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## REMOTE ACOUSTIC SEAFLOOR CHARACTERIZATION USING NUMERICAL MODEL AND STATISTICAL BASED STOCHASTIC MULTIFRACTALS

Bishwajit Chakraborty, K. Haris

CSIR- National Institute of Oceanography, India

Geological Oceanography Division, National Institute of Oceanography, Dona Paula, Goa, India: 403004, Tel: +91 832 2450 494, Fax: +91 832 2450 602. Electronic mail: bishwajit@nio.org

**Abstract:** *The spatial variability of sediment geoacoustic inversion parameters are estimated employing bathymetric systems such as multi-beam echo-sounder (MBES) and dual-frequency single-beam echo-sounder (SBES) operable at 95 kHz and 33/210 kHz, respectively. Relationships among the estimated model parameters (substrate and roughness) are investigated along with the benthic macro-fauna information. Distinct interclass separations between the sediment provinces are evident from the estimated mean grain size  $M_\phi$ , interface roughness spectral parameter  $w_2$ , and sediment volume scattering parameter  $\sigma_2$ . These interclass separations are found to be correlated with biologically active faunal functional group assemblages on the seafloor. On the other hand, the continuous form of seafloor heterogeneity (due to bioturbation, sediment deposition, seafloor seepages, or hydrodynamic processes) has received the most attention and necessitates the application of more versatile statistical techniques for determining seafloor roughness statistics. Therefore, 'stochastic multifractal' approach based technique using MBES seafloor image data has been introduced as an alternative approach in such situation. The application of stochastic multifractal technique is suitable for higher order dimensionality and predictability, which substantiates the hitherto applied numerical inversion model based seafloor characterization.*

**Keywords:** *Remote acoustic techniques, seafloor roughness, high-frequency systems, macro-fauna, numerical model, multifractal technique*

## 1. INTRODUCTION

Acoustic remote sensing using high-frequency single-beam (SBES) and multi-beam (MBES) echo-sounding systems allow rapid acquisition of high-resolution seafloor backscatter and bathymetric data, which enormously sustains the marine exploration applications [1]. The acoustic backscatter data obtained from such echo-sounding systems are frequently used to infer seafloor parameters using inversion of the acoustic impedance reflected from the seafloor. The numerical approach employed for extracting information from the data is commonly referred to as ‘inversion modeling’. However, measurements and subsequent inversion modeling of acoustic signals presents challenging task, particularly with the diversity in the benthic habitat of the area [2].

The bottom dwelling organisms often modify the physical properties of the sediment and create seabed structures, both of which affect the acoustic reflections from the seafloor.<sup>7</sup> These multiple processes which are continuously occurring at the water sediment interface and within the volume significantly affect the acoustic energy backscattered from the seafloor, and are strongly depending on both substrate type and benthic macro-fauna present on the seafloor. The collective displacement and mixing of sediment particle by benthic macro-fauna on the seafloor is termed as bioturbation. Thus, the behavior of the estimated seafloor parameters with three frequencies employing MBES and dual-frequency SBES operable at 95 kHz and 33/210 kHz, respectively were analyzed along with sediment texture and benthic macro-faunal information from the same location. The obtained information is analyzed to understand the interrelationship between roughness parameters, grain size, and benthic macro-faunal abundance along the central part of the western continental shelf of India (WCMI).

Apart from the research issues mentioned in the preceding paragraph, the continuous form of seafloor heterogeneity (due to bioturbation, sediment deposition, seafloor seepages, or hydrodynamic processes) has received the most attention to develop statistical techniques for determining seafloor roughness statistics. Besides, the aforesaid model derived parameters represent the spatial variability of seafloor within the insonified area (beam footprint), and are not adequate to characterize seafloor roughness over wide range of spatial scales. Therefore, ‘stochastic multifractal’ approach based technique using MBES seafloor image data has been initiated as an alternative approach in such situation [3]. This method builds on the fact that the seafloor bathymetry and the related backscatter images can be modeled taking into consideration a small number of (generally deterministic) or many (stochastic) degrees of freedom. In order to incorporate high degree of freedom and variability over a wide range of scales, stochastic multifractal approaches are preferred as they have infinite dimensional probability space. The multifractal formalism introduced here allows quantification of the seafloor image blocks (from kilometre to metre range) with three fundamental parameters namely, degree of multifractality  $\alpha$ , sparseness  $C_1$ , and degree of smoothness  $H$ . The properties of estimated multifractal parameters as a measure of complexity and roughness will proffer useful information for seafloor characterization and could substantiate the hitherto applied numerical inversion based characterization.

## 2. METHODS APPLIED

### 2.1 Spatial variability of inversion results and benthic diversity

In this section, the geo-acoustic inversion results estimated using the angular backscatter MBES and the echo-envelope data of normal incidence SBES systems are presented. This

study provides a comparison between the estimated seafloor parameters at three frequencies to assess the model performance [4, 5]. The estimated  $M_\phi$  values using three different acoustic frequencies are presented as a function of the measured  $M_\phi$  values (Fig. 1a). On the whole, the estimated  $M_\phi$  values agree well with the measured sediment data, having correlation coefficients of 0.97, 0.98, and 0.96 for 33, 95, and 210 kHz, respectively. The scatter diagram (Fig. 1b) between measured values of  $M_\phi$  and estimated  $\gamma_2$  delineated that higher values of  $\gamma_2$  are associated with fine sediments, and in contrast lower values of  $\gamma_2$  are associated with coarse sediments. The scatter diagram (Fig. 1c) between the measured values of  $M_\phi$  and estimated  $w_2$  revealed that the estimated values of  $w_2$  are less than  $0.001 \text{ cm}^4$  for fine sediments and are confined within  $0.002$  to  $0.005 \text{ cm}^4$  for coarse sediments from all the three inversion results. It is observed that higher values of  $w_2$  and lower values of  $\gamma_2$  are associated with coarse sediments, while lower values of  $w_2$  and higher values of  $\gamma_2$  are the characteristics of fine sediments. In the present study, for fine sediments, the average estimates of  $\sigma_2$  are found to be higher as compared to coarse sediment region (Fig. 1d) [5].

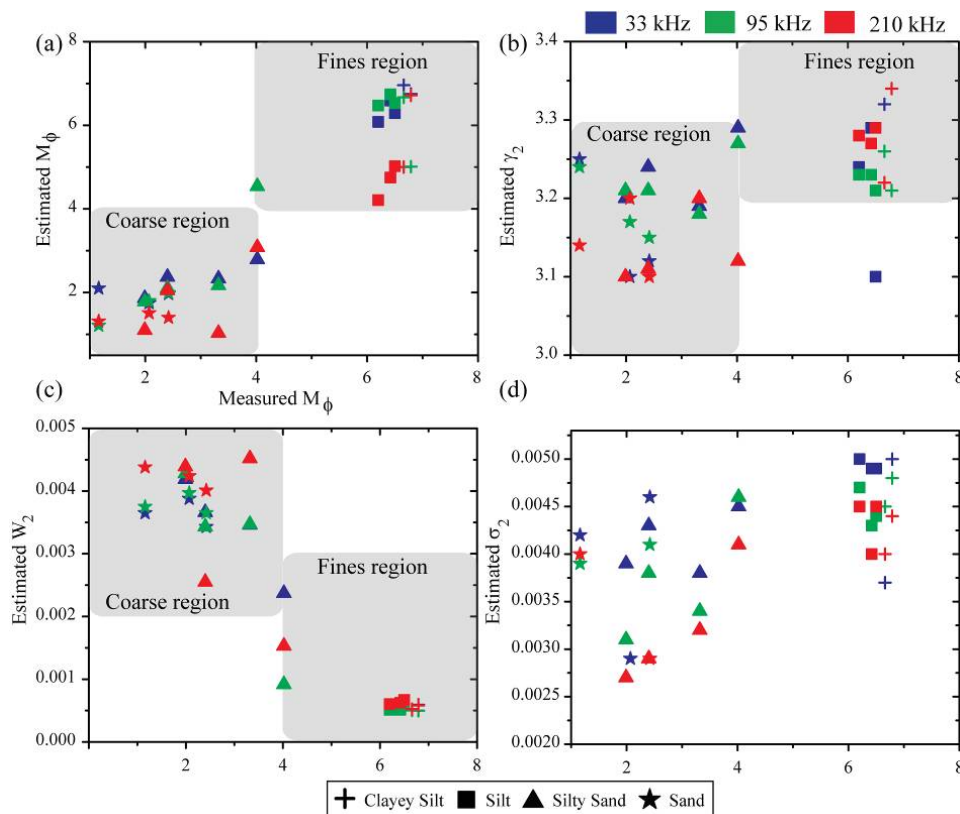
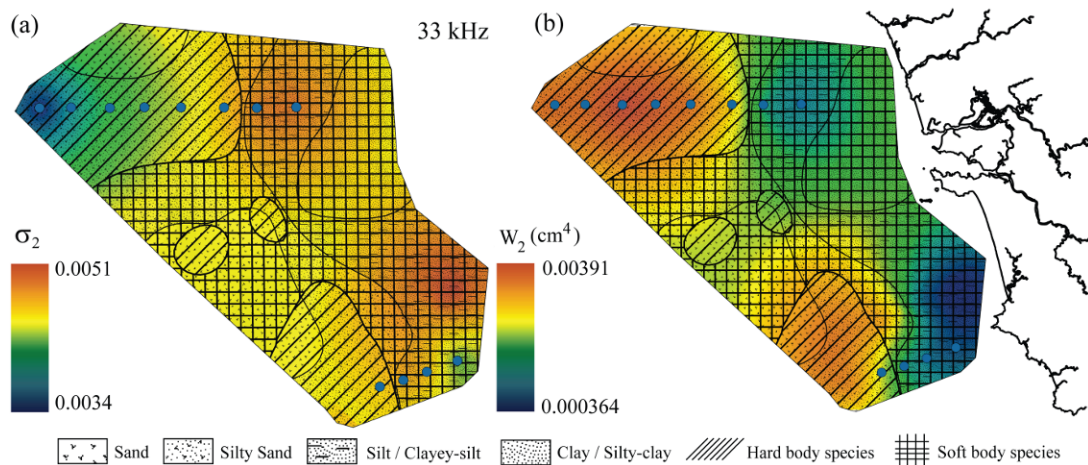


Fig. 1: The scatter plot showing multi-frequency inversion results, reprinted from [5].

The number density of both hard and soft body organisms were compared with estimated values of  $M_\phi$  to assess the potentiality of inversion results to characterize benthic habitat of the seafloor. The correlation coefficients, which assess the animal-sediment relationships, show that the number density of hard body organism is inversely correlated with estimated values of  $M_\phi$ . As the percentage of the sand fraction increases (i.e.,  $M_\phi$  decreases), the number density of hard body organism also increases linearly. Conversely, the number density of soft body organism is directly correlated with estimated values of  $M_\phi$ . Two distinct feeding groups were observed from this study area: namely, deposit feeding infauna (soft body benthic macro-fauna) mainly in shallow region and filter feeding epifauna (hard body benthic macro-fauna) in deeper depths (Fig. 2). The sediments from those locations where the

deposit feeders dominates are mainly fines in nature (estimated  $M_\phi > 4$ ) and conversely, where the filter feeders dominates are characterized as coarse in nature (estimated  $M_\phi < 4$ ). The estimated geoacoustic data  $w_2$  and  $\sigma_2$ , which represent the interplay of interface and volume scattering in the study area is analyzed along with area macrobenthos information to understand macrobenthos-roughness relationship. The echo-envelope shape parameters such as peak along with its width, rise, fall time, and tail part are modified due to the activities of benthic macro-fauna at seafloor interface and sediment volume. A higher value of  $w_2$  produces less-steep slopes in the response curve with the reduced amplitude of the echo-envelope. A change in the value of  $w_2$  has significant effect on the interface component of scattering and marginal effect on the tail part which account sediment volume component of scattering. However, as  $\sigma_2$  increases the contribution of sub-bottom scattering becomes prominent near the tail portion of the echo-envelope. This indicates that, for soft sediments, penetration of the energy at low acoustic frequency increases significantly and the sediment volume scattering component also increases in comparison with the interface scattering component.



*Fig. 2: GIS based image classification representing the variation of interface roughness spectral parameter  $w_2$  and volume scattering parameter  $\sigma_2$  in relation to the benthic macro-fauna and sediment types.*

The comprehensive application of Geographic Information System (GIS) is then implemented to have roughness map in conjunction with the sediment type and macrobenthos habitat in the continental shelf area (Fig. 2). The higher values of  $w_2$  are associated with coarse sediments with substantial occupancy of hard body organisms. Meanwhile, lower values of  $w_2$  characteristics are found for fine sediments with dominant soft body benthos. The image classification also reveals that relatively low  $\sigma_2$  values for coarse sediments where the hard body organisms dominates. Conversely, higher values of  $\sigma_2$  characteristics are found for fine sediments with dominant soft body benthos. In short, high  $w_2$  values, low  $\sigma_2$  values, coarse sediments, and hard body organisms were present towards deeper depths. Besides, low  $w_2$  values, high  $\sigma_2$  values, fine sediments, and soft body organisms were the major components towards shallower depths.

Biologically active sediments are continually modified by epifauna (organisms that live on the sediment surface) and infauna (organisms living within the sediment). Epifaunal activity, such as locomotion and home building, creates roughness at the sediment-water interface. As a result, it is expected to have dominant interface scattering from such region where the hard body epifauna such as bivalves and gastropods are dominant. Whereas, the infaunal activity,

such as tube building, is responsible for the vertical and horizontal redistribution of solid material within the volume of the sediment, creating spatial and temporal inhomogeneities in sediment bulk properties (density, porosity, and compressibility). Such changes arise due to burrowing and tube building by soft body fauna mainly dominated by polychaete worms. Consequently, there will be a strong volume inhomogeneity within the sediment and volume scattering is expected to be dominant in that habitat region.

## 2.2 Multifractal characterization of heterogeneous seafloor

The continuous form of seafloor heterogeneity (due to bioturbation, sediment deposition, seafloor seepages, or hydrodynamic processes) has received the most attention with regard to multifractal approach based characterization and is the focus of this section. Dandapath *et al.* [6] had reported seafloor seepages in the study area using MBES backscatter and bathymetry data. A total of 112 pockmarks related to the seepages were identified from the seafloor maps generated using ArcGIS (Fig. 3). The investigations were related to the underlying geology, pockmark occurrences, overlying sediment texture, and sediment movements due to strong influences of monsoonal bottom currents. Thereafter Dandapath *et al.* [7] had noted the possible multifractal behaviour of the MBES backscatter and bathymetry image data.

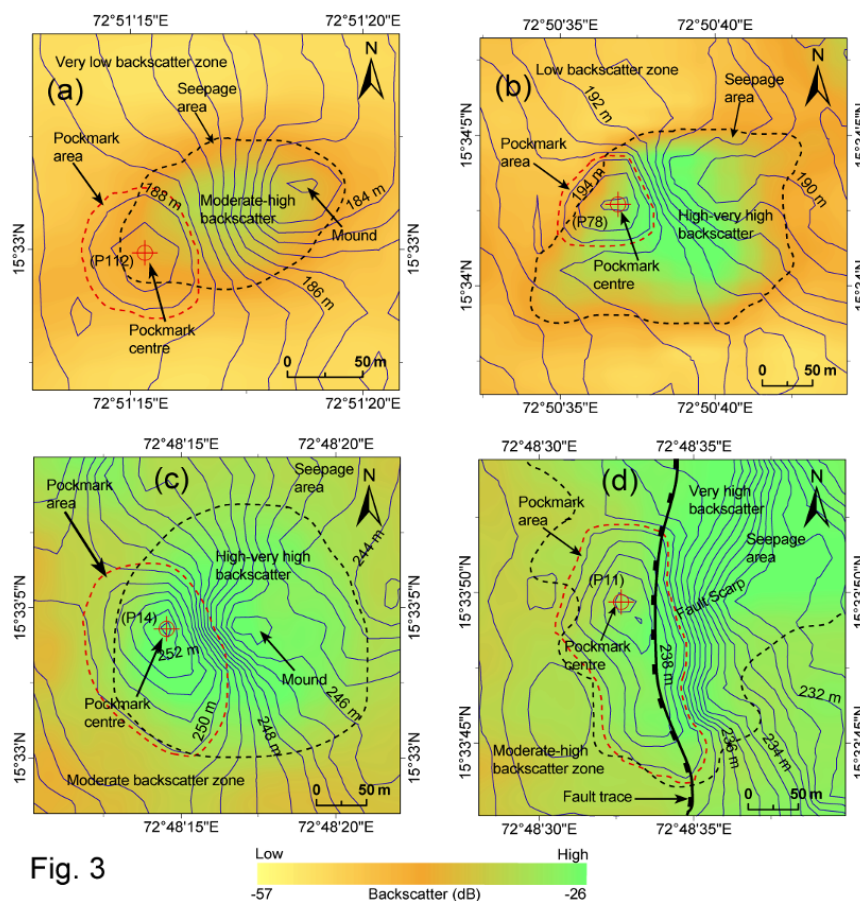


Fig. 3

Fig. 3: Seepage characteristics associated with some selected pockmarks. Dashed lines in red and black indicate pockmark area and seepage area respectively. Diffusive type of seepage over a large area is observed in the panel d, while panel a-c showing concentrated seepage over relatively small area, reprinted from [6].

Based on the previous studies mentioned in the above paragraph, six representative blocks of backscatter and bathymetry co-registered image data were used to establish multifractal approach based techniques to statistically characterize the patchiness of the seafloor (Table 1). The backscatter and bathymetry image blocks having 400 x 400 pixels, were classified according to the degree of seepage based on the backscatter strength as well as fractal dimension (determined using box-dimension technique).

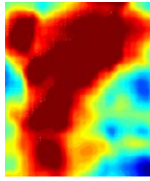
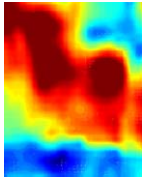
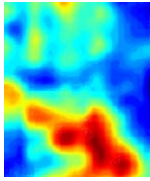
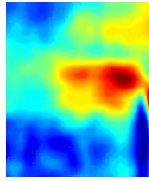
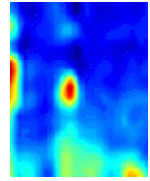
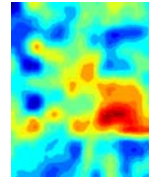
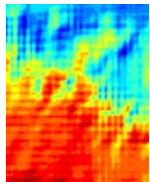
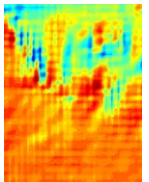
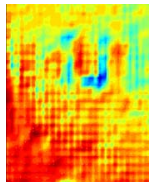
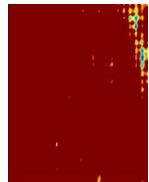
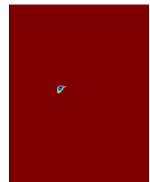
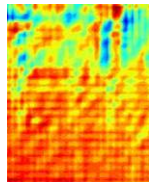
Sample blocks	F20	J19	F07	Q19	S23	N25
Seepage type	Very high	High	Moderate	Low	Very low	No
Mean Backscatter (dB)	-31.58	-34.40	-38.99	-38.96	-43.28	-42.62
Backscatter image						
Bathymetry image						

Table 1: Backscatter and bathymetry seepage blocks selected for multifractal analyses, reprinted from [7].

The  $\alpha$  values of the bathymetry and backscatter blocks show identical trend ( $\approx 2$ ) expressing similar degree of multifractality excluding Q19 and S23 of the bathymetry blocks (Fig. 4a). The  $C_1$  values of the backscatter and bathymetry blocks are found to be varying between 0.058 and 0.091 and between 0.038 and 0.690 respectively. Excluding the S23 bathymetry block ( $C_1 = 0.690$ ), the lower values of  $C_1$  attributed to the remaining blocks, indicate that the field values are close to the mean values. Fluctuations in higher values of  $H$  between 0.636 and 0.706 are observed in the backscatter image blocks, except in the N25 block (0.412) having no evidence of seepages. Whereas, lower  $H$  values (0.255–0.480) are observed in the bathymetry as compared to the backscatter blocks at the same location. The estimated  $H$  value of N25 bathymetry block is the lowest.

Cluster analyses output (Fig. 4b) of  $H$  vs.  $\alpha$  reveals a uniform  $\alpha$  in the backscatter and bathymetry blocks except in the Q19 bathymetry block. Remarkably the clustering tendency around the high  $\alpha$  ( $\approx 2$ ) and low  $C_1$  of the bathymetry and backscatter data, show extremely close relationship among, the six backscatter and four bathymetry blocks (Fig. 4b). However both Q19 and S23 bathymetry blocks possess comparable  $\alpha$  values and relatively higher  $C_1$  values. The  $C_1$  (0.690) value of the S23 bathymetry block espouse the setting wherein the depths at specific locations (i.e., center of the pockmark) are higher as compared to the rest of the locations within the block. In this study, the 'stochastic' multifractal based technique show no significant variation in  $\alpha$  and  $C_1$  of the backscatter field data, except parameter  $H$

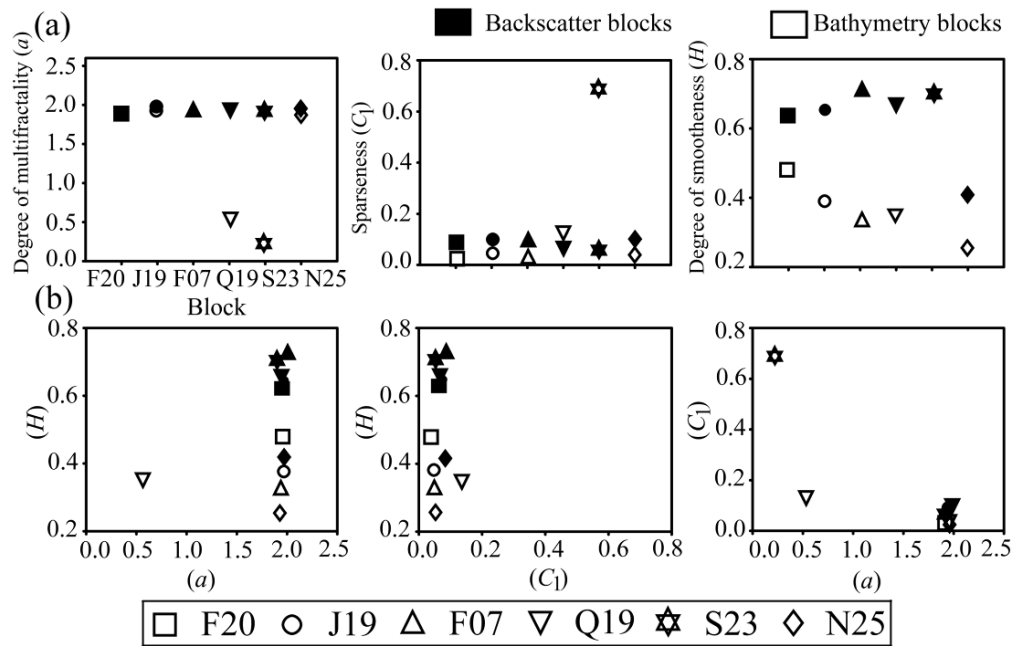


Fig. 4: (a) Block wise multifractal parameters estimated using 'stochastic' multifractal formalism. (b) Scatter plots of the three multifractal parameters ( $\alpha$ ,  $C_1$  and  $H$ ). The solid and hollow shapes represent different study blocks as shown in the legend, reprinted from [3].

### 3. CONCLUSION

The work presented in this article describes the technological approach related to remote acoustic seafloor characterization using high-frequency echo-sounding systems. The geoacoustic inversion results obtained using MBES and SBES data provide important information that can be utilized for acoustic seafloor characterization. On the other hand, the continuous form of seafloor heterogeneity (due to bioturbation, sediment deposition, seafloor seepages, or hydrodynamic processes) necessitates the application of multifractal approach based techniques to statistically characterize the patchiness of the seafloor. The multifractal technique utilized in our work is a first-time attempt to analyze the high resolution MBES backscatter and bathymetry data.

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