Mid Frequency Sonar Backscatter Measurements from a Rippled Bottom

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Abstract. Seafloor ripple reverberation is associated with a peak in the scattering frequency spectrum at a frequency around $c/(2\lambda_r \cos\theta)$, where c is the sound speed in water, λ_r is the ripple wavelength, and θ is the incident grazing angle. In the vicinity of this peak, perturbation theory predicts the reverberation level to be high enough to be a concern for detection of targets buried under ripple. In order to validate such predictions, an experiment was conducted in the Naval Surface Warfare Center Panama City (NSWC-PC) Facility 383, which is a 13.7-m deep, 110-m long, 80-m wide test pool that has 1.5 m of sand covering the bottom. Backscatter reverberation levels from two bottom configurations were measured using a parametric source that was operated in the 1 to 10 kHz frequency range. One bottom configuration corresponded to a non-rippled, near-flat bottom. The second was a rippled bottom with a Gaussian spectrum centered on a wavelength of 20 cm. The rippled bottom was artificially formed with the aid of a sand scraper. Results showed the reverberation levels were significantly higher in the 3 to 5 kHz frequency range for the rippled bottom than for the non-rippled bottom. The maximum reverberation level for the rippled bottom occurred at 4 kHz, which is consistent with perturbation theory predictions.

INTRODUCTION

There is an interest in using sonar systems that operate in the Mid Frequency (MF) regime, taken here to be 1 to 10 kHz, for seafloor reconnaissance in littoral areas. In this frequency range, longer detection ranges are possible when compared to sonar systems that operate at higher frequencies. In addition, in the MF regime, penetration into a sandy bottom is possible and may permit the detection of buried targets. A critical component impacting sonar performance against bottom targets is bottom reverberation. In this frequency range, bottom reverberation will consist of scattering from the interface, within the sediment volume, and any layers within the sediment volume. The dominant mechanism is dependent upon sonar frequency, grazing angle, and the water-sediment interface roughness. If ripples are present, scattering from the interface may be a significant source of reverberation. The frequency of the dominant scattering peak associated with rippled interface roughness readily follows from first-order perturbation theory to be

$$f = c/\left(2\lambda_r \cos\theta\right). \tag{1}$$

Here c is the sound speed in water, λ_r is the ripple wavelength, and θ is the incident grazing angle. Thus, for a 20^o grazing angle and ripple wavelengths of 20 cm and 100 cm, the scattering peak will be near 4 kHz and 0.8 kHz, respectively. This may impact MF sonar's capability against bottom targets, whether these targets are proud, partially buried, or completely buried.

This point is clearly illustrated in Fig. 1, which shows model predictions of backscatter from a buried target insonified at a subcritical grazing angle.[1] In this model the roughness on the interface over the buried target is represented as ripple with a shifted Gaussian spectral distribution in a given direction, combined with an isotropic small-scale roughness with a power law spectral distribution. The model uses perturbation theory to calculate penetration and reverberation. The figure shows predictions associated with a ripple orientation of 0^o (acoustic propagation direction perpendicular to the ripple crest) and with mean ripple wavelengths of 25, 50, and 75 cm. In each case the projected beam is incident on bottom sediment at a 10^o grazing angle, the reverberating area is assumed to be 40 cm long by 15 cm wide, and the target has a target strength of about -11 dB. The ripple has a 2-cm root-mean-square (RMS) height, and the top of the target is buried under 6.4 cm of sand. The solid lines designate the backscatter from the target, while the dashed lines correspond to reverberation levels. The salient point to note is that, in part of the MF region, the model predicts a negative signal-to-noise ratio due to high reverberation levels from these ripples. In addition, the frequency in which these high reverberation levels appear are dependent upon ripple spacing as described above. Thus, a sonar operating at a higher frequency than an MF system may detect buried targets while an MF system might not detect the same target.

The scientific community lacks specific information on MF bottom scattering strength that is necessary for careful evaluation of sonar systems. The objective of this work is to measure the reverberation levels from a rippled bottom under controlled conditions in the MF frequency range and compare these levels to predictions of the model. This paper documents the progress to date of this effort. In particular, the backscatter levels obtained from a rippled bottom are compared to those collected from a non-rippled bottom as well as to predictions of a model that uses first-order perturbation theory.

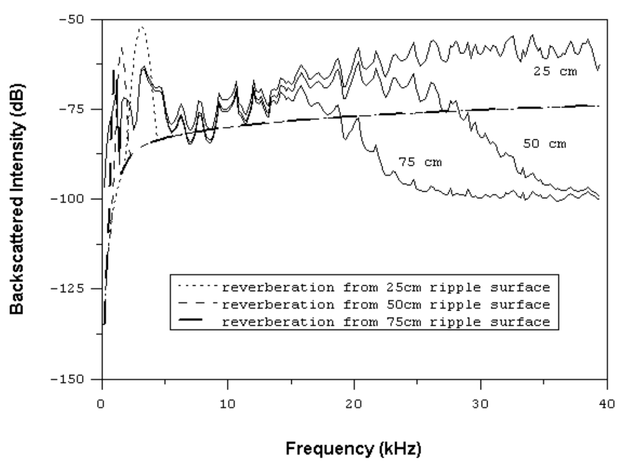

FIGURE 1. Backscatter predictions for various ripple wavelengths.

MEASUREMENT SETUP

The measurement was conducted in the Naval Surface Warfare Center - Panama City (NSWC-PC) Facility 383 test pool, which is shown in Fig. 2. This is a fresh-water pool that is 13.7 m deep, 110 m long and 80 m wide with approximately 1.5 m of sand covering the bottom. A filtration system provided approximately 12 m (~ 40 ft) water visibility and mixed the water column. The sound speed in the water was measured to be 1495 m/s with no velocity gradients.

The scattering geometry is depicted in Fig. 3, which corresponds to a view from directly overhead. The scattering region consisted of a bottom area that had rippled and non-rippled regions, and the experimental equipment included a rail system with a sonar tower, a parametric sonar, a transducer located next to the parametric sonar, and a free-field transducer. In addition, a sand-scraping apparatus was used to create the ripple profile on the bottom sediment. Each of these components is described below.

FIGURE 2. Aerial view of Facility 383.

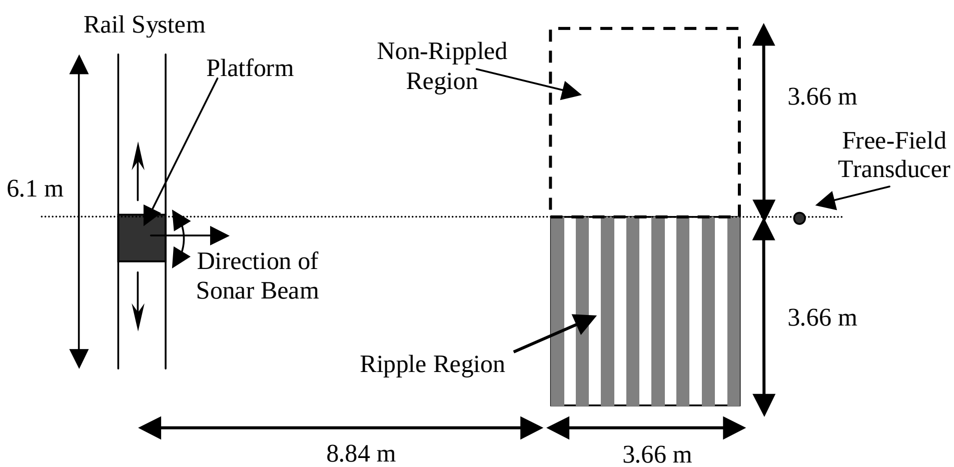

FIGURE 3. Scattering geometry.

The bottom area, from which the backscattered signals were recorded, was approximately 7.32 m in width by 3.66 m in length. This area started about 8.84 m from the rail system (see Fig. 3) and consisted of two adjacent bottom regions. One region corresponded to a non-rippled bottom while the second was a rippled bottom. Both of these regions were about 3.66 m in length by 3.66 m in width. The non-rippled bottom was somewhat flat and was created by divers dragging a weighted bar over its surface. The contour of the rippled bottom was artificially formed with the aid of a sand scraper, which consisted of a frame and a “rake” that glided along the frame. The rake was pulled across the sand using two winches, one located on each side of the test pool. The ripple profile was determined by an insert placed on the rake. Previous measurements using the sand scraper have shown good agreement between the intended ripples (wavelength and RMS height) and those formed.[2,3] In this measurement, the one ripple profile formed had a 0.57-cm RMS height and was consistent with a Gaussian spectrum having a 20 cm center wavelength and 0.000987cm^{-2} wavenumber variance.

A rail system that sat on the bottom sediment was also used in the measurement. A photo of the rail system is shown in Fig 4. The system included a 6.1-m (20-ft) long rail, a platform on wheels that was translated along the rail using a translation motor, and a sonar tower. A 2.1-m long extender attached the sonar tower to the platform and permitted the sonar tower to stand 3.89 m above the bottom sediment. This geometry provided insonification at the center of the two bottom regions at a 20^{o} grazing angle.

The sonar tower supported a parametric sonar, a receiver, and scanning (horizontal pan and vertical tilt) motors such that both transducers had an almost 360^{o} (180^{o}) rotational (tilt) capability. The parametric sonar was developed for NSWC-PC by the Naval Underwater Warfare Center – Newport (NUWC/NPT) and was employed as the projector. This sonar produced a conical beam with a 3-dB beam width of about 5^{o} with side lobes that are down by approximately 50 dB across its entire operational frequency band of 1 to 20 kHz. This sonar was oriented such that the direction of its main response axis (MRA) was perpendicular to the rail. An International Transducer Corporation (ITC) 1001 transducer was located next to the parametric sonar as shown in Fig. 5. This transducer has an omni-directional response and was used to record the backscattered signals from the bottom. The parametric sonar and ITC 1001 transducer could be translated linearly to any position along the rail, enabling the acoustic beam to be projected to, and received from, either the rippled or non-rippled bottom region. An encoder that employed a wire cable attached to the platform was used to verify the position of the platform as it translated along the rail, and a pendulum tilt sensor was used to monitor the inclination angle of the parametric sonar’s MRA.

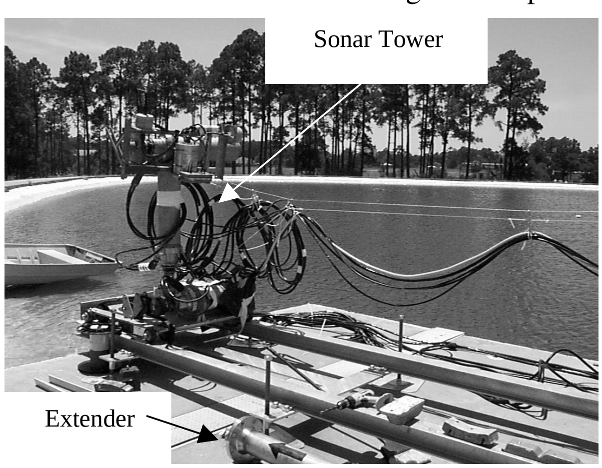

FIGURE 4. Photo of rail system.

FIGURE 5. Photo of parametric sonar (bottom) and ITC 1001 transducer (top).

The free-field transducer indicated in Fig. 3 was an ITC 1001 transducer. This transducer was placed on the bottom about 12.9 m from the rail system and was used to record the waveforms and levels transmitted by the parametric sonar.

Transmitted signals were generated using a National Instruments DAQ Card-6062E digital-to-analog board at a sample frequency of 500 kHz. These signals were amplified and then sent to the parametric sonar. Transmit signals were sinusoidal waveforms with a pulse length of 1 ms. The received signals were amplified and filtered, then digitized by a GageScope analog-to-digital card. All receive signals were sampled at a frequency of 1 MHz.

The procedure for preparing the scattering regions was as follows. First, divers deployed the rail system to the desired location in the facility. Next, the non-rippled, bottom region was flattened by divers. Third, the sand scraper was carefully positioned at the appropriate location from the rail system. Fourth, ripples were formed with the sand scraper, which took several iterations to ensure a well-formed bottom contour. Next, divers carefully removed the sand scraper, and then they visually re-inspected the formed bottoms by swimming either well above, or around the perimeter of, the two bottom regions. After the divers confirmed that the two bottom contours were reasonably well formed, acoustic data were acquired.

Data were obtained in the frequency range of 2 to 10 kHz at an average grazing angle of 20^{o} by translating the rail platform and taking data in about 2.5-cm (1-inch) increments. The waveforms recorded at each rail location were the resultant of an 8-ping average.

RESULTS AND DISCUSSION

Data Reduction

MATLAB code was written to read and analyze the collected data. The data were first processed and displayed in a backscattered intensity image. This image is a plot of the backscatter intensity (in dB) in range versus sonar location along the rail system. The processed data were further analyzed to determine the calibrated bottom backscatter level from the rippled bottom region. An estimate of the reverberation level was determined by taking an average of the reverberation intensities in a patch of about 1.3 m wide in cross-range by 1 m long in range. The calibrated backscatter level, EL in dB, was calculated using,

$$EL = EL_{MEASURED} - SPL_{INTERFACE.} \qquad (2)$$

Here $EL_{MEASURED}$ is the measured backscatter level in dB and $SPL_{INTERFACE}$ is the sound pressure level in dB incident on the rippled bottom. $SPL_{INTERFACE}$ was obtained by using the level measured with the free-field transducer and accounting for the difference in propagation loss to the location where the beam is incident at the rippled bottom with the parametric sonar code CONVOL.[4] Both $EL_{MEASURED}$ and

$SPL_{INTERFACE}$ were obtained after correcting for the particular receiver's system response (transducer with pre-amplifier).

Backscattered Intensity Images

Figures 6, 7, 8, and 9 illustrate bottom backscatter intensity images corresponding to frequencies of 3, 4, 5, and 6 kHz, respectively. In each figure there are two images. The image on the left refers to the non-rippled bottom while the image on the right is associated with the rippled bottom. To facilitate comparison of the non-rippled and rippled bottom backscatter intensities within the figures, the same dB-level gray scale is used for all images. The images in the figures clearly show increased reverberation levels in the 3 to 5 kHz frequency range for the rippled bottom when compared to the corresponding non-rippled bottom. In addition, the maximum reverberation level for the rippled bottom occurred at 4 kHz, corresponding to that predicted using Eq. (1).

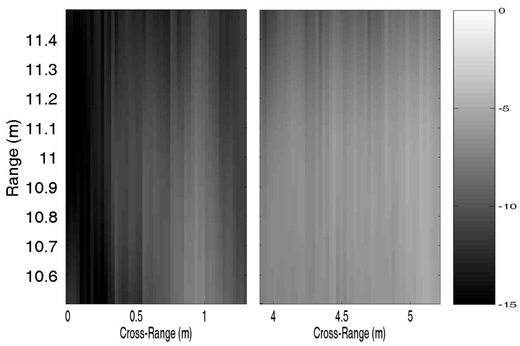

FIGURE 6. Frequency of 3 kHz.

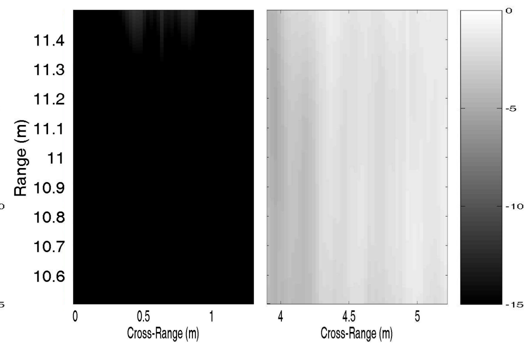

FIGURE 7. Frequency of 4 kHz.

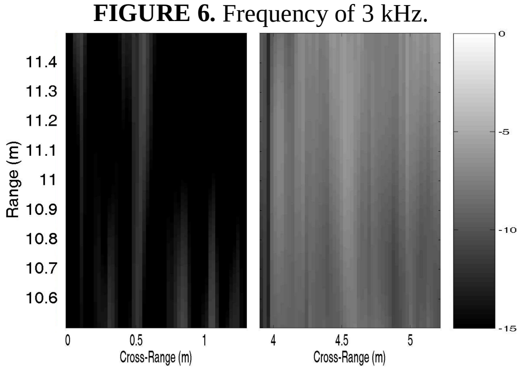

FIGURE 8. Frequency of 5 kHz.

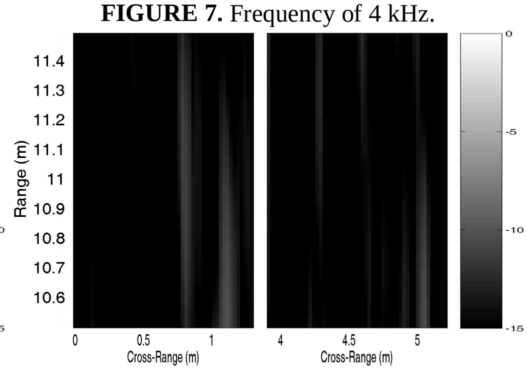

FIGURE 9. Frequency of 6 kHz.

Calibrated Backscattered Levels

Predicted (solid lines) and measured (filled circles) calibrated backscatter intensity levels from the rippled bottom are compared in Fig. 10. The model assumes a unit amplitude, monochromatic plane wave incident on the bottom. Intensity predictions are calculated using a steady-state Rayleigh-Rice perturbation theory to account for ensemble-averaged scattering from interface roughness. Since the statistical roughness parameters were not measured, the small-scale roughness superimposed on the scraped Gaussian ripple profile was assumed to be similar to the small-scale roughness observed in past measurements with sinusoidal ripple profiles.[3] Therefore, four curves are plotted, corresponding to four different assumptions for the statistical parameters of the superimposed roughness. In regions exhibiting significant differences in these curves, the measured reverberation level is expected to be spanned by the reverberation range of these curves. An average of the steady-state predictions over a moving 2 kHz window weighted by the spectrum of the pulse employed in the experiments was performed in order to compare with the measured results. Also, the overall level of the reverberation must be scaled to the area of the effective bottom patch contributing to the detected reverberation. This area is the product of the range and cross-range resolutions in the measurements. For a 1 ms source pulse incident on the bottom at a 20^{o} grazing angle, the range resolution is about 0.79 m. For a 5^{o} beam width, the cross-range resolution at the rippled bottom is approximately 0.93 m. The measured calibrated level at each frequency represents the mean reverberation level from patches observed between 10.5 and 11.5 m in range by 1.3 m in cross-range of the ripple region depicted in Fig. 3. This patch size corresponds to almost two sonar resolution cells.

The error range for the measured data points is indicated by vertical bars and is based on the sum of (a) the statistical uncertainty in our estimate of the mean reverberation intensity, (b) an estimate for the uncertainty in transducer calibration, and (c) the CONVOL predicted variation of the incident field at the interface where the reverberation is calculated. The statistical uncertainty is taken to be $\pm\sigma/\sqrt{N}$, where σ is the standard deviation of reverberation intensity, and N is the number of independent resolution cells in the 1 m by 1.3 m region used to obtain the mean background noise level. The uncertainty in transducer calibration was estimated to be about ±0.7 dB.

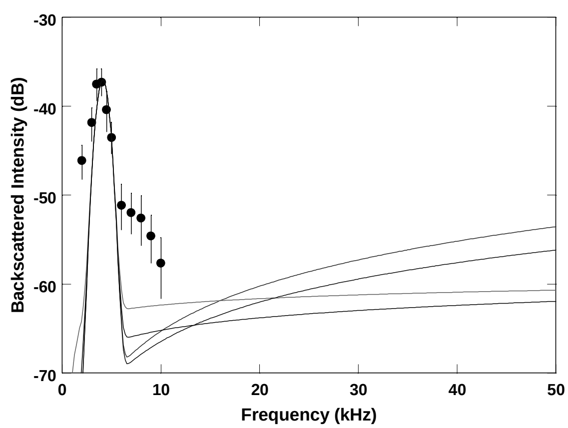

FIGURE 10. Measured (filled circles) and predicted backscatter intensity levels (solid lines).

The measured backscatter levels in Fig. 10 appear in good agreement with the model predictions around the spectral peak, with the maximum level occurring at 4 kHz as expected. However, even when taking into account the range in errors of the data points, there is some discrepancy in the data-model comparison at frequencies of 7 kHz and higher. The cause for this discrepancy is unknown, but it could be due to either inadequate assumptions used in the model and/or data analysis, or deviations from the scraped ripple profile. The assumption that the statistics of these deviations can be described by the same small-scale roughness statistics observed superimposed on roughness profiles created in previous measurements may not be accurate.

SUMMARY

A laboratory-type measurement was conducted to investigate reverberation levels from a rippled bottom in the MF range. Measured backscatter levels obtained from a rippled bottom with a 20 cm average ripple wavelength and a RMS height of 0.57 cm were compared to those collected from a non-rippled bottom. The measured levels from the rippled bottom were further compared to predictions of a model based on first-order perturbation theory.

The results showed increased reverberation levels in the 3 to 5 kHz frequency range when compared to the corresponding non-rippled bottom. The maximum reverberation level for the rippled bottom occurred at 4 kHz, which corresponds to that predicted using Eq. (1). In addition, the measured calibrated scattering levels were in good agreement with model predictions in the vicinity of the spectral peak. Data-model agreement compared very well for frequencies less than or equal to 6 kHz. The comparison at 7 kHz and above is not as good, and remains to be resolved.

Future work includes: (a) measuring and verifying the parametric sonar projected sound pressure levels as functions of range, (b) conducting additional measurements using ripple profiles centered on different ripple wavelengths to validate the trend associated with Eq. (1), and (c) analyzing the data to determine the calibrated levels for each ripple configuration and comparing the results to model predictions.

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