Effects of changing roughness on acoustic scattering: (2) anthropogenic changes

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Abstract

Deliberate modification of bottom roughness, including smoothing to eliminate centimetre scale natural roughness and raking to induce quasiperiodic roughness, was investigated using diver observations, quantification of bottom roughness from stereo photography, and measurement of acoustic backscattering strength. At 40 kHz, raking perpendicular to the acoustic line-of-sight with a tine spacing equal to one-half wavelength increased scattering by 12-18 dB, which decayed to background levels within 24 hours due to biological modification of seafloor roughness. Raking parallel to the acoustic line-of-sight had little effect. Measured and modelled acoustic scattering strengths are not in total agreement suggesting, a failure of perturbation theory for these roughness conditions.

1. Introduction

Acoustic seafloor scattering and penetration experiments were conducted in the northeastern Gulf of Mexico (30°22.7'N; 86°38.7'W) as part of the Office of Naval Research (ONR) Seafloor Acoustic Experiment – 1999 "SAX99". Thorsos *et al*. [1] and Richardson *et al.* [2] describe the overall objectives of these experiments and report preliminary environmental and acoustic results. As part of those experiments, temporal changes in backscatter strengths were measured and correlated with the changes in seafloor roughness that were induced and/or altered by environmental and anthropogenic processes. Briggs *et al.* [3], in this issue, describe the effects of hydrodynamic and biological processes on natural seafloor roughness and the subsequent temporal changes in high-frequency seafloor scattering strengths. In this paper, we present the effects of artificial manipulations of the seafloor on seafloor roughness and acoustic backscattering strengths and the subsequent decay of roughness and reduction of scattering strengths that result from biological modifications of the artificially manipulated seafloor. Scattering strengths, based on seafloor roughness and physical properties, were predicted using perturbation theory [4] and compared to measured scattering strengths.

2. Methods

2.1 Acoustic Measurements

Acoustic backscattering measurements were made at 40 kHz with the Benthic Acoustic Measurement System (BAMS) [4]. BAMS is autonomous system, which allows acoustic scattering measurements to be made within a 30-40 meter radius circle around the bottom-mounted tower. A 40 kHz transducer is mounted 3.2 meters above the seafloor at the apex of the BAMS tripod. The transducer has a horizontal beam width of 5 degrees and uses a FM pulse to obtain a 0.4 m range resolution. The water depth of 19 meters and height of the BAMS transducer above the seafloor restricted the effective radius of backscatter measurements to 18 meters because of interference from scattering from the air-water interface. BAMS rotates in 5° increments with about 6 minutes required for a full 360° rotation. Measurements were made once every 90 minutes during the first 18 days of the experiments (7-25 October) and once every 30 minutes for the last 11 days (26 October -5 November). During the time of the experiments 600 scans were carried out by BAMS. Seafloor manipulations (section 2.4) carried out in the field of view of BAMS were scheduled to try to avoid periods when it was transmitting. The BAMS transducer resolution allowed 9 values of scattered intensity to be calculated in each 2 m by 2 m manipulation area. The 9 intensity values were averaged and scattering strengths determined.

2.2 Seafloor characteristics

In situ and laboratory methods were used to characterize surficial sediment physical properties near the BAMS tower [1]. Based on two short cores (16 cm in depth) collected by divers at the BAMS site, the sediment is comprised mostly of medium-sized quartz sand (0.25 to 0.50 mm grain size) with low porosity (36-38 %) and high density (2060-2100 kg m^3). *In situ* values of sound speed (1730-1771 m s^{-1}) and attenuation (8.6-17.2 dB m^{-1} at 38 kHz) measured near the BAMS site were typical for medium-sized sand. For modelling acoustic scattering (section 4), mean values of sound speed ratio (1.14), density ratio (2.033) and loss parameter (0.0102) were used.

2.3 Sediment manipulations

Seafloor manipulations were conducted in 4 meter square areas located between 10 and 12 meters from the center of the BAMS tower. Divers used plastic tent stakes and # 18 nylon mason twine to mark off five separate experimental areas. Two of these were used for the discrete scattering experiments described by Williams *et al*. [5], in this volume, and two others were used for the roughness manipulations described in this paper. Exact locations relative to the acoustic tower were determined by use of 0.2 m liquid butane filled target spheres set just behind each of area prior to experimental manipulations. A serrated dry wall knife “Bragg rake” with 45° pitch and 19.5 mm wavelength teeth was used to create a roughness either parallel or perpendicular to the direction of the incident acoustic energy. Prior to each manipulation divers smoothed the sediment surface removing any residual fine scale roughness.

2.4 Bottom roughness measurements

Digital and analog stereo-pair photography was used to characterize the changes in seafloor roughness [1,3]. Over 75 analog stereo photographs were made at the BAMS tower experiments before (5 October) and during (19, 22, 23, 26, 27, 29 October and 4 & 5 November 1999) the manipulative experiments using a Photosea 2000 diver-operated stereo camera. Digital stereo photographs were also made using a pair of Kodak DC120 digital cameras mounted on a frame, which was directly hardwired to research platform located approximately 150 meters west of the site of the BAMS tower. Photographs were made before and after raking under the camera platform (4-7 November 1999) for periods up to 12 hours after manipulative raking in order to document the decay of roughness previously observed by divers. Analog stereo photographs were analysed by digitising roughness height values at regularly spaced intervals (0.105 cm) using a Benima (Hasselblad) AB photogrammetric stereocomparator. The stereo comparator enabled digitisation of bottom roughness with a horizontal accuracy of nearly 0.01 mm. Three 54 cm long profiles oriented parallel to the azimuth of the acoustic transmitter were digitised from each of the stereo photographic images. The roughness profiles were evaluated for height fluctuations as a function of spatial frequency with the roughness power spectrum suggested by D. Percival of the Applied Physics Laboratory-University of Washington [3]. Periodograms were filtered by the ensemble averaging of spectra derived from digitised data collected from the same site, orientation and date. The stereo-correlation of digital images using area-based matching was performed by the Desktop Mapping System (DMS) by R-Wel Inc. 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 [7].

3. Results

3.1 Backscatter Strengths

Backscatter strengths show considerable variability over the 15 days (21 October through 5 November 1999) of the experimental manipulations (Figures 1-3). Most obvious are the 12-18 dB increases in scattering strength after raking orthogonal to the radial path of acoustic ensonification. In all cases of orthogonal raking, there was a rapid decrease in scattering strength to the average or ambient backscatter strength (-32 dB) within 24 hours (Figure 3). Raking parallel to the path of acoustic ensonification had a much smaller effect with an occasional increase in scattering strengths followed by an almost immediate return to background scattering strengths. It is possible that the presence of divers manipulating or photographing the bottom may have contributed to short-term increase in scattering strengths. Smoothing the bottom generally resulted in a decrease in backscattering strengths, especially for areas previously raked.

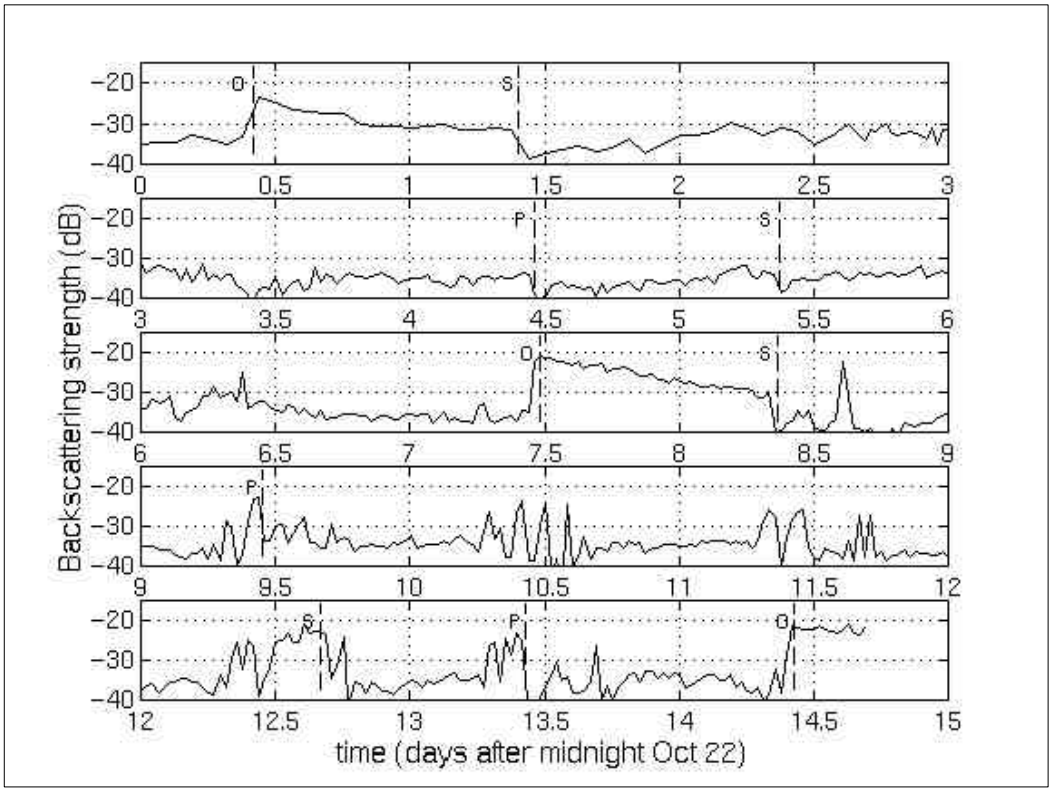

Figure 1. Backscatter strength measured at site # 4 where the seafloor roughness was artificially altered by smoothing the seafloor or raking either parallel or orthogonal to the incident acoustic energy. Time is measured relative to 0000 hours on October 22 1999. Vertical dashed lines indicate time of manipulations: (S) smoothing, (O) raking orthogonal, and (P) raking parallel.

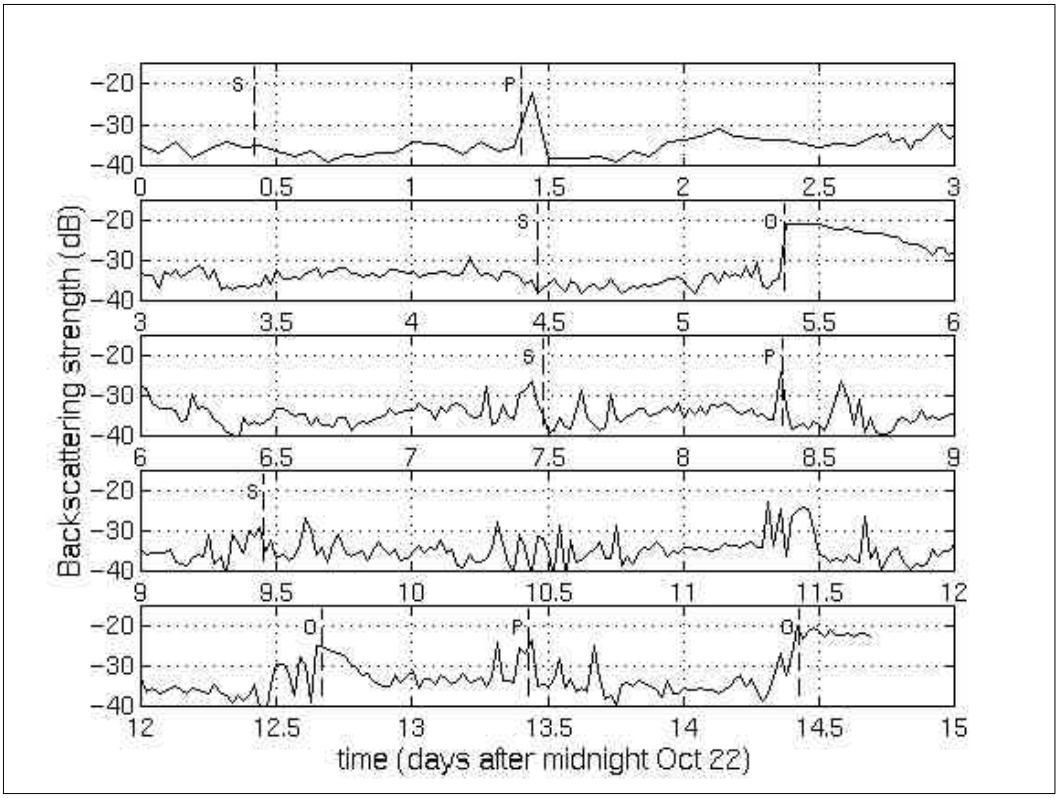

Figure 2. Backscatter strength measured at site # 5 where the seafloor roughness was artificially altered by smoothing the seafloor or raking either parallel or orthogonal to the incident acoustic energy. Time is measured relative to 0000 hours on October 22 1999. Vertical dashed lines indicate time of manipulations: (S) smoothing, (O) raking orthogonal, and (P) raking parallel.

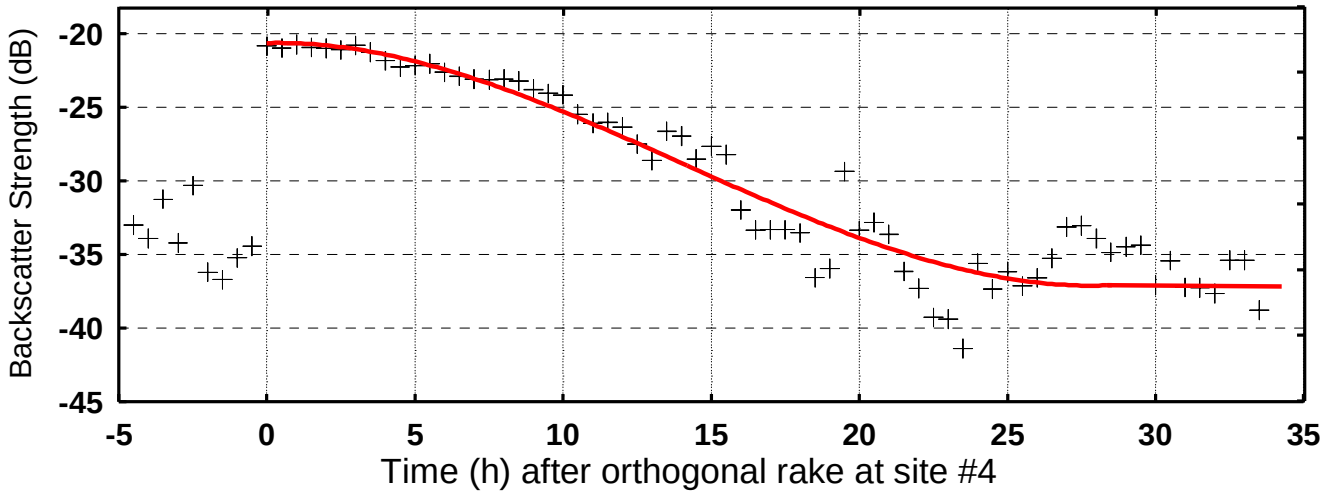

Figure 3. Decay of acoustic scattering after raking orthogonal to the incident acoustic energy. Background scattering strengths were averaged –32 dB but were closer to –35 dB at this area.

3.2 Diver and photographic observations

Divers observed a rapid decay in roughness patterns created by raking the seafloor (Figure 4). The decay of induced roughness patterns was the result of the activities of a variety of fish and bottom dwelling invertebrates common to this environment. Flounder, pinfish, crabs, and gastropods were observed, directly by divers and remotely by bottom photography, altering seafloor roughness. Bottom currents measured using bottom-mounted ADCP (< 30 cm s^{-1} at 2 m above the seafloor) and surface gravity waves (< 1.0 m significant wave heights) were generally insufficient to initiate particle motion, given the 19 m water depth and grain size of the sandy substrate [1].

3.3 Quantification of bottom roughness

Both digital and analog stereo pair photographs were used to quantify bottom roughness power. The artificial anisotopic roughness generated by raking the seafloor and the subsequent return to isotopic roughness are evident in two-dimensional roughness spectra generated from the stereo photographs presented in Figure 4. Prior to the raking (SAX 27) the mean values of the slope and intercept of the roughness spectrum varied little with azimuth (Figure 4 and Table 1). After raking (SAX 28) there was a significant azimuthal dependence (Table 1).

Slice	slope	intercept ($x10^{-5}$ m^4)	Time after raking
SAX 27 (angular average)	-3.03	1.18	before
SAX 27 (0 degrees)	-3.19	2.07	before
SAX 27 (45 degrees)	-3.29	1.65	before
SAX 27 (90 degrees)	-3.08	1.06	before
SAX 27 (135 degrees)	-3.25	1.33	before
SAX 28 (0 degrees)	-2.60	0.16	6 minutes
SAX 28 (90 degrees)	-3.30	16.40	6 minutes
SAX 32 (0 degrees)	-2.73	0.31	6 hours
SAX 32 (90 degrees)	-3.35	9.26	6 hours
SAX 33 (0 degrees)	-2.84	0.72	7 hours
SAX 33 (90 degrees)	-3.20	3.32	7 hours
SAX 34 (0 degrees)	-3.14	1.93	16 hours
SAX 34 (90 degrees)	-3.14	2.04	16 hours

Table 1. Values of slope and intercept for 2-D spectra estimated from the digital images

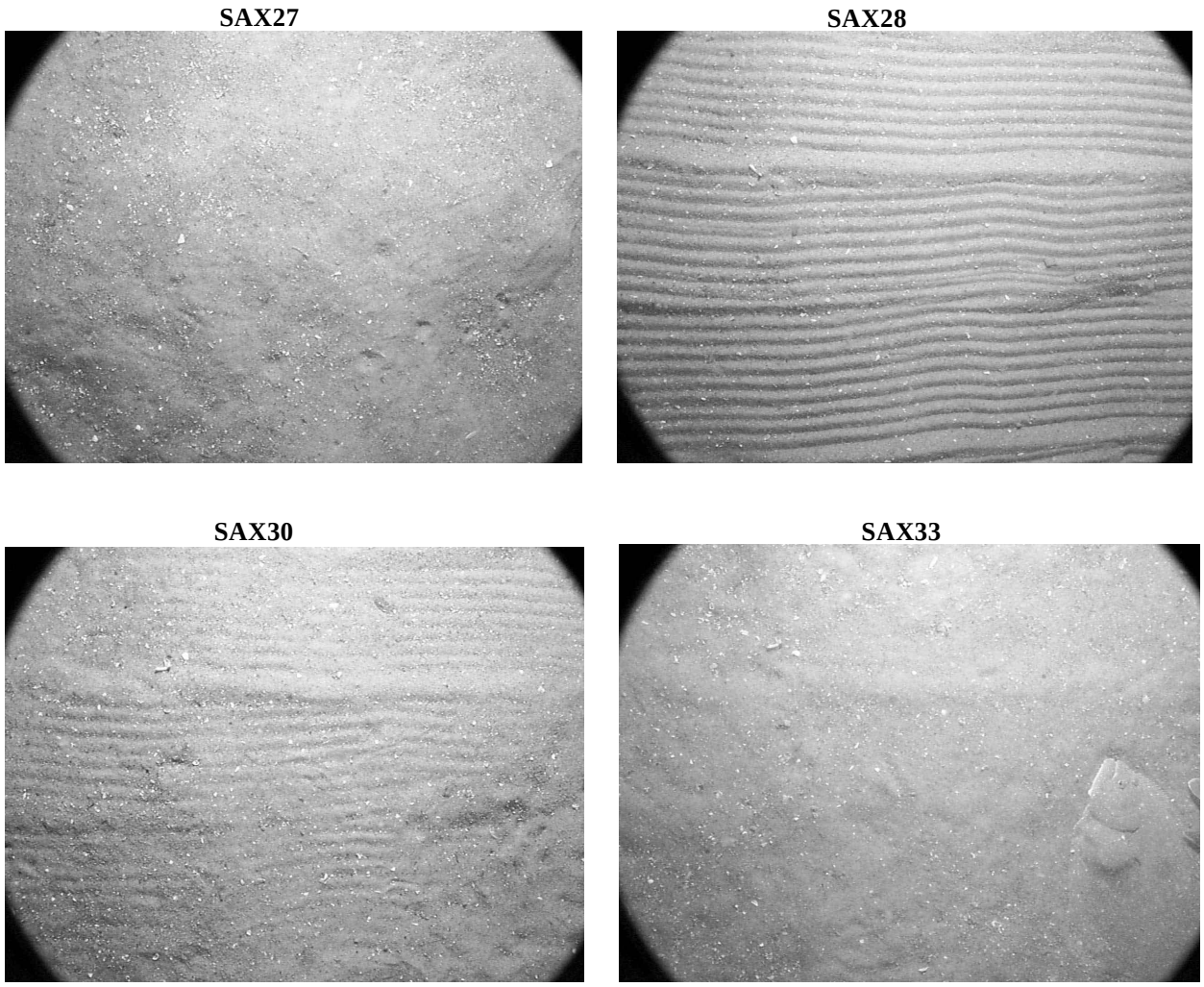

Figure 4. Photographs taken 91 cm from the seafloor using a Kodak DC120 digital camera with a resolution of 1280 x 960 pixels. The photographs show the seafloor under the camera frame (A) before manipulation, (B) 6 minutes after raking, (C) 3 hours after raking, and (D) 7 hours after raking. The wavelength of the raked seafloor is 19.5 cm. A flounder, partially responsible for the decay of the anthropogenic changes in the seafloor, can be seem in the lower right-hand corner of photograph D.

The azimuthal dependence and spectral content of bottom roughness returned to pre-raked conditions after less than 24 hours. The photographic observations (Figure 4) of temporal changes in bottom roughness are very similar to the diver and photographic observations made near the BAMS tower, although the rates of decay of bottom roughness created by raking may be more rapid under the digital camera compared to near the BAMS tower. This more rapid decay probably results from a higher density of megafauna capable of altering bottom roughness under the camera compared to near the BAMS tower. Larger megafauna may be attracted to the camera frame or to the presence of a ship just above the camera frame. Divers noted a much greater density of small and large fish swimming in the water column near the ship compared to the BAMS tower, which was 150 m distant. The presence of this pelagic fauna not only provides prey for larger fauna but increases the amount of surficial sediment organic detritus, a potential source of food, under the ship. The artificial manipulation of the bottom may also dislodge buried macrofauna at either site thus attracting predators which, in turn, are responsible for the decay of the anthropogenic changes of the seafloor. We realize that our presence alters the experimental results, especially rates of biological processes, and that the artificial nature of our seafloor manipulations does not mimic natural hydrodynamic or biological processes at the sediment-water interface. The experimental manipulations do however provide an opportunity to test acoustic scattering models under controlled conditions and provide insights into the effects of natural processes on seafloor acoustic scattering.

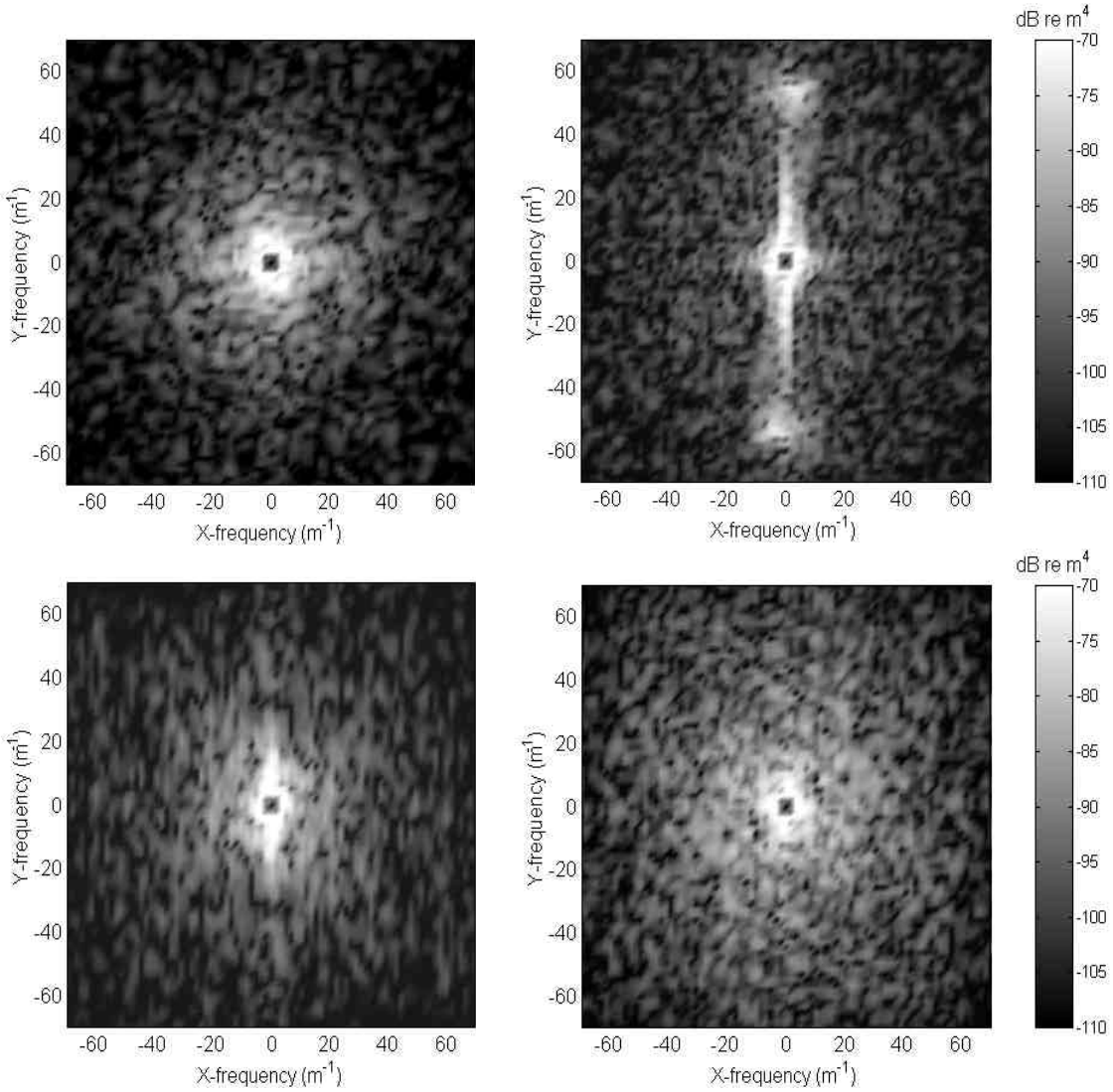

Figure 5. Two-dimensional height spectral density levels (dB re m^4) calculated from the stereo pair photographs depicted in Figure 4.

The bottom roughness spectral exponent and strength was also calculated from analog stereo photographs made near the BAMS tower during the manipulative experiments. Seven pairs of photographs were chosen to represent roughness spectra before manipulations (BA-1-2-3 on 19 October 1999), raking orthogonal to the incident acoustic energy (BB-1-2 on 22 October 1999) and parallel to the incident acoustic energy (BC-9-10 on 23 October 1999). The area used for stereo photographs before manipulations and for orthogonal raking was directly north of the BAMS tower and all roughness spectra were calculated along a north-south heading, whereas the parallel raking was conducted in an area west of the BAMS tower and the roughness spectra were calculated along a east-west heading. These roughness data show the same trends as in the 2-D spectrum (Table 1). Raking increased the mid-to-high frequency components (>0.3 cycles cm^{-1}) of the spectrum representing roughness orthogonal to the direction of raking while having little effect to the mid-to-high frequency components in the parallel direction (Figure 6). The apparent reduction in lower frequency components (<0.1 cycle cm^{-1}) in the parallel direction may be the result of smoothing of the seafloor prior to raking or to the azimuthal orientation of the sampling areas. The along-strike orientation of the larger surface gravity wave-induce ripples was approximately east-to-west. Roughness spectra calculated from the digital and analog images are used as inputs to acoustic models in section 4.

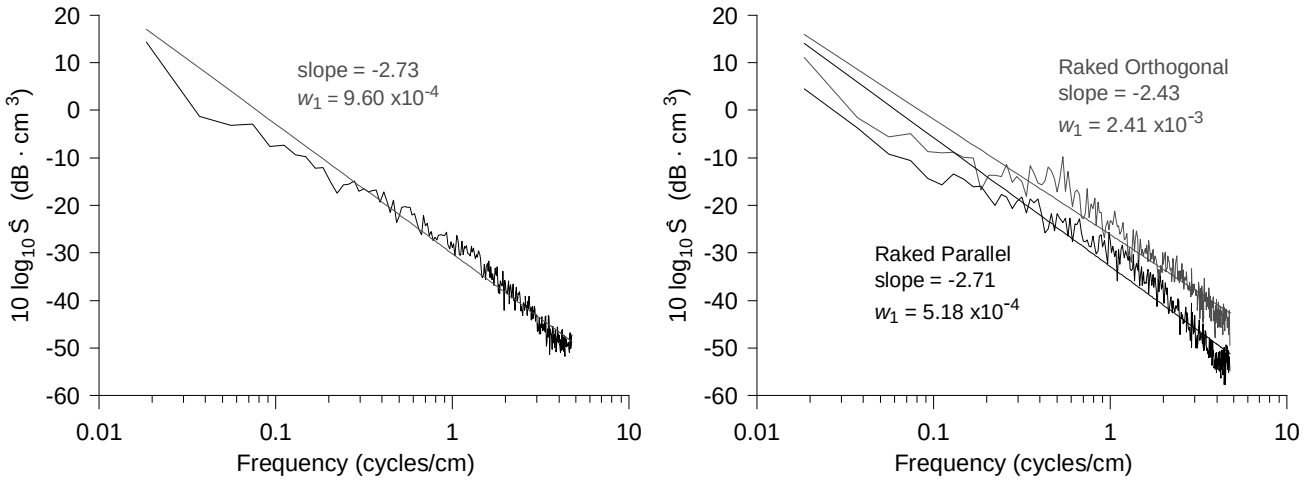

Figure 6. One-dimensional roughness spectrum calculated from stereo photographs taken near the BAMS site prior to anthropogenic manipulations (left) and orthogonal and parallel to raking areas near the BAMS towers. Three lines per photograph for a total of 9 lines prior to manipulations and 6 lines parallel and orthogonal to the raking were averaged to obtain these power spectra.

4. Acoustic modelling

Scattering from surface roughness is the major contributor to backscattering at 40 kHz at the SAX99 experimental site [2]. Scattering due to surface roughness was modeled as in [5], thus excluding the effects of volume heterogeneity. It is important to note for what follows that this model is based on perturbation theory. The model requires as inputs the ratio of the longitudinal sound speed in the sediment to that in the water, their density ratios, the attenuation of sound in the sediment as incorporated into a loss parameter, and the 2d spectrum of the bottom roughness. The sound speed ratio (1.14) and the loss parameter (0.0102) were measured *in situ* and the density ratio (2.033) was measured from core samples (see section 2.4).

For natural roughness conditions the 2d spectrum was modeled as a power law, i.e., $W(K) = (w_2)/K^{?}_{2}$ where K is the magnitude of the two-dimensional wavevector (in radians/cm). The parameters g_2 and w_2 are related to the slope and intercept measured using the analog stereo camera as given in [6]. Using an average of the roughness from Oct. 23 and Nov. 5 (see Figure 6), a time period when the spectral measurements from the natural seafloor seemed stable, the values obtained by fitting the average spectrum in the 0.2 to 2 cycle/cm range were w_2=0.00397 cm$^{0.95}$, $g_2 = 3.05$. (Note that the dimensions of w_2 equal cm$^{4-g_2}$ so that the integration of $W(K)$ gives units of cm^2). The 95% confidence limits of the spectral estimate translate to a range for w_2 of 0.0020 to 0.0066. With these parameters, the model predicts a scattering strength between –31 and –26 dB. This range of values is slightly higher than the average measured values of scattering strength for natural conditions [3]. The uncertainty in the scattering strength measurements is estimated to be +/- 1.5 dB.

For the anthropogenic roughness a two-dimensional roughness spectrum measured via digital stereo camera (Figure 5 and Table 1) was used to fit a two dimensional roughness model that is the sum of two power law spectra, of the form

$$W(K) = \frac{(w_{21}/2)}{\left[a_1 K_x^{\,2} + (K_y - K_{01})^2 + (1/l_{21})^2\right]^{g_{21}/2}} + \frac{(w_{22}/2)}{\left[a_2 K_x^{\,2} + (K_y - K_{02})^2 + (1/l_{22})^2\right]^{g_{22}/2}} \qquad (1)$$

The parameters K_{01} and K_{02} allow introduction of spectral peaks. The parameters a_1 and a_2 control the anisotropy between the x and y directions in wavenumber space (K_x, K_y) that is in addition to any spectral peaks. In matching to the spectral data, the low wavenumber behavior of the spectrum was set via the first term on the right hand side of (2) with K_{01} set to zero. Parameters a_1, l_{21}, w_{21}, and g_{21} were set to, 2, 3 cm, 0.05 cm^{-1} and 5, to match the low frequency behavior of the measured spectra. K_{02} was set to the wavenumber of the anthropogenic roughness, 2p/(0.0195 m). The parameter a_2, l_{22}, w_{22}, and g_{22} were set to, 0.7, 7 cm, 0.002 cm$^{1.5}$ and 2.5, to match the width of the measured peak due to the anthropogenic roughness and the spectral behavior at high wavenumbers.

When the model was used with these parameters it predicted a scattering strength of –30.9 dB for the parallel raking treatments and a scattering strength of +0.7 dB for the orthogonal raking. It is somewhat difficult to assess

uncertainties in these results given the method of the fits to this point. However the parallel raking results seem to be consistent with the model/measured results for natural conditions where the measured values of backscatter strength are slightly higher than model predictions (Figures 1-3). However, the model results for the orthogonal raking are on the order of 20 dB higher than the data. At present, we believe this is due to a combination of factors, all of which tend to increase the discrepancy between theory and experiment. Misalignment of the sonar pointing direction relative to the normal to the raking direction is one such factor as is degradation in the ripple pattern due to bioturbation. A further reduction in signal level is expected due to partial saturation of the measurement system, as recorded signal levels were at times near the maximum allowed by the analog-to-digital converter. Finally, it is likely that perturbation theory overestimates scattering levels and that a more accurate theory, such as the small slope approximation [8], should be used. None of these factors is expected to contribute more than 3-6 dB to the discrepancy, but collectively, they could account for the 20 dB difference between experiment and theory.

5. Conclusions and Speculations

It is obvious from our data that anthropogenic modifications of seafloor roughness can result in significant changes in backscatter strength and these changes in roughness and scattering strength decay rapidly as a result of the bioturbation. The lack of agreement between measured and modelled acoustic scattering strengths for conditions where raking was orthogonal to the incident acoustic energy suggest a failure of perturbation theory for these roughness conditions. Further acoustic modelling work is needed. The question remains as to what insights into the effects of natural phenomenon on seafloor roughness and subsequent acoustic bottom scattering can be gained from these manipulation experiments. Similar seafloor roughness manipulations were conducted in the field of view the Sediment Transmission Measurement System (STMS) tower over the acoustic frequencies in the 10-150 kHz range [2]. These data should provide backscatter data both below and above the ½ wavelength tine spacing “Bragg frequency” reported in this paper.

Under storm conditions typical to the northeastern Gulf of Mexico, wave-induced ripples with 50-100 cm wavelengths and 5-15 cm amplitudes are to be expected directly after a storm [1]. Weeks-to-months are required for biological processes to destroy the anisotopic roughness structure [3]. Under winter conditions, with frequent storms the ripple fields are often rebuilt before they can be destroyed. Based on these manipulation experiments, it should be expected that the temporal changes in longer wavelength seafloor roughness (ripples) created by waves and destroyed by biological processes should result in significant temporal changes in values of lower frequency acoustic scattering. Work supported by the Office of Naval Research (ONR) and Naval Research Laboratory Program Element 061153N.

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