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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
08/16/2013	Final	01 Jan 2010 - 31 Dec 2012

4. TITLE AND SUBTITLE
Synthetic Aperture Sonar Forward Modeling and Inversion

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-10-1-0047

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lyons, Anthony P.

5d. PROJECT NUMBER
17244

5e. TASK NUMBER
01

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Pennsylvania State University, Applied Research Laboratory, P. O. Box 30, State College, PA 16804-0030

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research, 875 North Randolph Street, Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Work carried out during this project improved our ability to link SAS image statistics to measurable environmental properties such as seafloor roughness. During the course of this project we: 1. Examined relationships of acoustic scattering properties to SAS means levels and statistics; 2. Developed predictive physics-based forward models of mean levels and statistics relevant to SAS; 3. Developed inversion tools for estimating seafloor properties based on forward models; and 4. Validated forward models and inversion results against at-sea experimental data.

15. SUBJECT TERMS
synthetic aperture sonar, seafloor scatter, seafloor properties

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Anthony P. Lyons
U	U	U	U	6	19b. TELEPHONE NUMBER (Include area code) 814-863-9895

Contract Information

Contract Number	Award Number: N00014-10-1-0047
Title of Research	Synthetic Aperture Sonar Forward Modeling and Inversion
Principal Investigator	Anthony P. Lyons
Organization	The Pennsylvania State University Applied Research Laboratory

Technical Section

Objectives

Long term goals:

Current and future high-resolution MCM systems such as Synthetic Aperture Sonar are actively being developed. Unfortunately, this development is proceeding in many cases without a solid understanding of how environmental effects might degrade performance or how data inversion can be used to extract information about the environment. While these systems have been largely successful in achieving their goals of producing high-resolution imagery (on the order of square centimeters), there has been little effort in linking scattering physics to both the mean levels and statistics of the resulting sonar returns seen in the images. This type of knowledge is crucial for producing both realistic forward and inverse models.

The long-term goals of the present research are to develop and validate physics-based models and inversion tools relevant to current and future synthetic aperture sonar systems. The influence of the properties of the boundaries to the scattered envelope statistics will be examined in detail as will methods to invert system data for environmental parameters. This study will yield an improved understanding of the link between environmental parameters and system factors which contribute to SAS image statistics, as well as models and methods for characterizing, predicting and mitigating environmental effects. This effort may lead to improved methods for environmental characterization (i.e., 'through-the-sensor' inversion of seafloor properties), have direct application to performance prediction, and possibly provide guidance for adaptive strategies for speckle reduction based on the operational environment.

Objectives:

The importance of the present work lies in the ability to link SAS image statistics to measurable environmental properties such as seafloor roughness. In conjunction with sonar system parameters, this link will provide the foundation necessary for solving several important problems related to the detection of targets with SAS. The direct link between system and environmental parameters via scattering models to the statistical distributions will allow: performance prediction for different systems based on environmental properties, extrapolation of performance to other

systems/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment.

Concisely the proposed objectives are:

1. Examine relationships of acoustic scattering properties (sediment interface and possibly volume for low-frequency systems) to SAS mean levels and statistics;

2. Develop predictive physics-based forward models of mean levels and statistics relevant to SAS;

3. Develop inversion tools for estimating seafloor properties based on forward models;

4. Validate forward models and inversion results against at-sea experimental data.

Approach

Work has been conducted recently at the Applied Research Laboratory – Penn State University (ARL-PSU) to characterize and model high-frequency scattered amplitude statistics of SAS imagery as a function of resolution, relationship to correlated seafloor structures (ripples) and propagation conditions. Work conducted with scientists at the University of Canterbury in Christchurch, New Zealand, has also shown promising initial results on the possibility of inverting SAS data for large scale 2-dimensional height fields. As a follow on, the proposed research program intends to increase our understanding of how acoustic scattering processes impact SAS data in terms of both mean levels and statistics. Knowledge gained will be included in models aimed at aiding in the prediction of environmental effects on current and future MCM acoustic systems and on inversion for environmental parameters. These goals will be achieved through a close association with current PIs and projects being performed by the NSWC-Panama City. Model development will be guided by feedback from real data collected by the NSWC-Panama City.

Initial focus will be on acoustic characterization and modeling of speckle in images of ripple sandy seafloors and we will later look at more complicated scattering scenarios (e.g. seagrasses, rocky outcrops, and possibly sediment volume effects). Collaboration with the NSWC-PCD will facilitate use of their quality SAS data and results will be fed back into their program. Inversion of component forward models will also be a main priority.

Work Completed

The goals of the project were achieved through a combination of characterization and modeling of SAS imagery statistics. Images for this study have been obtained from various SAS systems including the 300 kHz MUSCLE system operated by the NATO Undersea Research Centre, La Spezia, Italy, the 120 kHz SSAM system operated by the Naval Surface Warfare System – Panama City Detachment, from measurements collected over a variety of frequencies by the Applied Physics Lab – University of Washington during the SAX04 experiment that took place in 2004 off of Ft. Walton Beach, Florida and data collected off of Larvik, Norway, with the HISAS system operated by the Norwegian Defence Research Establishment (FFI) as part of a multinational collaboration. Work has been performed during this project on the topics of temporal coherence of acoustic scatter in the context of SAS coherent change detection (CCD) and also on the impact of roughness on SAS image statistics.

Work was performed in 2010 on the temporal coherence of acoustic scatter in the context of SAS coherent change detection (CCD). Acoustic data and seafloor roughness ground truth data collected during the ONR sponsored Sediment Acoustics Experiment '04 (SAX04) experiment were used to estimate the decorrelation of acoustic signals scattered from the seafloor due to changes in the shape of the seafloor interface. Acoustic data was obtained by a rail-mounted synthetic aperture sonar apparatus operated by the Applied Physics Laboratory –University of Washington and roughness by a digital stereo photogrammetry system. Small-roughness perturbation-theory was used to relate decorrelation of seafloor roughness spectral estimates to the decorrelation of scattered acoustic signals. The roughness ground truth-based correlation estimates ignore other probable sources of decorrelation, such as multipath, system noise, baseline decorrelation, etc., and so can be considered an upper limit to scene correlation at a given time. Results of this analysis are presented in the following section.

During FY2011, a wide variety of topics were investigated, some a continuation of work begun in FY10. Work on understanding the effects of random roughness on texture statistics was continued. One interesting result found during this work was that in some cases speckle that appears non-Rayleigh is in reality caused by random roughness and can be used to estimate random roughness in terms of rms slope/height from the statistics of speckle. A recent NSCW pond experiment performed in August, 2011, will be used to test this type of inversion measurement. We also learned that a Lambertian shape for the scattering strength curve at low grazing angles provided better a fit to scattering statistics data than first-order perturbation theory or the lowest-order small slope approximation curves.

Work was performed with graduate student Dan Brown to understand speckle statistics for very wideband systems (those with a bandwidth to center frequency greater than 1). Numerical models showed that speckle still be Rayleigh distributed even for cases when the theoretical resolution became smaller than a wavelength. This result wasn't obvious or intuitive and data from a recent experiment at the NSWC test pond should help in clarifying this outcome. Work was performed with graduate student Derek Olson on developing a method for in-the-field pseudo-calibration for uncalibrated SAS systems which uses the 'known' scattering strength of a uniform area (sand, rock) to estimate the combined transmit/receive response of the imaging system (including effects

of SAS processing). Calibrated systems will allow areas to be mapped for scattering strength, slope, etc. and should aid ATR.

A variety of topics were investigated in FY2012, some a completion of work begun in FY10 and FY11. Work continued this year with graduate student Derek Olson on using SAS systems to characterize rocky outcrops. This year's work also included a continuation of a study on understanding the effects of random roughness on SAS texture statistics. This study involved the use of data provided by the NATO Undersea Research Centre. With graduate student Dan Brown we continued our investigation into SAS speckle statistics for very wideband systems (those with a bandwidth to center frequency greater than 1. Models of speckle for these types of systems showed that speckle will still be Rayleigh distributed for cases when the theoretical resolution becomes smaller than a wavelength. Data from the recent pond experiment was also used to help us clarify this finding and although not conclusive, did not contradict the model results.

Our work this year also included the completion of an analysis of experimental data on the temporal coherence of acoustic scattering in the context of SAS coherent change detection and the use of the results of this analysis in the development of methods for simulating temporal changes in SAS images between repeat passes. In the analysis of experimental data, acoustic data and seafloor roughness ground truth data collected during the ONR sponsored Sediment Acoustics Experiment '04 (SAX04) experiment were used to estimate the decorrelation of acoustic signals scattered from the seafloor due to changes in the shape of the seafloor interface. Small-roughness perturbation-theory was used to relate decorrelation of seafloor roughness spectral estimates to the decorrelation of scattered acoustic signals. The effect of the environment on temporal coherence for a given site was quantified in a single parameter, the diffusion coefficient which indicates how fast the environment changes at a given location. This parameter could serve as a possible metric for the performance of CCD for different sites.

A portion of the SAS data analyzed this year was collected in April, 2011 during a joint field experiment that took place near Larvik, Norway, as part of a collaborative work with the Norwegian Defence Research Establishment (FFI). As virtually no information exists on scattering from rock outcrops, we have worked on obtaining quantitative measurements of acoustic properties, such as the scattering cross-section, using SAS. The FFI SAS system operated at a center frequency of 100 kHz, has a bandwidth of 30 kHz and was operated from the HUGIN Autonomous Underwater Vehicle (AUV). To take advantage of the high-resolution capabilities of this SAS data and still obtain physically meaningful results, an 'effective' combined source strength and receiver sensitivity was found by comparing the scattering cross-section from a smooth, featureless rock imaged with the SAS system with estimates made with the small slope approximation using known geo-acoustic parameters. Local slopes on the rock were estimated with the high-resolution interferometric bathymetry available with the HISAS system. Figure 1 shows the rock and model fit used to estimate the effective combined source strength and receive sensitivity. Sample scattering strength estimates for rock determined using the 'calibrated' SAS system will be shown in the next section.

Impact/applications:

SAS image statistics research is providing an improved understanding of the environmental parameters that affect high-frequency imaging systems. This study is leading to methods for modeling and predicting these environmental effects that may be used to minimize their negative impact on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of simulation tools, adaptive systems for sonar systems and rapid environmental assessment techniques for estimating environmental parameters for a given area.

Related Projects:

A related ONR project (Grant N00014-10-1-0051) is Statistics of High-Resolution Synthetic Aperture Sonar Imagery: Physics-Based Speckle/Texture Analysis and Simulation managed by Jason Stack, code 321OE.

Publications supported by this project:

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