in the 4-10 kHz frequency range. Corrections were

applied for various effects that arise due to interaction between the sediment sample and the impedance tube walls. Measured sediment sound speeds and low frequency attenuation are in good agreement with values reported in the literature and with an effective density fluid model [8] when used with typical sand parameters.

The frequency range from 0.5-4 kHz was compromised by difficulty in modeling the Styrofoam sample holder termination. Improvements in the sample holder termination technique and its modeling would render the lower part of the frequency range usable. The higher-frequency 10-32 kHz attenuation measurements are in poor agreement with other measurements and the Williams model. Data from this frequency range was not usable because of a departure from plane-wave behavior. A tube with a smaller inner diameter could be used at these higher frequencies. In order to use the existing tube above 10 kHz, elastic waveguide and higher order mode effects would have to be accounted for.

The overall conclusion is that the water-filled impedance tube is currently useful for measuring the sound speed in water-saturated sandy sediments in vitro. A better understanding, quantification, and control of acoustic energy loss mechanisms within the impedance tube is needed to relate the impedance measurements to the intrinsic sediment attenuation. Further details on the impedance tube study may be found in BU's final report [9].

2) ***Theoretical model developments for buried targets***. A method was derived to speed up transition (T)-matrix scattering calculations for bottom targets based on an application of the complex image method [10-12] to the integrals that arise in target/seabed scattering problems. In the T-matrix method [6], the incident and scattered wave fields are expanded in terms of a basis set with regular and outgoing functions. Eigenfunctions of the Helmholtz equation in spherical coordinates are often used. When an object is located on or above an interface, a portion of the scattered field from the target will reflect off the interface before propagating to a receiver. Also, the wave field reflected from the interface will impinge upon the object and rescatter. The wave field that results from the reflection of a spherical eigenfunction off an interface can be expressed in terms of a wave number integral. The spherical eigenfunction expansion coefficients for this reflected wave field, in terms of the incoming regular spherical eigenfunctions, can also be expressed in terms of wave number integrals [13, 14]. These wave number integrals are generally a time consuming part of a T-matrix calculation but are needed for the complete scattering solution when a target lying on top of a seabed is considered. We demonstrated a very efficient and accurate method of computing these integrals results by using the method of complex images.

   For a buried target, the computation of the integrals expressing the propagation of a spherical eigenfunction in a fluid below a half-space and the integrals representing the conversion coefficients of outgoing spherical eigenfunctions into incident spherical eigenfunctions after a seabed reflection proceeds as for the target above the seabed. A very efficient and accurate method of computing these integrals, using the method of complex images, is derived. However, the computation of the scattered field transmitted back into the water is more problematic. For these computations, we derived a generalized image method that allowed us to replace the wave number integral computations with small sets of image terms for each azimuthal order. Numerical comparisons with the exact integral expressions show the accuracy of this approach.

The significance of this work is that it yields a significant reduction in computation time for low to mid frequency scattering calculations based on T-matrix scattering models of plane-stratified environments (such as shallow water areas). Such calculations were used as benchmarks to test the buried target physics models included in the latest versions of PCSWAT. Complete details on the derivation of the scattering solutions described above were published in the Journal of the Acoustical Society of America [15].

In addition to scattering solutions for targets buried in plane-stratified environments, an ongoing modeling and measurement effort investigating shallow grazing angle acoustic detection of targets buried in sand was carried out in FY02-03 with model comparisons against new data for a sphere buried under sinusoidal ripple with different ripple wavelength, ripple heights and sphere burial depths. The model used perturbation theory evaluated out to second order in the ripple height to represent the field propagated to and scattered from the sphere. The scattering response of the sphere was represented with a T-matrix. By making the sediment surface roughness sinusoidal, the complete scattering solution was formulated in analogy to previous models investigated [16] except ensemble averaging is not needed and, as a consequence, higher order effects can be included. This allows effects to be studied over a greater acoustic frequency range.

Validation of acoustic scattering models for targets buried under rough surfaces in FY03 depended on comparisons between controlled measurements and model predictions for shallow grazing angle acoustic backscatter by spherical targets buried under a sinusoidally rippled surface [17, 18]. Except for some of the higher roughness height cases, these original comparisons showed good agreement, which lent confidence to the hypothesis that diffraction by ripple can significantly improve sonar target detection performance. The exceptions to model agreement showed even greater detection signal-to-noise due to surface diffraction than predicted. Because the modeling was based on low-order small-height perturbation theory to handle sound transmission through the bottom roughness, these exceptions had been attributed to failure of the perturbation theory. From a modeling perspective, efforts in FY04 concentrated on developing an iterative algorithm to generate target scattering predictions correct to arbitrary order in roughness height for an idealized sinusoidal ripple.

Recursion formulas were derived and computer code written to compute arbitrary-order corrections to the sound reflection and transmission coefficients for a surface with sinusoidal ripple. However, the resulting perturbation series was found to yield divergent results when the acoustic wavelength becomes small enough relative to the rms surface wave height; i.e., the frequency-scaled surface height becomes large. Since the frequency-scaled surface heights used in the controlled measurements and in current sonar testing are sufficiently high to fall within the divergent range of the perturbation theory, methods to resolve these problems were sought. Two methods to resolve the divergences were tried. First, a small-slope approximation of scattering from ripples was formulated to second order based on the existing small-height perturbation theory. A computer code based on the 2^{nd}-order small-slope approximation was completed. The advantage of the small-slope approximation is that it reduces to perturbation theory for small amplitude ripple but it is valid for large amplitude ripple as long as surface slopes remain small. The disadvantage is that corrections beyond second order are difficult to obtain if surface slopes become large, but this is not common for bottom sediments.

In the second approach to resolve divergence issues, Padé approximants were applied to the small-height perturbation series to try and stably resum the series. This approach was found to give stable, well-converged reflection and transmission predictions for most problems of interest. Often, enough terms of the perturbation series could be resummed with Padé approximant representations to achieve benchmark quality precision in the reflected or transmitted field values.

Due to its greater accuracy, the reformulated transmission coefficient based on Padé approximants was incorporated into existing transition-matrix-based scattering algorithms used to predict backscatter levels for spheres buried under sinusoidal ripple. Revised backscatter predictions were calculated for comparison with the existing sphere data. Results now show good agreement provided the input for bottom attenuation estimated from measurements is revised toward the lower end of observed values.

More details on the model extensions discussed here and the comparisons with data are documented in a paper presented at the Oceans 2004 conference in Kobe, Japan and published in the proceedings [19]. Our future efforts in this direction will involve validation of a scattering model for more complex buried targets using the data collected in the controlled backscatter measurements with a 5 ft long, 1 ft-diameter Al cylinder. Calculations for such an elongated target typically become unstable with transition (T) matrix formulations based on spherical expansion functions as frequency increases. A special transition matrix formulation is required to stabilize the calculations. Therefore, a computer code for free-field scattering by elongated axisymmetric elastic targets has been written and tested in C. The algorithm is based on the T-matrix formulation of Hackman [20], which uses spheroidal basis functions to expand all fields interior and exterior to the target, allowing superior convergence for long elastic targets out to moderate frequencies. This will be incorporated into the benchmark buried target codes used to investigate rippled surface effects in on-going work.

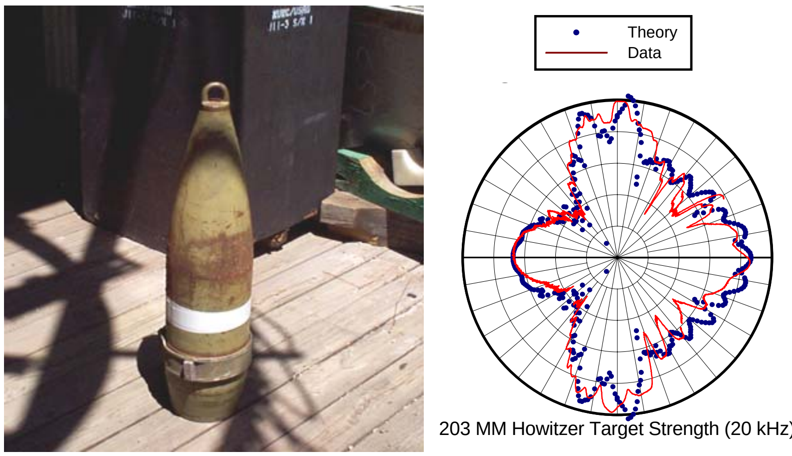
3) ***Controlled sonar tests of model predictions***. Laboratory measurements with buried targets were performed in NSWCPC's Facility 383, a 13.7-m deep, 110-m long, 80-m wide test-pool with a 1.5-m layer of sand on the bottom. Initially, a silicone-oil-filled target sphere was buried under a rippled surface with contours formed by scraping the sand with a machined rake. Broad band (10 to 50 kHz) transducers were placed onto the shaft of a tilting motor, which in turn was attached to an elevated rail that enabled this assembly to be translated horizontally, permitting acquired data to be processed using synthetic aperture sonar (SAS) techniques. Acoustic backscatter data were acquired at subcritical grazing angles for various ripple wavelengths and heights. In addition, the backscattered signals from a calibrated free-field sphere and the transmitted signals received with a free-field hydrophone were recorded. For each bottom configuration, the seabed roughness over the buried target was measured

using APL-UW's IMP2 system to determine the ripple parameters and to estimate the small-scale roughness spectrum. This roughness information was used in scattering models to calculate the backscattered signal levels from the target and bottom. In previous work [17], measured signal-to-reverberation ratios were found to compare well with model predictions, demonstrating the accuracy of first-order perturbation theory (for the ripple heights used in those experiments) for frequencies up to 30 kHz. By taking advantage of the backscattered data collected using the free-field sphere and of the acquired transmitted data, more stringent comparisons of predicted buried target backscatter levels to measured levels were made here.

Details of the measurements done and the model comparison/analysis with regard to using larger ripple heights to investigate the impact of second-order scattering effects on buried target detection were presented at the Oceans 2003 Conference and published in the proceedings [18]. [Many of these results were also summarized in posters presented at the annual SERDP Workshops and Symposia.] Most of the data-model comparisons exhibited good agreement in the trends across the experimental bandwidth, even when compared against models based on first-order perturbation theory only. These results confirm that ripple diffraction is a valid mechanism for enhancing the detection of buried targets at shallow sonar grazing angles. However, exceptions to this agreement with low-order perturbation theory appeared when the ripple amplitude is high. To ascertain whether this was due to inadequacy of second-order perturbation theory, comparisons were made with the high-order corrections summed with Padé approximants when these became available. As noted in the modeling accomplishments, the discrepancies appear to be more a consequence of variation in the bottom attenuation than in failure of the low-order perturbation theory.

Backscatter measurements on spheres buried in well-characterized underwater sediments provided the best data for testing physics-based sonar models. However, more complex targets were also considered to study whether these models could resolve unexplained buried target detections observed in field measurements such as the ONR-sponsored SAX99 [21, 22]. In FY04, further data collection was carried out for validation of models toward this end. The data collected this year investigated the contribution of ripple roughness to reverberant noise and also emphasized the use of a more realistically shaped target. A 5ft-long, 1ft-diameter, flat-ended Al cylinder was constructed for this purpose and measurements were performed in NSWCPC's Facility 383 freshwater pool, with the sand bottom configured with ripples using sand scrapers. By combining a parametric sonar and a broad-band transducer, backscatter data from surface ripple and from the buried Al cylinder were collected for 10 and 20 degree grazing angles over the 10-50kHz band at several ripple orientations relative to the source-target line. The data collected were processed to create images of the cylinder completely buried under surface ripple. The images obtained exhibited the good detection performance originally observed in field data, strengthening the idea that those results were a result of surface ripple diffraction. In these results, the buried cylinder could be unambiguously detected and imaged over the 10-40kHz band. Between 3-10kHz, images became less clear though the cylinder could still be detected. Below 2kHz, detection is arguable, with lower resolution and noise resulting from the scraped surface being a significant factor. In this case, the noise observed was also consistent with predictions of surface reverberation models. More details on these results are documented in 3 conference papers written in FY04 and published in the associated proceedings [23-25].

4) ***Free-field tests of UXO targets***. The initial updates to PCSWAT were based on incorporation of several representative UXO shapes. Five UXO spanning a typical range of sizes (a general purpose, 2.2 m long, 500-lb bomb; a modified version of the previous bomb; 203 mm Howitzer shell; 100 mm shell; and a mortar) were chosen and acquired for UXO laboratory and field tests. High frequency models of these targets were built into PCSWAT using the Kirchhoff approximation and generalized theory of diffraction corrections for edges. Free-field validation tests were performed on these targets at several frequencies and compared with PCSWAT predictions of the backscattered target strength to assess the fidelity of the models. The larger targets agree fairly well. An example of the level of agreement is shown



203 mm Howitzer shell

Figure 2. A comparison of measured vs. PCSWAT predicted free-field backscatter target strength for a 203 mm Howitzer shell rotated through 360°.

for the 203 mm Howitzer shell rotated through 360° in Fig. 2.

Of the smaller targets (100 mm shell and 81 mm mortar), agreement was limited by the low target strength of the targets because support lines used to suspend each target became a significant noise source. This was especially true for the mortar, which exhibited the lowest target strength and, therefore, the greatest discrepancies from predicted results. To try and resolve these discrepancies, further measurements were carried out for these UXO using a different scattering geometry, with ping-averaging to optimize signal-to-noise levels, and in a new barge facility at NSWCPC that allowed better isolation of the target during data collection. Moderate improvement in signal-to-noise was obtained with these measures at angles where the UXO exhibited strong reflections but, at other angles, reverberation from support apparatus could not be avoided. An example of the agreement obtained is shown for the 100 mm shell in Fig. 3.

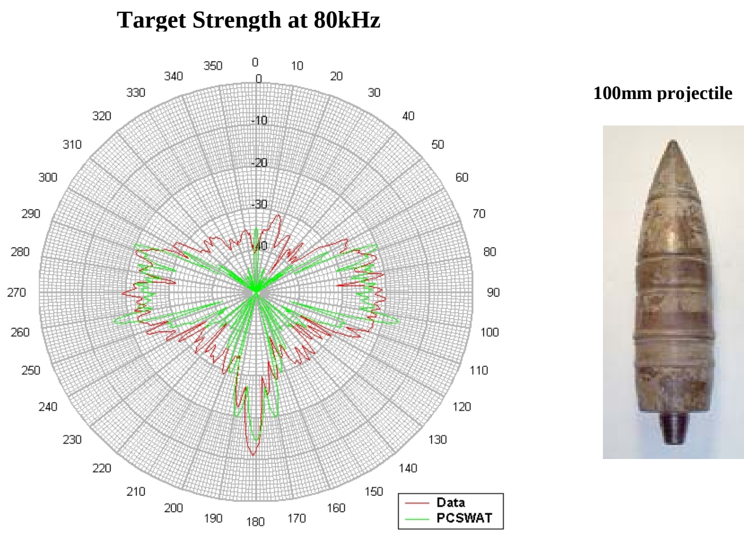


Figure 3. A comparison of measured vs. PCSWAT predicted free-field backscatter target strength for a 100 mm explosive shell rotated through 360^o.

At angles where the predicted target strength (green line) is below –30 dB, excess backscatter must still be attributed to suspension lines. Nevertheless, good agreement above –30 dB indicates the UXO models in PCSWAT should produce acceptable simulations of high-frequency sonar imagery.

5) ***UXO enhancements in PCSWAT and controlled tests of image simulations***. Further toward preparing PCSWAT for imaging simulations, the gaussian ray bundle algorithm used to account for propagation to and from targets in PCSWAT was extended to allow for high-frequency imaging of buried and partially buried targets. The five high-frequency UXO models built into PCSWAT were coupled to this ray algorithm to enable high-frequency sonar image simulations of these shapes in any stage of burial. In addition, some of the conclusions drawn from the ripple scattering measurements described above were incorporated into the new buried target imaging algorithms to allow enhancement of shallow-angle transmission coefficients at the interface when sinusoidal ripples are present. The iterative small-amplitude perturbation theory has been built into PCSWAT v.9.0, but limited to, at most, 6th order corrections to the reflection and transmission coefficients to be calculated in predictions of the bottom penetration. This limitation was adopted both as a safeguard against unstable convergence for large ripple amplitudes and to allow faster computations. For ripple amplitudes higher than can be accounted for with the 6^{th}-order theory, a second-order small-slope approximation calculation is substituted. The version of perturbation theory that uses a Padé approximant to accelerate convergence of the series is also being considered to improve performance of backscatter predictions but is not yet included because the additional precision may not be warranted given the reduction in computational speed.

To begin validating this new imaging capability for bottom UXO, the measurement set-up prepared for the work in the previously described ripple scattering study was used to also

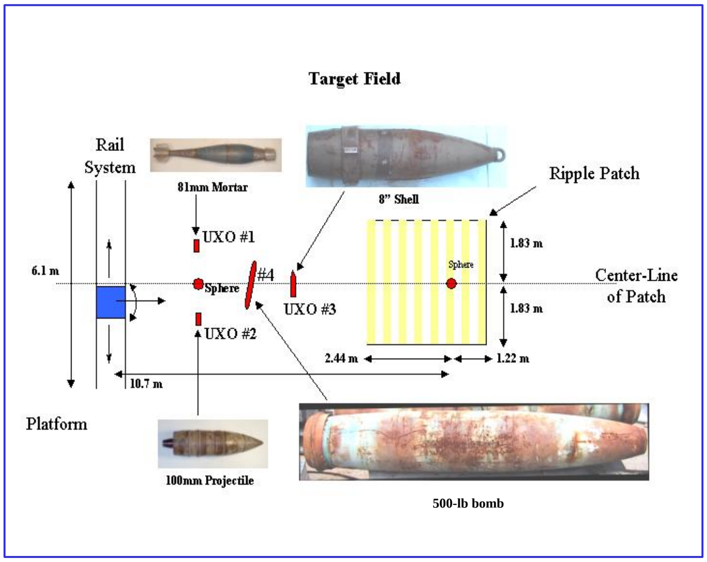
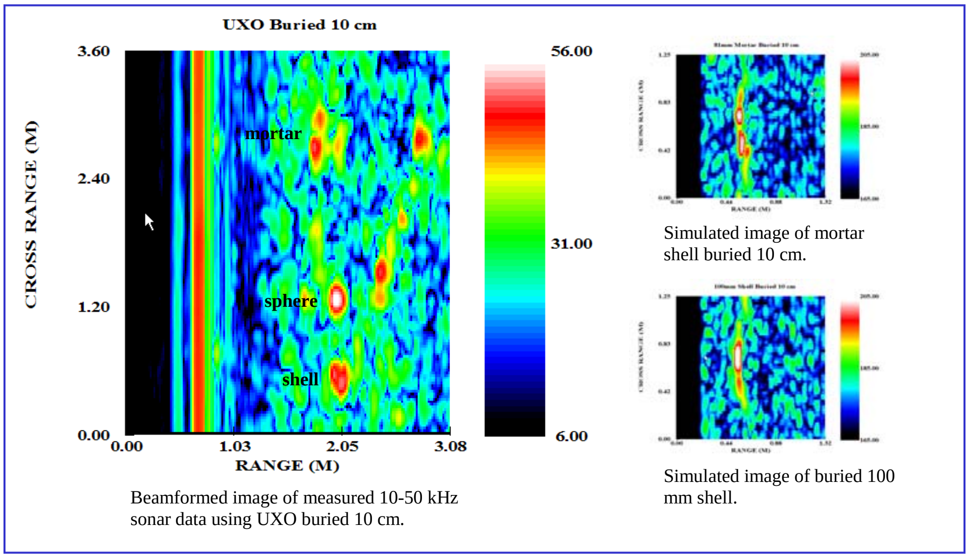


Figure 4. Schematic of setup for high-grazing angle sonar measurements of UXO in the Facility 383 freshwater pond.

collect scattering data from both proud and buried UXO. The UXO shapes available were deployed in an area in front of the scraped ripple field as depicted in Fig. 4.

This permitted collecting scattering data at high grazing angles using the same source/receive configuration employed in the ripple diffraction study. Images have been processed from the Facility 383 data for unburied (i.e., proud) UXO targets, both oriented broadside and at 45^{o} to the sonar, and compared to simulations using a high-frequency Kirchhoff/GTD approximation. Preliminary comparisons reproduce the observed signal-to-noise and target features. Target data were also obtained with the targets' long axis broadside to the source but now completely to partially buried on the sand bottom of the pond. Comparisons of PCSWAT image predictions with these processed data are good, with image resolution in agreement with predictions. Example comparisons are shown in Fig. 5 for the mortar and the 100 mm projectile buried by 10 cm. Image intensity comparisons (i.e., signal-to-noise) were slightly off on average due to the unknown statistics of the bottom roughness. In the tests, the bottom in the area of the targets was generally smoothed but the occurrence and placement of small bottom features could not be controlled. Methods will be pursued to measure the roughness statistics needed to account for bottom reverberation levels in the future. Further details on these comparisons as well as the high frequency modeling are provided in a paper presented at the Oceans 2003 conference [26]. These results were also summarized in a poster presented at the 2003 SERDP Workshop and Symposium.



Beamformed image of measured 10-50 kHz sonar data using UXO buried 10 cm.

Simulated image of mortar shell buried 10 cm.

Simulated image of buried 100 mm shell.

Figure 5. A comparison of measured and PCSWAT predicted high-grazing-angle imagery of the 81 mm mortar and the 100 mm shell.

For shallow grazing angles, PCSWAT image predictions for buried cylindrical targets seen in past field studies (such as the ONR sponsored SAX99) were also made and compared. In this case, significant differences in signal levels are still seen and remain to be understood. The discrepancy here seems too large to ascribe to inadequate knowledge of the roughness statistics and is thought to be either a consequence of inaccurate assessments of target depth or environmental parameters in the field, an inconsistency in the signal image processing, or some as yet unidentified target or environmental factor. Resolving this mandated the controlled measurements already discussed above on sound transmission into seafloor sediments at shallow angles using the 5 ft Al cylinder buried under bottom.ripple. Most recently, PCSWAT v.9.0, which recently completed beta testing, has been used to produce comparisons with the data collected from the NSWCPC Facility 383 pond on this Al cylinder. Examples of these comparisons are shown in Fig. 6, where the cylinder was buried by 10 cm below the median level of sinusoidal ripple of 75 cm wavelength, 2.7 cm height (rms), and the sonar grazing angle on the bottom was 20^{o}. These low-grazing-angle comparisons show discrepancies at certain frequencies (e.g., 10 kHz) that call for further investigation. The differences may be a result of inaccurate of sediment properties but comparisons are, nevertheless, promising because the measurements do confirm sonar enhancements due to roughness. This narrows the range of potential solutions towards understanding unresolved data from field measurements such as SAX99 but do not completely resolve the disagreement with the data. Thus, validation is on going. More details on the updated version of PCSWAT and how it performs in simulations of the buried cylinder sonar data is documented in a paper presented at the Undersea Defence Technology Conference in Honolulu, HI and published in the proceedings [27].

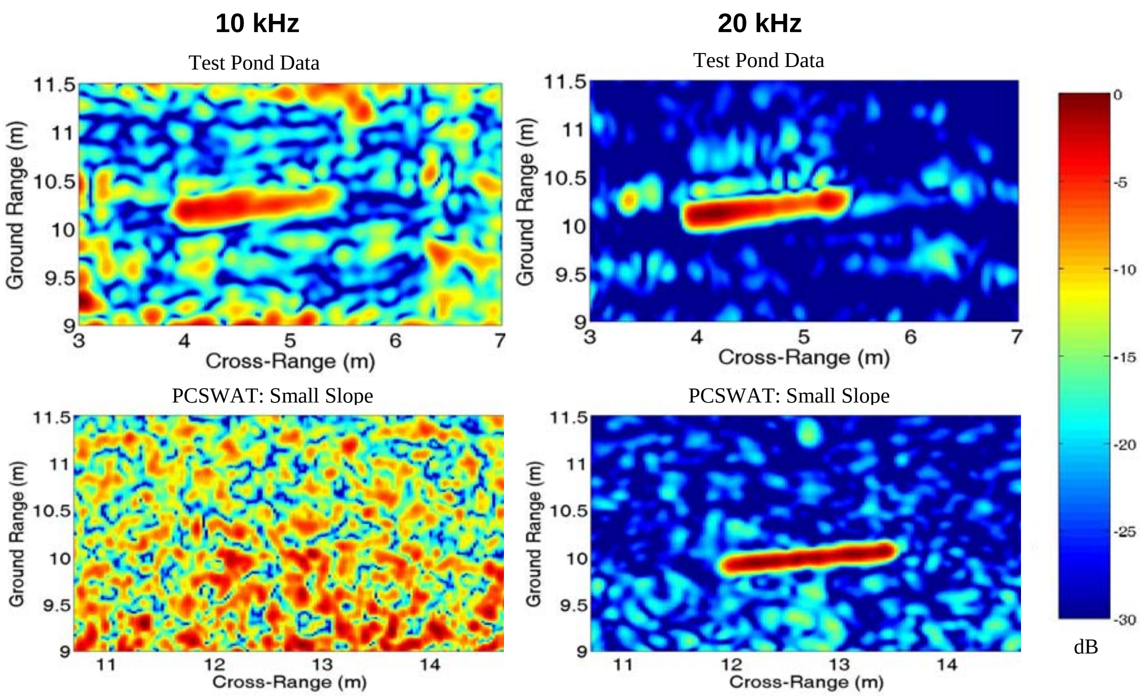


Figure 6. Cylinder data vs. PCSWAT comparisons.

As a final note on PCSWAT updates, a public-release version of PCSWAT 9.0 has been developed for SERDP and drafts of the necessary documentation written. Release of this version awaits approval by ONR, which funded the development of some possibly sensitive components of the software.

6) ***Field test data collection and analysis.*** Despite the greater difficulties controlling environmental parameters in field tests, these measurements provide opportunities for testing the algorithms in PCSWAT under realistic conditions, offer data from more diverse environments, and help to uncover sources of error unanticipated in more controlled settings. In FY03, preparations were made to participate in two sonar field tests funded by ONR in St Andrew's Bay off Panama City. These were planned to go off in the third quarter of FY03 but were delayed to beyond the first quarter of FY04 due to hardware issues. A Bluefin Robotics AUV system carrying an 8-50 kHz SAS and FAU's towed Bottom Object Scanning Sonar (BOSS) coupled with a Quantum Magnetics gradiometer were tested against UXO and other targets buried in a sand and a mud site. Preparations supported by the SERDP project included machining steel UXO mock-ups for the tests (to preclude loss of the real targets) and deployment of these mock-ups. The two test fields were placed in 25 ft water depth with 8 targets buried nominally 1 ft and 1 half-buried sphere. Two shallower 10 ft water depth test fields in the same areas were also prepared with additional support from the US Army Corp of Engineers. In the USACE fields, 10 UXO-sized targets are deployed at various burial depths from 3 ft to proud. The layout of the 25 ft and 10 ft depth test fields are depicted in Figs. 7 and 8.

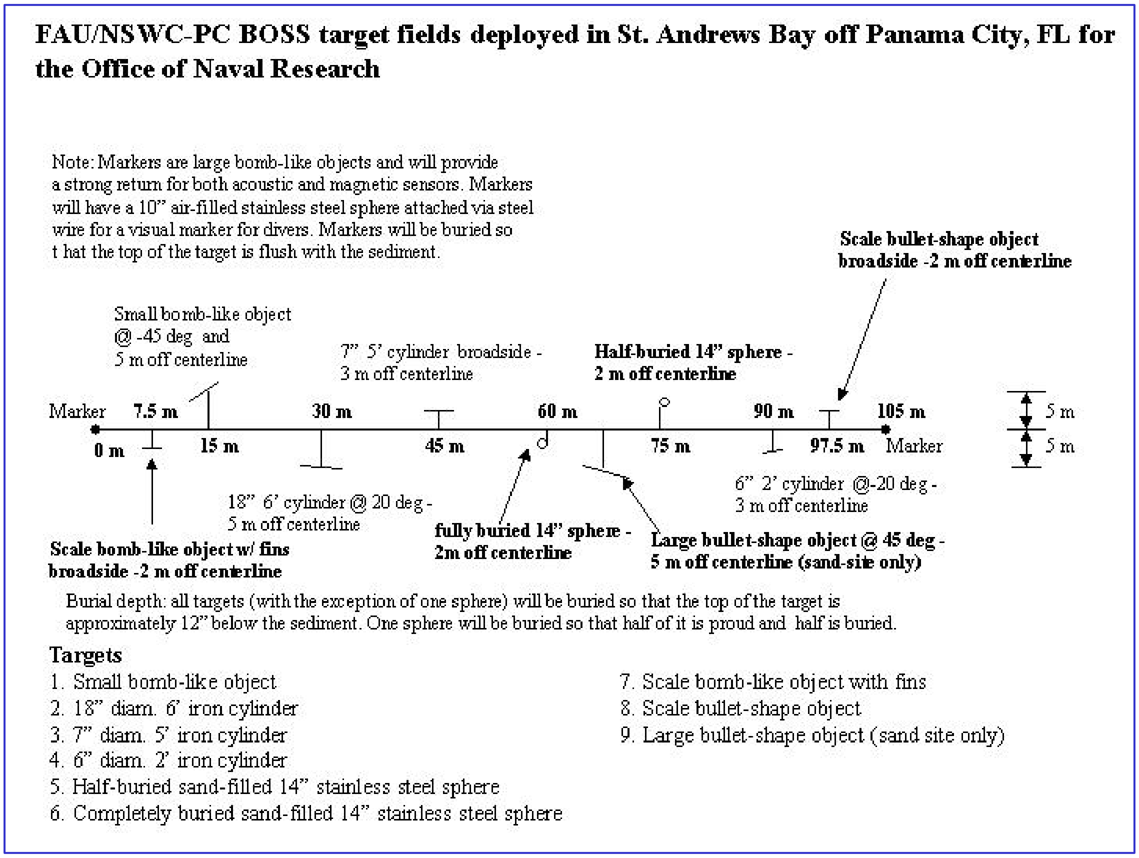


Figure 7. Layout of the 25 ft depth sand and mud NSWCPC BOSS sites.

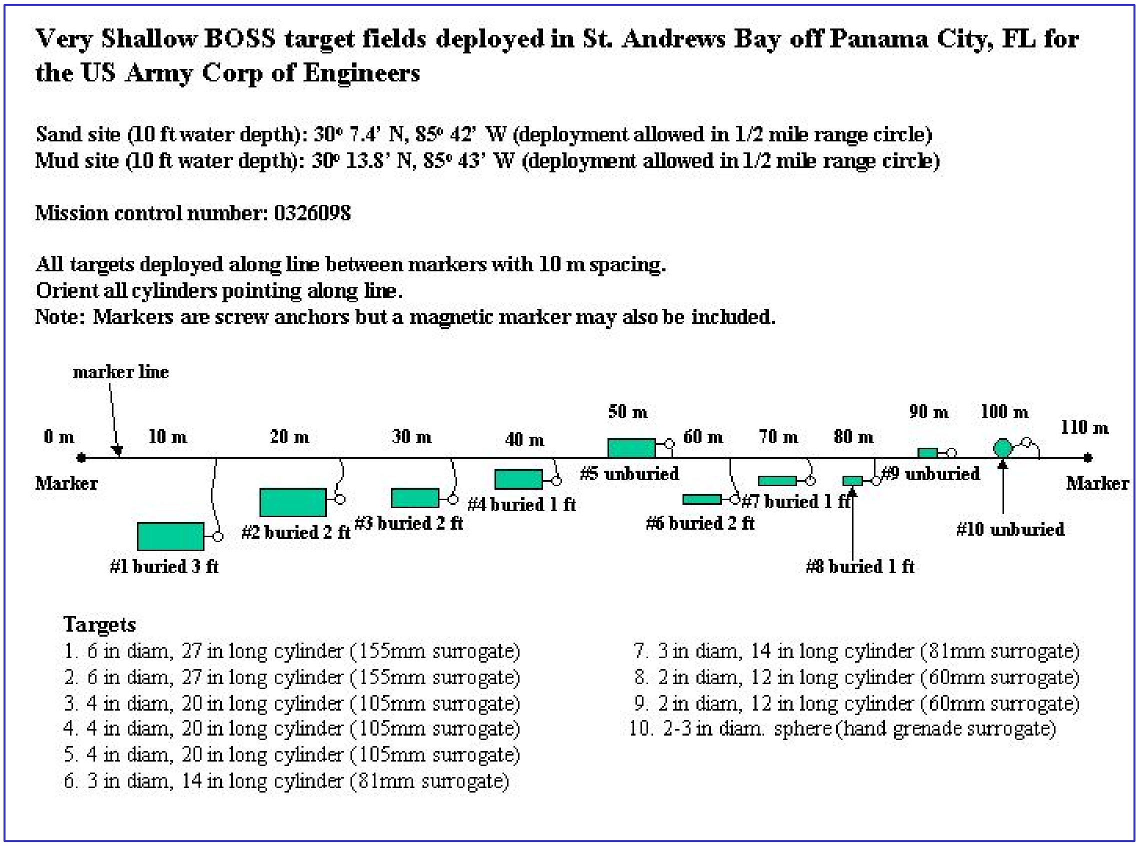


Figure 8. Layout of the 10 ft depth sand and mud NSWCPC BOSS test sites set up according to USACE specifications.

In preparation for analyzing the field data, a spotlight mode synthetic aperture sonar processing algorithm (steer beam at target as the array goes by) was developed. The utility of this algorithm can be understood as follows. Synthetic aperture processing generates large apertures, which yield high-resolution and high signal-to-noise images. Two modes are regularly used for synthetic aperture processing. Stripmap mode is a search mode with the beam steered to broadside. In this mode, a large number of adjacent pings are coherently combined into a long effective aperture. This is then used as input to the SAS beamformer, which constructs the image. This technique is most common since it produces good results in a search mode.

Spotlight mode can be used when a particular area or object is of interest. In this mode, the array is constantly steered towards the object of interest as the sonar goes by it. Again, a large number of adjacent pings are then used to construct a synthetic aperture, which is used as the input to a beamformer based on a polar coordinate system. There are a number of good references for its use in radar systems [28]–[30]. Sonar use of spotlight mode is rare. However, there are three significant advantages to using spotlight mode:

a. Higher signal-to-noise ratios are possible since the beam is always pointed at the target. It is expected that about 3 dB increase can be realized with this method.

b. Higher resolution is possible since the effective beamwidth and, therefore, aperture is larger. For our SAS system this can yield almost a factor of two increase in aperture size (i.e., ±30° to ±55°) with corresponding increases in along-track resolution. Also, man-made objects often exhibit strong aspect dependent target strengths, which are more likely to be seen with the larger beamwidths in spotlight mode.

c. It is possible to use the spotlight mode range-gated data to investigate aspect and frequency dependencies. These can often yield important clues for target identification. An example can be seen in the following low-frequency spotlight mode SAS figure (Fig. 9) of a shallow-buried (estimated 90% buried), bomb-shaped target. The target is illuminated with a 1 ms duration, 15-25 kHz linear frequency modulated pulse and backscattered pulses collected along the sonar platform's track are steered towards the target to obtain the raw composite pulses seen in the left plot. The strong aspect dependence around 0^o steering angle (corresponding to the point of closest approach to the target, at which point the target is viewed near broadside) comes from the central section of the target and the taper of the front end seen on one side of the point of closest approach (0^o) as the target is passed. Differences in the frequency transforms at these two target aspects are seen in the plot on the right, which suggest diffractive effects may be mixing in with the backscatter at one of these aspects.

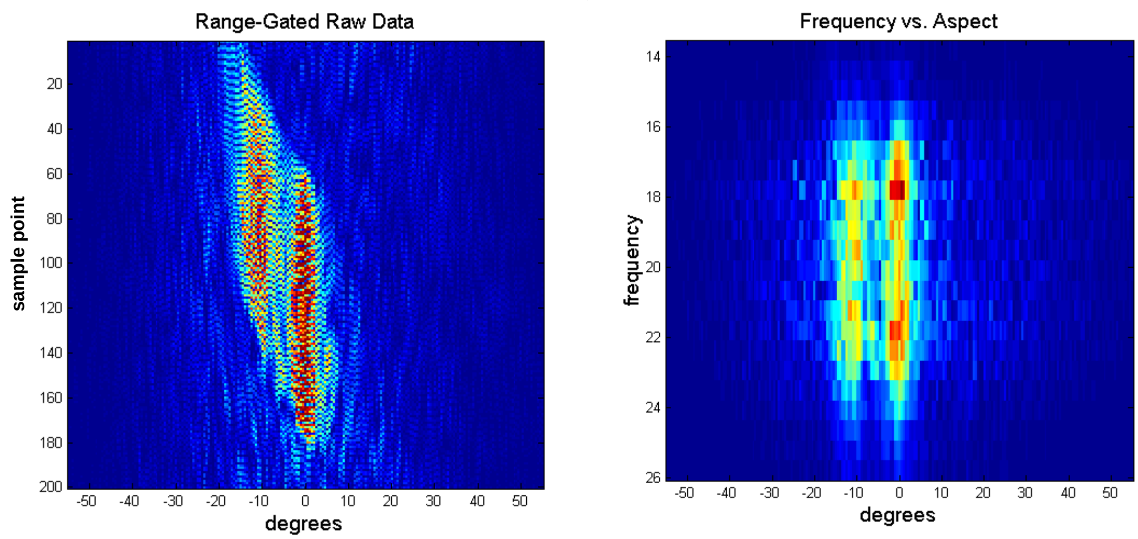


Figure 9. Spotlight mode raw data vs. aspect and frequency vs. aspect plots. Each sample point in the left plot corresponds to 8 μs.

This algorithm developed in FY03 has been used to look at buried targets from previous years and buried targets of interest from fields put out this year. Results have shown that deeper buried objects show only specular returns, while proud and shallow buried objects show diffractive effects.

In FY04, two field tests primarily funded through ONR were leveraged with SERDP funds to collect data for PCSWAT. In the first quarter of fiscal year 2004, an initial field test in St Andrews Bay off Panama City was carried out in collaboration with Florida Atlantic University using their towed Bottom Object Search Sonar (BOSS) coupled with the NSWC/Quantum Magnetics Room-Temperature Gradiometer (RTG). BOSS is a predominantly down-looking sonar that projects and receives FM pulses in the 3-20 kHz band. The projector is omnidirectional and hydrophone arrays configured on towed body wings measure the backscatter from targets on or buried in the seabed. These systems were taken over the buried target sites described previously in Figs. 7 and 8.

Following on the BOSS/RTG field test, preparations for another test in St Andrews Bay using a Bluefin Robotics AUV carrying an 8-50 kHz synthetic aperture sonar were leveraged by extending the AUV tests to include runs over the deeper BOSS sand and mud sites. (The shallower sites were not easily accessible to the Bluefin AUV.) Six runs were made at close ranges (above critical angle), and six runs were made at longer ranges (below critical angle). These were the first runs made with a new data acquisition system that features on-board preprocessing of the data using a field programmable gate array. Additionally, a Litton 250 inertial measurement unit, properly synchronized with the data to help with motion compensation, was employed. Results of the data processing showed good focusing in the test area. For the sand site, these results are illustrated in Fig. 10.

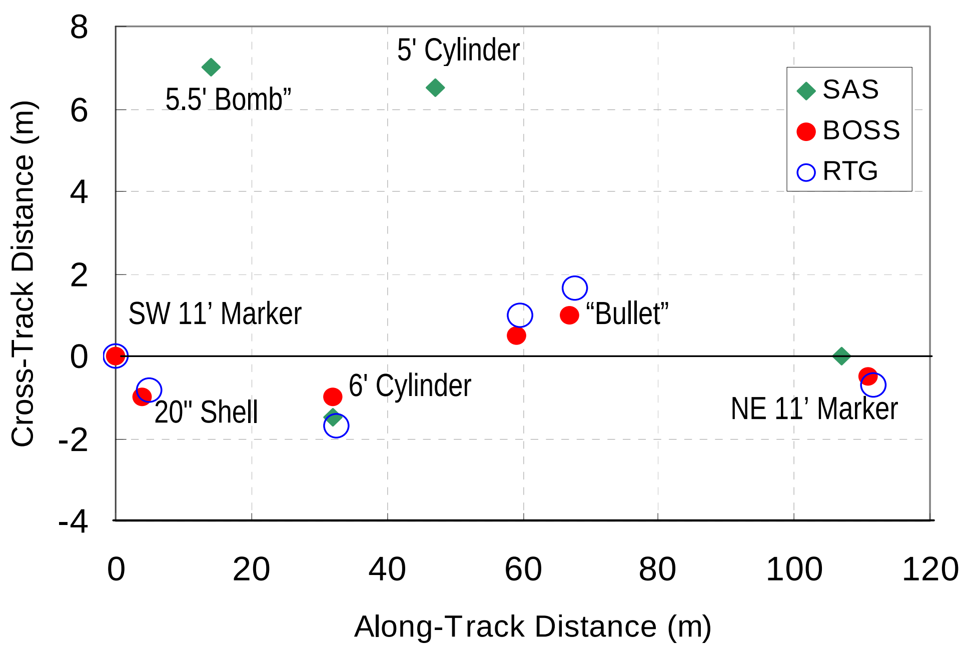


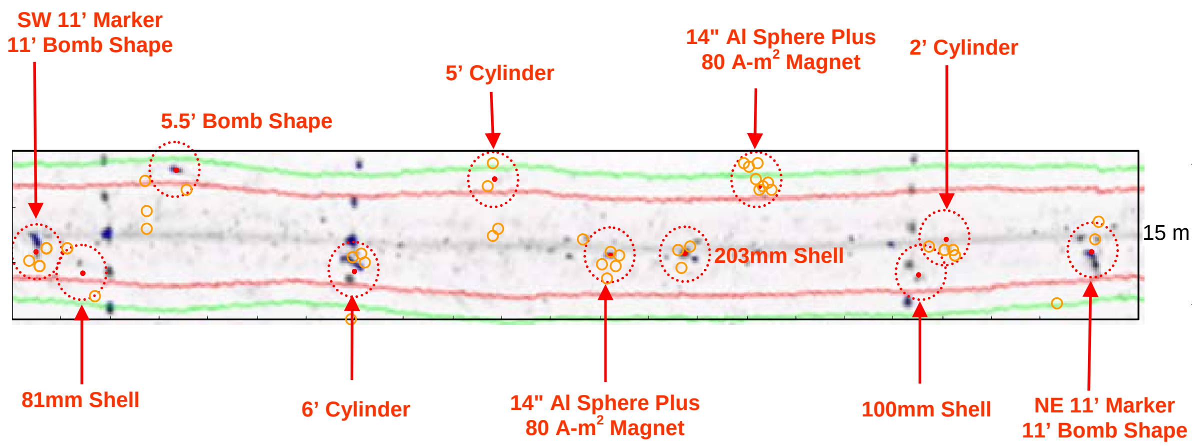
Figure 10. Composite target map from SAS, BOSS, and RTG data synthesized from Dec '03-Jan'04.

At the 30ft-deep sand site, 10 targets were deployed completely buried by about 1ft and a 14in sphere was deployed half-buried, although these configurations could not be guaranteed when the SAS, BOSS, and RTG were run through the test area because storms had passed over the sites prior to testing. The SAS was able to image 5 of the larger targets as shown by the green diamonds in Fig. 10 (including the SW marker target where the green diamond is covered by the red circle). The BOSS/RTG achieved 6 fused detections of the eleven targets as shown by the red dots and blue circles.

When the data collected from the deep sand site by the BOSS/RTG and the Bluefin Robotics AUV SAS systems were beamformed to form images and compared, the BOSS data were lower in resolution and noisy but fusion with the magnetic detections allowed several targets to be isolated that were missed by the SAS, including a buried 20"-long, 81mm artillary shell mock-up and a buried 8" Howitzer shell (marked “bullet” in Fig. 10). Since the SAS scans the bottom at shallow grazing angles, it typically has difficulty picking up smaller buried targets unless wave action generates bottom ripple that helps diffract the sound energy into the bottom. Bottom ripple was not present in the target areas during these tests. Nevertheless, the SAS detected and resolved several of the larger buried targets, such as a buried 500-lb bomb, that were out of the field of view of the BOSS/RTG system. The field of view of the BOSS/RTG was reduced because the RTG was damaged during test preparations and not operating optimally at the field test; an estimated 40dB of sensitivity was lost. Therefore, because the acoustic clutter was high, it was not clear whether the BOSS detected the remaining buried targets because of the difficulty distinguishing them from the clutter.

Due to the damaged RTG, the first test of the BOSS/RTG system was cut short so little data was collected at the shallow sand and mud sites. The few data runs over the deep mud site were found to be of low quality because acoustic bottom surveys showed the area contained a lot of gas, which prevented much sound penetration. A follow-up test of the BOSS/RTG was planned and, in May, 2004, the BOSS/RTG system with only two channels of the RTG working properly was brought back to NSWCPC for testing in the same 4 target fields. To mitigate uncertainty caused by clutter, divers located the previously buried targets and reflective clumps were set up in patterns around each target to mark target locations unambiguously in the BOSS imagery.

Initial analysis of the collected data focused on the deep sand site again. The results are shown in Fig. 11. With 2 out of 6 channels of the RTG operating at optimal sensitivity, 10 of the 11 deployed targets were detected magnetically and localized; the exception being the 100 mm shell. However, the scatter in RTG localizations demonstrates the need for additional channels to get target positions more precise.   When the magnetic localizations are fused with the BOSS imagery at least 8 of the 11 targets appear in the fused set. Ground truth on the target fields was attained with the acoustic marking of the targets and a post-mission diver survey, the last providing a check on burial depth of all targets and position for targets not imaged well by the BOSS. It is anticipated that PCSWAT simulations will help determine the reason the BOSS did not perform well against the 2 ft and 5 ft cylinders and the upper 14 in sphere in Fig. 10. Since BOSS is a downward looking sonar and the 5 ft cylinder and 14 in sphere are well off the track (as indicated by the faint blue line running midway through the target field) these missed detection could be just the result of low signal level. Missing the 2 ft cylinder is more mysterious. PCSWAT was configured to simulate the BOSS sonar under previous ONR funding and this is currently under investigation.



- *Magnetic Contacts from the Composite of 14 Runs are Displayed by Small ORANGE Circles*
- *Only 2 out of 6 RTG Channels were Operating at Full Performance*
- *All Targets had Steel Casings except for the two 14” Al Spheres (Coincident with the Magnets)*
- *The Large ORANGE Dotted Circles with 2.5-m Radii Reference Ground-Truth Positions*
- *Multi-Aspect BOSS Image Synthesized from 3-10 kHz Data*
- *Nominal 2.5-Meter Sled Altitude for Acoustic Run with 115 Meters of Run Displayed*

Figure 11. BOSS/RTG detections from the May, 2004 survey at the 30 ft sand site.

The first field test leveraged with SERDP funding in FY05 was the ONR sponsored SAX04 high frequency scattering experiment off Ft. Walton Beach in Oct-Nov, 2004. Surrogate UXO targets were constructed and deployed to participate in this field experiment. As part of this set of experiments, buried target detection was investigated using broadband acoustic sources and receivers deployed in novel multistatic configurations. Broadband 8-50kHz and high-frequency (180kHz) SAS sources were deployed on a tow body to collect data from the target sites. FAU’s BOSS was also brought over to collect data as part of their system assessment for ONR. The test area was well characterized so data collected would be useful for validation of PCSWAT. Figure 12 shows a schematic of the target field and the UXO shapes deployed in it.

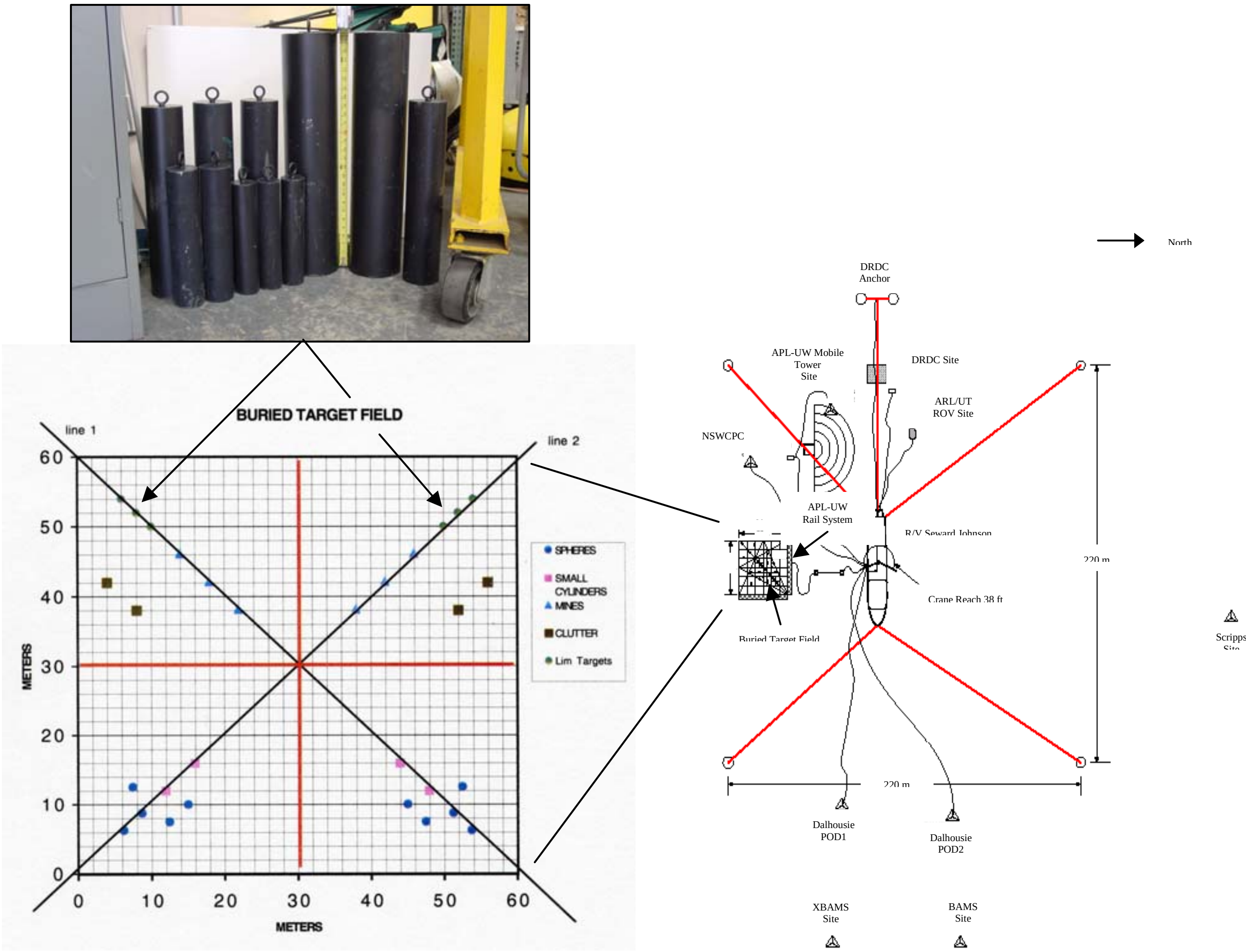


Figure 12. The cylindrical UXO surrogates and a schematic of the SAX04 target field showing their placement in the field.

In addition to construction and deployment of UXO surrogates, SERDP funds were used to support the processing of data collected from the towed NSWCPC SAS system to obtain imagery for comparison with PCSWAT simulations. However, since many of the NSWCPC SAS measurements were performed in November after Hurricanes Ivan and Jeanne, which came through the Florida panhandle area after targets were deployed, it was fairly certain that the target field would not be as originally deployed. In fact, post-experiment diver surveys found none of the buried targets except for a shallowly buried, 35 cm, fluid-filled sphere deployed after the hurricane activity. Only sonar deployed before the hurricanes came through collected good data for analysis on the field of cylindrical UXO surrogates. This included FAU's BOSS, which went over the UXO field in September of 2004. An analysis of their data was published by Schock et al. in the proceedings of the Oceans 2005 conference [31]. The PCSWAT validation performed by NSWCPC involved the buried sphere data only.

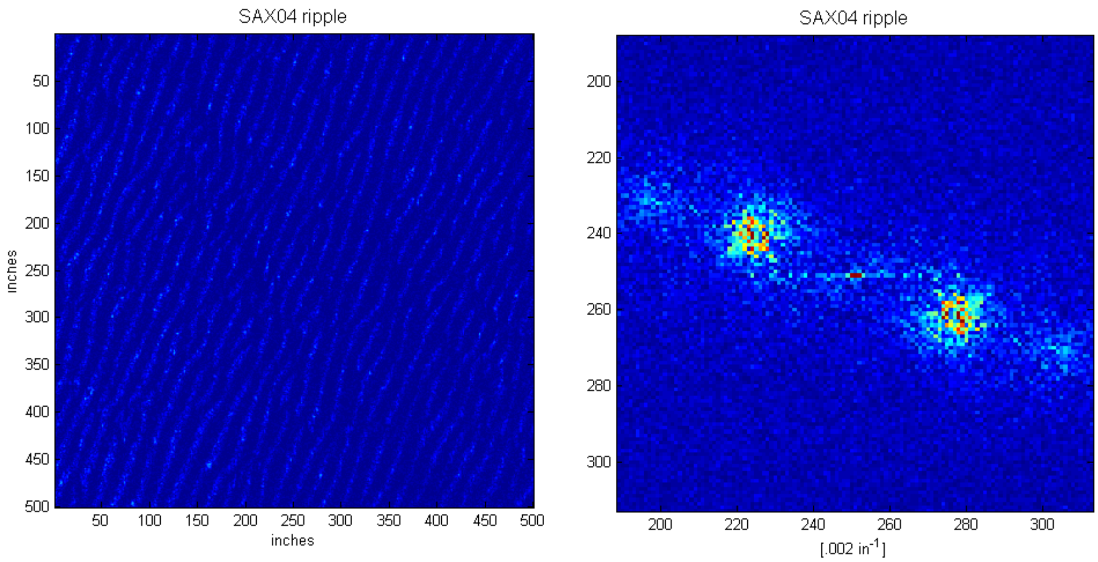


Figure 13. 180 kHz imagery of the bottom over a buried sphere (left) showing a clear ripple pattern and a 2-dimensional spatial Fourier transform of the image (right) indicating a predominant 42 cm wavelength.

In Fig. 13, high-frequency SAS imagery of the bottom over the buried sphere and a corresponding 2-dimensional Fourier transform is shown. Standard SAS processing methods [32] were used to synthesize an array along the track of the tow body of sufficient length to achieve a 2.5 cm resolution in the along-track direction at each range cell. A range resolution of 2.5 cm was achieved by pulse compressing backscattered 30 kHz bandwidth LFM signals generated by the sonar source. A ripple pattern with a predominant 42 cm wavelength is indicated. Note that high sound attenuation in the bottom at 180 kHz precludes detecting the sphere in the high-frequency imagery. However, using the ripple wavelength (42 cm), ripple wave vector orientation (20^o from SAS beam direction), estimates of the ripple height (2 cm), a burial depth of 3 cm for the sphere, a homogeneous water column sound speed of 150000 cm/s, and parameters for medium sand as inputs, PCSWAT imagery can be predicted for comparison in the frequency bands where detection was possible. Thus, Fig. 14 shows an image comparison between PCSWAT's predicted image and the processed broadband sonar image over the 20-50 kHz band. As in the high-frequency image 2.5 cm x 2.5 cm resolution is maintained. In this case, the sphere was detected at a range corresponding to a 14^o sonar grazing angle on the bottom, which is clearly below the critical grazing angle for a corresponding flat bottom. The signal-to-noise is in reasonable agreement considering the inherent uncertainty in some input parameter estimates. Note that the ripple pattern observed in the measured data does not appear in the PCSWAT image because, although PCSWAT treats ripple diffraction into the bottom deterministically to correctly determine the target strength level, the reverberation level from the ripple structure is determined in an average sense using a bottom reverberation model specified by APL-UW [33]. The signal-to-noise ratio (SNR) comparisons found for other looks at the sphere are summarized in Table 1.

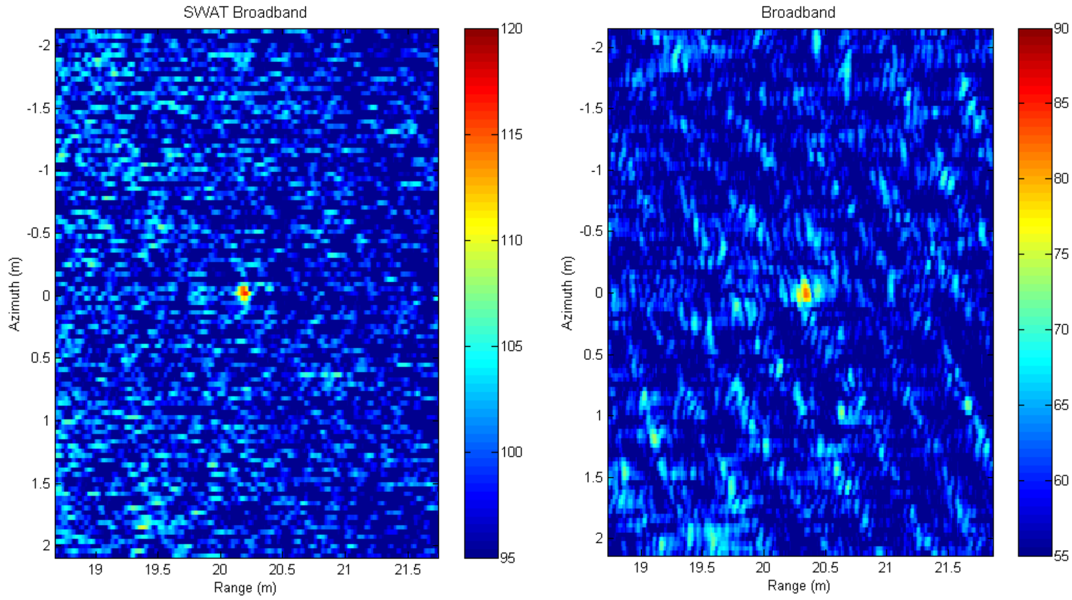


Figure 14. An image comparison between PCSWAT predicted imagery and processed SAX04 field data in the 20-50 kHz band for a shallowly buried, spherical, steel shell.

Table 1. SAS Data SNR Comparison with SWAT

Signal Band	SAS Data SNR	SWAT SNR	GRAZING ANGLE
15-25 kHz	20.3 ± 0.7 dB	20.8 dB	14º
20-50 kHz	23.9 ± 1.3 dB	19.2 dB	14º
20-50 kHz	33.8 ± 2.5 dB	27.3 dB	31º

In the last field test leveraged with support covered under SERDP project UXO-1329, a 12.75 in-diameter AUV (WHOI REMUS 600) carrying a 120 kHz high-frequency and a 8-55 kHz broadband sonar was run against a series of bottom targets in about 50 ft of water off the Gulf side of Shell Island near Panama City, FL. Included in the target field were three lines of cylindrical UXO-sized targets, each line containing the same targets deployed in a given burial state. One line had its cylinders laid unburied on the surface, another line had half-buried cylinders, and, in the last line, the cylinders were completely buried flush with the surface. As in previous tests, cylindrical UXO surrogates as depicted in Fig. 12 were constructed and used. For example, Fig. 15 shows a photograph of a 60% buried 10 cm x 50 cm cylinder from an end-on aspect, as deployed 6 days before data collection. The WHOI AUV spent three days collecting data from targets at many aspects and ranges. Since targets were imaged at all stages of burial, a great deal of data was available for comparisons against PCSWAT predictions.

Figure 15. An underwater photograph of a 10 cm x 50 cm cylinder deployed in the WHOI REMUS 600 test site off Shell Island, FL.

As discussed above in the description of the SAX04 sphere data, standard SAS and pulse compression processing methods were used to produce imagery of 2.5 cm x 2.5 cm resolution. However, the imagery processed from the data collected was generally less refined in appearance (i.e., less focused) compared to the PCSWAT simulations due to motion compensation errors. Nevertheless, SNR levels are in reasonable agreement. A comparison of a 120 kHz SAS image of the cylinder in Fig. 15 insonified at end-on aspect with a PCSWAT simulation is given in Fig. 16. The PCSWAT simulation yields a 47.6 dB signal peak, while the SAS data yields a somewhat broader 41.6 dB signal, which is likely a consequence of imperfect tracking of vehicle motion when the data is collected. This broadening of the peak signal also tends to drive the sidelobe structure down, which is very apparent in the PCSWAT image. Additionally, the background in the at-sea data may be a little higher due to a higher bottom roughness than assumed for the simulation. In PCSWAT

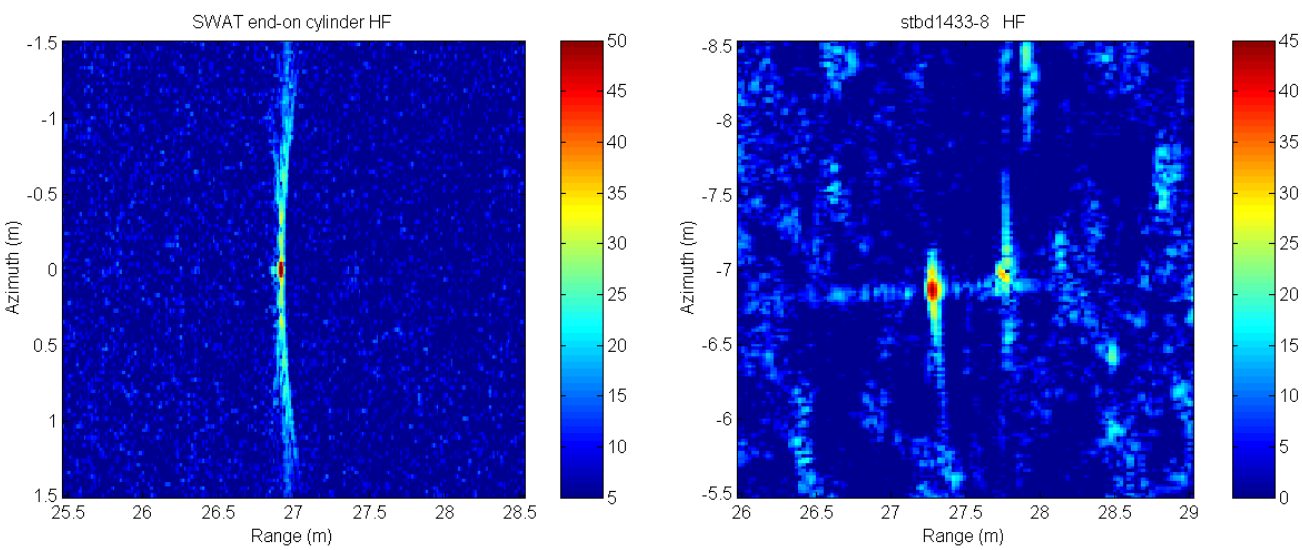


Figure 16. PCSWAT and at-sea SAS 120 kHz images of an end-on aspect of a 60% buried 10 cm x 50 cm cylinder.

the bottom type was simply modeled as “medium sand,” the water column was homogeneous with a sound speed of 150000 cm/s, and the sediment volume scattering was set to “low.” It should also be noted that the real data shows a second 29.7 dB signal, which corresponds to the far end of the cylinder. This end contains an eyebolt and attached parachute cord, which was not included in the PCSWAT simulation.

In another example, Fig. 17 shows a 2.5 cm x 2.5 cm resolution broadband image of a buried 7.5 cm x 35 cm cylinder near broadside. The range and height of the sonar in this case places the incident acoustic grazing angle at just above critical, and target burial under 3 cm of sediment was assumed in the PCSWAT simulation. PCSWAT predicted a 31.6 dB signal peak, while the at-sea data agrees quite well with a 31.7 dB signal peak. However, the SAS-processed at-sea data also shows a broader response in the range direction than the simulated image. Additional peaks close behind the first one appear with strengths of 28.1 dB, 23.3 dB, and 20.2 dB. Because the resolution achieved along the range direction is finer than the broader structure shown, the extra features are not thought to be due to motion compensation errors in the processing. This weaker structure could be due to elastic or diffractive responses from the target. Elastic effects are not accounted for with the Kirchhoff approximation used to calculate scattering by targets in PCSWAT. Neglect of elastic effects is usually justified by their secondary importance compared to the dominant specular reflection. The present comparison confirms that the simulated and measured specular components of the imagery are in good agreement.

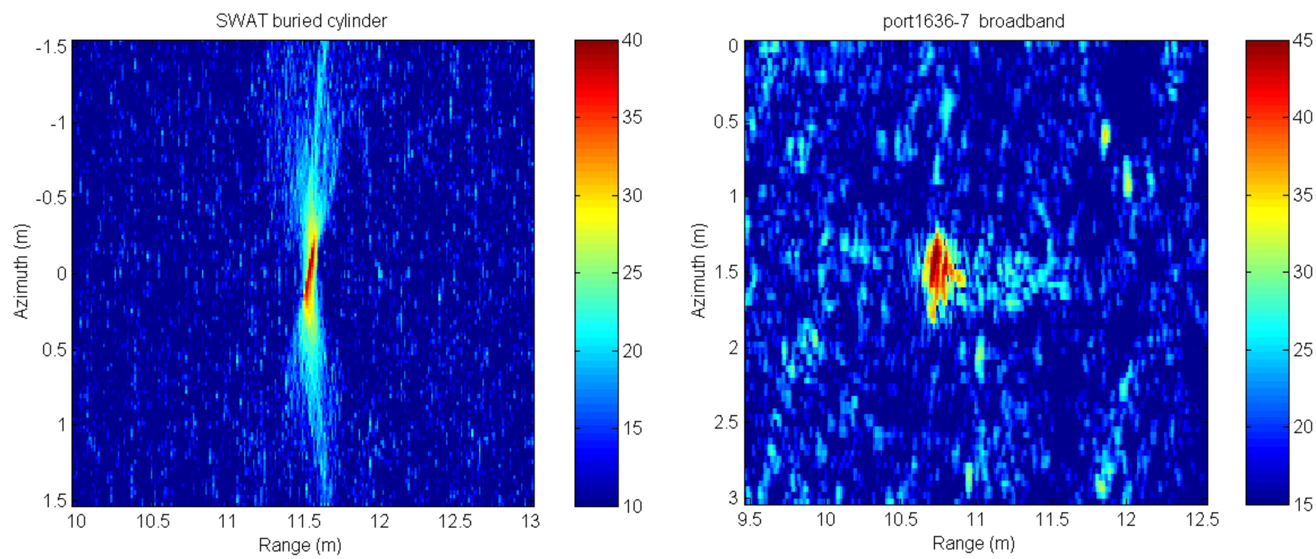


Figure 17. PCSWAT and at-sea SAS broadband images of a buried 7.5 cm x 35 cm cylinder.

Conclusions

This report summarizes progress made in the research effort funded by SERDP over the past 3 years to extend the Navy’s Personal Computer Shallow Water Acoustic Toolset (PCSWAT) to provide a simulation capability for sonar against underwater UXO. The extensions required include building in a wider range of target shapes and sizes and developing efficient scattering algorithms to model these targets in buried configurations. In addition to model development, experimental tests were integral to this effort to validate the models as well as uncover their deficiencies

A primary concern was the extension of PCSWAT to allow for buried targets in its simulation capability since this did not exist in previous versions except to allow generation of SNR curves. This required more than just building in ray algorithms that could refract sound through a water/sediment interface to a buried target because such approaches did not produce results in agreement with observations from past sonar field tests. In these tests, buried targets were detected at grazing angles lower than expected based on benchmark bottom transmission calculations for flat, layered underwater environments. An increasingly attractive theory was that shallow-angle sound transmission could be enhanced by surface ripple if such was present. Therefore, a concerted effort aimed at developing and testing buried target models including simple forms of ripple roughness at the interface was undertaken. Comparisons with measurements using buried spheres confirmed that ripple-induced shallow-angle backscatter mechanisms in sand bottoms are consistent with observations. As a result, ripple diffraction models were built into PCSWAT beginning with v. 8 and with improvements in v. 9 along with the ray theoretic machinery needed to account for propagation to and scattering from buried targets. Checks of the algorithms against data indicate PCSWAT works well for unburied targets and buried targets insonified at high grazing angles. However, even though the roughness diffraction mechanism for enhancing buried target detection appears to be confirmed in the data collected, quantitative agreement with imagery for buried targets insonified at low grazing angles is not consistently within acceptable bounds for reasons that are not yet fully understood. Part of the reason may be inaccuracies in estimates of environmental input parameters. Follow-on studies will work toward resolving these discrepancies.

The bottom line is that buried target models are a challenge to validate due to difficulties in obtaining ground truth (e.g., environmental parameters, final target position and orientation, etc.). Better efforts to obtain ground truth should be made where possible in future data collection efforts. As noted as part of the BOSS data assessment, mud environments can be especially challenging due to unknown dispersion caused by organic activity injecting gas into these sediments. Therefore, in addition to developing better environmental characterization tools, verification of PCSWAT with benchmark codes will continue to be valuable and future efforts should emphasize the development of these to some degree.

Finally, PCSWAT has been developed as a tool to simulate sonar imaging performance. Imaging is currently the best-developed mode of target identification for sonar but this mode may be insufficient for buried targets. Burial blocks high frequencies from reaching a target so high resolution imagery will be difficult to achieve. With low-to-mid frequency imaging, only gross features may be discernible with smaller UXO targets. Other ways to discriminate based on the target echo should be sought to complement imagery. Unique features accessible by viewing signals in other spaces (i.e., temporal frequency, spatial frequency, angle, etc.) are worth investigating. In future versions of PCSWAT, we hope to build in capabilities to view data in other spaces where there is sufficient promise.

As far as the transition status of the work carried out, we point out that PCSWAT has been updated to include a representative set of UXO targets, to account for burial of these targets in simulating sonar performance, and to account for detection enhancements attributed to bottom roughness effects. Although the updates still face validation challenges, the update included are well grounded in physics as confirmed by our controlled pond and tank tests. The distribution of these updates in current versions of PCSWAT is therefore provided as tools that can be used by sonar designers in government and industry to provide at least qualitative, if not quantitative, assessments of sonar performance. PCSWAT may be obtained by contacting Dr. Gary Sammelmann (NSWCPC).

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