

Model-Based Acoustic Remote Sensing of Seafloor Characteristics

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Abstract—The characterization of seafloor sediments by acoustic means is carried out using normal-incidence, dual-frequency, single-beam echo sounder backscatter data at 20 locations in the western continental shelf of India. A temporal backscatter model for a finite duration of transmitted signal is used to estimate the values of four sediment parameters through inversion—mean grain size, roughness spectrum strength, roughness spectrum exponent, and sediment volume scattering parameter. Ground truth information on sediment mean grain sizes at these locations is obtained from the laboratory analysis of grab samples. Applicability of the temporal backscatter model over different sediment compositions at 33 and 210 kHz is investigated here for characterizing the seafloor through inversion. Moreover, a combined two-frequency inversion approach has been attempted for improved characterization by estimating a single set of values for the aforementioned four sediment parameters, which is applicable to the backscatter data at both of the acoustic frequencies. A linear regression analysis demonstrates that the estimated values of sediment mean grain size obtained from these three inversion cases statistically agree with the ground truth data. In addition, correlations of the estimated values of seafloor roughness spectrum parameters with the values of sediment mean grain size are compared with published information available in the literature.

Index Terms—Acoustic remote sensing, backscatter model, echo envelope, inversion, mean grain size, seafloor roughness spectrum parameters.

I. INTRODUCTION

CHARACTERIZATION of seafloor sediments by acoustic methods has become important in many fields of research, including hydrography, marine geology, marine biology, marine engineering, and fisheries sciences. The most reliable and accurate information on seafloor sediments is obtained from the laboratory analysis of grab and/or core samples, high-resolution circularly scanning sonar, stereo photogrammetry, and *in situ* probes. However, these methods give information at discrete locations and are time consuming as well as expensive. Remote sensing by acoustic means has been well recognized as a rapid and cost-effective method for characterization of seafloor sediments over a wide area. Conventional normal-

incidence, single-beam echo sounders, and multi-beam echo sounders typically have been used for seafloor sediment characterization [1]–[12]. However, there are challenges associated with the acoustic methods to interpret the frequency-dependent backscatter energies. Therefore, studies on acoustic backscatter from the seafloor have gained importance [13]–[16]. Seafloor interface roughness and sediment volume scattering are the dominant factors in acoustic backscatter from the seafloor [17]–[24]. However, it is a very difficult task to measure the fine-scale seafloor roughness accurately. The technique of digital stereo photogrammetry can be used for accurate measurements of seafloor roughness parameters [25]–[27]. However, mapping of seafloor properties with fine resolution over a wide area is not possible with these systems. This difficulty warrants the development of remote acoustic techniques for characterization of seafloor sediment. Remote sensing of the characteristics of seafloor sediments through inversions of physics-based backscatter models are often utilized for this purpose [28], [29]. The accuracy of the inversion results greatly depends on the forward backscatter models. Sternlicht and de Moustier [24] developed a physics-based temporal backscatter model [17], [19], in which the acoustic backscatter at the water–sediment interface and the scattering from the sediment volume are modeled independently for a finite duration of transmission and then summed to compute the total backscatter intensity. The values of sediment parameters were estimated using this temporal model through inversion and validated using the backscatter data collected at 33 and 93 kHz over three sites in San Diego Bay [29].

The aim of this paper is to investigate the applicability of the temporal backscatter model [24] for characterizing the seafloor sediments with varied compositions in the western continental shelf of India using single-beam echo sounder data. For this purpose, the values of seafloor sediment parameters such as mean grain size, roughness spectrum strength, roughness spectrum exponent, and sediment volume scattering parameter are estimated through inversion at two conventional frequencies (33 and 210 kHz) of an echo sounder. In addition, a combined two-frequency inversion approach (hereafter referred as 2F inversion) has been explored for achieving improved characterization of the seafloor sediment. In general, the use of multiple acoustic frequencies increases the ability to characterize the seafloor sediment because the roughness spectrum and the volume backscattering strength may vary with acoustic frequency [2], [30]. Lower acoustic frequencies penetrate the seafloor to greater depths, whereas higher frequencies have greater resolving capability. Therefore, it is expected that two or more frequencies of a single-beam echo sounder will improve the

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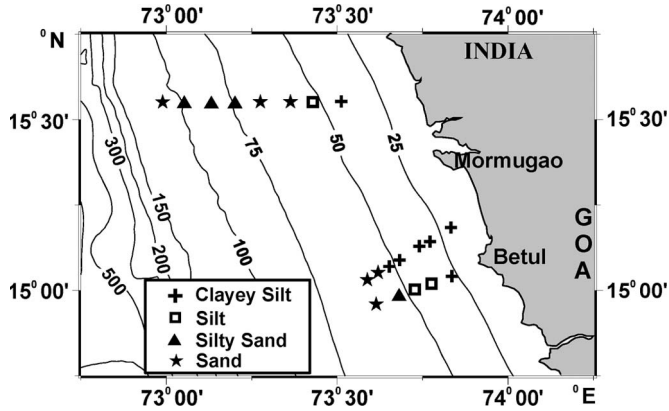


Fig. 1. Study area showing the sediment type at 20 sample locations (Depth contours are in meters).

understanding of acoustic backscatter from different seafloor sediments. In this 2F inversion approach, the data collected with 33 and 210 kHz are jointly inverted for estimating the values of a single set of seafloor sediment parameters applicable to the backscatter data at both the frequencies. The values of seafloor parameters estimated from 33 kHz, 210 kHz, and 2F inversions are compared with ground truth as well as available published information.

II. MEASUREMENTS

A. Echo Envelope Data

Dual-frequency (33 and 210 kHz) backscatter echo data were acquired at 20 locations (Fig. 1) in the central part of the western continental shelf of India using a hull-mounted Reson Navitronic NS-420 normal-incidence single-beam echo sounder in calm sea conditions [31], [32]. The beam widths of the echo sounder transducer for 33 and 210 kHz are 20° and 9°, respectively. The transmission pulse lengths are 0.97 and 0.61 ms, respectively, for 33 and 210 kHz. The single-beam echo sounder outputs were tapped and connected to a PCL 1712L 12-bit A/D converter. The echo data were sampled at 1 MHz (instrument details on data collection are given in Navelkar *et al.* [33]). For individual frequencies, about 600–800 acoustic backscatter pings were acquired (when the ship was stopped for collection of sediment samples) at each location. In the pre-processing stage, echo data with saturated voltage are removed from the stack. The remaining echo data are subjected to Hilbert transforms to obtain echo envelopes. As we are interested to estimate the values of seafloor sediment properties by optimized echo envelope matching [29], the echo envelopes, characterized by a well-defined initial rise and peak amplitude, followed by a slow decay, are selected by visual check for further analysis [24], [34]. Due to the transducer heave motion and small seafloor depth variations over consecutive pings (while recording the data), initial rise times of the envelopes (which correspond to seafloor depths) are not same for all the echoes collected at a particular location. To obtain stable acoustic signals, echo envelopes are first aligned and then averaged using 20 successive echo envelopes with 50% overlaps (i.e., the echoes are averaged in moving average sense with sequences

TABLE I
GROUND TRUTH DATA

Stn. No.	% Sand	% Silt	% Clay	Laboratory Measured ^a M_ϕ (phi)	Sorting Coefficient ^b , σ (phi)	Sediment Type
1	1.49	65.28	33.23	6.71	1.51	Clayey Silt
2	0.41	71.59	27.99	6.68	1.40	Clayey Silt
3	1.78	70.06	28.16	6.67	1.43	Clayey Silt
4	3.17	71.93	24.90	6.32	1.66	Clayey Silt
5	8.03	71.52	20.45	5.83	1.96	Clayey Silt
8	0.78	70.95	28.27	6.66	1.44	Clayey Silt
13	0.13	70.66	29.21	6.79	1.32	Clayey Silt
9	0.54	75.86	23.60	6.42	1.48	Silt
10	0.64	75.91	23.45	6.50	1.43	Silt
14	0.92	79.05	20.03	6.20	1.58	Silt
11	57.42	32.30	10.28	4.02	2.24	Silty Sand
17	70.31	24.45	5.24	2.40	2.19	Silty Sand
18	73.64	22.29	4.07	1.99	2.11	Silty Sand
19	54.58	38.52	6.90	3.32	2.21	Silty Sand
6	95.33	3.08	1.59	1.69	0.99	Sand
7	91.26	6.13	2.61	2.31	1.27	Sand
12	91.26	6.87	1.87	2.03	1.27	Sand
15	80.90	14.24	4.86	2.42	1.81	Sand
16	89.05	8.65	2.30	1.16	1.39	Sand
20	83.77	14.01	2.23	2.07	1.62	Sand

^a $M_\phi = -\log_2(d)$, with d the grain size diameter in mm and M_ϕ is calculated from cumulative weight distribution curve using $M_\phi = (\phi_{16} + \phi_{50} + \phi_{84})/3$

^bSorting Coefficient or Folk's inclusive graphic standard deviation (σ) is calculated using $\sigma = (\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_5)/6.6$

1–20, 11–30, and so on till the end of the number of consistent echo envelopes available).

B. Ground Truth

Sediment samples were collected using a Van Veen grab sampler (at the same 20 locations, where the echo data were acquired) to obtain ground truth on the mean grain size of the sediment. As mentioned earlier, the acoustic backscattering from the seafloor is primarily influenced by the contributions of the energy scattered at the water–sediment interface and from the sediment volume. Interface scattering can be described by the interface roughness coupled with acoustic impedance. Volume scattering depends on the water–sediment interface characteristics for transmission of the energies and then absorption inside the sediment volume. A significant contribution, due to volume scattering (in addition to interface scattering) from various scatterers (e.g., shells, pebbles, gas bubbles, living organisms, sediment layering etc.), is expected at 33 kHz due to greater penetration of energies. However, the effect of volume scattering is expected to decrease (in contrast with the interface scattering) with the increase in the acoustic frequency because of enhanced absorption. The absorption in seafloor sediments typically varies in the range 0.1–1.0 dB/wavelength [35]. In this paper, the acoustic wavelengths for 33 and 210 kHz are 4.5 and 0.7 cm, respectively. Thus, surficial sediments collected by a grab sampler can be considered as the property representative of the portion of sediment probed by the echo sounder, providing quantitative information on seafloor sediment grain size distribution. The percentage compositions of sand, silt, and clay in surface sediment samples are determined in the laboratory using a laser particle size analyzer [36]. The results are given in Table I. Because sediment samples at the experimental sites do not contain any gravel portion,

Shepard's scheme [37] is used to decide the sediment types based on the percentage compositions of sand, silt, and clay. The analyses reveal that four types of sediments are available in the study area, namely, clayey silt, silt, silty sand, and sand (Fig. 1). Folk's inclusive graphic standard deviation values (or the sorting coefficients given in Table I) indicate that sediments in the experimental area are mainly poorly to very poorly sorted. The sorting coefficients for clayey silt and silt samples vary within a range of 1.32ϕ to 1.96ϕ , whereas for silty sand and sand samples the sorting coefficients vary within 0.99ϕ to 2.24ϕ .

III. ESTIMATION OF SEAFLOOR CHARACTERISTICS

It is mentioned earlier that the temporal backscatter model developed by Sternlicht and de Moustier [24] is employed here for model-based characterization of seafloor sediments. The total backscatter intensity (measured at the transducer face) for a finite duration of transmitted signal is modeled by summing the intensities from the water–sediment interface and from the sediment volume inhomogeneities. Sternlicht and de Moustier [24] implemented the Helmholtz diffraction integral based on the Kirchhoff approximation and the composite roughness approach for seafloor classification. This total backscatter intensity is a function of the sediment mean grain size (M_ϕ), roughness spectrum strength (w_2), roughness spectrum exponent (γ_2), and the sediment volume scattering parameter (σ_2) or the sediment volume scattering coefficient (σ_ν). The computation of total backscatter intensity also takes into account various environmental factors such as spherical spreading, absorption losses in the water column, transducer characteristics, transmitting pulse duration, and the altitude of the transducer from the seafloor. In addition, various geoacoustic parameters (which are used in this model) are estimated from the sediment mean grain size using the published relationships [38]. Based upon the approach of Jackson *et al.* [17], the sediment volume scattering parameter is assumed as a free parameter in this temporal backscatter model and is expressed as $\sigma_2 = \sigma_\nu/\alpha_s$, where α_s is the attenuation coefficient in sediment in dB/m.

As the solution from inversion of the acoustic backscatter model may not be unique, Sternlicht and de Moustier [29] proposed a well-constrained approach, which utilizes a two-stage inversion process to estimate the values of four sediment parameters (M_ϕ , w_2 , σ_ν , and γ_2). In the first stage, a representative value of M_ϕ and the sediment type (fine- or coarse-grained sediment based on the value of M_ϕ) are first estimated from the echo envelope peak amplitude through a one-dimensional (1-D) iterative search. Based on the estimated sediment type, the value of γ_2 is fixed at either 3.3 (for fine-grain sediment with $M_\phi \geq 4\phi$) or 3.0 (for coarse-grain sediment with $M_\phi < 4\phi$) for the second stage of the inversion process. In the second stage, a three-dimensional (3-D) global optimization is performed to estimate the values of (M_ϕ , w_2 , and σ_ν) using simulated annealing and a downhill simplex algorithm [29].

Following this two-stage inversion scheme (as proposed by Sternlicht and de Moustier [29]), initially, an attempt was made by the authors [5] to characterize the seafloor by estimating the

values of sediment property parameters (M_ϕ , w_2 , σ_ν , and γ_2) with a limited data set collected from the present experimental area. However, that study [5] revealed that the estimated values of the roughness spectrum strength w_2 are different at 33 and 210 kHz. Because the interface roughness is modeled (based on the assumption of isotropic Gaussian distribution of surface relief) by a single power law relief energy, the values of the roughness spectrum strength are not expected to vary with the acoustic frequency.

In view of the above observations, the two-stage inversion scheme has been slightly modified in this paper to compare the estimated values of seafloor sediment properties at different acoustic frequencies. The following modifications are made:

- 1) Because the aim in this paper is to investigate the applicability of the temporal backscatter model for characterizing the seafloor sediments at two different acoustic frequencies, the sediment volume scattering parameter (σ_2) is used for better comparison instead of sediment volume scattering coefficient (σ_ν). The parameter σ_2 is assumed as a frequency-independent parameter in this paper [20].
- 2) Following Sternlicht and de Moustier [29], the earlier study by the authors [5] assumed only one of two values of γ_2 depending on the rough estimate (from the 1-D iterative search) of the sediment type (i.e., $\gamma_2 = 3.0$ for coarse sediments and $\gamma_2 = 3.3$ for fine sediments). However, if γ_2 is different from the assumed values, the error would be translated into the different values of w_2 at different acoustic frequencies. Thus, the values of γ_2 are not considered as constants in this paper. In the second stage of the inversion process, the value of γ_2 is also inverted along with M_ϕ , w_2 , and σ_2 . Thus, the inversion approach changes from 3-D to a four-dimensional (4-D) inversion scheme.
- 3) Furthermore, an attempt has been made to utilize the two-frequency backscatter data jointly for improved characterization of the seafloor sediment [39]. Accordingly, a 2F inversion is performed to estimate the values of a single set of sediment property parameters (M_ϕ , w_2 , γ_2 , and σ_2) applicable to the backscatter data at both the acoustic frequencies (i.e., applicable in the frequency range 33–210 kHz). As mentioned, all the four sediment parameters are assumed as frequency-independent in this paper.

To measure the match between the recorded field data and the model prediction, the signal-to-error (S/E) ratio is used as a merit function in this paper [29]. The S/E, which measures the energy to represent the discrepancy between the data and the model prediction, is expressed as $S/E = \sum_n p_a^2[n] / \sum_n (p_a[n] - p_m[n])^2$, where the terms $p_a[n]$ and $p_m[n]$ represent the averaged data and modeled echo envelopes with n samples, respectively [29]. The inverse of S/E ratio (i.e., error-to-signal ratio, E/S) is used as the objective function in this study and the 4-D inversion is carried out using simulated annealing with the downhill simplex algorithm [29], [40]. The parameters estimated through the inversion are

essentially constrained over a limited search range in the solution space to avoid unrealistic solutions. Accordingly, the value of M_ϕ obtained from the echo envelope peak amplitude (using the 1-D search) is allowed to vary within $M_\phi \pm 1.0\phi$ in the 4-D inversion scheme to adjust the data-model matches for estimating the values of sediment parameters (M_ϕ , w_2 , γ_2 , and σ_2). In 4-D inversion, a broad search range $0.0002 \leq w_2 \leq 0.009$ is chosen for w_2 based on the published observations from various other field experiments [20], [25]. The field experiments by Jackson and Briggs [20] and Briggs [25] over different sedimentary environments also revealed that a majority of the measured values of γ_2 lie within a range of 2.9–3.5. Thus, the values of γ_2 are varied within 2.9–3.5 in the 4-D inversion scheme. Moreover, the values of the free parameter σ_2 are varied in the range 0.0001–0.006. Though there is no hard upper limit in the search range for the parameter σ_2 , the value 0.006 is chosen in this study to avoid the large contribution of volume scattering components. Stewart and Chotiros [41] reported much higher values of σ_2 ($\gg 0.006$) to obtain data-model fit with their scattering data; however, the experiments by several other researchers [17], [18], [20], [42] revealed that in general, the maximum values of this free parameter σ_2 in the range 0.004–0.006 give the best fit to the measured scattering data. In this temporal backscatter model, unrealistically high values of the volume scattering parameter ($\sigma_2 > 0.006$) may exhibit very high values of S/E ratio (i.e., “good” data-model fit). Because only normal-incidence single-beam echo sounder backscatter data are considered in this paper, the interface scattering components are expected to have larger contributions than that of the volume scattering components. To avoid such instances (the best fit with the data using a high value of σ_2), an empirical penalty component is used in the 4-D inversion scheme [29].

Furthermore, in the 2F inversion scheme, the summation of two E/S values, computed at two individual frequencies, is used as the new objective function to measure the discrepancies between the data and the modeled echo energies [39]. Moreover, a 1-D search is not performed in the 2F inversion. Instead, an average of the two estimates of M_ϕ obtained from the 1-D search at two individual frequencies is used as the rough estimate of M_ϕ in the 4-D inversion scheme. This average value of M_ϕ is allowed to vary within $\pm 1.3\phi$ in the 4-D inversion for the 2F approach. A broader search range for M_ϕ is chosen in the 2F inversion scheme because of the differences in the rough estimation of M_ϕ (obtained from the 1-D search at two individual frequencies) for only a few samples. The search ranges for other sediment parameters (i.e., for w_2 , γ_2 , and σ_2) are kept unchanged from the individual frequency inversions.

For a particular sedimentary environment (i.e., at a particular site), estimations of the values of four parameters (at two individual frequencies as well as 2F inversions) are carried out using the available averaged echo envelopes and subsequently, an overall average value is computed from all the estimated values for that particular site. This overall average value (for every individual site) is referred to as the estimated mean value of the sediment parameter (e.g., estimated mean value of M_ϕ or estimated mean value of w_2 , etc.) in the following text.

IV. RESULTS AND DISCUSSION

We compare the estimated mean values of the seafloor property parameters obtained from the individual frequency and 2F inversions (given in Table II) with the ground truth as well as with the information available in published literature. In the last three columns of Table II, the average values of S/E ratio (in dB) are given for 33 kHz, 210 kHz, and 2F inversions. These values provide useful information on the comparison of data-model matching results, where a higher value represents a better match of the model with the field data. The averaged values of backscatter strength in dB (termed as the mean values of backscatter strength), computed from the available averaged echo envelopes using the echo sounder transceiver characteristics [43], are used for assessing the consistency of the estimated mean values of M_ϕ at both the frequencies. Silty sand and sand sediments will be referred to as coarse sediments (with estimated $M_\phi < 4\phi$); and clayey silt and silt sediments will be referred to as fine sediments (with estimated $M_\phi \geq 4\phi$) in the following text.

A. Mean Grain Size

The peak amplitudes of echo envelopes primarily depend on impedance contrast between water and seafloor sediments. In surficial sediments, the impedance contrast is often correlated with the mean grain size of sediments [24]. The estimated mean values of M_ϕ of surficial sediments obtained from the inversions of echo envelopes are therefore expected to correlate with the laboratory-measured values of M_ϕ . The linear regression analysis (between the estimated mean values of M_ϕ and the laboratory-measured values of M_ϕ) shows that the correlation coefficients are 0.98, 0.96, and 0.97, respectively for 33 kHz, 210 kHz, and 2F inversions [Fig. 2(a)]. For these three correlations, the associated p -values ($p \ll 0.0001$) are much smaller than the 5% level of significance (computed using a Student's t -distribution), which indicates that the probability in obtaining these correlation coefficients by chance is close to zero. Since $p < 0.05$, these correlations are statistically significant at 5% level of significance. The 95% confidence limits for the three regression lines are also shown in Fig. 2(a). The correlations also indicate that the regression models can explain about 92%–96% of the variances in the estimation of M_ϕ . Moreover, this result indicates that the least square line obtained from the best fit of the 33 kHz data gives the best estimation of M_ϕ when compared with the 1 : 1 straight line [shown as the dotted lines in Fig. 2(a)].

A linear regression analysis reveals that the correlation coefficients between the laboratory-measured values of M_ϕ and the mean values of backscatter strength are 0.75 and 0.69, respectively, at 33 and 210 kHz. It is expected that the estimated mean values of M_ϕ from the inversions should also exhibit similar correlations. Fig. 2(b) shows that the correlation coefficients between the estimated mean values of M_ϕ and the mean values of backscatter strength are 0.78 and 0.68, respectively, for 33 and 210 kHz. Since the p -values associated with these correlation coefficients (r) are less than the 5% level of significance (i.e., $p < 0.05$), the correlations 0.68 and 0.78 are statistically

TABLE II
INVERSION RESULTS

Stn. No.	Estimated mean values of M_ϕ (phi)			Estimated mean values of w_2 (cm ⁴)			Estimated mean values of σ_2			Estimated mean values of γ_2			Average signal to error ratio (dB)		
	33 kHz	210 kHz	2F	33 kHz	210 kHz	2F	33 kHz	210 kHz	2F	33 kHz	210 kHz	2F	33 kHz	210 kHz	2F
1	6.30	5.17	5.28	0.000313	0.000618	0.000498	0.0048	0.0042	0.0047	3.18	3.29	3.30	18	13	14
2	6.95	4.70	5.11	0.000284	0.000663	0.000480	0.0055	0.0044	0.0050	3.14	3.31	3.26	17	15	14
3	5.92	5.68	5.75	0.000476	0.000592	0.000525	0.0053	0.0049	0.0050	3.15	3.35	3.30	12	14	14
4	6.13	5.03	5.24	0.000285	0.000579	0.000544	0.0044	0.0037	0.0039	3.30	3.29	3.30	11	12	16
5	6.26	5.45	5.53	0.000408	0.000592	0.000512	0.0049	0.0040	0.0034	3.23	3.31	3.25	15	12	20
8	6.96	5.00	5.94	0.000527	0.000524	0.000516	0.0037	0.0040	0.0029	3.32	3.22	3.28	18	10	14
13	6.71	5.01	5.83	0.000593	0.000582	0.000516	0.0050	0.0044	0.0034	3.21	3.34	3.30	16	14	15
9	6.59	4.75	5.79	0.000561	0.000625	0.000469	0.0049	0.0040	0.0050	3.29	3.27	3.29	20	12	13
10	6.29	5.02	5.15	0.000643	0.000670	0.000625	0.0049	0.0045	0.0037	3.10	3.29	3.26	16	11	17
14	6.08	4.21	5.22	0.000516	0.000603	0.000479	0.0050	0.0045	0.0043	3.24	3.28	3.25	12	11	13
11	2.79	3.08	3.17	0.00237	0.00153	0.00222	0.0045	0.0041	0.0042	3.29	3.12	3.16	20	14	18
17	2.37	2.05	2.63	0.00366	0.00255	0.00243	0.0043	0.0029	0.0032	3.24	3.11	3.16	22	18	22
18	1.86	1.10	2.37	0.00419	0.00439	0.00293	0.0039	0.0027	0.0024	3.20	3.10	3.19	18	13	23
19	2.33	1.03	2.40	0.00346	0.00452	0.00318	0.0038	0.0032	0.0023	3.19	3.20	3.19	16	13	22
6	1.51	1.10	1.65	0.00355	0.00454	0.00388	0.0049	0.0032	0.0050	3.30	3.20	3.20	17	19	16
7	1.98	2.08	2.49	0.00375	0.00296	0.00294	0.0046	0.0035	0.0037	3.29	3.20	3.21	20	19	20
12	1.80	1.92	2.41	0.00371	0.00344	0.00212	0.0045	0.0035	0.0046	3.27	3.20	3.19	21	17	18
15	1.97	1.40	1.85	0.00343	0.00401	0.00398	0.0046	0.0029	0.0036	3.12	3.10	3.09	23	17	19
16	2.10	1.31	1.91	0.00365	0.00438	0.00235	0.0042	0.0040	0.0028	3.25	3.14	3.12	20	19	19
20	1.75	1.51	1.86	0.00388	0.00424	0.00376	0.0029	0.0028	0.0019	3.10	3.20	3.08	14	15	13

significant. The 95% confidence limits are shown in Fig. 2(b). These regression models can explain about 46%–60% of the variances in the data set.

As pointed out earlier, the backscatter strength from the seafloor is primarily controlled by the acoustic frequency, the contrast in acoustic impedances between water and sediment, and the contributions from seafloor interface roughness as well as sediment volume inhomogeneity. Scattering due to seafloor interface roughness is relatively more important at higher acoustic frequencies, while scattering due to volume inhomogeneity below the water–sediment interface is relatively more significant at lower acoustic frequencies. In soft sediments, the acoustic energy penetrates into the sediment and likely to be scattered from the buried inhomogeneities such as coarse sand particles, shell hash, mollusk shells, buried layers of coarse materials, etc. The intensity of the scattered energy depends on the sizes of these buried inhomogeneities relative to the impinging acoustic wavelength. This phenomenon might be responsible for the few outlying values of backscatter strength, observed particularly in fine-grained sediments. The rms value of the full grain size distribution, called grain size sorting coefficient (given in Table I), which provides an alternative measure of the coarse content in sediment, can also be used for assessing the fluctuations of the backscatter intensity [44]. To link the fluctuations of the backscatter data [as shown in Fig. 2(b)] with the grain size sorting coefficients (given in Table I), the station locations are used as labels against the symbols in Fig. 2(b). As evident from Table I, the sediments in the study area are mainly poorly to very poorly sorted. The effect of the fluctuations of backscatter strength on the correlation coefficient is examined by removing only two higher and outlying values of backscatter strength measured at stations 1 and 4 from the data set. It was observed that the values of the correlation coefficient increased to 0.90 and 0.79, respectively,

for 33 and 210 kHz. The p -values ($p < 0.05$) associated with these correlation coefficients indicate that these correlations are also statistically significant at 5% level of significance. This indicates that if the fluctuations of the backscatter data at two stations are removed, the regression models can explain about 62%–81% variances in the data set.

As mentioned, acoustic impedance contrast is one of the factors, which controls the seafloor backscatter strength. The acoustic impedance is the product of density and sound speed in sediment. The finer sediments with high porosity (that have low values of density and sound speed, i.e., small impedance contrast between water and sediment) are expected to exhibit low backscatter strengths. The coarser sediments with low porosity (that have higher values of density and sound speed, i.e., high impedance contrast between water and sediment) are expected to have higher backscatter strengths. These theoretical expectations are well supported by the field measurements [44]–[47]. In this paper, the statistically significant linear correlations (with 95% confidence level) between the estimated mean values of M_ϕ and the measured backscatter strength support these observations. Furthermore, the statistically significant linear correlations (with 95% confidence level) between the laboratory-measured values and the estimated values of sediment mean grain size [as shown in Fig. 2(a)] primarily support these estimations from inversions.

B. Roughness Spectrum Parameters

The estimated mean values of roughness spectrum parameters (w_2 and γ_2) of the seafloor relief and the estimated mean values of M_ϕ are plotted in a scatter diagram to understand their relationships. The scatter diagram [Fig. 3(a)] between the estimated mean values of M_ϕ and w_2 revealed that the values of w_2 are less than 0.001 cm⁴ for fine sediments and

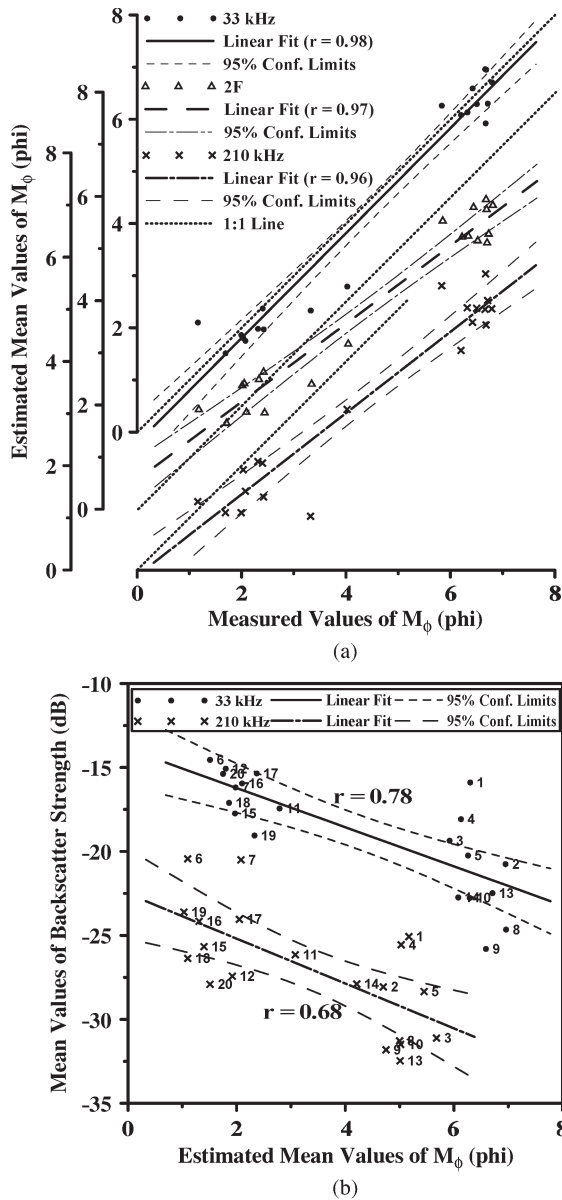


Fig. 2. (a) Scatter plot showing the relationship between the laboratory-measured values of M_ϕ (phi) and the estimated mean values of M_ϕ (phi) for the three inversion cases. Diagonal dotted lines indicate the 1 : 1 lines. (b) Scatter plot showing the relationship between the estimated mean values of M_ϕ (phi) and the mean values of backscatter strength (dB) at 33 and 210 kHz. The values of the correlation coefficients (r) are indicated in the plot. The labels against the symbols indicate the station locations.

are confined within 0.002–0.005 cm⁴ (except one value for a silty sand sample at 210 kHz inversion) for coarse sediments. In addition, the scatter diagram [Fig. 3(b)] between the estimated mean values of M_ϕ and γ_2 shows that the values of γ_2 are confined within 3.21–3.4 for fine sediments and within 3.0–3.21 for coarse sediments at 210 kHz and 2F inversions. In contrast, the estimated mean values of γ_2 at 33 kHz inversions do not exhibit any clear trend distinguishing between fine and coarse sediments.

It is observed [Fig. 3(a)] that the estimated mean values of w_2 are clustered with less fluctuation for fine sediments for all the three inversion cases. For coarse sediments, the estimated mean values of w_2 are relatively scattered. In addition, the

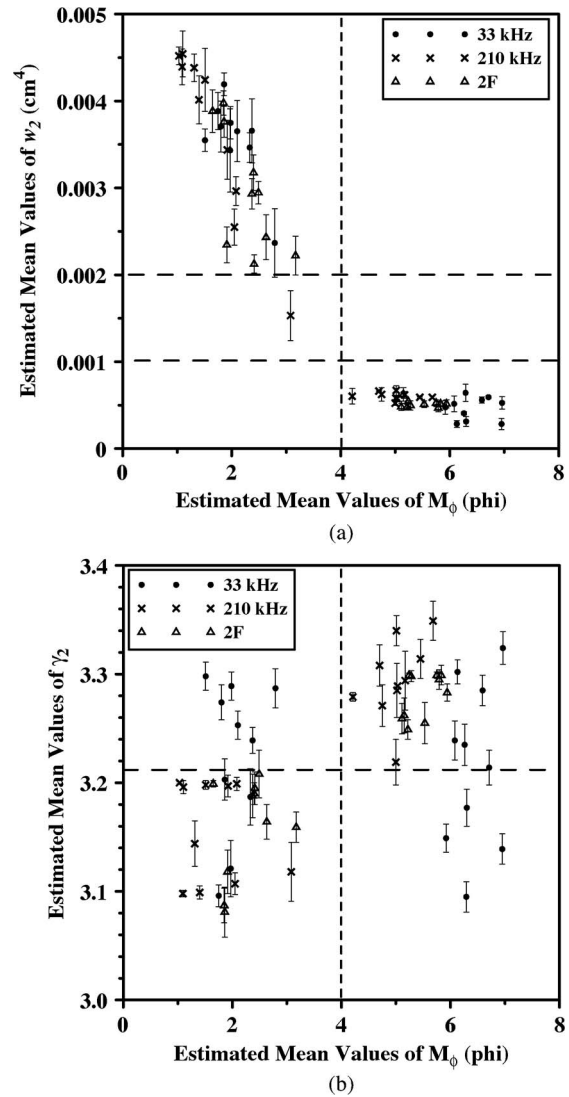


Fig. 3. (a) Scatter diagram between the estimated mean values of M_ϕ (phi) and w_2 (cm⁴). The vertical dashed line at $M_\phi = 4\phi$ demarcates the fine and the coarse sediments. The two horizontal dashed lines at $w_2 = 0.001$ cm⁴ and $w_2 = 0.002$ cm⁴ demarcate the maximum and minimum limits of w_2 for fine and coarse sediments, respectively. The error bars indicate one standard deviation in either direction. (b) Scatter diagram between the estimated mean values of M_ϕ (phi) and γ_2 . The vertical dashed line at $M_\phi = 4\phi$ demarcates the fine and the coarse sediments. The horizontal dashed line at $\gamma_2 = 3.21$ indicates the separation between fine and coarse sediments. The error bars indicate one standard deviation in either direction.

estimated mean values of γ_2 are relatively more clustered for 2F inversions than the individual frequency inversions. For coarse sediments, the overall average estimates of γ_2 (from 10 coarse sediment samples) are 3.23 ± 0.071 , 3.16 ± 0.047 , and 3.16 ± 0.047 , respectively, at 33 kHz, 210 kHz, and 2F inversions. For fine sediments, the overall average estimates of γ_2 (from 10 fine sediment samples) are 3.22 ± 0.074 , 3.30 ± 0.037 , and 3.28 ± 0.022 , respectively, at 33 kHz, 210 kHz, and 2F inversions. Moreover, it is observed that higher values of w_2 and lower values of γ_2 are associated with coarse sediments. In contrast, lower values of w_2 and higher values of γ_2 are associated with fine sediments.

The roughness spectrum parameters are usually calculated from the slope and intercept of the averaged 1-D spectrum

through a linear regression and then converted to two-dimensional (2-D) roughness spectrum parameters (w_2 and γ_2) under the assumption of isotropic sea bottom roughness [25]. A wide range of 2-D roughness spectrum parameters (which are computed from 1-D-averaged spectrum as well as from the 2-D digital elevation measurements) is thus available in the literature [25], [42], [48], [49]. The data on seafloor roughness spectrum parameters and sediment grain size obtained from the various field experiments [25], [42], [48], [49] revealed that the majority of the values of w_2 are greater than 0.002 cm^4 for coarser sediments and confined within $0.0\text{--}0.003 \text{ cm}^4$ for finer sediments [24]. In addition, these measured data indicated that the majority (after ignoring the outliers and redundant observations) of the values of γ_2 are confined within $2.9\text{--}3.3$ for coarse sediments and within $3.2\text{--}3.5$ for fine sediments [24]. In this paper, the estimated mean values of w_2 and γ_2 [Fig. 3(a) and (b)] are in general agreement with these published data.

Briggs *et al.* [48] attempted to construct regressions between the sediment grain size and the seafloor roughness spectrum parameters. The study by Briggs *et al.* [48] revealed that there is no unique empirical relationship between sediment grain size and roughness spectrum strength or sediment grain size and roughness spectrum exponent. However, Briggs *et al.* [48] and Jackson and Richardson [50] reported that the values of roughness spectrum strength and roughness spectrum exponent appear to cluster according to the sediment type with separate trends for sand and mud. This apparent clustering of roughness spectrum parameters according to fine- and coarse-grained sediments is also evident in Fig. 3(a) and (b). This cluster nature is more prominent for 2F inversion data. However, further assessment of this 2F inversion approach in conjunction with ground truth data may be required (probably in the frequency range $20\text{--}150 \text{ kHz}$, the reason for choosing this frequency range is discussed later).

Briggs [25] reported that the roughness parameters derived from a power spectrum vary with the sediment type. Seafloor characterized by coarse sediments has less-steep decay (i.e., lower value of γ_2) in the power-law relationship [25]. One of the possibilities for a power spectrum to have less-steep decay (i.e., less-steep slope of the regression line) is that the intercept energy of the spectrum at a unit spatial frequency is higher (i.e., higher value of w_2). Thus, in general, coarse sediments are associated with higher values of w_2 and lower values of γ_2 . On the contrary, fine sediments are associated with comparatively lower values of w_2 and higher values of γ_2 . This is also evident in the study area [Fig. 3(a) and (b)].

Gaussian distribution of relief height deviations about a mean surface is used in the model for describing the interface relief statistics [17], [24]. Since a pure power-law relief spectrum is assumed in the scattering model, the height difference between two points on the surface separated by a fixed horizontal distance (r_f) can be used for computation of relief statistics. The structure function provides a measure of roughness, which is easier to interpret than the power spectrum [17]. The structure function for the pure power-law spectrum has the form $D(r) = C_h^2 r_f^{2\alpha}$, where the square of the "structure constant (C_h)" is related to the parameters of the power-law spectrum through an expression $C_h^2 = [2\pi w_2 \Gamma(2 -$

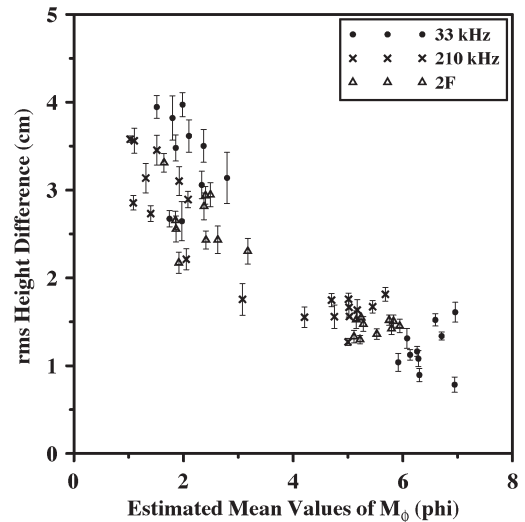


Fig. 4. Scatter diagram showing the relationship between the estimated mean values of M_ϕ (phi) and the computed rms height difference in cm (for the points separated by 100 cm). The error bars indicate one standard deviation in either direction.

$\alpha)2^{-2\alpha}]/[\alpha(1 - \alpha)\Gamma(1 + \alpha)]$. In this expression, Γ is the gamma function and the exponent α is related to the roughness spectrum exponent γ_2 as follows $\alpha = (\gamma_2/2) - 1$. The constant C_h is used in this paper to compute the rms height difference ($C_h r_f^\alpha$) for the points separated by 100 cm (i.e., $r_f = 100 \text{ cm}$, chosen arbitrarily for comparison). The values of rms height difference, computed using the estimated mean values of roughness spectrum parameters (w_2 and γ_2) for all the three inversion cases, are plotted in Fig. 4 against the estimated mean values of M_ϕ . The rms height difference statistic, in general, does not provide any information on the sediment grain size or the spacing of seafloor roughness features [48]. However, Briggs *et al.* [48] reported a general decrease in the relative height variations as the sediment grains become finer. In addition, Jackson and Richardson [50] observed that there is no predictive relationship between rms height difference and sediment grain size. In this study area, the decrease in the relative rms height variation with reference to the sediment type is also evident (Fig. 4).

C. Sediment Volume Scattering Parameter

The sediment volume scattering parameter (σ_2) is dimensionless and is used as a free parameter in the data-model match [17]. For fine sediments, the overall averages of the estimated mean values of σ_2 are 0.0048 ± 0.0005 , 0.0043 ± 0.0003 , and 0.0041 ± 0.0008 , respectively, for 33 kHz , 210 kHz , and 2F inversions (Table II). For coarse sediments, the overall average values of the estimated mean values of σ_2 are 0.0042 ± 0.0006 , 0.0033 ± 0.0005 , and 0.0034 ± 0.001 , respectively, for 33 kHz , 210 kHz , and 2F inversions. The overall average of the estimated mean value of σ_2 is higher than 0.004 (but less than 0.005) for fine as well as coarse sediments at 33 kHz . Only two individual fine samples have values slightly higher than 0.005 at 33 kHz . However, the overall average estimates of σ_2 are more than 0.004 (but less

than 0.005) for fine sediments only at 210 kHz and 2F inversion. It is also noticed (Table II) that the individual estimations of σ_2 are slightly higher at 33 kHz compared to 210 kHz and 2F estimations at all the sample locations. In addition, no definite relationship between the estimated mean values of σ_2 and the mean grain size or sediment sorting coefficient is found in the study area.

Because the inhomogeneities within the sediment volume are difficult to measure, Jackson and Briggs [20] suggested that the sediment volume scattering parameter can be considered as a free parameter in the backscatter model and could be reasonably estimated by means of data-model fit. Jackson and Briggs [20] also reported that the contributions of the volume scattering component are significant for “soft” sediments. Though low values of σ_2 are generally used for fine-grained sediments [17], the experiments by Jackson and Briggs [20] and Briggs [25] revealed that the predicted data matches the observed data well in some experimental area if relatively large values for σ_2 (in the range 0.004–0.006) are used for the “soft” sediments. As mentioned earlier, coarser inhomogeneities, if embedded within the finer particle matrix, can act as strong volume scatterers. Thus, larger value of σ_2 may be required for best data-model fit in “soft” sediments [25]. In this study area, the low values of σ_2 (< 0.004) produced low values of S/E ratio in data-model matching process. By increasing the value of this free parameter σ_2 , the level of the predicted backscatter strength was increased to that of the observed data. The larger coarse particles embedded in fine sediment matrix may be the reason for higher backscatter strength in this study area and thus the higher values of σ_2 are obtained for 33 kHz. However, further study in conjunction with ground truth data is required for conclusion.

Jackson *et al.* [17] stated that the single-scattering assumption in their composite roughness model might be violated if the numerical value of σ_2 exceeds 0.004. The value 0.005 lies on the borderline between single and multiple scattering domains [20]. Though the estimations of σ_2 in the study area broadly fall within the limits of single scattering mechanism, the assessment on the correctness of these values is difficult in the absence of ground truth data.

V. CONCLUSION

The investigation made in this paper is useful to understand the applicability of the temporal backscatter model in a wide frequency range (33–210 kHz) over different types of sediments. The values of sediment mean grain size estimated from the 33 kHz inversions provide relatively improved results over the higher frequency inversion. Furthermore, in the absence of experimental ground truth data (e.g., photogrammetric and sediment density fluctuation data), the estimated values of roughness spectrum parameters and the sediment volume parameter are assessed with reference to the available published information. It seems that the estimated values of roughness spectrum parameters from the 2F inversion are reasonably more consistent with the published data than the estimated values of spectrum parameters from the individual single-frequency inversions.

It appears that the failure in obtaining the same values on roughness spectrum parameters at 33 and 210 kHz may be due to the fact that a single power-law relief (which is assumed in the scattering model) is too simple to describe seafloor roughness over a wide range of scales [50]. Williams *et al.* [51] compare the high-frequency (20–500 kHz) backscatter data and model predictions utilizing the measurements from two experiments SAX99 and SAX04. Earlier, the investigation by Williams *et al.* [23] revealed that the physics behind the backscattering mechanism appeared to be changing in the critical region of the frequency range from 150 to 300 kHz. Recently, Williams *et al.* [51] concluded that above 200 kHz, a new scattering mechanism is coming into play for the backscatter data obtained from both SAX99 and SAX04 experiments. At lower frequencies (20–150 kHz), the backscattering was dominated by roughness scattering during SAX99 experiments, whereas volume scattering was dominated during SAX04 experiments [51]. This dominant volume scattering in SAX04 experiments was explained by the scattering from the embedded shells [52]. At high frequencies (150 kHz–2 MHz), a revealing difference in scattering strength from the surrounded medium and the embedded coarse material is also observed in controlled laboratory experiments [53]. Ivakin [52] reported that at higher frequencies (above 200 kHz), even a small portion of embedded shell fragments (without affecting the mean grain size of sediments) could significantly change the scattering characteristics of the seafloor. This possible changing mechanism in the seafloor scattering in the critical region of the frequency range from 150–200 kHz may be responsible for obtaining the different values of the roughness spectrum parameters at 33 and 210 kHz in this study area. In addition, this possible new mechanism in scattering from the seafloor may be the reason for achieving a marginal success with 2F inversion in the frequency range 33–210 kHz.

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