Chapter 3

Model-based seafloor characterization

3.1 Introduction

The use of high-frequency SBES and MBES operable within the frequencies 300 kHz is well established for remote acoustic seafloor characterization. The acoustic backscatter data obtained from such echo-sounding systems can be matched with theoretical scattering models to interpret the information embedded in the data. The numerical approach employed for extracting information from the data is commonly referred to as “inversion modeling”. The inversion modeling primarily involves physics based model for inversion of echo-sounding data to obtain the seafloor roughness parameters, namely the sediment mean grain size ($M_\phi$); spectral parameters at the water-seafloor interface ($\gamma_2$, $w_2$); and sediment volume parameter ($\sigma_2$), that can be further used to examine fine scale seafloor processes (APL Handbook, 1994). The composite roughness model developed by Jackson et al. (1986), using the shape of the angular backscatter data has been extensively applied in this context (de Moustier and Alexandrou, 1991; Matsumoto et al., 1993; Chakraborty et al., 2003). In this chapter, a model-based seafloor characterization technique based on the composite-roughness theory has been developed and demonstrated utilizing the data acquired using a MBES operable at 95 kHz. The MBES angular backscatter data acquired over the substrates ranging from clayey silt
to sand (at 12 locations) in the central part of the WCMI are subject to inversion modeling (Fig. 3.1).

Fig. 3.1 Panel (a) illustrates the acoustic and sediment sample data acquisition locations with respective sediment types. The panel (b) demonstrates the effectiveness of the PROBASI-II algorithm to generate spatial image of the backscatter data. Presented in panel (c) are the processed MBES and SBES (angular backscatter and echo envelope) data used to carry out the inversion modeling.
Moving beyond the techniques that employ MBES angular backscatter data, Pouliquen and Lurton (1992) initiated a modeling method for seabed identification using the shape of the echosounder signals. Sternlicht and de Moustier (1997, 2003a, b) also developed a robust time-dependent seafloor acoustic backscatter model within the frequency range 10–100 kHz, that has been effectively demonstrated for seafloor characterization using the normal-incidence SBES (De and Chakraborty, 2011). The use of multiple acoustic frequencies (van Walree et al., 2006) highlighted in this work improves seafloor characterization, because the roughness spectrum and the sediment volume heterogeneities cause backscatter variation that can be conveniently substantiated using multi-frequency inversion results. In this chapter, the seafloor parameters computed using 95 kHz MBES data are compared with the ground-truth data as well as with the inversion results obtained using 33 and 210 kHz SBES data at the same locations (De and Chakraborty, 2011).

3.2 Model-data comparison

The composite roughness model\(^1\) using the shape of the angular backscatter data developed by Jackson et al. (1986) requires few geoacoustic parameters as the model input. In the absence of measured geoacoustic parameters in the study area, these parameters are computed in terms of the mean grain size (\(M_\phi\)). The equations relating geoacoustic model parameters to the mean grain size (\(M_\phi\)) are adapted from the APL-UW High-Frequency Ocean Environmental Acoustics Models Handbook (APL Handbook, 1994).

3.2.1 Computation of scaling parameter to calibrate the data

Even after implementing the pre- and post-processing procedures discussed in the preceding chapter, prior to the model-data comparison, there was an unfulfillment of absolute calibration, and a depth-dependent offset (scaling parameter in dB) was required to correct each of the processed data sets. The scaling

\(^1\) The basic equations formulating the composite roughness model is detailed in Jackson et al. (1986).
parameters (calibration offsets) were computed by comparing the model derived backscatter values with the measured data. The seabed scattering model combines the most dominant dimensionless scattering mechanism of the surface roughness coefficient $S_s(\theta_g)$ and volume scattering coefficient $S_v(\theta_g)$, as a superposition of the incoherent scatter to estimate the total seabed backscattering strength $BS_{\text{model}}(\theta_g)$ as:

$$BS_{\text{model}}(\theta_g) = 10\log_{10}[S_s(\theta_g) + S_v(\theta_g)] \text{ dB}$$

(3.1)

where $\theta_g$ is the grazing angle (90°-incidence angle). The scaling difference between the APL-UW model predicted backscatter values and the processed MBES data is apparent for the fine and coarse sediment regions (as can be seen in Fig. 3.2). These differences may be due to instrument calibration, model accuracy or erroneous TVG applied online (de Moustier and Matsumoto, 1993; Dziak et al., 1993; Kloser et al., 2010). Therefore, it would be convenient to treat the level of measured backscatter values as relative for appropriate model-data comparison.

The error-to-signal ($E/S$) ratio has been used as a merit function to evaluate the model-data matching procedure with the goal of minimizing the value. The $E/S$ is expressed as (Haris et al., 2011):

$$E/S = \frac{\sum_{\theta_g=35}^{\theta_g=65} (BS_{\text{data}}(\theta_g) - BS_{\text{model}}(\theta_g))^2}{\sum_{\theta_g=35}^{\theta_g=65} BS_{\text{data}}^2(\theta_g)},$$

(3.2)

where the terms $BS_{\text{data}}(\theta_g)$ and $BS_{\text{model}}(\theta_g)$ represent the data and model predicted backscatter values. This method is independent of the backscatter angular range, and provides a convenient numerical evaluation of the model-data comparison. The resulting scaling parameter (difference between model and data), which minimizes the $E/S$ ratio is used as the representative scaling factor to calibrate the data. Accordingly, the scaling parameters at 12 locations from the study area have been computed. The scatter diagram among the derived scaling parameter and water depth of the study depicts a linear relationship with a correlation coefficient of 0.85 (Fig. 3.3).
3.2). For model-data comparison and subsequent inversion modeling, the processed backscatter data for all the grazing angles were calibrated with the corresponding scaling parameter obtained from the linear trend line of the scatter diagram.

Fig. 3.2 (a) The differences between the model predicted backscatter values and the corresponding processed MBES data are significant for representative sediment types. Panel (b) depicts the linear relationship among the scaling parameter (in dB) and water depth (m) of the study area.
3.2.2 Two-stage parametric optimization

The computation of the correct set of geoacoustic parameters gets convoluted by the large number of good fits existing in the multidimensional search space. It is possible to obtain convincing model-data fits in the search space that do not necessarily represent correct set of seafloor parameters. Accordingly, we have parsed the problem into a two stage parametric optimization method (Sternlicht and de Moustier, 2003b) by constraining the search space (Fig. 3.3). Several options are available to quantify the corresponding results involving the data and model. Here, we have designated the cost-function the error to signal ratio ($E/S$) as the suitable parameter to evaluate the model-data matching procedure (with the goal of minimizing the value). A low value of $E/S$ signifies a finer model-data comparison.

In the frame work of a 3D global search based echo envelope matching procedure, Sternlicht and de Moustier (2003b) have applied simulated annealing with the downhill simplex method to compute the parameters $M_\phi$, $w_2$, and $\sigma_v$. In the present study, we have developed a 4D global search technique including $\gamma_2$, and have substituted the sediment volume scattering coefficient ($\sigma_v$) with the sediment volume scattering parameter ($\sigma_2$). The first stage of the model-data matching procedure employs a 1D search to estimate the general values of the sediment mean grain size ($M_\phi$). The output of the 1D search process provides the input $M_\phi$ value for the subsequent 4D global search method to calculate the precise mean grain size ($M_\phi$); the roughness spectral exponent ($\gamma_2$) and strength ($w_2$); and the sediment volume parameter ($\sigma_2$) (Fig. 3.3).

3.3 Inversion results and discussion

The following sections describe the analyses of the computed sediment geoacoustic inversion results (at 33, 95 and 210 kHz) along with the ground truth values of the mean grain size of the seabed sediment. The analyses provide a comparison among the computed seafloor parameters at three acoustic frequencies to evaluate and assess the modeling performance and bottom characterization.
potentialities. The end results (given in Table 3.1) have been statistically analyzed and compared with the ground truth data and published information available in the literature. Figure 3.4 shows the model-data comparison in three geologically distinct sediment provinces².

![Flow chart representing 4D inversion procedure for seafloor parameter computation.](image)

² For simplicity, throughout the thesis, silty-sand and sand sediments will be referred to as coarse sediments (with $M_\phi < 4$); and clayey-silt and silt sediments will be referred to as fine sediments (with $M_\phi > 4$).
Table 3.1 Summary of the seafloor parameters derived from three acoustic frequencies, 33 and 210 kHz (SBES) and 95 kHz (MBES).

<table>
<thead>
<tr>
<th>Station</th>
<th>Measured $M_\phi$ (phi)</th>
<th>Computed seafloor parameters at 33 kHz</th>
<th>Computed seafloor parameters at 95 kHz</th>
<th>$E/S$ at 95 kHz</th>
<th>Computed seafloor parameters at 210 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_\phi$ (phi)</td>
<td>$\gamma_2$</td>
<td>$w_2$ (cm$^2$)</td>
<td>$\sigma_2$</td>
<td>$M_\phi$ (phi)</td>
</tr>
<tr>
<td>1</td>
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<td>6.96</td>
<td>3.32</td>
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<td>0.0037</td>
</tr>
<tr>
<td>2</td>
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<td>6.59</td>
<td>3.29</td>
<td>0.000561</td>
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</tr>
<tr>
<td>3</td>
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<td>3.10</td>
<td>0.000643</td>
<td>0.0049</td>
</tr>
<tr>
<td>4</td>
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<td>3.29</td>
<td>0.002370</td>
<td>0.0045</td>
</tr>
<tr>
<td>5</td>
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<td>0.0050</td>
</tr>
<tr>
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<td>0.000516</td>
<td>0.0050</td>
</tr>
<tr>
<td>7</td>
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<td>0.00343</td>
<td>0.0046</td>
</tr>
<tr>
<td>8</td>
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</tr>
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</tr>
<tr>
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<td>1.75</td>
<td>3.10</td>
<td>0.00388</td>
<td>0.0029</td>
</tr>
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</table>
Fig. 3.4 Panels (a), (b) and (c) represent the model-data comparison for three geologically distinct sediment provinces: clayey-silt (location 1), silty-sand (location 10) and sand (location 8) with respective 33-, 210-(SBES) and 95-kHz (MBES) frequencies. The model-data matching procedure for the 95 kHz angular MBES data was carried out within the grazing angles 35° to 65°. The excluded data (star) between 65° and 90° is also plotted to depict the relationship with the data.

3.3.1 Mean grain size ($M_\phi$)

The peak amplitudes of the echo envelopes fundamentally depend on the impedance contrast between the water-sediment interfaces. The impedance contrast is often correlated with the mean grain size of sediments (Sternlicht and de Moustier, 2003a). With reference to the inversion modeling study carried out by De and Chakraborty (2011), the computed $M_\phi$ values of the surficial sediments obtained employing SBES inversions were found to be correlated well with the measurements.
(having 95% of confidence limit). Similarly, the $M_\phi$ values derived from the inversion of MBES data is expected to exhibit correlation with the measurements (based on the sediment ground truth) or information available in De and Chakraborty (2011). Accordingly, the computed $M_\phi$ values at the three acoustic frequencies are analyzed with respect to the measured $M_\phi$ values (Fig. 3.5). The computed $M_\phi$ values are in good corroboration with the measured $M_\phi$, indicating statistically significant correlation coefficients of 0.97, 0.98, and 0.96, respectively, at 33, 95, and 210 kHz.

The linear regression analyses carried out to validate the SBES inversion results indicate marginally better computation of $M_\phi$ at 33 kHz as compared with 210 kHz. The correlation analyses have been carried out including the published SBES inversion results to substantiate the estimated $M_\phi$ values at 95 kHz. Statistically significant correlation coefficients of 0.97, 0.97 and 0.98 is evident among the model derived $M_\phi$ values at 33 and 210 kHz, 33 and 95 kHz, and 95 and 210 kHz respectively, indicating the suitability of MBES data for inversion modeling.

The model derived $M_\phi$ values are in good corroboration with the ground-truth measurements (laboratory derived $M_\phi$ values). However, variations are noticeable among the computed $M_\phi$ values at three acoustic frequencies. The backscattering from the seabed can be generally ascribed to two contributing factors, namely interface and volume scattering. The strength of the backscatter signal is primarily controlled by the acoustic frequency, the acoustic impedance contrast between water and sediment, the contributions from seafloor interface roughness, as well as the sediment volume heterogeneity. In fine sediment region, a part of the transmitted acoustic energy penetrates the sediment and is scattered back by the buried inhomogeneities including coarse sand particles and mollusk shells (De and Chakraborty, 2011). The buried heterogeneities can cause local impedance contrast resulting in deviation of the geoacoustic parameters (values correlated with $M_\phi$) calculated in the model-data matching procedure (Sternlicht and de Moustier, 2003a). The input geoacoustic parameters are sensitive to the acoustic impedance contrast (the product of density and sound speed in the sediment), and the variation
of density within the sediment layers can contribute to disparity between the model derived and the ground-truth $M_\phi$ values.

Fig. 3.5 The scatter plot showing multi-frequency inversion results.

### 3.3.2 Seafloor roughness parameters ($\gamma_2$ and $w_2$)

The computed seafloor roughness parameters ($\gamma_2$ and $w_2$) at 95 kHz along with the SBES inversion results have been analyzed to evaluate the relationship between the backscatter and relief spectral parameters (Fig. 3.5). The scatter diagram between the measured $M_\phi$ and estimated $\gamma_2$ reveals that, in the coarse sediment region, the $\gamma_2$ values are confined within the limits of 3.10–3.25, 3.15–3.24, and 3.10–3.20, respectively, at 33, 95, and 210 kHz, but that in fine sediments, the $\gamma_2$ values are found to vary between 3.21–3.32, 3.21–3.27, 3.22–3.34, respectively, at 33, 95, and
210 kHz. Moreover, in the coarse sediment region, the average $\gamma_2$ values are restricted to values around 3.18±0.061, 3.19±0.032, and 3.14±0.047, respectively, at 33, 95, and 210 kHz. In the fine sediment region, the average $\gamma_2$ values are found to be within 3.23±0.085, 3.22±0.020, and 3.28±0.043, respectively, for 33, 95, and 210 kHz. It is observed that the relatively higher values of $\gamma_2$ are associated with fine sediments, while the lower values of $\gamma_2$ are the characteristics of coarse sediments (Fig. 3.5).

The seafloor “roughness power spectrum” estimated from the SBES and MBES data characterizes the size and periodicity of the seafloor height fluctuations as a function of the spatial frequency (Briggs et al., 2005). The roughness power spectrum is often parameterized using a power law by slope and intercept of a linear regression line through the points of the periodogram estimate in log–log space. The parameters $\gamma_2$ and $w_2$ used in the scattering model of Jackson et al. (1986) are the slope and intercept, respectively, of the 2D roughness power spectrum, which are calculated from the 1D power-law values. A wide range of 2D roughness power spectrum parameters can be gleaned from the literature (Briggs, 1989; Stanic et al., 1989; Jackson et al., 1996a; Briggs et al., 2005), and indicate that the majority of the 2D spectral exponent values are confined within 2.90–3.30 in coarse sediments and 3.20–3.50 in fine sediments. In the present study, the computed $\gamma_2$ values are corroborated well with the published data, but have a narrower range of values.

Several studies (Jackson et al., 1986; Stanic et al., 1989) have concluded that the majority of measured 2D spectral strength ($w_2$) values are greater than 0.002 cm$^4$ in coarse sediments and restricted to values around 0.003 cm$^4$ in fine sediments (Sternlicht and de Moustier, 2003a). The scatter diagram between the measured $M_\phi$ and estimated $w_2$ (Fig. 3.5) reveals that the $w_2$ values are less than 0.001 cm$^4$ in fine sediments and confined within the limit 0.002–0.005 cm$^4$ in coarse sediments. Moreover, in the coarse sediment region, the average $w_2$ values are restricted to values around 0.0037±0.00028, 0.0037±0.00032 and 0.0040±0.00074, respectively, at 33, 95, and 210 kHz. In the fine sediment region, the average $w_2$ values are found to be within 0.00057±0.000052, 0.00052±0.000043, and 0.00060±0.000054,
respectively, for 33, 95, and 210 kHz. The computed $w_2$ values were validated with the published data. The $w_2$ values are well clustered at the three acoustic frequencies, having fewer fluctuations for the fine sediment as compared with the coarse sediment region (Fig. 3.5). It is also observed that the relatively higher values of $w_2$ and lower values of $\gamma_2$ are associated with coarse sediments, while the lower values $w_2$ and higher values of $\gamma_2$ are the characteristics of fine sediments.

Briggs et al. (2005) and Jackson and Richardson (2007) have reported that the computed $w_2$ and $\gamma_2$ values can cluster depending on the sediment type with distinct trends in coarse and fine sediment regions. Similar clustering patterns of roughness parameters are conspicuous in the present study, demarcating the coarse and sediment provinces (Fig. 3.5). Briggs (1989) also reported that the parameters derived from a roughness power spectrum can vary with respect to the sediment type, such that the roughness spectra characteristic of coarse sediments have a less-steep decay (i.e., lower value of $\gamma_2$) in the power-law relationship. The less-steep decay (i.e., less-steep slope of the regression line) in the power spectrum can be attributed to relatively high intercept energy of the spectrum at a unit spatial frequency (1 cm). Therefore, it is likely to have higher values of $w_2$ and lower values of $\gamma_2$ for coarse sediments and comparatively lower values $w_2$ and higher values of $\gamma_2$ characteristics in fine sediments. Apparently, these aspects are evident in the presented analyses (Fig. 3.5).

### 3.3.3 Sediment volume scattering parameter ($\sigma_2$)

The shape of the SBES echo envelope has two distinct parts, the initial part and the tail part. The initial part of the data represents the reflection from the water-sediment interface (interface scattering and the related $\gamma_2$ and $w_2$), and the tail portion corresponds to the backscatter from the sediment volume (volume scattering and the associated parameter $\sigma_2$). The $\sigma_2$ values are generally related to the sediment type (fine or coarse) and seafloor inhomogeneities (Jackson et al., 1986). Jackson and Briggs (1992) have demonstrated dominant sediment volume backscatter in finer sediments, and Jackson et al. (1986) used $\sigma_2$ as a variable parameter with a
maximum range up to 0.004 in soft sediments. However, Stewart and Chotiros (1992) have experimentally demonstrated that the limit of $\sigma_2$ designated in soft sediment is low, and the sediment volume scattering coefficient is usually much higher than the predicted value. Nonetheless, it is convenient to use $\sigma_2$ as a variable parameter in the model-data matching procedure. The sensitivity analyses carried out on the shape of the SBES data\(^3\) indicates significant contribution of sub-bottom scattering conspicuous near the tail of the echo-envelope with relatively higher $\sigma_2$ value. The higher $\sigma_2$ has marginal effect on the peak amplitude of the echo-envelope. With reference to the recent study carried out by De and Chakraborty (2011), the selection of low $\sigma_2$ values (<0.004) resulted in higher values of $E/S$ ratio during the inversion modeling. Improved model-data comparisons (with low values of $E/S$ ratio) were achieved by increasing the $\sigma_2$ values (>0.004). The variation of the computed $\sigma_2$ among the coarse and fine sediments was subtle because it has been chosen as a variable parameter that varies with the locations. In the absence of measured $\sigma_2$ parameters in the study area, based on the published SBES inversion results (De and Chakraborty, 2011), the input value of $\sigma_2$ is assigned as 0.004 for MBES inversion modeling irrespective of the sediment type.

In the coarse sediment region, the average $\sigma_2$ values are restricted to values around 0.0039±0.00059, 0.0034±0.00063, and 0.0031±0.00048, respectively, at 33, 95, and 210 kHz. In the fine sediment region, the average $\sigma_2$ values are found to be within 0.0047±0.00056, 0.0045±0.00021, and 0.0043±0.00026, respectively, for 33, 95, and 210 kHz. The computed $\sigma_2$ are important to provide convincing model-data comparison at the three acoustic frequencies (Fig. 3.5). Jackson and Briggs (1992) have reported dominant volume scattering in fine sediments. The experiment carried out by Jackson and Briggs (1992) demonstrated improved model-data comparison in the fine sediment region with relatively higher values of $\sigma_2$ (0.004–0.006). In the present study, the $\sigma_2$ values computed in the fine sediments have been found to be

\(^3\) The method used to examine relative importance of input parameters to the model output is commonly termed as sensitivity analyses. The readers are referred to the PhD thesis of De. (2010), for more information on the sensitivity analyses of SBES model.
relatively higher as compared with the coarse sediment region. An appropriate assessment on the accurateness of the estimated $\sigma^2$ values is difficult due to lack of supporting data and further studies are required to draw better conclusion.

### 3.4 Concluding remarks

The composite roughness scattering model (Jackson et al., 1986) derived seafloor parameters ($M_\varphi$, $\gamma^2$ and $w^2$) using the 95 kHz MBES data are compared with the ground-truth data as well as with the inversion results obtained using 33 and 210 kHz SBES data at the same locations. The resulting geoacoustic parameters provide important information that can be utilized for acoustic seafloor characterization. Statistically significant correlations are noticeable between the model derived $M_\varphi$ values and the ground truth sediment information, substantiating the multi-frequency inversion results. The $M_\varphi$ values estimated at 33 and 95 kHz appears to be marginally better as compared with 210 kHz. In the absence of measured roughness data, the computed roughness spectrum parameters ($\gamma^2$ and $w^2$) are compared with the published information available in the literature. The computed $\gamma^2$ and $w^2$ values are corroborated well with the published data, displaying subtle variations among 33, 95, and 210 kHz.

Williams et al. (2002) have postulated transition of the scattering theory in the critical frequency range of 150–300 kHz. Utilizing the backscatter data of the experiments SAX99 and SAX04, Williams et al. (2009) have reported the emergence of a new scattering mechanism at 200 kHz or higher frequencies. Significant difference in scattering strength from the surrounding medium and the embedded

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4 The analyses of multi-frequency inversion results and related geoacoustic parameters for different combination of sediment substrate, operating frequency, and transducer orientation suggests that the moderate frequencies (33 and 95 kHz) are more appropriate for model-based seafloor characterization. The subtle difference among the roughness parameters computed at 33, 95, and 210 kHz is possibly due to limitations of Helmholtz-Kirchhoff theory implemented in the SBES temporal backscatter model. The Helmholtz-Kirchhoff theory basically computes the seafloor interface roughness (and the resulting model) with the assumption of isotropic Gaussian distribution of the surface relief. The assumption restricts the application of Helmholtz-Kirchhoff theory to extremely rough (rocky) seafloor and higher operating frequencies (>100 kHz), where the Kirchhoff’s criterion fails (Sternlicht and de Moustier, 2003b). However, De. (2010) computed the Kirchhoff’s criterion for 210 kHz and demonstrated its suitability for seafloor characterization.
coarse material in the controlled laboratory experiments is also obvious at higher frequencies between 150 kHz to 2 MHz (Ivakin and Sessarego, 2007). Besides, it has been reported that at higher frequencies (> 200 kHz), even a small portion of the embedded shell fragments can significantly alter the seafloor scattering characteristics, resulting in the subtle difference among the roughness parameters computed at 33, 95, and 210 kHz. In the context of multi-frequency inversion, the results derived using the 95 kHz MBES data are more correlated with the seafloor parameters corresponding to 33 kHz as compared with 210 kHz SBES data.