Chapter 1

Introduction

1.1 BACKGROUND

Acoustic interaction with the seafloor and the properties of seafloor sediments are extensively researched over the past few decades, both experimentally and theoretically. Characteristics of seafloor sediments have wide range of applications in several fields such as economic, scientific, and defence. This has become an important subject for providing essential inputs to efficient management, monitoring, and exploitation of offshore petroleum products as well as marine biological resources especially fisheries. These studies are also useful for differentiating various marine habitats. Though acoustic techniques do not provide direct information on marine habitats, acoustic seafloor characteristics are indirectly important to fisheries sciences (Padian et al., 2009). Mapping of marine habitats, relationships of seafloor sediment characteristics with the associated biomass and benthic communities are being studied extensively (Siwabessy, 2001; Kostylev et al., 2001; Quintino et al., 2010). Moreover, seafloor sediment properties are essential for dredging of harbors and shipping channels; and pipeline as well as cable laying operations. Geo-technical characteristics (shear strength, bulk properties etc.) and acoustical properties of seafloor sediments are the essential inputs for designing offshore engineering structures, marine archeology
studies, and various types of underwater mooring applications (Hamilton, 2001). Therefore, detail knowledge of the seafloor sediment characteristics and their mapping are indispensable for efficient management of all these socio-economic activities.

Several defence applications such as submarine surveillances, navigations of submarines as well as surface vessels (Hamilton, 2001), acoustic homing torpedoes (Jackson and Richardson, 2007), and efficient use of a sonar for underwater target detection require an extensive knowledge on the interaction of sound energies with seafloor sediments. Interference of the scattering of acoustic energies from the seafloor degrades the capability of a sonar to detect and classify underwater targets such as submarines, buried mines etc. On the contrary, scattered acoustic energy (recorded by a sonar) provides useful information on the characteristics of seafloor sediments. In either case, detail knowledge on acoustic scattering from the seafloor, reverberation, seafloor roughness characteristics, and attenuation coefficients of seafloor sediments is essential for improving the performances of a sonar.

Characterization of seafloor sediment is a process to determine or to estimate various physical, chemical, geological, and biological characteristics of sediments. In other words, direct or indirect assessment of the seafloor sediment properties is called characterization of seafloor sediments. There are two basic approaches for characterization - empirical approach and model-based approach. Empirical approaches commonly utilize an experimental or observational dataset. Experimental data are calibrated in these methods to predict the properties of seafloor sediments in the vicinity of ground-truth sample locations. Several empirical approaches are available in literature (McKinney and Anderson, 1964; Stanton, 1985; Stanic et al., 1988) for seafloor sediment characterization. On the contrary, model-based approaches utilize physics-based theoretical models for characterization of the seafloor sediments.
Theoretical models are used to predict the characteristics of sediments for a given environmental condition. Once these theoretical models are validated against ground-truth, these model-based approaches essentially eliminate the need for collecting a large number of seafloor sediment samples and analyzing them in a laboratory. A number of acoustic models exist for predicting the interaction of acoustic energy with the seafloor (Ivakin and Lysanov, 1981a, 1981b; Boehme et al., 1985; Hines, 1990). In addition, various frequency dependent backscatter models have been developed utilizing the sediment geo-acoustic parameters, seafloor roughness characteristics, water-sediment interface scattering, and volume scattering coefficients as a function of grazing or incidence angles (Jackson et al., 1986a; de Moustier and Alexandrou, 1991; Sternlicht and de Moustier, 2003a). It is established from various field experiments (Jackson et al., 1986a, 1986b; Stanic et al., 1988, 1989; Jackson and Briggs, 1992; Williams et al., 2002, 2009) that acoustic backscatter energies contain information on the characteristics of surficial seafloor sediments such as seafloor roughness, volume in-homogeneity, mean grain size of sediment, etc. Therefore, scientific interests on the characterization of seafloor sediment either by direct measurements of backscatter energies or by indirect estimation of the sediment properties utilizing theoretical models have been increasing.

Classification of seafloor sediment is a process of segmenting or qualitative grouping of surficial sediments based on their properties (such as sand, silt, clay, and their mixtures). This means that classification is a process of segmenting different sedimentary regions on the seafloor with distinct physical entities (but similar properties within a segment or cluster) based on their characteristic features. Therefore, this process is complex in nature. In general, it would be easy to classify the seafloor sediments after the characterization has been done. However, only qualitative
assessment of the seafloor characteristics could be possible after the seafloor has been
classified. Acoustic classification techniques have now become standard tools for
classification and mapping of the seafloor sediments. Many approaches have been
evolved in the recent years for classification of seafloor such as statistical analysis
( Legendre et al., 2002), cluster analysis ( Preston and Kirlin, 2003; Legendre, 2003),
discriminant analysis ( Hutin et al., 2005), neural network analysis ( Dung and
Stepnowski, 2000; Moszynski et al., 2000; Stepnowski et al., 2003), wavelet analysis
( Atallah et al., 2002), and Fractal analysis ( Lubniewski and Stepnowski, 1998;
Chakraborty et al., 2007b).

Qualitative and quantitative information on the sediment characteristics, when
obtained from the measurements in a laboratory or in-situ (in the field) analysis of
seafloor sediment samples, is called ground-truth. Grabs and corers are the widely used
instruments for obtaining sediment samples from the seafloor. Visual observations
(video or still photography) of seafloor also provide supportive evidence on the seafloor
roughness characteristics. Laboratory analyses of sediment samples from grab or corer
provide the most reliable information on the characteristics of sediment. Though
laboratory analyses of seafloor sediment samples provide an accurate assessment of the
properties of sediment; collection and analyses of large number of samples over a wide
area is time consuming and expensive job. Moreover, most of these methods fail to
collect undisturbed sediment samples in the field and these methods can provide
information on the sediment characteristics only at selected discrete locations. In
addition, it is known that the seafloor is not a static environment over a long time
period, because of the natural phenomena. Therefore, labeling (i.e., classification) of the
seafloor sediments (as sand, silt, clay, and their mixtures) over a wide area, based on the
quantitative analysis of a small portion of sediment at discrete locations, is inadequate
as well as inaccurate. Other methods such as optical methods (stereo photogrammetry) and laser scanning systems have also been developed for precision mapping and assessment of the characteristics of seafloor sediments (Richardson et al., 2001; Moore and Jaffe, 2002; Briggs et al., 2002; Lyons et al., 2002; Wang et al., 2009, Wang and Tang, 2009). However, the applications of these high precision methods are again restricted at discrete locations due to the operational limitations.

Hence, in analogy with Satellite Remote Sensing, which senses certain properties on the earth’s surface, underwater acoustic remote sensing has become one of the most widely investigated subjects in the recent years for rapid assessment of the sediment properties over a large area as well as for its easy operations and cost effective nature. Characterization and classification of seafloor sediments based on the properties of surficial sediments (Orlowski, 1984; Chivers et al., 1990; Chakraborty and Pathak, 1999; Chakraborty et al., 2000; Briggs et al., 2002) and habitat characteristics (Kostylev et al., 2001; Anderson et al., 2002) are being investigated extensively.

Various complex dynamic processes affect the interaction and scattering mechanism of acoustic energies from the seafloor. Understanding of these mechanisms at different levels led to the development of numerous theoretical models to describe the seafloor scattering processes. Every theoretical model is based on certain understanding of sound scattering mechanism from the seafloor. Therefore, it is important and essential to appreciate the limitations of various acoustic models for effective characterization of the seafloor. In addition, studies on the validation and applicability of these theoretical models over a wide range of acoustic frequencies are indispensable.

The choice of instrumentation to characterize seafloor sediments primarily depends on the purpose of operations such as classification of sediments, surface and sub-surface object detection, searching for mineral deposits etc. Four types of
instruments are generally used in the field namely, single-beam normal-incidence echo sounder, side-scan sonar, multi-beam echo sounder, and sub-bottom profiler. Single-beam echo sounder utilizes backscatter data for the characterization of seafloor (Stanton and Clay, 1986; Pouliquen and Lurton, 1992; Lurton, 2002). Side-scan sonar exploits the information on texture analysis of acoustic images for describing the seafloor sediments. The use of spectral analysis for classification of seafloor with side-scan sonar data is also demonstrated (Pace and Gao, 1988). Many other investigations also demonstrate the characterization of seafloor using side-scan sonar images (Stewart et al., 1992, 1994; Zerr et al., 1994). Mapping of seafloor bathymetry and characterization of sediments using multi-beam echo sounder are most common (de Moustier and Matsumoto, 1993; Chakraborty et al., 2000, 2004; Collins and Preston, 2002; Zhou and Chen, 2005). Acoustic sub-bottom profilers, which include seismic system, parametric sonar, and chirp sonar are also used for seafloor sediment characterization (LeBlanc et al., 1992; Schock, 2004a, 2004b).

Though several instruments could be used for the purpose of characterization and classification of seafloor sediments, emphasis is given only on the normal-incidence, single-beam echo sounder in this work. Studies on the acoustic seafloor sediment classification have gained momentum after the development of few systems in 1990s. The advantages of these systems are that these can be attached to any existing echo sounder available on a research vessel for classification purposes. Most of these available systems use certain proprietary signal processing algorithms, which are not fully revealed to the users. Once these systems are calibrated properly in a known sedimentary environment, these systems or devices are capable of providing a real-time classification of the seafloor sediments. Therefore, these classifications are not absolute and highly dependent on the training (or calibration) dataset as well as on the
sedimentary environment in the experimental area, where the calibrations are carried out. In addition, the success of classification is a function of the sediment characteristics as well as echo sounder characteristics such as frequency of operation, pulse length, and beam width. Moreover, calibrations of these systems in a given sedimentary environment are not always very easy and unambiguous tasks. Therefore, there is a need for an extensive research in the field of classification of seafloor sediment utilizing various techniques such as principal component analysis, cluster analysis, and neural network analysis. These methods mostly based on the empirical approaches for classification of seafloor sediments and are often called model-free techniques. There is no quantitative physics-based theory behind the inferred relationships between the acoustical parameters and the sediment characteristics.

It is already mentioned that there are several acoustic systems for the classification of seafloor. An overview of the few existing available systems and their practical issues are briefed in the following sections to understand the need for further research on this subject.

1.2 SYSTEMS FOR SEAFLOOR CLASSIFICATION

There are several systems for acoustic classification of seafloor sediments. These systems provide automatic classification of seafloor along survey tracks, when attached to an echo sounder. Sediment classification systems were first developed for normal-incidence, single-beam echo sounder. Thus, single-beam echo sounders are often called as Acoustic Ground Discrimination Systems (ADGS). Classification systems for side-scan sonar, multi-beam, and sub-bottom profilers have also been developed
subsequently. However, in this section, the classification systems that are generally used with normal-incidence, single-beam echo sounder are briefed. RoxAnn, ECHOplus, QTC View, and VBT Bottom Classifier are the few widely used systems. The comparisons on the performances of different classification systems (such as RoxAnn and QTC View) are also investigated in detail (Hamilton et al., 1999).

RoxAnn system is designed and manufactured by M/s Stenmar Marine Micro Systems Ltd., UK. This system was probably the first system used for the classification of seafloor sediments. The RoxAnn system utilizes two parameters called E1 and E2. These parameters are derived from the first and the second acoustic returns from the seafloor. The first acoustic return is a direct reflection from the seafloor, whereas the second return suffers reflection twice at the seafloor and once at the sea surface. The second return follows an acoustic path: transducer-to-seafloor-to-sea surface-to-seafloor-to-receiver. The parameter, E1 is a measure of the total energy in the trail portion of the first acoustic return from the seafloor and it provides an index of roughness of the seafloor. Since the second acoustic return reflected twice at the seafloor, the energy within the second return is strongly affected by the hardness of the seafloor. Therefore, the parameter, E2 provides an index of hardness of the seafloor. E2 is derived from the total energy of the complete second acoustic return from the seafloor. Roughness and hardness characteristics are different for different seafloor materials. Scatter plots between E1 and E2 (roughness vs. hardness) are used for the classification of seafloor sediment. The total region of a plot is divided into a number of areas, called RoxAnn squares, where each square represents a particular seafloor sediment type or substrate. Seafloor sediment samplings are required to identify and correlate the sediment types associated with the clustering of each E1-E2 space. The lesser values of E1-E2 pair are generally associated with softer sediments, and rocky
seafloors have higher values of E1-E2 pair. Orlowski (1984) first reported this method of classification and later Chivers et al. (1990) refined this methodology.

The ECHOplus system (of M/s SEA Ltd., UK) comprises of hardware as well as software. It uses a patented technique for analyzing an echo trace to derive the integrals of the first and the second echo of the acoustic returns. Ground-truth data from sediment samples are initially used to associate each hardness-roughness space with the sediment type. Subsequently, different unknown seabed sediment types are identified in this hardness-roughness space. Essentially, the working principle of RoxAnn and ECHOplus are similar (Bates and Whitehead, 2001).

Quester Tangent Corporation, Canada developed QTC view system. It utilizes different characteristics of the first acoustic returns from the seafloor (Prager et al., 1995; Collins, 1996; Tsemahman et al., 1997). This system extracts 166 "echo features" from raw digital echo envelopes of the first bottom echo. These 166 features are called full feature vectors (FFV). The QTC system utilizes its built-in software based on Principal Component Analysis (PCA) to reduce the dimensionality of 166 echo features. PCA is used to identify the dominant FFVs, which explain at least 90% of the total variability of acoustic diversity. Finally, three parameters, called Q-values (Q1, Q2, and Q3) are derived. The clusters of these Q-values in three-dimensional space are used to differentiate different seafloor sediment type (Prager et al., 1995; Collins and McConnaughey, 1998; Legendre et al., 2002; Freitas et al., 2008). Later, an improved version of the software called QTC Impact was introduced. This software processes raw waveforms and automatically provides the clusters using an unsupervised mode of operations (Collins et al., 1996; Anderson et al., 2002) for seafloor discrimination. In the supervised mode of operation, the software uses a catalogue of Q-space clusters with reference to the data of known seafloor sediment types.
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1.3 Limitations of Available Systems

The VBT (Visual Bottom Typing) sediment classifier (from M/s BioSonics Inc., USA) is a post-processing software package (Burczynski, 1999; Hamilton, 2001) to analyze the acoustic returns from seafloor. It does not have any hardware components. This system uses four different methods for the classification of seafloor sediments. One of the methods of VBT software uses roughness and hardness features (same as RoxAnn and ECHOplus). Another method of VBT software utilizes hardness of sediments as the basis for classification. The hardness of sediment is assessed from the cumulative energy in the first echo. This method is based on a concept that hard seafloor sediments tend to have a sharp increase in the cumulative energy curves, while soft sediments tend to have a gradual increase in the cumulative energy curves. The next method of VBT software utilizes scatter plots between the energy of the first part of the first echo and the energy of the second part of the same first echo to differentiate sediment types. The last method of VBT software utilizes scatter plots between the roughness signature of sediments derived from the first echo and the fractal dimensions of echo envelopes (Burczynski, 1999).

1.3 LIMITATIONS OF AVAILABLE SYSTEMS

The afore-mentioned classification systems utilize empirical approaches. Hence, it becomes a prerequisite to establish an essential database before using these systems.

Studies on the performance of RoxAnn system indicate that the parameter E2 is inversely related to vessel speed (Hamilton et al., 1999). The system could produce optimal results only at a constant vessel speed during the operations and a prior knowledge on the maximum depth to be surveyed was necessary for selecting a suitable
depth range of the echo sounder for the entire survey area (Schlagentweit, 1993). This imposes constraints in operating RoxAnn in a coastal area. Moreover, the result obtained from RoxAnn system changes with the variation of seafloor depth, even if the sediment type remains unchanged (Kloser et al., 2001; Greenstreet et al., 1997).

Limited studies on the use of ECHOplus system restrict a comprehensive assessment on the performance of the system in discriminating seafloor sediments (Penrose et al., 2005).

QTC view system uses echo features for classification of sediments. However, physical and mathematical expressions for extracting these features are not revealed to the users (Hamilton, 2001). Information on the various stages of data processing (or the processing algorithms) of QTC system is also not revealed, thereby imposing difficulties in carrying out further research on the improvement of the processing algorithm.

It is reported (Hamilton, 2001) that VBT software for the classification of seafloor sediments does not use depth normalization and the method for selection of echo envelopes from raw data is not very robust in this software. This software is suitable for the classification of sediments, if seafloor depth is constant over the entire survey area.

All these qualitative systems could be used to achieve average to good results for the classification of sediments and these results depend on the accuracies of training in a known seafloor sedimentary environment. The main limitation of these seafloor classification systems is that the raw acoustic echo data are not available to the users for further studies. Hence, there is a need for an extensive research on the theoretical model-based characterization and model-free classification of the seafloor sediments.
1.4 RESEARCH OBJECTIVES

The main objective of the research is model-based characterization and model-free classification of seafloor sediments by acoustic means in the central part of the western continental shelf of India in the Arabian Sea. The studies on the characterization of seafloor sediments aim at investigating the applicability of a temporal backscatter model, utilizing the echo data obtained from normal-incidence, single-beam echo sounder at two conventional frequencies. Furthermore, the studies on model-free techniques for the classification of seafloor sediments aim at developing a hybrid scheme, which combines unsupervised and supervised approaches for achieving improved success in the classification.

It is understood that backscatter echo from the seafloor contains information on the characteristics of seafloor sediments such as mean grain size, seafloor roughness spectrum parameters, sediment volume scattering parameter, density of sediments, sound speed, etc. (Holliday, 2007). Thus, a temporal acoustic backscatter model (Sternlicht and de Moustier, 2003a) has been employed here for estimating the seafloor sediment parameters namely, mean grain size, roughness spectrum strength, roughness spectrum exponent, and volume scattering parameter through inversions. The applicability of this temporal model is investigated by comparing the estimated values of sediment parameters with the ground-truth in the study area. Moreover, it is reported (van Walree et al., 2006; Anderson et al., 2008) that the use of multiple frequencies enhances the ability to characterize the seafloor sediments considerably, because the interface roughness spectrum and the sediment volume backscattering strength may vary with acoustic frequencies. Lower acoustic frequencies penetrate the seabed to
greater depths, whereas higher frequencies will have improved resolving capability. Therefore, it is expected that the use of two conventional frequencies of a single-beam echo sounder will provide improved understanding on the interaction of acoustic energy with the seafloor sediments. Therefore, a combined two-frequency inversion scheme has been explored for obtaining the improved estimation on the various seafloor sediment parameters. In this combined two-frequency inversion approach, the backscatter echo data collected at two conventional frequencies (33 and 210 kHz) of a single-beam echo sounder are jointly inverted for estimating a single set of seafloor sediment parameters applicable to echo data at both of the frequencies.

Seafloor sediment classifications using model-free techniques are generally based on a-priori information on the number of sediment classes (or cluster centers), which specifies different sedimentary environments available in a given dataset. However, this information could be obtained only from the ground-truth. Hence, in the absence of any prior information, the decision on the plausible number of sediment classes is very important for achieving a significant success in classifying the seafloor sediments. An unsupervised approach, based on Kohonen’s self-organizing feature map (Kohonen, 1989, 1990), is developed to estimate the plausible number of sediment classes available in a given dataset without any a-priori information. The effectiveness of this proposed method is also assessed with the simulated data at two different frequencies.

Moreover, selection of an optimum subset of features with dominant discriminatory characteristics is another important aspect for achieving the improved success in the classification of seafloor sediments. Therefore, two methods are developed to address this feature selection issue utilizing neural networks and fuzzy
cluster algorithm. The successes of classification with different subsets of echo features are analyzed in these two methods to select an optimum subset.

Therefore, the unsupervised scheme (for estimating the plausible number of sediment classes) in combination with any one of the methods, based on either neural networks or fuzzy cluster algorithm, provides an efficient hybrid scheme for the classification of seafloor sediments.

1.5 OUTLINE OF THE THESIS

The work has been divided into eight chapters. This chapter discusses the importance of this study. In addition, four widely used seafloor classification systems along with the practical issues are discussed to understand the need for further research on this subject.

Chapter 2 describes the study area, acoustic data collection, and methodology for pre-processing the backscatter echo data obtained from a normal-incidence, single-beam echo sounder. The details of sediment ground-truth based on the percentage compositions of sand, silt, and clay obtained from the laboratory analysis are presented.

Chapter 3 introduces the basic theoretical concepts of acoustic interactions with the seafloor sediments. Subsequently, a concise review on the relevant acoustic models for interpreting the backscatter echo data is presented.

Chapter 4 discusses the theory of a temporal backscatter model. This theoretical model is used for indirect estimation of the values of seafloor sediment parameters. The sensitivity analyses of this model with reference to various model parameters are discussed. The procedures adopted for estimating the values of seafloor sediment parameters using the backscatter echo envelopes collected at two conventional
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1.5 Outline of the Thesis

frequencies of a single-beam echo sounder and a combined two-frequency inversion scheme are discussed in this chapter. Finally, comparisons of the inversion results with the ground-truth and other published information are presented.

Chapter 5 reviews several existing model-free approaches for the classification of seafloor sediments. Following this, the background for computing seafloor echo features and two model-free techniques namely principal component analysis and fuzzy cluster algorithms are presented. This chapter discusses the results obtained from the cluster analysis using the first three principal components along with the comparisons with ground-truth.

Chapter 6 introduces the basics of artificial neural networks relevant to the present study. Following this, a neural network based supervised method is presented for the selection of an optimal subset of echo features to achieve a significant success in the classification of seafloor sediments.

In Chapter 7, a hybrid scheme is proposed for the classification of seafloor sediments utilizing an unsupervised neural network and fuzzy cluster analysis. The unsupervised approach, based on Kohonen’s self-organizing feature map, is discussed for estimating the plausible number of sediment classes in a given dataset without any a-priori information. This proposed method is also demonstrated with the simulated data. A fuzzy cluster algorithm based features selection method (in addition to the neural network based method, as mentioned in Chapter 6) is discussed in this chapter. Subsequently, the comparison of results obtained from the proposed hybrid scheme (consisting of the unsupervised approach and the fuzzy cluster algorithm based method) with that of another existing hybrid scheme is discussed. In addition, the results of two proposed features selection methods are compared.

Chapter 8 summarizes the results from this study. The practical utilities and future work are also presented in this chapter.