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1. REPORT DATE (DD-MM-YYYY) 09-09-2005		2. REPORT TYPE Proceeding		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE The effects of seafloor roughness on acoustic scattering: Manipulative experiments				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) M.D. Richardson, K.B. Briggs, K.L. Williams, D. Tang, D.R. Jackson, and E.I Thorsos				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory Seafloor Sciences Branch Stennis Space Center, MS 39529				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/PP/7430-05-12	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 North Quincy Street Arlington, VA 22217-5660				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 Boundary Influences in High Frequency, Shallow Water Acoustics, University of Bath, Sept. 5th-9th 2005.					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON Michael Richardson
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) 228-688-4621

THE EFFECTS OF SEAFLOOR ROUGHNESS ON ACOUSTIC SCATTERING: MANIPULATIVE EXPERIMENTS

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Deliberate manipulations of the seafloor during SAX04 (Sediment Acoustics Experiment-2004) in the form of quasi-periodic ripple features were carried out to examine the effects of interface roughness on high-frequency acoustic scattering. Manipulative experiments were conducted in the field of view of a bottom-mounted acoustic tower (40 kHz) and in the field of view of acoustic transducers (30-90 kHz) attached to a mobile rail system. The center wavelength of ripple-like features varied between 2 and 3 cm and the strike of the ripples was oriented parallel, perpendicular and at 30° to the axis of propagation of the incident acoustic waves. Backscattering strength was greatest when the ripple spacing was close to one-half the acoustic wavelength and the strike of the ripples was perpendicular to the incident acoustic propagation path. Preliminary analysis suggests agreement between measured and modeled backscatter strength.

1 Introduction

High-frequency acoustic scattering and penetration experiments were conducted on shallow-water sandy sediments in the northeastern Gulf of Mexico, as part of two Sediment Acoustics Experiments in 1999 (SAX99) [1,2] and in 2004 (SAX04) [3,4]. During the SAX99 experiments, the seafloor was raked in the acoustic field of view of the Benthic Acoustic Measurement System (BAMS) [5,6]. This bottom-mounted tower allowed acoustic scattering measurements (40 kHz) to be made within a 30-m radius circle that included several 4-m² areas modified by divers. The time spacing (ripple wavelength) of the artificial roughness was approximately equal to the acoustic "Bragg wavelength" (approximately half the acoustic wavelength) at the incident grazing angle appropriate for 40-kHz backscattering measurements. Values of acoustic backscattering strength increased by 12-18 dB immediately after raking; then decayed to background levels within 24 hours due to biological modification of seafloor roughness (Fig. 1).

The high rate of decay of man-made ripples and the related change in backscatter strength provided considerable insight into temporal dependence of high-frequency

scattering from surface roughness features. Modelled scattering strengths (1st order perturbation theory) were about the same as measured scattering strengths for the natural environment (before and 24 hours after manipulations). However, the model results for raking orthogonal to the incident ensonification (+0.7 dB) were almost 20 dB higher than values of backscatter strength measured immediately after raking (-20 dB). The discrepancy between measured and modeled values of acoustic backscatter strength from artificial bottom roughness features created during SAX99 provided the motivation for additional manipulative experiments during SAX04.

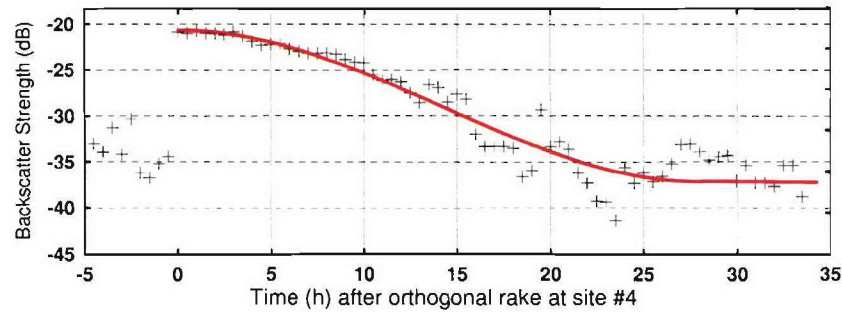


Figure 1. Decay of acoustic scattering after raking orthogonal to the incident acoustic energy during SAX99.

2 Methods

2.1 Acoustic Methods

Acoustic backscattering measurements were made at 40 kHz using BAMS during SAX99 [5] and SAX04 and between 30-90 kHz during SAX04 using piston transducers mounted on a moveable tower affixed to a bottom mounted rail system [7]. BAMS is an autonomous system, which allows acoustic scattering measurements to be made within a 30-m radius circle around the bottom-mounted tower. The 40-kHz transducer is mounted 3.2 m above the seafloor at the apex of the BAMS tripod. The transducer has a horizontal beam width of 5° and uses a FM pulse to obtain a 0.4-m range resolution. BAMS rotates in 5° increments with about 6 minutes required for a full 360° rotation. This resolution allows 9 values of scattered intensity to be calculated within each 4-m² manipulation area from which average scattering strengths are determined. During SAX99, experimental quadrates were placed 10-12 m distance from BAMS producing a mean grazing angle of 16°. During the SAX04 measurements the quadrates were slightly closer (8-10 m) with a mean grazing angle of 20°. The transducers on the rail tower were mounted at a fixed orientation 4.8 m above the seafloor. For many of the acoustic measurements, the tower translated over the entire 27-m length of the rail; however, for these manipulative experiments, six rail tower locations separated by 30 cm were used to obtain average scattering strengths. Divers conducted manipulations in a single 4-m² quadrate 8-10 m from the base of the platform yielding a 28° mean grazing angle.

2.2 *Sediment Physical Properties*

In situ and laboratory methods were used to characterize surficial sediment physical properties during SAX99 and SAX04 [1,3,8-10]. Both sites consisted of well sorted medium quartz sand with slightly larger mean grain size (420 μm) at the more offshore, deeper (19-m water depth) site of SAX99 compared to the more inshore, shallower (17-m water depth) site of SAX04 (350 μm). Values of sediment sound speed (at 400 kHz) measured in cores from SAX04 (mean sediment-to-seawater water sound speed ratio = 1.162) were slightly higher than those measured at the SAX99 site (mean sound speed ratio = 1.155), whereas values of attenuation measured during SAX99 (173 $\text{dB}\cdot\text{m}^{-1}$) were significantly higher than those measured during SAX04 (92 $\text{dB}\cdot\text{m}^{-1}$). Values of sound speed show no significant dispersion over the frequency range of 20-400 kHz [8,9] justifying the use of the sound speed measured at 400 kHz for modelling scattering strengths at 20-90 kHz. Values of sediment porosity and bulk density were not significantly different between the two sites with ranges of 35-38% for porosity and 2000-2100 $\text{kg}\cdot\text{m}^{-3}$ for bulk density. These values of sound speed, attenuation and sediment physical properties are typical for medium-sized sands. For modelling acoustic scattering (section 3.2), mean values of sound speed ratio (1.16), density ratio (2.0) and attenuation (0.31 $\text{dB}\cdot\text{m}^{-1}\text{kHz}^{-1}$) are used for both SAX99 and SAX04.

2.3 *Seafloor Roughness*

Considerable effort was made to characterize seafloor roughness during both SAX99 and SAX04 using a variety of manual, optical, laser, and electrical techniques [1,11]. For the purposes of this paper, digital stereo photographs collected during SAX99 will be used to characterize two-dimensional (2-D) seafloor roughness for the manipulative experiments. Photographs were made before, immediately after, and for periods up to 24 hours after raking (4-7 November 1999) in order to document the decay of roughness previously observed by divers. The stereo-correlation of digital images using area-based matching was performed to create a 2-D height field, or digital elevation model, from which the full 2-D roughness power spectrum was estimated. The effective resolution of the system is on the order of a millimeter in both the horizontal and vertical [12]. The images along with values of spectral strength and spectral exponent for 2-D spectra estimated from the digital images were presented in [5]. Given the similarity in sediment properties it is assumed that the initial 2-D spectra for all surfaces raked during both SAX99 and SAX04 are nearly identical when using rakes with the same tine spacing. In the future, when visibility improves 2-D roughness measurements will be made for fresh ripples at the site of the SAX04 manipulations.

2.4 *Seafloor Manipulations*

Rakes with tine spacing of 1.95 and 3.0 cm were used to create quasi-periodic roughness features on the seafloor in the acoustic field of view of both BAMS and the mobile rail system [7]. Quadrates (4- m^2 area) were staked out between 8 and 12 m from the base of BAMS. During SAX99 raking, ripples with a tine spacing of 1.95 cm were created near BAMS both parallel and perpendicular to the direction of acoustic propagation. During SAX04, ripples with tine spacing of 1.95 cm and 3.0 cm were created parallel, perpendicular and at 30° to the direction of acoustic propagation. Acoustic scattering

measurements were made each hour for at least 24 hours after manipulations during both experiments. Manipulative experiments at the rail tower did not attempt to measure temporal changes in backscatter strength due to decay of ripples, but instead concentrated on scattering from fresh ripples over a range of acoustic frequencies. Acoustic measurements were limited to two, 3-hour periods on October 18-19, 2004. Divers raked the entire 4-m² quadrat at angles parallel, at 30°, and perpendicular to the path of the incident acoustic energy (Fig. 2). This was repeated 8 times with divers smoothing the surface between each treatment.

3 Results

3.1 Acoustic Scattering Measurements at BAMS

Scattering measurements made during SAX99 were summarized in the introduction, have been previously published [5], and consequently will not be repeated herein. As reported elsewhere [4], hurricanes during SAX04 changed experimental plans, especially during the early part of the experiment when diver operations were severely hampered by poor visibility. Divers not only had problems establishing 4-m² quadrates but could not assess the quality of the manipulations. In addition, the backwash from Hurricane Ivan deposited fine-grained, clayey, lagoonal sediments throughout the experimental site changing the sediment impedance and roughness characteristics [3]. Often, raked quadrates around BAMS exhibited both sand and mud interfaces. Both the poor visibility and variable seafloor impedance restrict presentation of the backscatter strength measured during BAMS manipulative experiments to qualitative observations.



Figure 2. Photograph of the sediment surface raked with a 1.95-cm tine spacing during the SAX99 experiments. The rake had triangular teeth cut at 45° but raking was accomplished with the rake held at an angle roughly 30° to the sediment surface. The resultant ripple amplitude (0.57 cm) was approximately equal to amplitude for a ripple given the measured angle of repose (28°) of the sediment.

As in SAX99 experiments, the values of scattering strength rapidly diminished over time, generally returning to background levels with 24 hours. Values of backscattering strength were greatest when the ripple spacing was close to one-half the acoustic wavelength (1.95-cm versus 3.0-cm tine spacing) and when the strike of the ripples was perpendicular to the incident acoustic propagation path.

3.2 Acoustic Scattering Measurement at the Rail Tower

The manipulative experiments that were conducted later in SAX04 (18-19 October) and within the field of view of the acoustic rail had the benefit of good visibility, and a 4-m² quadrate that was free of surface mud deposits. This allowed the following quantitative analysis of the backscattering data (30-90 kHz) and a comparison to model simulations. Backscattering strength (Fig. 3) *versus* grazing angle shows a strong peak in scattering strength at 45 kHz for the grazing angles between 25° and 30°. These grazing angles correspond geometrically to backscattering from the raked quadrate (8-10 m from the base of the tower). Moreover, the tine spacing, and thus the ripple spacing of the raked sediment surface, is very close to the "Bragg wavelength" given by $\lambda/(2\cos\theta)$ for the acoustic wavelength (λ) at 45 kHz, where θ is the incident angle.

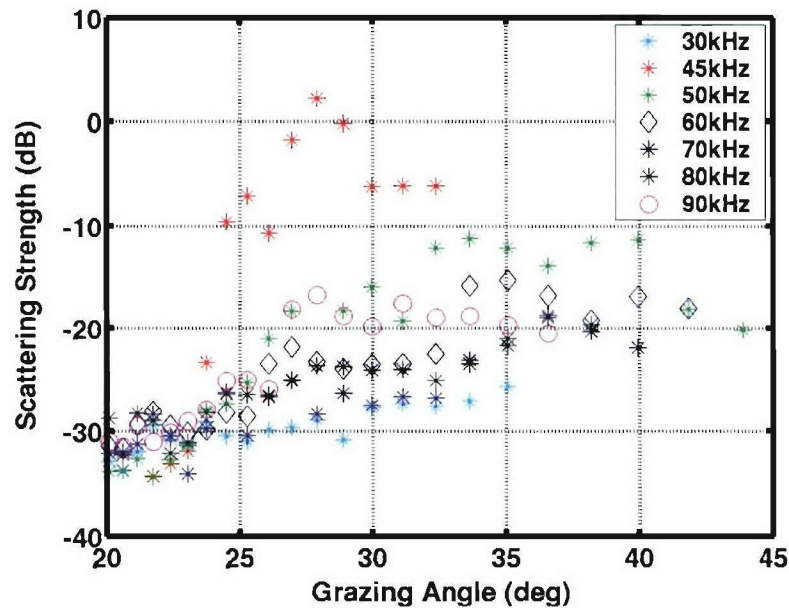


Figure 3. Backscattering strength (dB) vs. grazing angle measured over the frequency range of 20-90 kHz. Measurements were made within 10 minutes of raking the seafloor using a tine spacing of 1.95 cm.

3.3 Environmental Model

For the anthropogenic roughness a two-dimensional roughness spectrum measured during SAX99 was used. This spectrum was obtained from digital stereo camera data collected by A.P. Lyons [5]. This spectrum is composed of two power-law forms, and when properly symmetrized is expressed as the sum of four terms:

$$W(\mathbf{K}) = W_1(\mathbf{K}) + W_1(-\mathbf{K}) + W_2(\mathbf{K}) + W_2(-\mathbf{K})$$

where

$$W_n(\mathbf{K}) = \frac{w_{2n}/2}{[a_n^2 K_x^2 + (K_y - K_n)^2 + (1/L_n)^2]^{\gamma_{2n}/2}}.$$

(It should be noted that due to a typographical error, the spectrum given by Eq. (1) in [5] was not properly symmetrized. However, the proper symmetrized form was used for the model results described in [5].) The parameters K_n , $n = 1, 2$, allow introduction of spectral peaks. The parameters a_1 and a_2 control the anisotropy between the x and y directions in wavenumber space, $\mathbf{K} = (K_x, K_y)$. In matching the spectral data, the low-wavenumber behavior of the spectrum was set via W_1 with K_1 set to zero. Parameters a_1 , L_1 , w_{21} , and γ_{21} were set to 2, 3 cm, 0.05 cm^{-1} and 5, respectively, to match the low-frequency behavior of the measured spectrum. K_2 was set to the wavenumber of the anthropogenic roughness, $2\pi/(0.0195 \text{ m})$. The parameters a_2 , L_2 , w_{22} , and γ_{22} were set to 0.7, 7 cm, $0.002 \text{ cm}^{-1.5}$, and 2.5, respectively, to match the width of the measured peak due to the anthropogenic roughness and the spectral behavior at high wavenumbers. The mean-square ripple height is equal to the integral of the ripple spectrum over all $\mathbf{K}$, and yields an RMS roughness of $h = 0.0031 \text{ m}$. Similarly, the RMS roughness due to the low-wavenumber portion of the spectrum is 0.012 m .

There is considerable uncertainty in applying this spectrum to the SAX04 data, as it was not determined contemporaneously. Further, there are substantial statistical errors in this spectral estimate, which is based upon a single stereo photo pair. Nevertheless, this spectrum is a reasonable starting point, as it was central to the attempted model-data comparison reported in [5] and was obtained using the same raking procedure as in SAX04. The acoustic modeling and simulations to be described employ the mean values of sediment parameters given in Section 2.2 and a water sound speed of $1530 \text{ m}\cdot\text{s}^{-1}$. Changing the attenuation from the SAX99 to SAX04 value makes no discernable difference in the modeling results presented in the next section.

3.4 Acoustic Modeling

First-order, small-roughness perturbation theory was used to model the scattering strength as a function of grazing angle and frequency. The applicability of perturbation theory to a given rough interface is usually judged by the size of the dimensionless number, kh , where k is the acoustic wavenumber and h is the RMS roughness defined above. At 45 kHz, the frequency of primary interest in this data set, $kh = 0.57$. This is sufficiently small that perturbation theory should be valid [13]. As a check, exact 2-D Monte Carlo simulations using randomly-generated 1-D ripple realizations were

compared with perturbation theory. For 45 kHz with an RMS roughness $h = 0.004$ m, the exact result was approximately 3 dB below the perturbation result at a grazing angle of 28° . Given the smaller roughness estimate (0.0031 m) used in the model-data comparisons, the simulations should have little error due to the use of perturbation theory. Even though the low-wavenumber part of the spectrum has $kh = 2.2$, this is not a concern with regard to accuracy of perturbation theory at 45 kHz, as the wavelengths responsible for most of this roughness are longer than the acoustic wavelength and do not contribute appreciably to scattering.

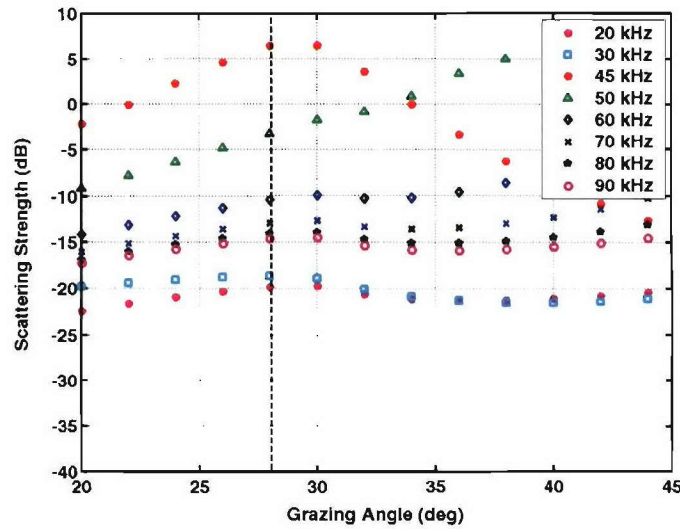


Figure 4. Simulated scattering strength vs. grazing angle at the SAX04 measurement frequencies, using SAX99 roughness parameters for the raked seafloor. The vertical dashed line indicates the grazing angle corresponding to the center of the raked patch. The approximate extent of the raked patch spans $\pm 3^\circ$ from this line, thus comparisons to measured backscatter strengths (Fig 3) should be restricted to this range of grazing angles.

Figure 4 shows the modeled scattering strengths *versus* grazing angle at each of the measurement frequencies. The measured and modeled backscattering strengths show a large peak for 45 kHz at the grazing angle corresponding to the treatment location. This peak is about 20 dB above the scattering strength levels at frequencies removed from the Bragg resonant frequency. As the data have essentially the same behavior, it can be concluded that roughness scattering is dominant in the raked location.

The simulated scattering strength at 45 kHz matches the measured value satisfactorily, given that the measured value is subject to a statistical fluctuation of about ± 2 dB due to finite sample size. In [5], the measured scattering strength was about 20 dB below the model prediction. It appears that the measurement errors listed in [5] were responsible for the lack of agreement. Detailed model-data comparisons are hampered by uncertainties in the roughness spectrum. In particular, uncertainty in the width of the spectral peak representing the ripple does not allow a serious discussion of frequency dependence.

Acknowledgements

We thank the Captain and crew of the RV Seward Johnson for providing the stable platform and support for acoustic experiments and diving operations. Diver support was provided by Chad Vaughan, Ricky Ray, Dan Lott, Paul Aguilar and Sam Sublett. SAX99 and SAX04 were supported by the U.S. Office of Naval Research.

References

1. Richardson, M. D. and 23 others, An overview of SAX99: Environmental considerations. *IEEE J. Ocean. Engin.* **26**, 26-53 (2001).
2. Thorsos, E. I., Williams, K. L., Chotiros, N. P., Christoff, J. T., Commander, K. W., Greenlaw, C. F., Holliday, D. V., Jackson, D. R., Lopes, J. L., McGehee, D. E., Richardson, M. D., Piper, J. E. and Tang, D., An overview of SAX99: Acoustics measurements. *IEEE J. Ocean. Engin.* **26**, 4-25 (2001).
3. Richardson, M. D., Briggs, K. B., Reed, A. H., Vaughan, C., Zimmer, M. A., Bibee, L. D. and Ray, R. I., Characterization of the environment during SAX04: preliminary results. In *Underwater Acoustic Measurements: Technologies and Results*, ed. by J. P. Papadakis and L. Bjorno, A conference held in Heraklion, Crete, 28 June – 1 July 2005.
4. Thorsos, E. I., SAX04 overview. In *Boundary Influences in High-Frequency, Shallow-Water Acoustics*, A conference held in Bath, UK, 5-9 September 2005.
5. Richardson, M. D., Briggs, K. B., Williams, K. L. and Jackson, D. R., Effects of changing roughness on acoustic scattering: (2) anthropogenic changes, pp. 383-390. In *Acoustical Oceanography, Proc. Inst. Acoust.*, Vol. 23, pt. 2, ed. by T. G. Leighton, G. J. Heald, H. D. Griffiths and G. Griffiths (Inst. Acoust., Bath, 2001).
6. Jackson, D. R., Williams, K. L. and Briggs, K. B., High-frequency observations of benthic and temporal variability. *Geo-Mar. Lett.* **16**, 212-218 (1996).
7. Williams, K. L., Light, R. D., Miller, V. W. and Kenney, M. F., Bottom mounted rail system for Synthetic Aperture Sonar (SAS) imaging & acoustic scattering strength measurements: design/operations/preliminary results. In *Underwater Acoustic Measurements: Technologies and Results*, ed. by J. P. Papadakis and L. Bjørnø, A conference held in Heraklion, Crete, 28 June – 1 July 2005.
8. Zimmer, M. A., Bibee, L. D. and Richardson, M. D., Acoustic velocity dispersion measurements in seafloor sands from 1 to 400 kHz. In *Boundary Influences in High-Frequency, Shallow-Water Acoustics*, A conference held in Bath, UK, 5-9 September 2005.
9. Buckingham, M. J. and Richardson, M. D., On tone-burst measurements of sound speed and attenuation. *IEEE J. Ocean. Engin.* **27**, 429-453 (2002).
10. Briggs, K. B., Zimmer, M. A. and Richardson, M. D., Spatial and temporal variations in sediment compressional wave speed and attenuation measured at 400 kHz for SAX04. In *Boundary Influences in High-Frequency, Shallow-Water Acoustics*. A conference held in Bath, UK, 5-9 September 2005.
11. Briggs, K. B., Tang, D. and Williams, K. L., Characterization of interface roughness of rippled sand off Fort Walton Beach, Florida. *IEEE J. Ocean. Engin.* **27**, 505-514 (2002).
12. Lyons, A. P., Fox, W. L. J., Hasiotis, T. and Pouliquen, E., Characterization of the two-dimensional roughness of wave-rippled sea floors using digital photogrammetry. *IEEE J. Ocean. Engin.* **27**, 515-524 (2002).
13. Thorsos, E. I., Jackson, D. R. and Williams, K. L., Modeling of subcritical penetration into sediments due to interface roughness. *J. Acoust. Soc. Am.* **107**, 263-277 (2000).