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# Seabed attenuation in water saturated sands on New Jersey continental shelf in 50-3000 Hz band

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**Abstract.** The Shallow Water 2006 ocean acoustics experiment on the New Jersey continental shelf was designed in part to determine the frequency dependence of sound speed and attenuation for a sandy sediment in the 50-3000 Hz band. Two acoustic arrays in L-geometries were positioned about 25 km apart on a ridge of coarse sand. Segments of narrowband and impulsive acoustic data were analyzed for the information they contain on the seabed geoacoustic structure and the frequency dependence of the top sediment layer attenuation. The results clearly demonstrate a non-linear frequency dependence of the absorption.

**Keywords:** Shallow water acoustics, seabed geoacoustics, attenuation

**PACS:** 43.30.Ma, 43.30.Pc, 43.20Jr, and 43.30Ky.

## INTRODUCTION

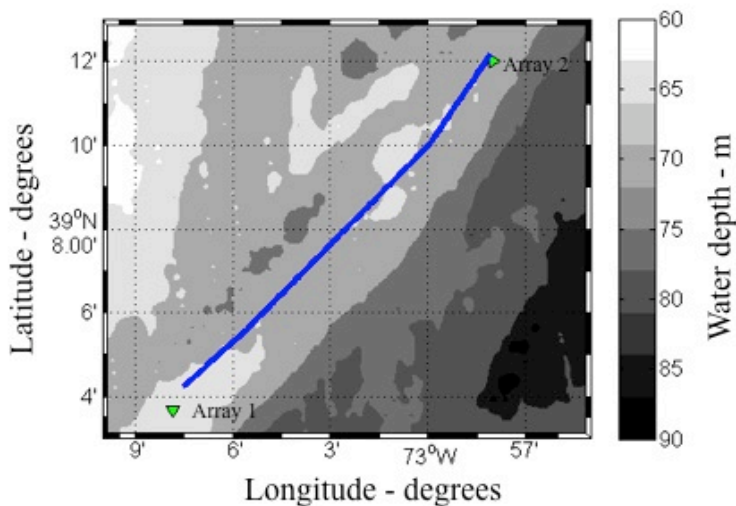
In 1980 Hamilton noted that the absorption loss associated with water-saturated sands below 1 kHz was an issue that needed to be addressed with carefully controlled experiments [1]. His remark was part of a discussion on the frequency dependence of attenuation in marine sediments, i.e., the value of the exponent  $n$  for  $A(f) = \alpha (f/1000)^n$  where  $A$ ,  $\alpha$ , and  $f$  have units of dB/m, dB/m @ 1 kHz, and Hz, respectively. For clays and muddy sediments Hamilton noted that experimental evidence indicated  $n = 1$  below 1 kHz. For sandy sediments that are commonly found in shallow littoral ocean environments, Hamilton noted that some researchers suggested  $n = 2$ , which would be consistent with a Biot-Stoll theory of low-frequency ( $< 1$  kHz) acoustics for water-saturated sandy sediments [2-7]. Both prior to and after the paper by Hamilton, reports in the literature suggested the frequency dependence of the absorption in sandy sediments to be described with  $n \approx 1.8$  for  $f < 1$  kHz [see for example 8-11]. There is not a consensus in the scientific community on the attenuation in sandy sediments, due in large measure to the scarcity of measurements. Some researchers argue that the frequency dependence of the attenuation for water-saturated sands is linear at all frequencies, and that the observed frequency dependence of the loss is caused by other mechanisms [12-14]. In all discussions of this debate, it is of critical importance to keep in mind not only the sediment type but also the frequency band. For example, in the Biot-Stoll theory for water-saturated sand, the exponent changes smoothly from  $n = 2$  at the low frequencies to  $n = 0.5$  at the higher frequencies. The frequency where

the transition occurs depends on a number of parameters such as porosity, grain size, and permeability.

This paper reports on an experiment designed in part to infer the seabed attenuation over a large frequency band (50-3000 Hz) for a unique shallow water area where the surface seabed is known to be a coarse water-saturated sand with an average grain size of about  $\phi=1.0$ . Continuous wave (CW) sources, that produced tonals in the 50-3000 Hz band, were towed over a 20 km track. From these data the frequency dependence of the attenuation was deduced. Further, a tropical storm passed through the experimental area. The acoustic measurements and sea surface measurements during the storm provide sufficient information to test the validity of the frequency dependence of the attenuation obtained from the long-range transmission loss measurements.

## DESCRIPTION OF EXPERIMENT

Figure 1 shows the geographical location of part of an acoustic experiment (known as Shallow Water 2006 or SW06) performed in August-September 2006 on the New Jersey continental shelf. The line connecting the positions of two acoustic arrays lies approximately along the 70 m depth bathymetry contour in the middle of a *sand ridge* encompassing an area about 180 km<sup>2</sup> in which the first 2-5 m of sediment is a uniform coarse sand.

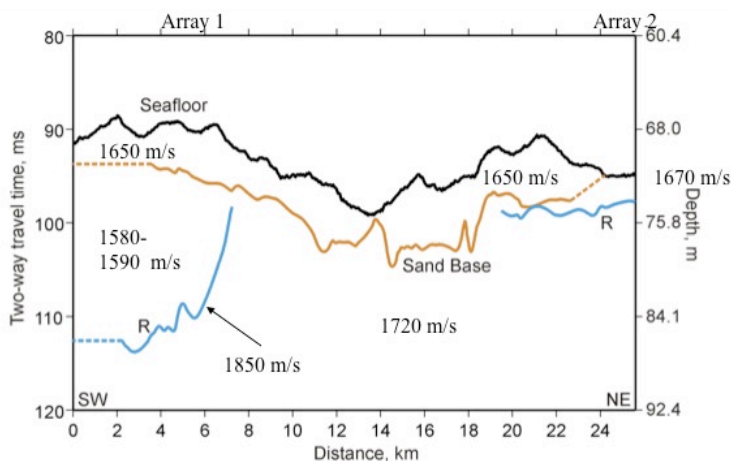


**FIGURE 1.** Locations of two acoustic arrays and a propagation track in the sand ridge portion of the SW06 experiment.

The unique properties of the sand ridge provide an ideal experimental setting in which to make a large bandwidth (50-3000 Hz) study of the attenuation in water-saturated sand. The sediments to the southeast at the 80 m depth contour are less ideal for such

a study because of their reportedly large clay content [15]. Figure 1 also shows a track where the RV KNORR towed a J-15-1 (50-900 Hz band) source and an ITC 250 (1-4 kHz band) source that produced narrowband CW lines. The track over which these sources were towed starts near Array 2 in the NW direction and passes within about 100 m of Array 1. Further, along this track broadband light bulb implosions and combusive sound source (CSS) were deployed.

The seabed layering structure of the region was mapped by CHIRP bottom reflection measurements from two surveys prior to the acoustic experiment. Figure 2 shows the seabed layering structure between Array 1 and Array 2. For most of the track the surface sediment is a sand layer with an average thickness of about 3 m. Inversion analyses suggest that the sound speed in this layer is about 1650 m/s [16]. In the proximity of Array 1 the sediment beneath the sand layer is known as the outer shelf wedge and is composed of thin layers of clay in addition to sand. This causes the average sound speed to about 60 m/s less than the speed in the sand layer. Beneath the sand layer starting about 5 km from Array 1, is a layer comprised of consolidated sand with a higher sound speed ( $\sim 1720$  m/s).

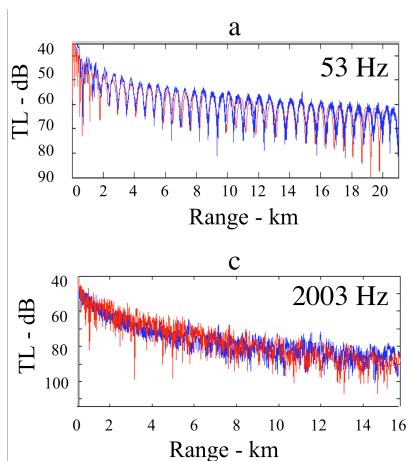


**FIGURE 2.** Seabed layering structure between Array 1 and Array 2.

## ANALYSIS OF ACOUSTICAL MEASUREMENTS

Short-ranged CW tow data collected on Array 2 in the 50-250 Hz band and the received time series in the 50-325 Hz band from a CSS impulsive source collected at Array 1 were used to infer average parameter values for parameters such as the sound speed in the top sediment layer, the layer thickness, the layer density, the sound speed in the second sediment layer, etc. [16]. For frequencies above 50 Hz, the geoacoustic structure (not including the attenuation) of the seabed on the sand ridge is reasonably well described by a half-space with a sound speed and density of 1650 m/s and 1.85 g/cc, respectively. For a bottom water sound speed of 1495 m/s, the sound speed ratio

of the surface sediment is about 1.104, a value that is consistent with a water-saturated sand classified as coarse with a mean value for the grain size  $\phi=1$ .

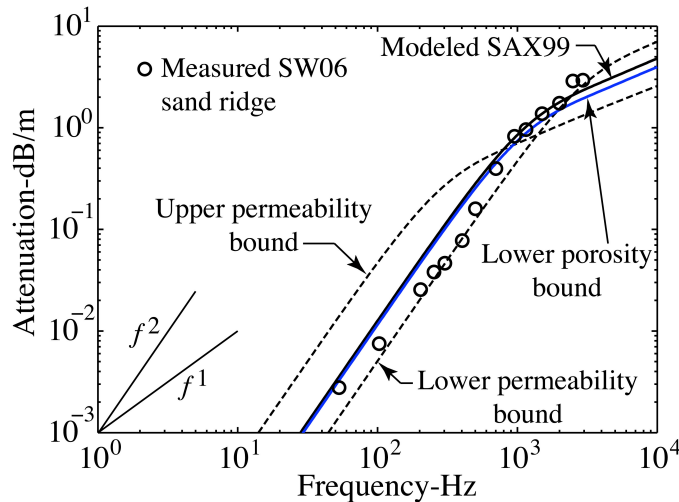


**FIGURE 3.** TL model (red)-data (blue) comparisons at 53 and 2003 Hz after attenuation optimization.

The results of the geoacoustic inversions performed at Array 1 and Array 2, the measured bathymetry and sub-bottom layering along the propagation track shown in Fig. 2, and the measured SSPs near the two arrays during the time of the multi-frequency source tows give an approximate representation of the range-dependent waveguide. For the 1-3 kHz and the 50-900 Hz data, the range over which there was adequate SNR was about 15 and 20 km, respectively. Absorption in the water column is included with a standard Thorp attenuation relationship. A parabolic equation model [17] then found the value for the sediment attenuation in the first sediment layer that gave the optimal fit to the measured TL versus range for each frequency in the 50-3000 Hz band. Figure 3 shows comparisons of modeled and measured TL at 53 and 2003 Hz. Matching both the measured TL levels and overall range modal interference structure were important considerations in estimating the attenuation.

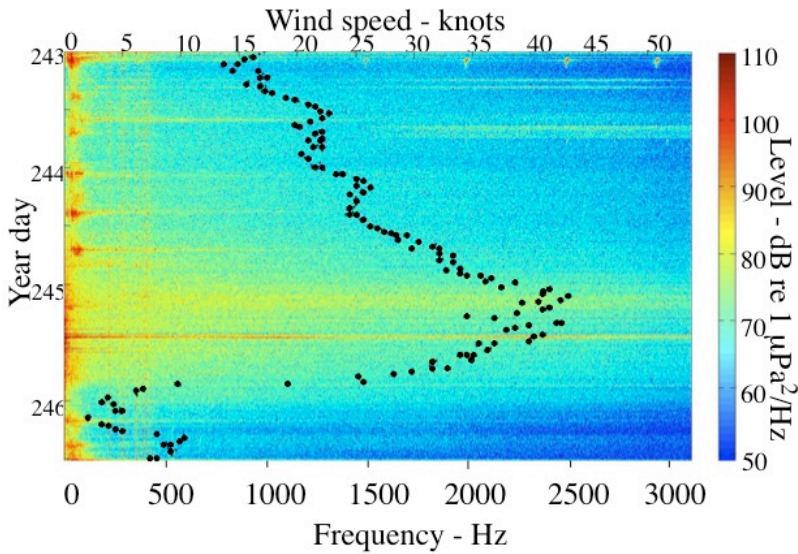
Figure 4 shows the inferred attenuation values for the first sediment layer as a function of frequency. For purposes of comparison Fig. 4 includes several predictions of the Biot theory [2-3]. The specific Biot calculations are based on the formulation of Stoll and Kan [7]. The solid black line is the prediction using the Biot parameters listed in Table I of Ref. 18, which were derived from measurements made during the Sediment Acoustics Experiment in 1999 (SAX99). The solid blue line is derived from the SAX99 parameters but with a lower bound estimate ( $\beta=0.363$ ) for the porosity at the New Jersey shelf location [19]. The two dotted lines are derived from the SAX99 parameters but with upper and lower bound estimates for the permeability,  $\kappa=1.0 \times 10^{-10} \text{ m}^2$  and  $\kappa=1.0 \times 10^{-11} \text{ m}^2$ , respectively. Permeability was not measured at the New Jersey shelf site, but these estimates were derived from sediment physical models that relate permeability to porosity and grain size [20]. Core samples for the New Jersey site yielded a mean grain size  $\phi=1$ . For frequencies  $f$  below about 2 kHz the

dependence of the inferred attenuation is approximately proportional to  $f^{1.85}$ . These results are consistent with other studies that have inferred a non-linear frequency dependence of the attenuation from analyses of forward propagation data [8-11, 21]. While the data are not inconsistent with the Biot predictions above 2 kHz, one cannot draw any definitive conclusions concerning the frequency exponent because of the sparseness of data there the observed dependence is about  $f^{1.1}$ .



**FIGURE 4.** Inferred attenuation in top sediment layer on sand ridge

Figure 5 shows an omni-directional spectrogram from a hydrophone on the horizontal segment of Array 1 during a time period when tropical storm Ernesto passed through the experimental area [22]. The wind speed, measured on an Air Sea Interaction Spar (ASIS) buoy positioned about 150 m from Array 1, is superimposed on the spectrogram. The ambient noise levels are clearly well correlated with the wind speed. The wind-generated noise extends above 400 Hz for wind speeds above 3 knots. Below 400 Hz it is difficult to separate the distant shipping and wind components of ambient noise in shallow water. It was observed (not shown here) that the averaged ambient noise levels in the 200-1000 Hz band at the Array 2 location were within about 1 dB of the ambient noise levels measured at the Array 1 site.



**FIGURE 5.** Spectrogram measured on Array 1 for tropical storm Ernesto

In shallow water, the wind-generated noise spectrum should be sensitive to the frequency dependence of the seabed attenuation. This hypothesis is tested by examining modeled and measured difference spectra [22]. A difference spectrum is the difference between the ambient noise levels for a site of interest, for example the New Jersey shelf location, and the ambient noise level for a reference deep-water location. In this manner the shape of the difference spectrum does not depend on wind source level. However, evaluating the difference spectrum at high wind speeds results in greater accuracy due to the asymptotic behavior of noise levels with increasing wind speed [22]. The difference in ambient noise at two locations for a specific frequency,  $f$ , and wind speed,  $V$ , is

$$\Delta AN_{1,2}(f, V) = AN_1(f, V) - AN_2(f, V) \quad (1)$$

Assuming that the effective source levels for a specific wind speed are independent of site,  $\Delta AN_{1,2}(f, V)$  is approximately independent of  $V$ . Further, define for site  $j$

$$L_j(z_0, z_j, f) = 10 \log_{10} (2\pi \int_0^\infty dr r 10^{-TL_j(r, z_0, z_j, f)/10}) \quad (2)$$

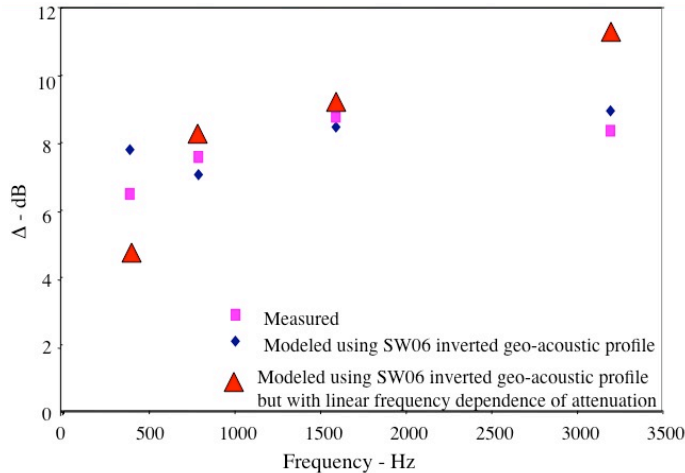
$L_j$  represents the ambient noise level at site  $j$  for frequency  $f$  at depth  $z_j$  with 0 dB source strength per unit area uniformly distributed in the  $x$ - $y$  plane at depth  $z_0$ .  $TL_j$  represents the modeled transmission loss as a function of range from a reference point below the sea surface to the receiver. It is assumed that the waveguide possesses azimuthal symmetry. Finally, define

$$\Delta L_{1,2}(f) = L_1(z_0, z_1, f) - L_2(z_0, z_2, f) \quad (3)$$

The premise of in this study is that

$$\Delta AN_{1,2}(f) = \Delta L_{1,2}(f) \quad (4)$$

The location of the *Church Opal* (CO) experiment [23] will be used as the deep-water reference site. As discussed in Ref. 23, the environment is well understood, and the transmission loss in Eq. 2 can thus be accurately modeled. Figure 6 compares the measured  $\Delta AN_{SW06,CO}$  and modeled  $\Delta L_{SW06,CO}$  values. The integrals in Eq. 2 were evaluated numerically. The  $\Delta AN_{SW06,CO}$  values lie approximately between 6 and 8 dB in the 400-3200 Hz band, and the  $\Delta L_{SW06,CO}$  values also lie between about 6 and 8 dB. In this sense the modeled results are in good agreement with the measured values. Figure 6 includes the result of making the frequency dependence of the attenuation for the SW06 seabed linear with  $\alpha=0.55$  dB/m at 1 kHz. An attenuation that depends linearly with frequency causes the modeled  $\Delta L_{SW06,CO}$  to have a spread of about 6 dB over the 500-3000 Hz band, whereas the spread of measured  $\Delta AN_{SW06,CO}$  values is only about 2 dB. Assuming that the sediment sound speed values deduced from the previous analysis [16] are approximately correct, a nonlinear frequency dependence of the sediment attenuation appears to be the reason that the  $\Delta AN_{SW06,CO}$  values have such a weak frequency dependence in the 500-3000 Hz band.



**FIGURE 6.** Mode-data comparison of frequency dependence of wind generated noise difference spectra



## SUMMARY

Both broadband and narrowband acoustic measurements in the 50-3000 Hz band made on the New Jersey continental shelf during the Shallow Water 2006 (SW06) Experiment were analyzed for the information they contain on the frequency dependence of the attenuation in the seabed. The array positions and propagation track were on a sand ridge. Geoacoustic inversions produced values for the sound speeds of the surface sand layer that were between 1650 and 1710 m/s, and that were consistent with the existing geophysical data. For frequencies below about 2 kHz the attenuation values varied approximately as  $f^{1.8}$ . The results of an analysis of wind-generated noise due to a tropical storm at the same location where the transmission loss measurements were made are in agreement with the inferred value for the frequency exponent below 2 kHz.

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