

# High-Frequency Sound Interaction in Ocean Sediments

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## LONG-TERM GOALS

Our long-term goals are to develop accurate models for high-frequency scattering from, penetration into, and propagation within shallow water sediments, and to understand the conditions for which objects buried in sediments can be detected acoustically. Reaching these goals requires a better understanding of several fundamental issues pertinent to high-frequency sediment acoustics. These issues include an understanding of the dominant scatterers versus frequency near the sediment surface, the potential need for poroelastic sediment models, the appropriateness of stochastic descriptions of sediment heterogeneity, the importance of single versus multiple scattering in sediments, and an understanding of the physical and biological processes that determine sediment structure.

## OBJECTIVES

Our specific objectives include the following: To measure backscattering levels from buried objects at subcritical grazing angles using synthetic aperture sonar (SAS) measurements in order to test buried-object-detection modeling accuracy. To identify the dominant high-frequency backscattering and subcritical penetration mechanisms, and to demonstrate that these acoustic processes can be quantitatively modeled based on measured sediment properties. To measure sediment attenuation and sound speed over a wide range of frequencies and to use these results, combined with measured sediment properties, to test the validity of sediment acoustic models, and in particular the poroelastic (Biot) model.

## APPROACH

The objectives were addressed with a major field experiment designated SAX04 (for sediment acoustics experiment–2004) carried out from the beginning of September to mid November 2004 in

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collaboration with other investigators. The site for SAX04 was about 1 km from the site of the earlier field experiment designated SAX99 [1]–[8]. The medium sand site (near Fort Walton Beach, Florida) was chosen to give a relatively high critical grazing angle (about 30° for frequencies above about 20 kHz). Most of the topics addressed in SAX99 were examined again, over a broader frequency range (2–500 kHz) and with other notable advances. In particular, a significant advance was implemented for SAS measurements on buried targets. To avoid motion effects inherent in a towed source/receiver system, a 27-m rail system for controlled SAS measurements was deployed by our group at the Applied Physics Laboratory (APL-UW).

Because of the importance of sediment ripples to acoustic penetration into sediments at subcritical grazing angles, acoustic predictions of target detection stands to benefit from a better understanding of ripple formation and evolution. In part because of this need, a new ONR Departmental Research Initiative (DRI) began in FY04. The DRI is known informally as the Ripples DRI, and DRI investigators carried out ripple-related studies at the SAX04 and nearby sites during Sept–Nov 2004.

## **WORK COMPLETED**

SAX04 and the Ripples DRI experiment began in September 2004 and continued until mid November. Two primary ships were used for the experimental work: The R/V Pelican and the R/V Seward Johnson. The R/V Pelican began work at the beginning of September with Ripples DRI related activity. The deployment of acoustic equipment was scheduled to begin in the middle of September from both vessels. Just before the acoustic equipment was to be deployed, Hurricane Ivan came ashore about 60 miles to the west of the SAX04 site on 16 September, leading to some delay in deployments. A high wave field (40–50 ft in the waters offshore from the site) moved through the experiment site as Ivan came ashore. The wave action was sufficient to form a “live bed” in the top 0.5–1.0 m of the sediment, that is, that upper portion of the sediment went into suspension in the water column, causing important changes to the structure of the upper meter of the sediment. In addition, the acoustic targets that had been buried the previous May were clearly affected. Some were moved within the target field while remaining buried or becoming partially buried, while other targets appeared to have been moved off the target field and have not been located to date. As planned, additional targets were placed on the surface of the sediment (i.e., proud) for acoustic scattering measurements.

The change in the sediment at the site was dramatic. In the post-Ivan sediment, most shell material had apparently settled out of the live bed first forming a dense shell layer beginning at about 50 cm or deeper. A layer of relatively clean sand 50 cm or greater formed above the shell layer, and above that was a deposit of mud, relatively thick in patches (5–10 cm) but thinner (1–2 cm) in many areas. Over time the mud either washed away or was covered over with a sand layer, but initially the mud at the sediment surface led to very poor visibility in the water column. The poor visibility during the first part of the experiment hampered diving operations necessary for acoustic equipment deployment and limited the usefulness of optical based environmental characterization such as stereo photography for roughness measurements. Nevertheless, all acoustic equipment was successfully deployed, and in time the visibility improved sufficiently to permit optical based measurements.

Ripples were produced at the SAX04 site by Hurricane Ivan and by later weather events, but the intermittent presence of surficial mud patches complicated the spatial structure of the ripple field and its characterization.

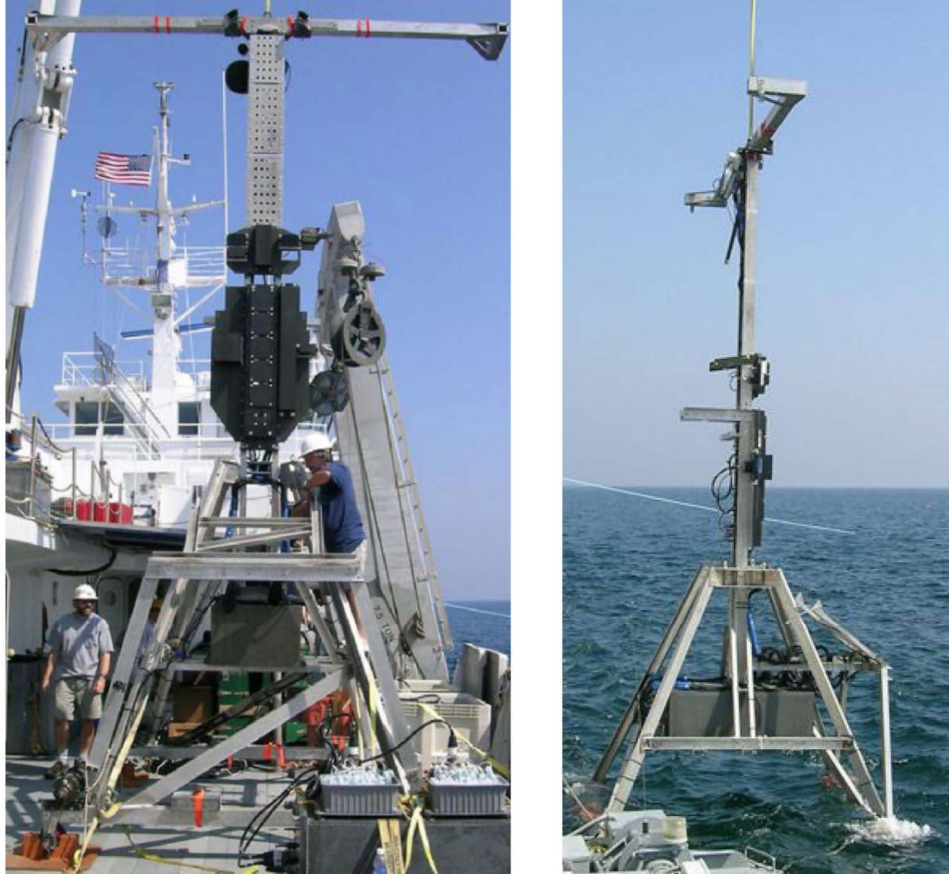
The APL-UW BAMS and XBAMS acoustic towers were deployed and collected backscattering data from the bottom in circular scans at 40 kHz (BAMS) and 300 kHz (XBAMS). (Undefined acronyms can be found in [1]. The APL-UW IMP2 system was also deployed. IMP2 has a probe that measures the sediment conductivity as a function of depth at a set of points spaced 1 cm apart along a 4 m track. The IMP2 system can measure the profile of a water/mud or water/sand interface and also of an interior mud/sand interface.

The APL-UW 27-m rail system [9] (Figures 1 and 2) was first set up by divers just inshore from the target field where the targets were initially buried to a 30-cm depth. Later it was moved 30 m to lie just inshore from the target field where the targets were initially flush buried. SAS backscatter measurements were taken for both rail positions. The SAS images of targets were obtained using chirp pulses in various frequency bands from 2 kHz up to 200 kHz.



***Figure 1. One 7-m rail section being prepared for deployment. Four sections were joined together on the bottom to form the full rail system.***

For both rail positions the tower that rides on the 27-m rail was folded down to its backscatter/forward scatter position. Backscatter data were obtained over the range of 20–500 kHz at grazing angles of 10 deg to 40 deg. Forward scatter data were obtained over the frequency range of 20–100 kHz for several specular grazing angles. About 80 independent surface patches were used for each backscatter and forward scatter data set.



*Figure 2. Rail tower: front view (left), side view (right).*

On 20 Oct the rail tower was returned to its upright position for SAS measurements, this time for both monostatic and bistatic backscatter measurements from 3 proud mine shapes and 3 proud clutter targets. The backscatter measurements were made using sources on the rail tower. For the bistatic measurements, the Naval Surface Warfare Center – Panama City (NSWC-PC) parametric source was used. Bistatic data were collected at 1–16 kHz using the secondary fields and at 56–72 kHz using the primary fields. In each case both the source and receiver heights were about 4 m and the range to the targets was about 10 m.

Equipment was also deployed for studying subcritical acoustic penetration to a 30-element buried array, as done during SAX99. The site chosen had no surficial mud layer. A cofferdam was excavated and sunk to a depth of 60 cm. From the cofferdam, divers inserted 30 hydrophones to form an array within the sediment without disturbing the sediment above the array. Four acoustic sources were located on a diver movable tower, and the tower was moved along circular arcs centered on the buried array. Penetration data were collected over the frequency range of 2–50 kHz for geometries above and below critical angle. Data were also collected on the size distribution of shell fragments from the excavated sediment for volume scattering modeling.

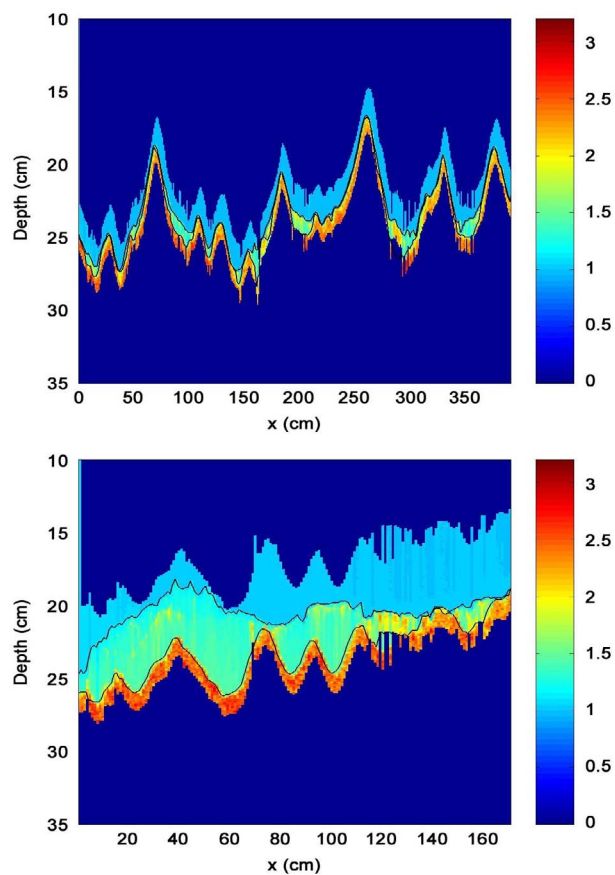
In addition to the efforts above, data were obtained with the APL-UW attenuation array and a new APL-UW stereo camera system at a variety of positions on the seafloor. To further study sediment

scattering and subcritical penetration, diver manipulations of the seafloor were done on the sediment over the buried array and, in collaboration with NRL-SSC, near the 27-m rail system.

A workshop for SAX04 and Ripples DRI investigators was organized and held in Seattle, Washington in May 2005; preliminary results were discussed.

## RESULTS

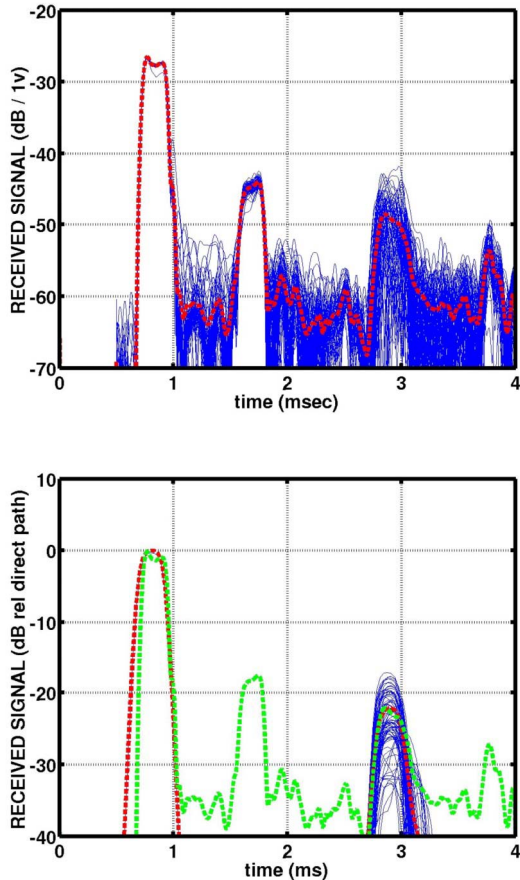
The situation encountered following Hurricane Ivan was unexpected, with some regions on the seafloor consisting of mud overlying sand ripples. Two examples are shown in Fig. 3, obtained with IMP2 [10]. The formation factor (shown in Fig. 3) is the ratio of the conductivity of seawater to that of a given medium. While the seafloor structure is complex, the effect of scattering by ripples on subcritical penetration is not necessarily affected because, at the frequencies of interest for buried target detection, sound experiences little refraction or attenuation by the overlying mud.



*Figure 3: Formation factor (color) for two IMP2 measurements. There are no data in the dark blue regions, the top light blue region is water, the lighter blue region is mud with some sand inclusions, and the orange region is sand. Data for the top panel were taken about 5 days after Hurricane Ivan; data for the lower panel were taken several weeks later.*

At times during SAX04 the seafloor had a surficial mud layer overlying a rippled sand surface, where the mud filled in the ripple troughs leaving a relatively smooth water/sediment interface. Under these conditions, the mud layer can preserve the sharply peaked profile of freshly made ripples, not appreciably affect the ripple-induced acoustic penetration, and at the same time reduce the level of seafloor backscatter. Thus, a surficial mud layer under some conditions may act to enhance subcritical target detection due to ripple scattering; this effect was observed in SAX04 buried target detection measurements.

Forward scatter measurements were made using the rail system with the rail tower folded down to the backscatter/forward scatter position [11]. For each source /receiver geometry, which determines the specular grazing angle, the tower was moved to 80 positions along the rail separated by 30 cm. Modeling carried out before SAX04 had indicated that ensemble averages of the forward scattered energy could be used to estimate the reflection coefficient for a flat water/sand interface, and that averaging 80 positions would be sufficient to discriminate between Biot model and fluid model predictions for sand.

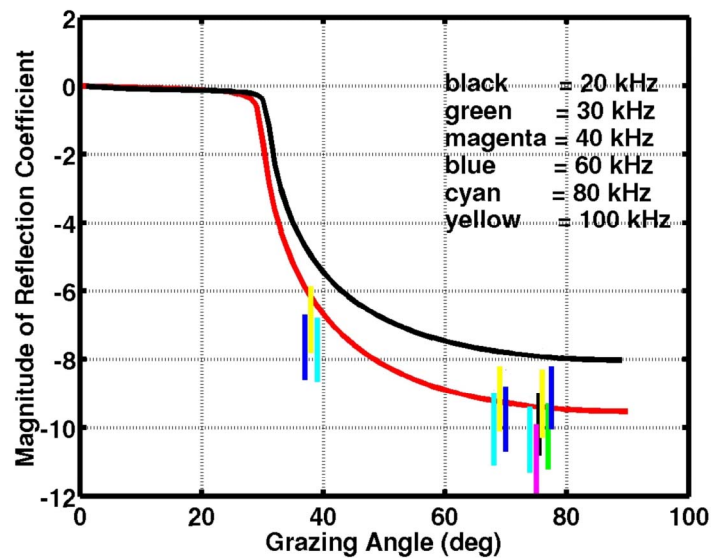


**Figure 4. Top: Forward scattering signals at 20 kHz for each of 80 positions of the rail tower (blue) and intensity averaged result (red). Bottom: Monte Carlo simulation of forward scattered signals for 80 rough seafloor realizations (blue), intensity averaged simulation result (red), and intensity averaged data result (green).**

The blue curves in the top panel of Fig. 4 show the signals recorded at each of the 80 positions. The dashed red curve is the intensity average of these signals. The first peak is the direct path, the second is scattering from a tower cross beam, and the third is the forward scattering signal from the water/sand interface. Note the large variation in the forward scattering level as a function of tower position, and

that this variation relative to the mean is not symmetric. This is consistent with Gaussian field statistics, implying an exponential distribution for intensity.

The bottom panel of Fig. 4 shows model results for forward scattering from 80 independent realizations of a rippled interface with rms roughness (1 cm) and average ripple wavelength (50 cm) similar to that measured during SAX04. Again, the signal for each realization is in blue and the ensemble average is in red. The green curve is the ensemble average for the experiment. The model used Biot theory for the reflection coefficient with sediment parameters from SAX99. The full set of Biot parameters for the SAX04 site has not been determined at this point. However, using the parameters that have been determined indicates that the predicted reflection coefficients for both the Biot and fluid sediment models may be slightly larger (less than 0.5 dB larger at normal incidence) than for SAX99 parameters.



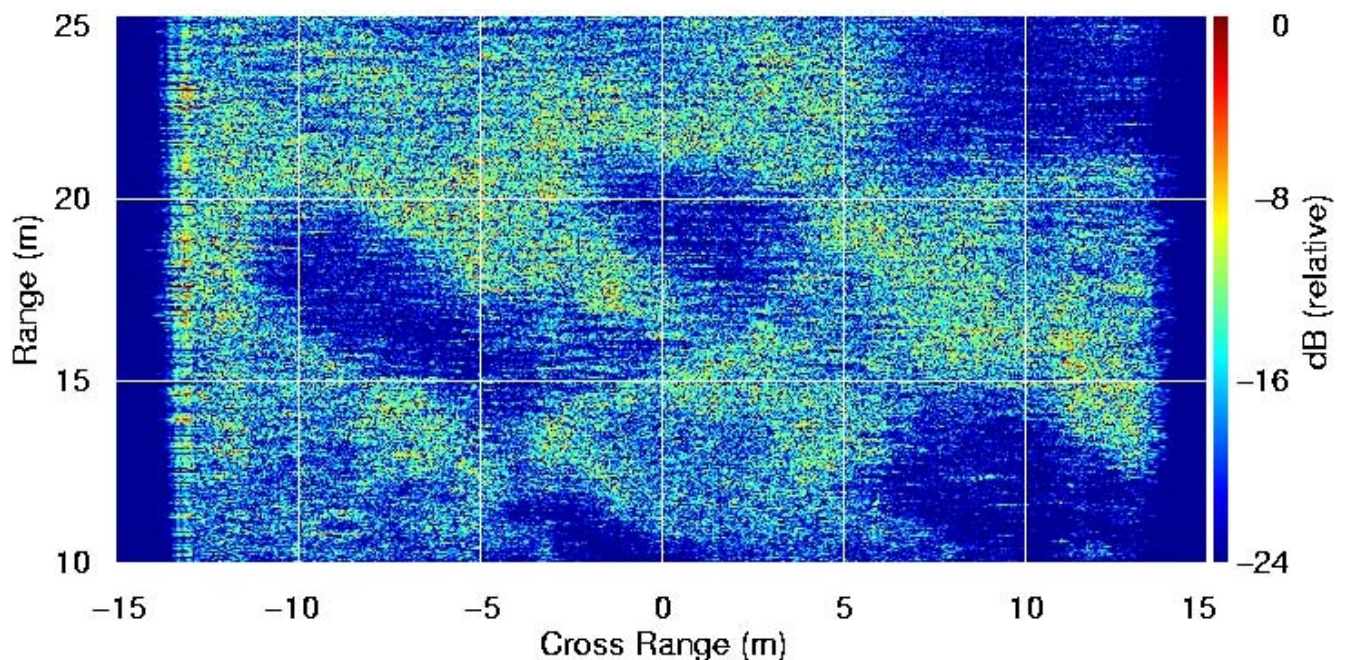
**Figure 5. Comparison of measured bottom reflection coefficients with fluid model (black) and Biot model (red) predictions.**

A comparison of measured (SAX04) and modeled reflection coefficients is given in Fig. 5, where SAX99 sediment parameters have been used. The slightly larger reflection coefficients mentioned in the previous paragraph would shift the model predictions (the red (Biot) and black (fluid) curves) in Fig. 5 up by a few tenths of a dB. The model curves in Fig. 5 are for 50 kHz, but in the 20 to 100 kHz range of the data the model results do not change significantly compared to the difference in Biot and fluid model predictions. Figure 5 also shows reflection coefficients (vertical lines of various colors) calculated from the experimental results at grazing angles of 38, 69, and 76 degrees. The 100 kHz data (yellow vertical lines) are plotted at the experimentally realized angles. The data for other frequencies are offset in angle a small amount for clarity. The vertical lines indicate the uncertainty in the measurements. The preliminary conclusion from the data/model comparison is that a Biot model is a better descriptor for sand at the SAX04 site.

Backscattering measurements versus grazing angle and frequency were also made using the rail system, and the results [11] were found to be more complex than for SAX99 because of the presence

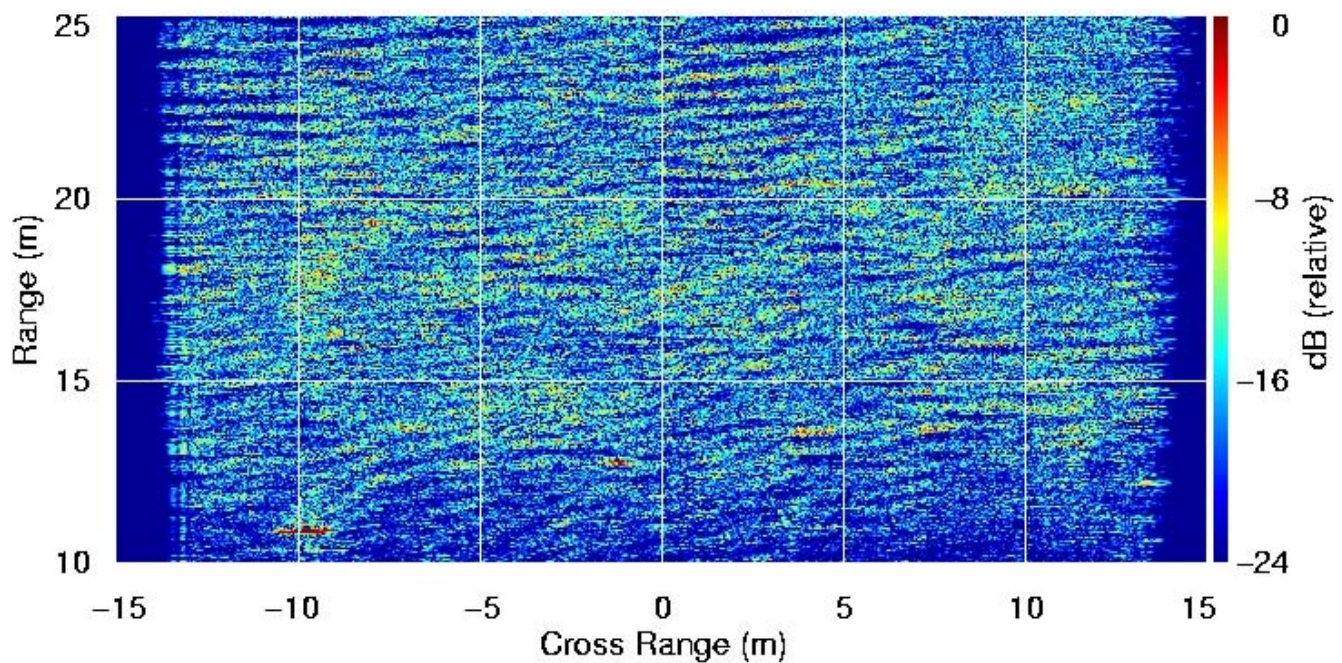
of mud patches. The effect of mud overlying sand was typically to reduce backscatter, and in these cases scattering from the underlying sand is thought to be the dominant backscattering mechanism. The reduction in backscattering level occurred even at lower frequencies, where attenuation due to the two-way transmission through the mud should not be significant. One possibility is that the reduction occurred because the mud-sand interface had less roughness than a typical water-sand interface [10]. This is reasonable since a mud-sand interface should be less subject to biological reworking than an exposed water-sand interface. At higher frequencies the attenuation due to two-way transmission through the mud may also play some role.

As time passed after Hurricane Ivan, other weather events affected the site, and in some areas sand migrated over the top of mud patches. In these cases, backscattering was found to be unusually high. IMP2 measurements showed that small sand inclusions were present in the mud below the overlying sand, and these inclusions likely lead to the higher scattering. Further analysis will be required to fully understand these complex effects.



***Figure 6. SAS image using 110–190 kHz FM pulses. Dark areas show regions with mud at surface of seafloor.***

The principle reason for deploying the 27-m rail system was to obtain controlled SAS images of proud and buried targets. Examples of SAS images of targets are given in the report on the project titled “Sonar Detection of Buried Target at Subcritical Grazing Angles: APL-UW Component,” with PIs K. L. Williams, E. I. Thorsos, and D. Tang. Figures 6 and 7 show SAS images of the seafloor that illustrate backscattering variability. These images were made using 110-190 kHz FM pulses (higher than appropriate for detecting buried targets), and the pixel size is 5 cm by 5 cm. The SAS image in Fig. 6 is for 4 Oct. 2004 and the dark patches show regions with mud overlying sand. The SAS image in Fig. 7 is for 14 Oct. 2004, and the intensity level reference is the same as for Fig. 6. At this time sand covered most of the sediment surface and ripples can be seen over almost all the image.



*Figure 7. SAS image using 110–190 kHz FM pulses showing the same region as Fig. 6, but 10 days later.*

## IMPACT/APPLICATIONS

Work under this program should lead to improved high-frequency models for acoustic scattering from sediments, for penetration into sediments, for propagation within sediments, and for modeling the detection and classification of buried objects. A corollary to acoustic model refinement should be a better understanding of the essential parameters that are needed for practical models.

## RELATED PROJECTS

1. Title: Measurement of seabed roughness, Grant # N00014-02-1-0008, D. Tang, PI. This project supports a collaborative experimental effort between NSWC-PC and APL-UW focused on controlled measurements of buried target detections in a test pond at NSWC-PC. APL-UW has deployed the bottom-mounted conductivity measurement system (IMP2) to measure interface roughness above the buried target. This grant also partially supports our work on acoustic inversion of ripple field properties.
2. Title: Acoustic scattering from heterogeneous rough seabeds, Grant # N00014-01-1-0087, A. N. Ivakin, PI. This project is focused on improving understanding of scattering from seabed roughness and volume heterogeneity, central elements of SAX99 and SAX04 measurements. In particular, scattering from shell fragments and other discrete inclusions is being modeled under this program, and the results will likely have important applications in SAX04 analysis.
3. Title: Laboratory Investigations and Numerical Modeling of Loss Mechanisms in Sound Propagation in Sandy Sediments. Grant # N00014-05-1-0225, B. T. Hefner, PI. The scientific

objectives of this grant include quantifying the relative importance of scattering and frictional losses in the attenuation of sound in sand sediments.

4. Title: Environmental complexity and stochastic modeling of high frequency acoustic scattering from the seafloor, Grant # N00014-02-1-0341, C. D. Jones, PI. A digital stereo photography system was developed under this grant and was used for seafloor roughness characterization during SAX04.

5. Title: Support for Creation of Classification Data Set from SAX04 Synthetic Aperture Sonar Collection, ONR BOA # N00014-01-G-0460, K. L. Williams, PI. This is an applied research task to include buried clutter in the SAX04 target field and to use the data acquired on both clutter and mine-like objects to develop classification algorithms.

6. Title: APL-UW contribution to SAX04 bistatic measurements of VLF Bottom Reverberation and Target Strength, ONR BOA # N00014-01-G-0460, K. L. Williams, PI. The objective of this proposed effort is to obtain bistatic bottom reverberation and target strength data in the Very Low Frequency (VLF, 1-10 kHz) range under controlled conditions during SAX04.

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