ICES Cooperative Research Report

Rapport des Recherches Collectives

No. 286

August 2007

Acoustic seabed classification of marine physical and biological landscapes

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Recommended format for purposes of citation:

ICES. 2007. Acoustic seabed classification of marine physical and biological landscapes. ICES Cooperative Research Report No. 286. 183 pp.

This document is a report of an Expert Group under the auspices of the International Council for the Exploration of the Sea and does not necessarily represent the view of the Council.

ISBN 87-7482-058-3

ISSN 1017-6195

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John T. Anderson

1.1 Introduction

The natural world is structured hierarchically, and processes within natural regions operate across a number of spatial and temporal scales (Turner *et al.*, 2001). Managing marine ecosystems requires that natural regions be identified and mapped over a range of hierarchically nested scales, and management of resources across multiple spatial scales requires a classification system. The development of classification schemes is an active area of marine research. The EUNIS (European Nature Information System) classification scheme is being developed and managed by the European Topic Centre of Nature Protection and Biodiversity (ETC/NPB in Paris) for the European Environment Agency (EEA) and the European Environmental Information Observation Network (EIONET; Davies and Moss, 1999). Alternatively, top–down habitat classification schemes have been developed for global applications in the management of marine resources (e.g. Greene *et al.*, 1999; Valentine *et al.*, 2005). The further development and application of these classification schemes require explicit information that characterizes marine habitats on a variety of spatial scales. Acoustics is increasingly regarded as the remote-sensing tool that will provide the basis for classifying and mapping ocean resources. Existing acoustic systems can measure seabed sediment properties and bedform morphology from scales of centimetres to kilometres.

It has long been understood that details about the character of the seabed (roughness, sediment type, grain-size distribution, porosity, material density, tortuosity, etc.) are embedded in the acoustical echoes from the seabed. Because sound may penetrate into the sediments and the basement material, the echoes can also contain information about the zone below the water–sediment interface. Increasingly, acoustical echosounding and related technologies are being used to assess, characterize, and map nearshore coastal environments. Scientists now regard acoustical sensors as a cost-effective means to assess seabed roughness, sediment and substrate types, small-scale details of the benthic habitat, and even community structure of the organisms and plants that make up a part of benthic ecosystems. The seabed is not a static environment but changes on varying timescales as the result of natural phenomena. Increasingly, attention is being directed to human impacts on benthic habitats, such as fishing, pollution, and dredging. Important questions also arise regarding the timescales on which disturbed ecosystems recover from anthropogenic disturbances (e.g. Collie *et al.*, 2000). The confluence of interests expressed by resource managers and fishery scientists and the need to preserve ecosystems are leading acousticians to revisit single-beam echosounding methods as well as complex methods, such as sidescan sonar, multibeam ship-mounted swathe systems, multiple frequency acoustical sensors and, in some cases, passive acoustical sensors, and to evaluate their application in quantitative surveys of the seabed and what lives there.

Work within ICES has evolved to recognize the challenges of identifying and mapping marine habitats with the creation of the Working Group on Marine Habitat Mapping (WGMHM) in 2000 and special theme sessions during the ICES Annual Science Conferences in 2000, 2002, and 2004. The use of acoustics to remotely classify and map marine habitats at different spatial scales was addressed by the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT; Kenney *et al.*, 2000). Work within the Working Group on Fisheries Acoustics and Science Technology (WGFAST) led to the creation of the Study Group on Acoustic Seabed Classification (SGASC) in 2003 (Anderson, 2003). The study group reviewed the status of acoustic seabed classification over three years.

1.2 Defining acoustic seabed classification

The definition of seabed habitat features that would be acoustically classified and mapped includes both physical and biological attributes. At traditional echosounding frequencies (approximately 10–300 kHz), most of the acoustic information for bottom classification will be from the topography and materials of the immediate water–sediment interface. We defined the extent of interest for acoustic seabed classification to be from up to one metre below to one or more metres above the seabed surface. This zone was intended to include biogenic structures directly associated with the seabed. It also acknowledges the fuzzy boundary that constitutes the benthic layer, where many organisms are ephemeral residents on varying timescales. Acoustic seabed classification results are related to the shape and geological nature of the seabed itself and to the marine organisms present, including finfish, invertebrates, and benthic species. We did not specifically address the pelagic component of acoustic classification but acknowledge the importance of coupling demersal and pelagic habitats. We note that the biological component of the water column was recently addressed by ICES (Reid, 2000). Integration of pelagic and demersal habitats using acoustic technologies awaits future consideration. Acoustic classification of subsurface geological features was not addressed by the study group because such features are only measured by low-frequency seismic systems, and this was beyond the scope of the study group's mandate.

The science of correlating acoustic properties with marine surficial sediments dates from the early use of marine acoustics (Nafe and Drake, 1964; Morris *et al.*, 1978). The science of acoustic seabed classification is more recent, largely driven by the development of commercial systems in the 1990s to classify surficial sediments and demersal habitats. Acoustic seabed classification developed from the application of the normal-incidence single-beam echosounder systems (SBES) used for marine sciences. More recently, oblique incident sidescan sonar systems (SSS) and multibeam acoustic systems (MBES) are being used to acoustically classify and map marine landscapes (e.g. Kostylev *et al.*, 2001). Today, acoustic remote sensing of seabeds is concerned with identifying, classifying, and mapping surficial geological features and biological habitats.

Acoustic seabed classification is based on the early observation that the on-axis (near nadir) acoustic echo contained information that could classify surficial sediment properties relating to median grain size and porosity. In addition, the roughness of the water–sediment interface causes sound to be scattered, which affects the coherency of the echo (Parrott *et al.*, 1980). In this way, the echo can be divided into coherent and incoherent components (Figure 1.1). The coherent component captures the energy in a time window equal in duration to the outgoing pulse, while the incoherent component captures the energy arriving after this time (Parrott *et al.*, 1980). As the amplitude and wavelength of the surface roughness increase, relative to the acoustic wavelength, the amount of coherent energy decreases, and the amount and duration of the incoherent energy increase (Clay and Leong, 1974; Sternlicht and de Moustier, 2003a). It is often convenient to categorize the acoustic echo into hardness (coherent) and roughness (incoherent) components that relate to surficial seabed sediment and geomorphology, respectively. The coherent zone is typically less than 20 degrees off nadir, where a direct and coherent reflection from the seabed is recorded from objects larger than the acoustic wavelength. However, acoustic signals returned from the seabed are complex, and there is no simple relationship between the backscatter signal and surficial sediment type and structure.

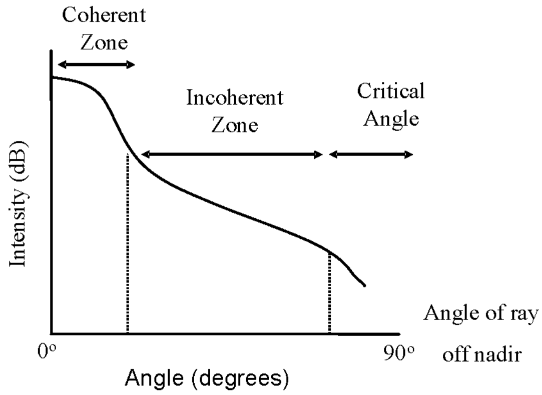


Figure 1.1. Schematic representation of the acoustic backscatter (dB) returned from the seabed (after R. Courtney, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada).

Initial work on acoustic seabed classification was based on vertical incident systems that categorized seabed hardness (E2) and roughness (E1) components. A significant limitation of vertical incident systems is the narrow footprint that is typically sampled; large areas of the seabed remain unsampled between sampling transects. The use of sidescan sonar systems greatly increases the spatial coverage, but these data are restricted to the off-axis roughness component and have largely relied on visual interpretations of texture as opposed to image processing and classification. Use of multibeam systems has significantly extended the classification and mapping of seabeds by their fine-scale and continuous coverage. Combined use of these acoustic systems is providing the opportunity to classify and map seabed features from the scale of boulders (<1 m^2) to the scale of banks (>10 000 km^2) and shelves (>100 000 km^2).

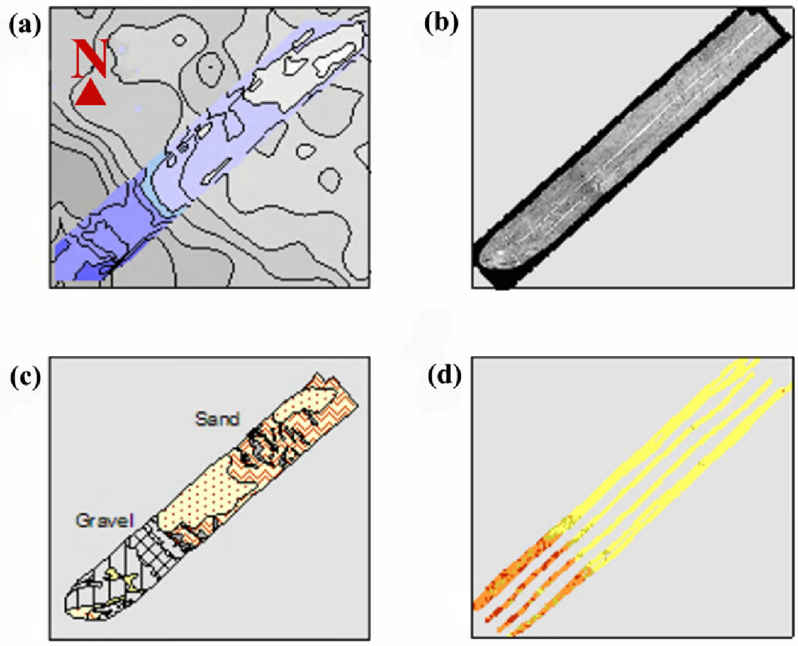


Figure 1.2. Fish habitat study corridor on Western Bank, Scotian Shelf (1 km by 5 km). The bathymetric surface is shown for the entire area at 400-m spatial resolution (a – grey surface, 1-m contours) and for the study corridor at 50-m spatial resolution (a – blue surface, 1-m contours) where depths are shallowest to the northeast. A sidescan sonar mosaic at 1-m spatial resolution (b) provided a textured surface for the interpretation of surficial geology (c) where gravel (grey) occurred in five classes and sand (yellow) in three classes. Acoustic backscatter (dB) from a single-beam acoustic system (d) detected four acoustic classes that mapped from high (red) over gravel to low (yellow) over sand along the corridor.

Typically, acoustic classification of the seabed has depended on determining different categories of backscatter. In one instance, this depends on a visual interpretation of the surface texture based on the reflectivity from SSS data (Figure 1.2b, c). Aids to such interpretations typically include photographs of the seabed and benthic grabs or trawls, as well as a bathymetric surface generated here by a normal-incidence SBES (Figure 1.2a). The bathymetric surface was generated at two spatial resolutions, 400-m spacing for the entire area and 50-m spacing for the more densely sampled corridor. The seabed surficial geology was classified into three categories of sand and five of gravel (Courtney *et al.*, 2005). Backscatter (dB) from normal-incidence echosounder data yielded four unsupervised acoustic classes in which high backscatter occurred over gravel and low backscatter occurred over sand (op. cit.). Therefore, based on interpreted data from the SSS and processed data from the SBES, we can now describe this area as a relatively flat area, dominated by sand that sloped gently from the northeast to the southwest, then the seabed dropped abruptly several metres to a deeper area dominated by a gravel boulder field. An estimate of rugosity (surface area standardized by planar area) demonstrated that the gravel boulder field was more rugged at spatial scales from 8 m to 50 m. Multibeam acoustic systems provide a significant extension of both acoustic classification and mapping capabilities by providing depth, rugosity, and backscatter data continuously at small spatial scales over large areas. A multibeam surface generated at 2-m spatial resolution for the fish habitat study area on Western Bank revealed a rich variety of bedforms that included bedrock outcroppings, buried rivers and subglacial channels, extensive areas of megaripples, and ridges of glacial till (Figure 1.3). These comparisons serve to demonstrate the range of acoustic data available to classify and map seabeds. Further work will add biological attributes to these surfaces towards defining seabed habitats on the Scotian Shelf.

1.3 ICES Study Group on Acoustic Seabed Classification

The terms of reference for the study group were broad and comprehensive (Annex 1); to meet them it was felt that a review of existing knowledge and technologies was necessary. To that end, the study group met over three years to develop a cooperative research report (Anderson, 2004, 2005, 2006). We begin with a review of physical models based on current theoretical understanding of sound-scattering from the seabed (Section 2). It is important for researchers, managers, and stakeholders to appreciate the limitations of these models, the acoustic measurement process, and the resulting limits to seabed classification. As theories and instrumentation improve, we can expect that advances will be achieved. We review the effectiveness of data generated by current technologies to classify seabeds in the context of the precision, repeatability, and comparability among systems and frequencies, including issues of calibration and standardization towards data quality assurance (Section 3). An important step in the process of acoustic seabed classification is an understanding of the issues relating to the data quality and the machine–operator interface. To this end, we review issues of data collection, quality, and display, and standardization methods are proposed (Section 4). The next step is to use the objective methods to classify acoustic data for interpretation and mapping. This classification can stand by itself (unsupervised) or can be linked to interpretations of seabed habitats (supervised). The statistical methods available to classify seabeds are reviewed and evaluated (Section 5). We address the issue of defining the relevant scales of observation with respect to fishery conservation, ecosystem-based management, and biodiversity issues (Section 6). Defining the relevant spatial and temporal scales is a necessary step towards defining the types of management questions that may be addressed with acoustic seabed classification methods. We review the existing technologies and summarize their capabilities to objectively classify marine habitats (Section 7). These technologies include SBES, MBES, sidescan sonar, and calibrated phase-difference bathymetric sidescan sonar systems. Sometimes SBES are referred to as acoustic ground discrimination systems (ADGS).

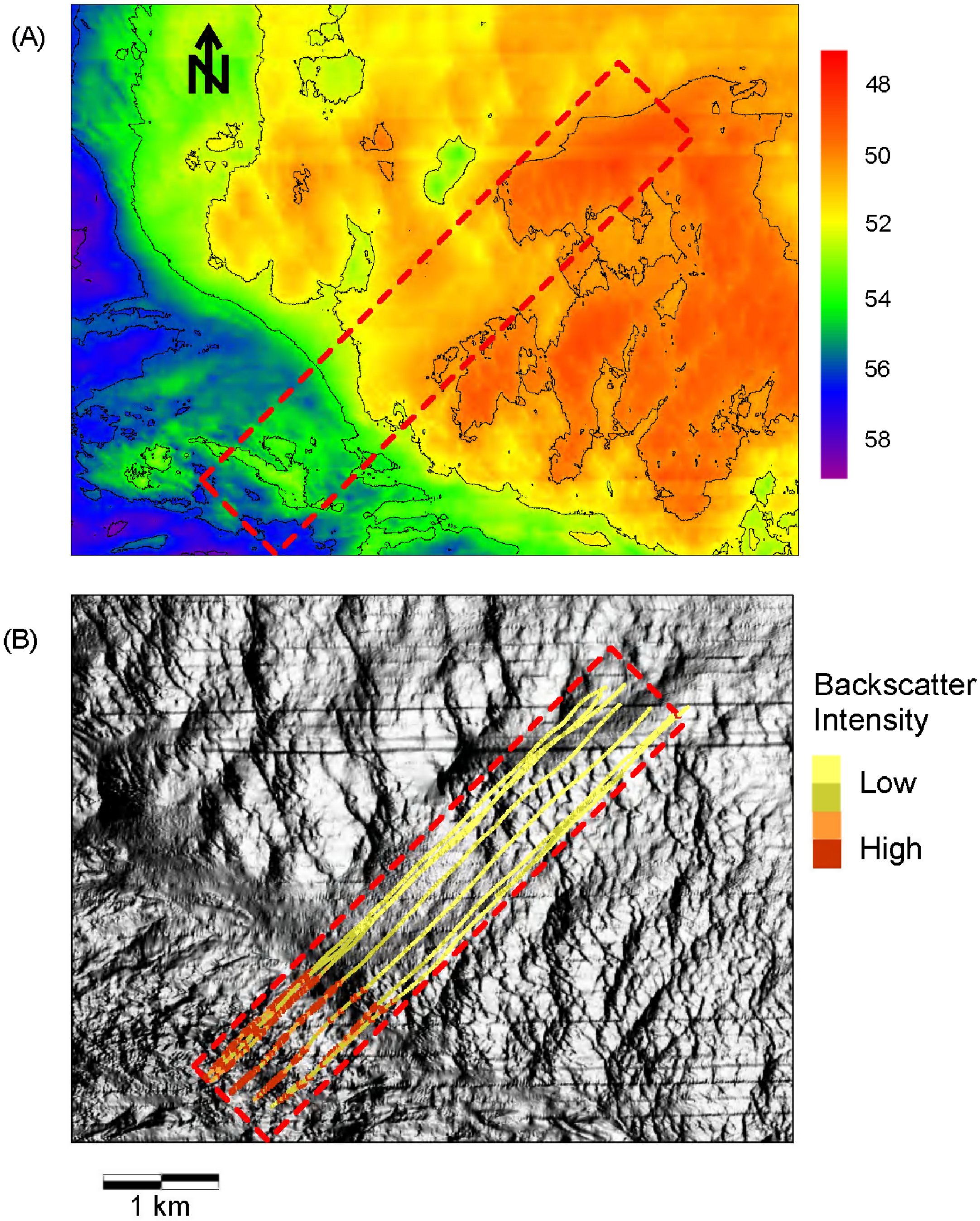


Figure 1.3. Multibeam image of the fish habitat study site on Western Bank, Scotian Shelf showing a bathymetric surface (a) at 2-m spatial resolution (shaded shallow-orange to deep-blue), the black lines are 2-m contours. The rectangle (dashed red line) outlines the detailed study area (see Figure 1.2). The same data are projected as a shaded relief surface (b) to show surface rugosity.

A summary of currently available classification systems is included in this review. Acoustics is a remote-sensing technique, therefore, it is always necessary to verify what has been sampled (i.e. the ground-truth). We review the existing techniques that are used to verify acoustic data and relate these techniques to issues of matching spatial scales to acoustic seabed classification products (Section 8). Combining single-beam acoustic systems with multibeam swathe systems requires a careful consideration of survey design and an evaluation of the effectiveness and limitations of survey data (Section 9). Many nations are now starting to classify and map their coastal environments. The study group felt a need to address how acoustic seabed classification products can be used in the context of habitat mapping and conservation management. We attempt to provide guidance on issues that must be addressed by the international scientific community (Section 10). Finally, we provide a glossary for clarification and standardization of terms and acronyms (Section 11).

The aim of this report was to review the state-of-the-art in acoustic seabed classification. The report provides an overview of the major issues and applications in this field and a comprehensive review of technologies and techniques. Acoustic technology and classification science is rapidly evolving to meet the needs of nations to manage and conserve coastal resources. As such, this report must be seen as representing a snapshot of the discipline at the time of writing. Although we anticipate that new developments will occur regularly and that this subject must be revisited in the future, we hope that this document will form the basis of our current understanding and will provide guidelines for the coordination of developments in this field.

2 Theory of sound-scattering from the seabed

D. V. Holliday

2.1 Introduction

We begin our discussion of acoustic seabed classification with a section about acoustical scattering theory. Why are we concerned with having a quantitative mathematical theory to describe the interaction of sound with the seabed? Bottom reverberation, the sum of individual echoes from the seabed, contains information about the physical structure of the seabed. Simply put, if one can reliably predict the character of an echo from a part of the seabed with known characteristics, then there is a chance that one can combine *in situ* scattering measurements and a model that describes the echo's formation and extract the characteristics of the seabed from the details of the bottom reverberation record.

Our exploration of bottom scattering theory starts with what may initially seem to be an unsettling assessment of the complexity of the seabed and the theoretical challenges that are implied. Fully understanding the interaction of sound with the seabed is a daunting task, mostly because there is so much diversity, both in the physical structure of the seabed and in the benthic community for which it is a habitat. Even when the scattering is not from members of the benthic community, bottom-dwelling organisms often locally modify the physical properties of the sediments and create seabed structures, both of which often affect the acoustic reflections from the seabed.

As if modelling the scattering from an extremely complex seabed were not sufficiently challenging, it must also be taken into account that *the seabed is not static*. Numerous dynamic processes are constantly occurring at the sediment–water interface and within the volume of the sediment. Timescales for these changes range from geological periods to seconds. These processes affect how much sound scatters into the water column, how much penetrates, and whether that which penetrates ever returns to the water column.

Even in the face of such complexity, over only a few decades much progress has been made in predicting acoustical seabed scattering from the basic physics of the scattering process. Prediction of echo characteristics from the physical nature of the scattering, whether sea surface, seabed, or within the ocean's volume, is sufficiently important in acoustical oceanography that it has a name: the forward problem. Reversing that process – estimating the parameters that describe the surfaces or objects whose presence leads to the scattering based on the information embedded in echoes – has come to be called "the inverse problem". If unique, quantitative answers are to be obtained, one should understand the forward problem before attempting the inverse one. Working with these kinds of problems is the focus of acoustical oceanographers in numerous disciplines, including acoustical characterization of the seabed.

The diversity of the seabed and the underlying strata has stimulated acousticians to formulate numerous models to describe bottom scattering. We will introduce some basic concepts by briefly examining some of the simpler relevant mathematical scattering models. These models are introduced roughly in the order of their appearance in the modern acoustics literature. The first models were developed from very limited field data and were largely empirical. As instrumentation and measurement methods improved, most of the simpler empirical models were shown to have limited validity, usually only for specific environments or geometries. In general, scattering problems are among a short list of the more challenging classical problems in physics. Initially, acousticians working on scattering from the seabed and the sea surface adapted some of the relevant methods from electromagnetics (i.e. optics, radio, and radar) to treat the problem. Increasing computational capabilities, differences in the underlying physics, and new field measurements eventually required the development of more realistic, but also more complicated models. For our purposes, we introduce only the more common models and concepts, relying on extensive references to the scientific literature to convey the more complex details to the interested reader. Further reading can be found in Annex 2.

2.2 The complexity of the problem

Structural diversity is the rule rather than the exception in marine sediments. Large contrasts in the density and compressibility of air and water translate into a large impedance difference at the air–water interface. This means that little sound crosses that boundary. For the seabed, however, in most cases the acoustical impedances are considerably better matched, and sound does enter the bottom. This means that some of the incident sound is lost to a variety of physical processes, like absorption, ending up as heat. Unlike the situation in the water column, the materials in the bottom are "elastic" and allow acoustic energy to propagate as shear waves, as well as by compressional wave motion. Some of the sound energy is usually converted from compressional waves to shear and surface waves as the sound interacts with the boundaries and the underlying material. After entering the bottom, sound may also be scattered from the volume that lies within the seabed. Additional challenges in describing the scattering of sound arise if the dependence of sound speed on depth below the bottom causes sound to be refracted upwards, and it re-enters the water column. The mechanisms by which marine sediments are deposited often cause them to be layered. This means that there is an opportunity for reflected and refracted waves to be generated at each boundary between subsurface layers. Additional complexities arise when the sediment is spatially inhomogeneous. This is often the case because rocks and shell fragments often tend to sort vertically into layers. In some locations, gas bubbles add to the scattering from the sediment's volume. Thus, both refraction and scattering are important processes in describing a seabed when one attempts to characterize the sound-scattering process.

A review of the scientific literature suggests that as many as 80 parameters have been used to fully describe the physical structure of the seabed and the materials that reside at and below the sediment–water interface. Adding biological organisms and their effects on the physics of sediments complicates the situation even further. Many parameters influence the amount of sound that is reflected and the spectral (and the equivalent temporal) characteristics of the echoes that are formed in the reflection/refraction process. Fortunately, many of the parameters one can list have relatively little influence on the formation of the echoes. Other characteristic parameters may be correlated with, or strongly co-vary with, one or more of these seabed descriptors. For example, the sound speed in the pore water depends on the *in situ* water density and its compressibility, each of which depends on the water depth, the temperature, and the salinity. Thus, the number of independent measurements required to describe the water column–seabed interface is usually far fewer than 80. Unfortunately, many of the parameters with a known, readily measured impact on the acoustic signature of the seabed are not independent, nor are their effects orthogonal (in a mathematical sense) to those of other measurable properties. This complicates our attempts to use an inverse calculation and extract many of the descriptors that have been traditionally used in marine geology and geophysics. Based on current knowledge, it appears that nominally 6 to 12 independent physical descriptors will control the majority of the extractable features embedded in an acoustic echo from the seabed. Although non-trivial, identifying these descriptors and finding the relationships between them and a set of unique descriptors of echoes from the seabed is not an overwhelming task. If this can be done successfully, then there is the potential to extract a great deal of unique, quantitative information from methods that use acoustics to rapidly, accurately, and remotely describe the ocean floor in great detail. This task is not unique to the solution of problems posed by acoustic seabed classification. One can draw on methods and experiences in a wide range of technologies to identify approaches that have worked in similar problems in other fields. This is "the inverse problem" in acoustical oceanography. Methods associated with solving inverse problems have been applied successfully in fields as diverse as zooplankton acoustics, geophysics, orbital mechanics, basin scale ocean tomography, economics, and biochemical engineering. In some senses, the problems facing the community that needs to assess and describe the seabed habitat are more closely related to "technology transfer" than to the need to "invent" new techniques. This statement should not be taken as minimizing the amount of effort and insight needed to make progress. It should, however, be considered a strong indication that the problem is not, necessarily, intractable.

When a problem is particularly complex, it helps sometimes to segregate it into parts with similar characteristics. To simplify the problem of how to model the scattering of sound from the seabed, a number of generalized seabed descriptions have been proposed by geologists and acousticians. They are not necessarily the same, although there is often overlap. The descriptions usually reflect terminology that was traditionally used in the specific discipline or experience of a paper's authors. Generally, the top level of partitioning has proven inadequate for the formulation of mathematical/physical models for sound-scattering from the seabed. Hamilton (1971b), originally a geophysicist who worked in acoustics, first proposed an environmental classification: continental terrace (shelf and slope), abyssal hill (pelagic), and abyssal plain (turbidite). Within those environments, bottom materials were further subdivided into multiple sediment types, e.g. sand (coarse, fine, and very fine); silty sand; sandy silt; sand-silt-clay; clayey silt; and silty clay (Hamilton, 1971b). Although Hamilton focused primarily on water-saturated porous media and did not deal in much detail with other substrates in his classic papers, he also recognized various types of rocks (e.g. basalt, mudstone, limestone) and calcareous ooze as categories that were important components of the ocean floor. None of these descriptors, in themselves, are directly useful as parameters in a physics-based model for describing the process of echo formation when sound is scattered from the seabed. They are somewhat useful, however, in segmenting the problem into groups of materials with similar properties that can be described using physical models with relatively narrow scopes. Hamilton spent much of his career developing new methods and then measuring the physical descriptors needed for the development of mathematical models that would relate the properties of seabed materials within each of these general categories to the way sound scatters from their surfaces and volumes (Hamilton, 1956a, 1956b, 1963, 1964, 1969, 1970a, 1970b, 1971a, 1971b, 1972, 1974a, 1974b, 1976a, 1976b, 1976c, 1976d, 1978, 1979a, 1979b, 1980, 1985; Hamilton *et al.*, 1970; Hamilton and Bachman, 1982). Numerous investigators have considered these problems, and although they are far too numerous to list here, in addition to the previously-cited papers by Hamilton, your attention should be drawn to work by Nolle *et al.* (1963), McKinney and Anderson (1964), Hampton (1967), and Anderson and Hampton (1980a, 1980b).

As interest in characterizing the seabed using sound developed, numerous descriptors were identified that had a basis in the seabed's physical and biological properties and its spatial structure. Many of these descriptors were related to previous work in terrestrial environments. An incomplete list of these descriptive parameters can be assembled under the following eight headings:

- Sediment physical properties (n = 13)
- Bulk and frame physical properties (n = 25)
- Properties of the interstitial fluid and porometry (n = 8)
- Properties of the overlying water column (n = 7)
- Surface morphology/topology (n = 2)
- Subsurface morphology/topology (n = 4)
- Discrete scatterers (surface and volume heterogeneity; n = 5)
- Biological organisms, communities, and processes (n = 9)

Only a few of the descriptors are independent, and most depend on the depth into the seabed. The sensitivity of sound-scattering to each descriptor often depends on the specific environment, the local ecosystem, its history, and more often than not, the structure and activity of the biological community present (e.g. seagrass, bacteria, benthic, and bentho-pelagic organisms present, primary production by benthic microalgae, bioturbation).

2.3 The forward problem

The first step in solving any inverse problem is to solve the forward problem. Basically, in the case at hand, this means that quantitative mathematical expressions (equations or "models") must be found that relate the physical and biological structure of the seabed to the changes that the seabed's character imposes on an incident acoustic pulse when it interacts with the bottom. Although it may be convenient to assign a stochastic part to these relationships, to allow for unknown variables or variability in known parameters, at the root of the process, the formation of an acoustic echo is essentially deterministic in nature. If one knows enough about the physical and biological structures and how they vary with time, in principle one can often write down the relationships that will allow the precise prediction of the details of the acoustic echo from the source/reflector(s)/receiver geometry and the physical and biological properties of the seabed. In practice, one may also need to include the properties of the propagation path from the acoustic source (the echosounder or sonar), the seabed, and the path(s) that the reflected and refracted sound takes on its way back to the receiver, separating those effects from the effect of the seabed on the incident sound.

Methods for finding and describing the relationships we use to describe the forward problem can be of several types. Historically, the one most often employed has been an empirical approach, in which the acoustical reflectivity at normal incidence is measured and mapped over an area with a single-frequency echosounder. This was the approach that most underwater acousticians took in the early post-World War II era (e.g. Gerjuoy and Yaspan, 1947; Eyring *et al.*, 1948; Mackenzie, 1961; Urick and Saling, 1962). When combined with ground-truth collected in areas that have different reflectivities, one might try to associate the amount of acoustical energy reflected (the bottom scattering strength) with the results of the "ground-truth" survey. One might assume that soft mud, sand, and rock would reflect increasing percentages of the incident acoustical signal. Indeed, this may be so (unless the surfaces have different degrees of roughness, volume heterogeneity, or gas inclusions, slopes, or one or more of several dozen other differences). Although this is the simplest approach, it is clearly also the most risky in terms of the potential for making a mistake about the nature of the ocean floor, and it is almost never used alone. First, one must realize that what one is mapping with any acoustical sensor is "acoustic diversity" or "acoustic variability". This is usually related to, but often *does not uniquely reflect*, the physical character of the seabed.

Faced with the non-uniqueness of a measurement of reverberation level alone, various investigators began to examine the possibility that adding information, by making different measurements of the characteristics of seabed echoes, would allow the discrimination of different seabed types with less chance of error. This may work, at least to the degree that the different measures used are independent, i.e. if one measures quantities that sense different physical or biological properties of the ocean floor. For example, there are empirical relationships that show a dependence of the acoustic reflectivity on the acoustic frequency employed, and on the angle at which a sound wave interacts with the bottom. When the angles of sound incidence and reflection are the same, then one is measuring the bottom *backscattering* strength. For a specific angle of sound incidence, there is a beam pattern or directivity associated with the reflected energy. It has been determined that the directional character of the scattered sound depends on the acoustic impedance of the seabed material and the surficial topography at scales that are comparable with the wavelength of the sound. It also depends on any anisotropy in the near-surface seabed structure, particularly the constantly varying current and wind wave-generated sand ripples and waves. At high acoustic frequencies, the roughness and surface structures dominate the scattering responses. At low frequencies, the sound tends to penetrate into the seabed, and volume scattering from the heterogeneity tends to be more important. Of course, any bottom-associated flora or fauna also creates heterogeneity on the sediment's surface and within the volume, and this usually increases variability in the observed scattering. Still, the different sensitivities of the echo-formation process at high and low sensor frequencies have proven very useful in separating sediment surface and volume characteristics, even without complete independence in response to the two kinds of acoustical stimuli.

2.4 A survey of scattering models for the seabed

2.4.1 Empirical approaches

The simplest models, and the first developed to describe sound-scattering from the seabed, were empirical. Early attempts to relate the scattering strengths of the seabed were focused on sorting the results of acoustical measurements of backscattering by general seabed descriptors, e.g. particle sizes in the sediment. This approach largely conformed to the conventional sediment classification schemes used by geologists and geophysicists for sediments in the marine littoral zone. Most investigators focused on the dependence of scattering on the bottom type, the angles of incidence and reflection, and the acoustic frequency. Intuitively, the scattering from rock should be higher than scattering from silt, or that from gravel higher than from sand or mud. Intuition also suggested that more sound would be scattered back in the direction of the source when near normal incidence than would be the case if the source was at a shallower grazing angle.

Using backscattering data from a number of published sources, collected at frequencies ranging from 24 kHz to 100 kHz, Bob Urick compiled plots with which he could examine these concepts (e.g. Figures 8.21–8.24; Urick, 1967). His description of the result was: "A relatively large number of discordant measurements have been reported in the literature." Although some trends were evident, it was clear that, at some angles of incidence, more sound was sometimes backscattered from mud or silt than was scattered from sand. Sand and rock sometimes scattered sound better than did rock. Clearly, although there was a trend towards higher scattering near normal incidence than at shallower grazing angles, a good theory for scattering had to include more than sediment type or grain size. A similar compilation of data from the deep sea, all at frequencies of a few kHz, revealed a similar result.

The result of Urick's assessment of the non-uniqueness of average scattering strengths from different seabed materials and the large variances associated with bottom scattering strengths with both angle and frequency was quickly apparent. There was a quick, stark realization within the community of interested acousticians, geologists, and geophysicists that a systematic, quantitative approach to the problem would be required. The approach would have to involve careful measurements of scattering, good ground-truth (independent assessment of seabed topography, identification of the key material properties of the seabed that impact sound-scattering, laboratory and *in situ* measurement of those properties, as well as new physics-based mathematical models of the important scattering processes). This realization has led to the training and support of a large group of scientists who are producing a wealth of relevant scientific literature, a very small sample of which is cited in the Reference section and in Annex 2. Unfortunately, many of the issues that Urick raised in 1967 (and in his earlier papers) have either been missed or have not been heeded, by many new investigators who are under pressure to provide quick, inexpensive results by conducting surveys to classify and map shallow water habitats. In part, this section is intended to highlight the facts that there are numerous quantitative tools that could be adapted for use in supporting current survey requirements, and that results obtained by attempting to extrapolate from a few ground-truth measurements to wider areas by using simple empirical, statistical, or correlative procedures should be very carefully examined. The physics of sound-scattering has not changed since Urick's time. Substantial potential for oversimplification or even serious error is embedded in some of the simplistic approaches being considered for use today.

McKinney and Anderson (1964) collected scattering data from depths less than 61 m (200 feet) at 16 coastal sites on the east, west, and Gulf coasts of the US. The data included backscattering strengths at frequencies between 12.5 kHz and 290 kHz. Most of the data were at grazing angles between 5° and 60°, but some data were collected for the interval between 1° and normal incidence (90°). They obtained results similar to those of Urick (Urick, 1954, 1956, 1960; Urick and Saling, 1962), but found slightly more consistency, in that solid rock seemed to scatter more sound than did gravel or coral. Gravel was a better scatterer than were any of the sands encountered. In line with intuition, mud appeared to scatter less sound than the other types of sediments. For the sands, sediment grain size did not seem to be a reliable predictor of scattering. The scattering values for the sands did tend to be grouped, with a spread of approximately ± 5 dB. Although backscattering tended to be less at low angles of incidence, efforts to associate different sediments with simple dependences on frequency or backscattering angle were not particularly successful.

There appears to be no simple predictor or small set of parameters that can be used to describe how much sound will be scattered from the seabed given only knowledge of bottom composition, angle, or frequency. At first, this appears to be a difficulty. In fact, however, when there is an extremely simple relationship for the forward problem, one often finds that the inverse problem is ill conditioned. An ill-conditioned problem would clearly limit the amount of information one could eventually extract about the seabed using acoustics. Obviously, relationships or models can be too complex, defying our attempts to build quantitative models; however, if the relationships that describe a forward problem have some degree of complexity, or what is often called character, problems of non-uniqueness and ill-conditioning are frequently less severe than would otherwise be the case.

Faced with a complicated modelling problem, acousticians began to attempt to break the problem up into parts that are more tractable. A variety of ways to look at the problem of modelling backscattering evolved during this process. For example, some investigators segregated the scattering data by bottom and sediment types. Deep-sea data were separated from shallow-water data. Scattering from silts, muds, sands, gravel, and rock were each examined for self-consistency. For sediments, models based on particle size were formulated. Other investigators examined the problem from the "acoustics" point of view. Data collected at high acoustical frequencies were examined apart from those collected at low or medium frequencies. The problem became one in which the bottom was considered as a two-fluid boundary value problem: a fluid overlying a porous medium, a fluid over a visco-elastic medium, a fluid over a fully elastic medium, and several combinations of these theoretical constructs. Others considered scattering from the boundary only, then added scattering from the volume of sediments below the water column–sediment interface. Discrete scatterers, simulating biologicals and shells, were eventually added to a model for a homogeneous sediment with a rough boundary surface in an attempt to more accurately represent reality. Each of these constructs has some basis in reality, and each is also inadequate for describing the general case.

A smooth, impenetrable seabed

Analogous to geometric optics, the simplest seabed to model would be one that appears to be an acoustical "mirror" – an analogy with an optical mirror for light. Such an ocean bottom would be characterized as a perfect, specular reflector of sound. Sound waves would be reflected, without loss or distortion, at angles that are completely determined by their angle of incidence relative to the normal to the plane of the ocean floor.

Unfortunately, in the real world, “smooth” and “impenetrable” are only theoretical constructs, which are relatively easy to model with simple equations. Although such models are useful in working out the basic geometry of a scattering problem, and in providing insight into scattering when one approaches the assumed conditions in their “limits”, it would be quite rare that such a seabed would actually be encountered.

It should be noted that, when the ratio of acoustical roughness to the wavelength of the incident sound is small, the effects of the roughness are diminished. Thus, for long acoustical wavelengths one may approach “smooth” in the limit. The amount of sound that enters the bottom depends on both geometry and the acoustical impedance of the seabed. However, if sound does penetrate the bottom, then low-frequency sound usually suffers less absorption within the sediments, and scattering from below the water–sediment interface tends to be more obvious than at higher frequencies. At the limit of very high frequencies, the seabed may appear to be more nearly “impenetrable” than it is at low frequencies.

A randomly rough, impenetrable seabed

Acoustically, any real seabed has some degree of roughness, even if it is in the order of the scales of the inhomogeneities of the material properties in an igneous rock or of the grain-size variations in microtopography at the surface of unconsolidated sediment. How that roughness is encoded in an echo depends on the ratio of the roughness scale at the substrate interface to the wavelength of the sound. When the ratio of acoustical roughness-to-wavelength is large, regardless of the absolute physical scale of the roughness, an incident signal is substantially modified during its reflection. The information encoded in an echo can then potentially be extracted to reveal the roughness scale (in either physical properties or topography). When the ratio is small, i.e. the “roughness” is much less than the wavelength of the sound being used, there is often only a small effect on the incident signal. In that case, the bottom may appear “acoustically smooth”. Acoustically, roughness should be considered both as a physical measure that depends on the surface topography and as an acoustic descriptor determined by variability in acoustic impedance. These two measures may, or may not, be correlated. The acoustic impedance varies with numerous physical attributes of the sediment, a few of which are material density, compressibility, grain packing, void fraction, particle shape, the presence of gas, and a plethora of biological phenomena. The manner in which sound appears to interact with the seabed depends on both the physical and acoustical characteristics of the ocean floor and the parameters (e.g. frequency, pulse length, bandwidth) that characterize the sound that is being used as a “probe”.

Recognizing that simple geological descriptions of sediments were insufficient, Urick and his contemporaries initially drew parallels between scattering from a rough seabed and theories in geometric optics. In optics, Lambert’s Rule states that a perfect, randomly rough surface or source reflects or emits light according to a cosine law. For such a reflector, scattered energy is radiated equally in all directions. In scattering problems, the intensity of light reflected from such a surface is proportional to the cosine of the angle between the vector that describes the direction to the light source and the normal vector, perpendicular to the surface. The amount of reflected light depends on the relative positions of the light source and the scattering surface, but is independent of the observer’s position. Although acousticians tend to use grazing angle, measured from the scattering surface, instead of using the normal as a reference, by analogy with the optics, one might describe the intensity of a sound wave (I_s) after reflection from a rough bottom as,

$$I_s = \mu I_0 \sin\theta \sin\phi \, dA$$

where I_0 is the sound intensity incident on a small seabed area, dA, arriving at an angle θ from a point source that is sufficiently distant that the arriving sound-wave front is effectively in a plane, i.e. the source is in the “far field”. The term μ is the plane-wave reflection coefficient, and the receiver is located at an angle ϕ. At a unit distance, e.g. one metre, from the incremental surface dA, the scattered intensity would be I_s. Were the bottom perfectly reflective, then all of the incident sound would be redistributed into the water column, with the result that $\mu = 1/\pi$. The geometry is as illustrated in Figure 2.1.

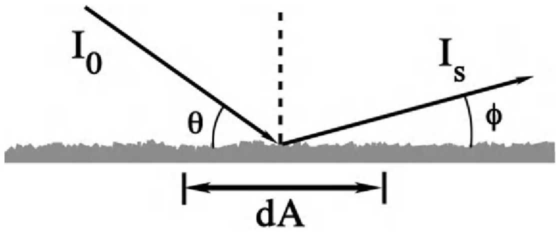


Figure 2.1. A two-dimensional representation of the geometry describing Lambert's Rule for scattering.

For *backscattering*, where $\phi = \pi - \theta$ when one expresses the bottom scattering strength S_s in logarithmic form, $S_s = 10 \log_{10} \mu + 10 \log_{10} (\sin^2 \theta)$.

This is probably the simplest of all the models proposed to describe sound-scattering from the seabed. Clearly, however, such a model would not account for any situation in which sound penetrates into the sediment volume nor can it adequately describe a surface with spatially coherent ripples.

A number of investigators have compared predictions from Lambert's Rule to experimental results. Most of those comparisons have been for acoustical frequencies between 1 kHz and 200 kHz (McKinney and Anderson, 1964; Boehme and Chotiros, 1988). Greenlaw *et al.* (2004) extended the frequency range to examine wavelengths that approximated the grain size and small-scale variability in surficial roughness and physical properties. The results agreed with previous measurements at long wavelengths compared with grain size. A broad maximum in scattering was observed for frequencies with wavelengths that were comparable with mean grain sizes. These results were similar to those obtained by Williams *et al.* (1988). Although the maximum in scattering is close to the frequency that is predicted by Faran's model for scattering from an elastic sphere (Faran, 1951; Holliday, 1987; Sheng, 1991; Hay, 1991; Crawford and Hay, 1993), the dependence of the scattering on grazing angle suggests that additional mechanisms are involved (Greenlaw and Holliday, 2004). Scattering data at high frequencies appear to follow Lambert's Rule with acceptable precision. The low-frequency data tend to depart from this behaviour at steeper grazing angles, above about 50° (well above the critical angle). This suggests a transition to a different mechanism for controlling the scattering in this region. A similar behaviour for backscattering with grazing angle was observed by Ivakin and Lysanov (1981a) for data from a shallow-water experiment performed at 100 kHz.

One explanation for the observed anomalies involves near-surface volume scattering, especially at high grazing angles, even at 200 kHz to 4 MHz. This suggests that even at very high acoustical frequencies, a seabed may not always appear perfectly smooth, or impenetrable.

A stochastically rough seabed

Aside from its depth below the sea's surface, one of the most useful descriptors of a seabed is its roughness. In recognition of the quasi-random nature of the small-scale topography of an ocean bottom, roughness is often expressed as a root mean square (rms) amplitude. Higher order moments, or an approximation of a full description of the probability density function (PDF), may also be useful. Roughness seems to be one of the more natural acoustically measurable descriptors of a biological habitat, although one should recognize that "acoustical roughness" is not always identical to "physical roughness". Variations in acoustical roughness can also occur when the topography is featureless if there is spatial heterogeneity in the properties that control the scattering process. Seabed roughness can be generated in many ways; it will vary with the physical and biological mechanisms present, as well as with the kind of material in the substrate. Irregularities on the seabed can involve both large and small ripples generated by wave or current action, megaripples, the presence of mineral nodules, rock outcroppings, cobbles, shells, benthic plants, and a wide variety of biological entities or the structures that they create (e.g. mounds of sediment piled up near burrows, corals, crabs, etc.) In many natural situations, combinations of these phenomena co-occur.

When a rough seabed is investigated at different locations with an echosounder or sonar beam, the effects of roughness can be seen as ping-to-ping fluctuations in the detected envelope of the echoes. Stanton (1984, 1985) recognized that a useful analogy could be drawn between the statistical probability distribution functions described by Rice (1954) that describe the envelope statistics of sinusoidal signals in a background of random noise and the scattering one gets from a stochastically rough seabed. Mathematically in this analogy, the echo from a rough seabed is thought to consist of a coherent or specularly reflected component and an incoherent or randomly scattered component. In the development of the Rician PDF, the analogous components are the (coherent) sinusoidal component and the (incoherent) noise. Stanton recognized that Rice's PDF and Clay's generalized formulation of Eckart's theory for plane waves scattering from a rough surface (Eckart, 1953; Clay and Leong, 1974; Clay and Medwin, 1977), as modified by Melton and Horton (1970) to include corrections for Fresnel zone contributions, had two common parameters – both involve expressions for the reflected and the scattered energy (i.e. the coherent and stochastic components of the echoes). Stanton combined the two approaches, revealing that the shape of the Rician PDF for the envelope of the scattered signal could be expressed as the rms roughness amplitude and the correlation function of the seabed. The key assumptions in the theoretical development are: (i) the transmit and receive beams are sufficiently narrow and/or the pulse is sufficiently long to include overlapping returns from all parts of the insonified surface; (ii) echoes from the seabed's volume are excluded from the echoes from the sediment–water column interface; (iii) the seabed is "flat" with the exception of isolated scatterers, or the bottom is uniformly rough over the insonified area; (iv) the average separation between discrete scatterers or patches of roughness is small compared with the dimensions of the insonified area; and (v) there is no appreciable shadowing of the reflected sound by topography within the insonified area. Stanton's analysis revealed that the products of the rms roughness amplitude and two orthogonal correlation lengths determined the shape of the PDF of the reverberation envelope. He defined a correlation area as the product of the x and y correlation lengths (measured in the plane of the seabed). The roughness parameter can be determined directly from coherent reflection measurements. The shape of the PDF was also shown to be very sensitive to small changes in microtopography, or roughness. He also pointed out that the shape of the PDF of the bottom reverberation envelope was determined by the integral of the correlation function rather than its exact shape, and that the PDF could be measured using an uncalibrated conventional echosounder. By utilizing the orthogonal correlation lengths and the roughness together, one may be able to discriminate between areas with the same roughness but differing anisotropic properties (e.g. well-defined ripple fields as opposed to a flat seabed covered with randomly placed shells, rocks, or cobbles resulting in the same rms roughness).

2.4.2 Theoretical approaches

Describing scattering from randomly rough surfaces is one of the classical problems in physics. Theoretical developments have come from researchers interested in optics, electromagnetics (e.g. radio and radar), and acoustics (Beckmann and Spizzichino, 1963). In acoustics, approaches have evolved from problems in both architectural acoustics and ocean sciences. For the ocean, applicable theories have been developed for scattering from the sea's surface, both for radar and for underwater sound (Eckart, 1953; Kinney and Clay, 1984, 1985). In addition to the original application, theories from these other disciplines are often adapted to describe acoustical scattering from the seabed.

Many of the papers cited in a later section on scattering from corrugated bedforms are also relevant to seabeds that are randomly rough, as opposed to those that exhibit locally coherent spatial patterns. Horton (1971) provides a summary of many of the key theoretical developments in surface scattering until about 1971. In many cases, theories developed to cover scattering from spatially coherent structures can be applied to randomly rough ones as well.

Morse and Ingard (1968, Section 8.3) treat the subject of acoustic scattering from a surface with irregularities in several successive steps. They introduce surface scattering by discussing the case in which the boundary is smooth and rigid (the Neumann boundary condition), then proceed to use Green's function to treat scattering from a physically smooth surface with irregularities in the surface impedance (expressed as changes in the local point acoustic admittance). If the impedance changes are relatively small, it is shown that one can address the scattering problem as a reflected plane wave, plus a scattered wave that effectively embeds the distortion caused by variability in the surface properties. The model is then extended to include random physical surface roughness. Finally, both variability in surface acoustical properties and random physical roughness are combined, and their effects on the scattered wave are differentiated for high- and low-frequency limits. Their approach is useful for understanding broad conceptual issues, but it uses standard descriptive parameters, such as impedance and admittance, taken from physical acoustics rather than descriptors that are more familiar to geologists or geophysicists (e.g. grain sizes, seabed material properties, etc.).

With a few exceptions, largely involving numerical modelling (e.g. Hastings *et al.,* 1995), most approaches to modelling for scattering from rough surfaces have been of two basic analytical types. One involves the application of some variant of first- or second-order perturbation theory (e.g. Thorsos and Jackson, 1989; Jackson and Ivakin, 1998). The other analytical approach involves invoking approximate semi-classical methods from the physics of wave propagation, such as the Eckart, Helmholtz, or Green's theorem methods, with Kirchhoff's approximation. Combinations of these approaches are not uncommon (e.g. Voronovich, 1985). Scientific papers by Proud *et al.* (1960) and Kur'yanov (1963) are typical of the state-of-the-art between 1950 and 1960.

A smooth, penetrable seabed

Recognizing that all of the energy is not normally reflected at the seabed and that some sound penetrates most sediment on the seabed, Tolstoy and Clay (1966) developed a slightly more realistic model for sound-scattering at the seabed. A model was first derived for the reflection of sound at a smooth liquid–solid interface and was based on Snell's Law. Snell's Law is familiar to physicists from the literature on geometric optics. In acoustics, it also applies to the superposition of two (or more) layers with differing sound speeds.

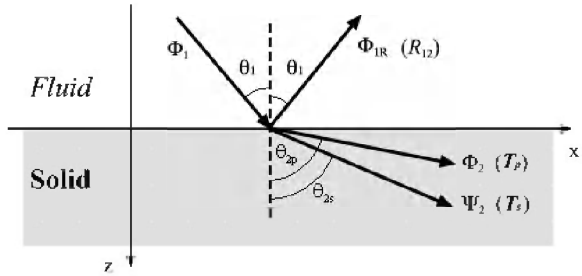


Figure 2.2. A two-dimensional representation of the geometry describing Snell's Law scattering from a smooth, planar liquid–solid elastic interface (perfectly rigid, Neumann boundary condition).

Water only supports compressional sound waves (ϕ_1, ϕ_{1R}), while an elastic solid will support both compressional (ϕ_2) and shear (Ψ_2) waves. In Figure 2.2, ϕ_1 is an incident sound wave with an angular frequency ω. When the compressional wave, travelling at angle θ_1 in the water column, intersects a planar elastic solid, a part of the energy is reflected back into the water at the complementary angle θ_1 to the normal, still travelling as a compressional wave. The reflection coefficient for this wave, θ_1, is R_{12}. Part of the energy is transmitted into the solid as a second compressional wave, ϕ_2, but at a different angle, θ_{2p}. The amplitude of the wave that is converted from the incident compressional wave to a compressional wave in the solid is designated T_p. Some of the water column compressional wave energy is also converted to a transverse, or shear wave in the solid, travelling at a third angle, θ_{2s}. The symbol T_s represents the amplitude of the shear wave.

With minor changes in subscript notation, following Tolstoy and Clay (1966; p. 23) and applying Snell's Law by matching boundary conditions, one can easily show that the angles of reflection and penetration for the different waves are related by:

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_{2p}}{c_{2p}} = \frac{\sin\theta_{2s}}{c_{2s}}.$$

Here, c_1 is the speed of sound in the water, c_{2p} is the speed of the compressional wave in the solid, and c_{2s} is the speed of the shear wave in the solid.

The reflection coefficient, R_{12}, is given by:

$$\mathcal{R}_{12} = \frac{4\gamma_2\delta_2\alpha^2 + (\delta_2^2 - \alpha^2)^2 - (\rho_1/\rho_2)(\gamma_2/\gamma_1)(\omega^4/c_{2s}^4)}{4\gamma_2\delta_2\alpha^2 + (\delta_2^2 - \alpha^2)^2 + (\rho_1/\rho_2)(\gamma_2/\gamma_1)(\omega^4/c_{2s}^4)}.$$

The terms ρ_1 and ρ_2 represent the density of the water and the solid (or seabed material). The symbols α, γ_1, γ_2, and δ_2 defined as:

$$\alpha = \frac{\omega}{c_1}\sin(\theta_1),$$

$$\gamma_1 = \frac{\omega}{c_1}\sin(\theta_1),$$

$$\gamma_2 = \frac{\omega}{c_{2p}}\left[1 - \left(\frac{c_{2p}}{c_1}\sin(\theta_1)\right)^2\right]^{1/2},$$

$$\delta_2 = \frac{\omega}{c_{2s}}\left[1 - \left(\frac{c_{2s}}{c_1}\sin(\theta_1)\right)^2\right]^{1/2}.$$

Ewing, Jardetzky, and Press (1957) give expressions for T_p and T_s, the coefficients that describe the amplitudes of the compressional and shear sound waves that enter the bottom. This simple model explains some, but not all, of the experimental data that have been collected for scattering from the seabed. For example, when $c_{2s} > c_{2p} > c_1$, these expressions define the "critical angle", beyond which *all* of the incident sound energy is reflected into the water column.

Note also, that by substituting the definitions of α, γ_1, γ_2 , and δ_2 into the expression for R_{12}, after a bit of algebra, one finds that the frequency terms cancel and there is no explicit functional dependence on the acoustic frequency (ω). Measurements reveal that frequency *is* a variable of consequence in predicting seabed scattering, so, generally, one must look towards more complex models than that expressed by Lambert's Rule or this simple model based on Snell's Law.

Such a simple model also fails to account for absorption losses in the scattering process. This is often addressed by introducing a complex notation for the speed of sound in the elastic solid (Clay and Medwin, 1977; pp. 492–493). When one accounts for absorption losses, the reflection coefficient is less than one, even at angles greater than the critical angle. Varying various parameters that describe the physical properties of the fluid and the solid, and the boundary conditions at the interface, one can describe certain boundary waves, e.g. Biot and Rayleigh waves. This type of model, however, does not reveal much detail about the physical mechanisms that are responsible for such energy losses.

If our assumptions are met, e.g. the reflections arise from a smooth, planar surface with no absorption loss, then, given measurements, one might solve for the speeds of acoustic propagation and reflection coefficients for various waves that are implicit in models such as those described above. Given good measurements of the acoustic reflection coefficients for different incident sound directions, one may solve for the densities of the overlying water and the seabed materials (ρ_1 and ρ_2) and the three sound speeds, c_1, c_{2p}, and c_{2s}, though one would normally be able to estimate or measure the sound speed in the water column just above the seabed. This would leave the water and bottom material densities, ρ_1 and ρ_2, and the two sound speeds, c_{2p} and c_{2s}, as unknown parameters. If one used the formula that includes a complex speed of sound in the seabed, then the real and imaginary parts of the sound speeds in the sediment could also be estimated. One would then attempt to associate these values with a particular kind of marine seabed. Although this example is quite simplistic, it does illustrate how an inverse problem might be addressed in an attempt to characterize the seabed.

As mentioned earlier, when a compression–rarefaction wave (p-wave) enters the seabed, the incident energy can be converted into a number of different wave motions (mode conversion). Mode conversion occurs when an acoustic wave interacts with a surface at which there is a change in the acoustic impedance and at which the angle of incidence is not normal to the interface. The particle motion for p-waves is along the direction of the wave propagation. For transverse, sometimes called shear, waves (s-waves), the particle motion is perpendicular to the direction in which the wave is travelling.

Surface-scattering problems are often simplified by characterizing extreme values of various parameter values or ratios. The truth often lies between these extremes. Nevertheless, such assumptions can be of value because they can make an otherwise unapproachable problem analytically tractable. Two extremes that apply to acoustical scattering from the seabed involve the concept of whether the interface is perfectly rigid (the Neumann boundary condition) or whether it is perfectly free to move (the Dirichlet boundary condition). Advances in computer speeds have led acousticians to adopt numerical approaches (e.g. Boundary Element Modelling – BEM), but sometimes these kinds of models lead to less intuitive results than one can obtain with analytical approaches involving the assessment of scattering at the practical or theoretical limits of parameter values embedded in the modelled process. A good example of this approach involves the generation and propagation of surface waves at the surface of the seabed and at boundaries of layers within the bottom.

A variety of acoustic waves can be generated where there is a distinct change in material properties, e.g. at the interface between two sediment layers. At oblique angles of incidence, some of the energy in the incident acoustic wave may be converted to interface (surface) waves. Surface waves are acoustic waves that transport energy at the boundary between two media as opposed to through a medium such as water, rock, or sediment. In some acoustic disciplines, the waves that travel in the medium itself are called body waves.

There are several kinds of surface waves. The most familiar Rayleigh wave is the wind-generated water wave at the ocean's surface. Particle motion for this common surface wave is approximately circular, with the major axis of the ellipse perpendicular to the surface. The amplitude of the wave motion decays rapidly with depth below the surface, persisting to depths of about one wavelength below the surface. Rayleigh surface waves on the seabed differ from surface waves at the air–water interface. For the sea surface, the orbital motions of particles are approximately circular and move clockwise for a wave travelling from left to right. Particles moved by Rayleigh waves travelling in the same direction at a liquid–solid interface trace anticlockwise elliptical orbits to depths of about one-fifth of the wavelength. Below that depth, they move in clockwise ellipses.

There are also two forms of "plate waves" that are classified as surface waves – Lamb waves and Love waves. These waves propagate in relatively thin layers, or "plates". Lamb, or extensional, waves, are characterized by components of particle motion that are perpendicular to the surface. They are similar to longitudinal waves, with compression and rarefaction, but they are bounded by the top and bottom surfaces of the thin layer. Whether they are generated and how they propagate depends strongly on the acoustic and physical properties of the material in the thin layer. Effectively, they travel in a waveguide. Multiple modes may be supported by the geometry of waveguides, and the most common for the particle motion in a Lamb wave are symmetrical and antisymmetrical. The orbital motion for Lamb waves is elliptical and is similar to the particle motion under a water wave at the sea's surface. Love waves, a second kind of plate wave, exhibit motion that is perpendicular to the direction of wave propagation. The motion is sideways in the horizontal plane within the thin layer.

In addition to those mentioned above, other kinds of surface waves include Stoneley waves (leaky Rayleigh waves) and Scholte waves. Stoneley waves, sometimes called head waves in geophysics, are the equivalent of Rayleigh waves for subsurface interfaces. They are very slow speed, dispersive, highly attenuated waves. Generally, they are produced when the p-wave passes through subsurface interfaces between layers with differing physical properties (e.g. sound speed), rapidly decaying in both directions as they move away from the interface where they originated.

Scholte waves are finite amplitude elastic waves generated by non-linear processes at a boundary. Scholte waves must be stimulated very near to, or on, the bottom. Small impulsive sources are usually employed to produce this kind of surface wave. These waves are normally dispersive (i.e. sound speed depends on the acoustic frequency), and this property of Scholte waves has been used to characterize ocean sediments (Dorman, 1977; Bibee and Dorman, 1995).

In practice, these general characteristics of surface waves on and in the ocean floor are modified by at least four practical factors: (i) when the seabed consists of sediments, the transition between the water column and the sediment is often a transition rather than an abrupt change; (ii) the physical properties that characterize unconsolidated sediments are more complicated than those that are usually used to describe true solids; (iii) many seabeds are layered, with gradients in depth for the physical parameters that control acoustic interactions; and (iv) lateral inhomogeneity in those same parameters is the rule, rather than the exception. Locally, these factors lead to the generation, propagation, and decay of different kinds of waves, with different mixes of wave types dominating according to the local physical and acoustical environment.

A number of investigators have worked on the theory of scattering from smooth, penetrable sediments. The reader's attention is specifically drawn to papers by Nolle *et al.* (1963); Jackson *et al.* (1986a); Boehme *et al.* (1985); Ivakin and Lysanov (1981b); and a particularly lucid thesis by Hines (1988). Special note should also be made of the citations in each of those publications.

Instructive animations and further information on acoustic waves in liquids and solids can be found at: http://www.gmi.edu/~drussell/Demos/waves/wavemotion.html.

A multilayered bottom structure

In a real ocean or lake, geological processes tend to create distinct layers of materials with distinctive characteristics above a basement material. In shallow coastal waters, these layers are subject to both continuous and episodic modification by waves, currents, terrestrial run-off, and biological activity. However, even in a dynamic environment, there are usually periods of relative stability, and when sedimentary materials are present they tend to become sorted by physical properties such as grain size. Numerous models have been proposed to deal with this layering phenomenon. They generally fall into two classes: (i) ray theory models, and (ii) normal mode theory models. Both have sound, rigorous mathematical underpinnings. In most cases, they will eventually produce similar results, but the choice of which to use usually depends on the numbers of layers, their physical geometry, including thickness relative to the wavelength(s) of sound being used, and the acoustical properties of the materials involved. Purely computational issues may sometimes suggest that one approach is more tractable than the other. Those issues are beyond the scope of this section, but as they are common, it is important to grasp the concept of how multilayered environments can be treated. To gain further insight into modelling in this kind of environment, we refer the reader to Medwin and Clay (1970, Sections 3.3 and 11). A brief discussion of the propagation and scattering in a multilayer geometry based on ray path acoustics is provided in their Section 3.3. Their treatment in Section 11 describes a normal mode approach to the multilayer problem. In addition to addressing layers with planar, horizontal boundaries, they also introduce methods with which one might deal with layers that have wedge-like geometries.

Ivakin (1998) utilizes a statistical approach to address different types of layering, including rough boundary surfaces and volume heterogeneity in physical properties.

In practice, modelling a seabed with only two layers is often inadequate. Ainslie (1995) addresses a multilayered elastic medium and some computationally efficient methods for dealing with extensions to the two-layer problem. His paper also provides numerous citations that are worth close examination if one intends to pursue multilayer computations. Ainslie and Burns (1995) discuss some pitfalls that may arise concerning energy conservation if the rigidity modulus is a complex quantity.

A refractive bottom structure

Stratigraphic history, overburden pressures, biological activity, and a number of other dynamic factors lead to gradients with depth for most, if not all, of the parameters discussed in Section 2.2. A few typical examples of the relevant physical parameters that vary with depth and impact sound speeds in a sediment would include material and overall sediment densities, grain-packing geometries, porosities or void fractions for permeable sediments, pressure effects (including the total overburden pressure or the geostatic pressure), and biological activity (e.g. bacterial growth, the presence of shells or shell fragments, bioturbation). Cracks, infiltration by water, and the activities of sessile benthic organisms can create near-surface gradients, even with exposed rock. Gradients in physical properties can appear both within the seabed as a whole and within individual strata of multilayered structures when present. Acoustically, gradients in such descriptors as sound speed will change the way sound propagates within the seabed. Although vertical gradients have probably received much more attention from researchers than have horizontal gradients, both are undoubtedly important. Often, these changes will involve refraction of the compressional and shear waves that travel in the sediment's volume. Sometimes conditions are right for downwards refraction; other times, waves are trapped in a layer and propagate horizontally, as in a waveguide. In other cases, a ray (or sound wave) will bend upwards, and the sound may even return to the water column. Different kinds of waves, e.g. p-waves and s-waves, are refracted at different rates (angles) by these gradients.

There have been extensive investigations of the vertical profiles of many of the geological and geophysical parameters that control sound speed profiles in the materials that are found in the ocean's floor. Much of Ed Hamilton's career was focused on the estimation of seabed physical parameters that impact the speed of sound and vertical gradients in the seabed (Hamilton, 1956a, 1956b, 1963, 1964, 1969, 1970a, 1970b, 1971a, 1971b, 1974b, 1976c, 1976d, 1978, 1979a, 1979b, 1985, 1987; Hamilton *et al.* 1956, 1970). Among many other publications, a few other papers are of special note: Hampton (1967), the oft-cited work by Hamilton and Bachman (1982), and two papers by Gassmann (1951, 1953). The reader's attention is also directed to papers by Jackson *et al.* (1978) and Richardson (1997). These papers, their references, and additional papers cited in Annex 2 should serve as a reasonable introduction to this extensive body of scientific literature on sediment properties and their gradients within the seabed.

A corrugated or rippled bedform

Surface ripples are frequently observed on shallow seabeds covered by unconsolidated sediments such as silt, mud, sand, or mixtures thereof. Causal mechanisms for generating these features, which are often coherent over limited areas but patchy over larger areas, include resuspension of sediments by both wave action and horizontal currents. Although a diver can only easily observe these features at the water column–seabed interface, ripple fields are often buried by the advection of other kinds of sediments to the site, followed by settling, which covers the original field in a more or less intact form. An example is a clean sand ripple field that becomes covered after a heavy rainstorm carries mud offshore to the site; here, the mud settles to fill the troughs or even blankets the entire field, obscuring visual evidence of the underlying ripple structures.

Lord Rayleigh was one of the first to address acoustical scattering from a sinusoidal surface (Lord Rayleigh, 1878, reprinted 1945). He treated the sound field scattered from a sinusoidal pressure-release surface by setting up an infinite set of simultaneous equations for which he could only obtain answers in limiting cases, i.e. when the wavelengths of the surface sinusoid and the incident acoustical waves were large compared with the amplitude of the surface height. LaCasce and Tamarkin (1956) adapted Rayleigh's approach to include arbitrary angles for the incident sound.

Much of the theory that acoustical oceanographers use to describe scattering from a corrugated or quasi-sinusoidal surface, whether surficial or buried, derives from work originally performed to treat electromagnetic scattering from waves at the ocean's upper boundary from above (e.g. Beckmann and Spizzichino 1963), or by sound from below (e.g.

Eckart, 1953). LaCasce and several co-authors (LaCasce, 1958, 1961; LaCasce *et al.*, 1961) used the results of previous investigators, including Eckart (1953) and Brekhovskikh (1952), to address underwater sound reflection from sinusoidally corrugated surfaces. Some of LaCasce's experimental work was done for rigid corrugated surfaces in air. Brekhovskikh (1952) limited his analysis to angles of incidence greater than the normal vector to the average surface plane and the direction of the maximum surface slope. This eliminates problems of shadowing, which is difficult to treat analytically.

Several approaches have been used to assess how sound scatters from rough and corrugated surfaces. Some theories approximate rough surfaces, with statistical measures involving probability distribution and correlation length descriptions of surface heights and wavelengths. These approaches are useful in selected instances, but many seabeds, at least locally, exhibit similarities to "bosses" on a flat surface (e.g. rough rock or coral outcroppings, cobbles, pebbles, or mineral nodules). Others are better described as having wave-like corrugations (e.g. ripples and sand or mud waves).

Among many others, Biot, Twersky, Ivan Tolstoy, Alex Tolstoy, and Clay and Medwin have at times each approached the general surface-scattering problem by approximating the topography with a variety of geometric projections (bosses) placed on planar surfaces (e.g. Twersky, 1950, 1951, 1952, 1957; Biot and Tolstoy, 1957; Tolstoy and Clay, 1966; Novarini and Medwin, 1978; Medwin and Novarini, 1984; Tolstoy *et al.*, 1985). A wide variety of "boss" shapes have been modelled, including cylinders, half-cylinders, circular semi-cylinders, hemispheres, hemi-ellipsoids, spheroids, oblate and prolate hemispheroids, etc. Twersky provides a somewhat dated, but still useful, tabulation of some of the early models in an appendix to his 1957 paper. Different investigators have modelled a variety of acoustical properties for the bosses, various distributions of the bosses in space, and assorted acoustical properties for the base plane on which they are arranged. Lucas and Twersky (1990) have generalized some of this work to obtain approximations for the coherent reflected intensity and incoherent differential scattering cross sections in terms of integrals of simple functions and a general probability density descriptor. This model allows for a continuous distribution of boss sizes distributed in multiple dimensions.

In his early work, Biot (1957, 1968) treated the case of sound scattered from a rough surface by replacing the rough surface with a smooth one with a continuous distribution of monopole and dipole sources. This approximation is useful for wavelengths that are large compared with characteristic surface roughness, i.e. measures that describe the spectra of the distributions of height and length scales for a surface. Tolstoy (1982) expanded this work to begin to address scattering from ripples on the ocean floor.

Second-order perturbation theory has been shown to be useful in describing the scattering of sound from statistically rough surfaces at relatively low frequencies (Wenzel, 1974). Tolstoy *et al.* (1985) demonstrated that similar approaches also work for oblate hemispheroids on a hard surface, but not as well for hemispheres or prolate hemispheroids.

Kinney, Clay, and Sandness (1983) utilized a facet-ensemble method to model corrugated surfaces with large roughness, but moderate slopes (Kinney *et al.*, 1983; Kinney and Clay, 1984, 1985). In this approach, long, finite-width strips with differing acoustical impedances are placed side-by-side. Each pair of adjacent facets simulates a ridge and trough. In the series of papers cited immediately above, they compared their facet theory results with experiments on sea surface waves and with results obtained using Eckart's theory and direct integration of the Helmholtz integral with the Kirchhoff approximation.

Eckart's paper (1953) is recommended as a starting point for the study of scattering from rough surfaces. His work presents important results, based on an exceptional physical insight into the problem, while minimizing mathematical complexity. Muir's PhD thesis applied

Eckart's work to a variety of surfaces, describing scattering results for a wide variety of autocovariance functions. He also obtained functional dependences for high- and low-frequency limits (Muir, 1965). A review and an excellent history of acoustical scattering and reverberation, including seabed scattering, was prepared by Horton (1971). It includes citations to most of the key publications to that date, including some not discussed here (e.g. Isakovich, Uretsky, Berman, Rice, and Middleton).

Non-linearity, volume heterogeneity, and scattering within the seabed

Non-linear effects in a porous medium

Structural diversity is the rule rather than the exception in marine sediments. As a result, the mathematical models, which describe acoustical properties including sound-scattering and propagation in terms of the physical properties and geological history of a seabed, are usually complex. The earliest approaches and some current ones start from a premise that fine-grained, unconsolidated sediments can be considered as suspensions of particles in a liquid (e.g. Urick, 1948; McCann and McCann, 1969; Wood, 1944, 1964). Although these models may work in special circumstances for some sediments, even very soft, high-porosity muds often support shear wave sound propagation (e.g. Hamilton, 1972).

Beginning with a paper in 1941, the subjects of sediment consolidation and elastic wave propagation in porous, fluid-saturated sediments were addressed by M. A. Biot in a series of classic publications that covered more than two decades (Biot, 1941, 1956a, 1956b, 1962a, 1962b; Biot and Willis, 1957). Biot's theoretical development used research by Wood and Gassmann as a starting point (Wood, 1944; Gassmann, 1951). The Biot theory that describes the scattering, intromission, and propagation of sound in fluid-filled porous media involves physical relationships between 11 critical parameters. To account for certain energy losses in the medium, Stoll and Bryan (1970) modified Biot's original concepts to make two of the original parameters complex (i.e. real and imaginary), the frame shear modulus and the bulk modulus (also see Stoll, 1989). This formulation is often called the Biot–Stoll model and, with the addition of these two imaginary terms to these parameters, 13 parameters are now needed to describe a consolidated, porous seabed. These key parameters are fluid density, fluid bulk modulus, fluid viscosity, sediment grain density, the bulk modulus of the grain material, porosity, pore size, tortuosity, permeability, the frame shear modulus, and the frame bulk modulus. The last two, which describe the properties of the connected frame in a consolidated sediment, are complex (i.e. mathematically they have both real and imaginary parts). Biot's equations are documented in numerous places and will not be repeated here (e.g. Stoll and Kan, 1981; Stern *et al.*, 1985; with corrections as noted by Chotiros *et al.*, 1997; Leurer, 1997). Leurer (1997) provides a good background for the development of the Biot-based theory as well as an extension that is thought to better treat "clay-like" sediments.

For natural sandy sediments, depending on the acoustic frequency, the sensitivity with which these parameters affect the scattering and propagation of sound at and in the seabed varies. For some sediments, and some acoustical frequencies, some of the parameters appear to be coupled, i.e. they may not be completely independent. For example, pore size and porosity are clearly coupled and, in many circumstances, may be correlated with tortuosity and permeability. There is also evidence that frame shear modulus and porosity may often not be completely independent.

Neilsen *et al.* (2003) tested the frequency dependence of the relative sensitivities of the Biot–Stoll parameters. Their result was that permeability, frame shear modulus, and porosity were most sensitive; tortuosity and the imaginary part of the frame shear modulus were sensitive; and the least frequency dependence was to changes in fluid density, fluid bulk modulus, grain density, grain bulk modulus, and both parts of the frame bulk modulus. For most realistic sediments, they also concluded that the reflection loss was most sensitive to changes in permeability, frame shear modulus, porosity, tortuosity, and viscosity. It was less sensitive to fluid density, fluid bulk modulus, grain density, grain bulk modulus, and the complex frame bulk modulus.

Biot's model predicts three (non-surficial) waves in a porous, fluid-saturated sediment. One is a shear wave and two are acoustic waves: a "fast wave", resulting from a nearly in-phase motion of the fluid in the interstitial pore water, and a "slow wave". The Biot slow wave occurs when the particle motion in the pore water and the motion of the sediment frame are out of phase, or nearly so. When present, the Biot slow wave travels at about one-tenth of the speed of the compressional wave. By Snell's Law, each of these waves propagates into the sediment at a different angle from its origin. Although laboratory experiments have suggested the existence of this slow wave, experimental evidence from unconsolidated natural sediments in coastal marine environments remains the subject of considerable debate and research.

Biot's model and subsequent modifications, such as were presented by Stoll, have explained much of the observed scattering from muddy and sandy seabeds. The primary drawback to these models is the large number of physical parameters needed to describe the acoustic interactions with the ocean floor. Unfortunately, it is clear that not all of the parameters are totally independent, and that the degree of correlation is variable from site to site, and probably also over time. Even so, current models based on these models have proven useful when carefully applied (e.g. OASES and SAFARI, http://acoustics.mit.edu/faculty/henrik/oases.html; and Schmidt 1987).

Scattering into the seabed at subcritical angles

Sound can enter the materials lying under the water column–seabed interface in a number of different ways, several of which have been described previously. Simple classical theories suggest that a grazing angle of incidence exists below which no sound can penetrate into the seabed. In other words, all of the acoustical energy would be reflected into the water column in an analogy with the more familiar optical critical angle beyond which light does not pass an air–water interface. However, there is nothing like a carefully executed experiment to spoil an elegant theory. Such experiments have revealed substantial anomalous levels of sound penetration into the seabed for grazing angles below the nominal acoustical "critical angle" for sediments (Chotiros, 1989, 1995; Boyle and Chotiros, 1992; Lopes, 1996).

Because the results of subcritical grazing angle experiments are not well explained by simple transmission, refraction, and mode-conversion models, considerable attention has been given to explaining this phenomenon. Various mechanisms and theoretical models have been proposed and continue to be debated on their merits in the light of new experiments, both those in the field and those in the laboratory (e.g. Richardson *et al.*, 2001; Thorsos *et al.*, 2001).

Chotiros (1995) pointed out that the slow wave predicted by Biot's theory could explain at least a part of the anomalous sound observed in the sediment volume if values of some parameters traditionally used for the grain and frame bulk moduli were modified. Although these modified parameter values resulted in "reasonable fits" to the experimental data, the speed of the predicted slow wave was significantly higher than was predicted by other models. Alternative explanations have been proposed that involve scattering or diffraction of sound energy by roughness at the water–sediment interface (Thorsos *et al.*, 1997, 2000) and scattering of an evanescent wave propagating at the sediment–water interface by volume heterogeneity, with the result that sound propagates more deeply into the seabed. An evanescent wave is an interface, or surface wave, as described in an earlier section. The word *evanescent* comes from a word that means brief, transitory, fleeting, or tending to vanish. These waves are formed when sound energy is (internally) reflected from an interface at an angle greater than the critical angle. They tend to decay exponentially with distance from their origin unless they are transformed to other kinds of waves by scattering from heterogeneous properties or discrete physical structures within the sediment's volume (Jackson and Briggs, 1992; Moe *et al.*, 1995; Lopes, 1996; Simpson and Houston, 1997; Thorsos *et al.*, 1997). Although estimates of precise boundaries vary from investigator to investigator, there is evidence that for acoustical frequencies below ca. 5–7 kHz, subcritical insonification of sandy sediment is dominated by phenomena involving the evanescent field. Scattering by surface roughness seems to be the dominant source of subsurface sound at subcritical grazing angles for higher frequencies (Maguer *et al.*, 2000).

Much has been learned about subcritical angle sound propagation in sediments during the past decade, but many of the details require additional research.

Non-linearity, volume heterogeneity, and scattering within the seabed

Geological, physical, and biological processes

Geological, physical, and biological processes may all create heterogeneity in sediments. These processes may be the result of historical events (e.g. inclusion of rocks, cobbles, or even boulders as a by-product of terrestrial erosion, the presence of fossils, or evidence of ancient burrows or mounds). Often heterogeneity is more recent in origin (e.g. the presence of living organisms and structures resulting from their activities: shells, shell hash, or live plants or animals). Even bacteria, which are extremely abundant in marine sediments, exude mucous or extracellular polysaccharides that can "glue" together the particles in sediment at the grain-to-grain contact points (Murray and Jumars, 2002). This may locally form quasi-rigid visco-elastic structures that then have bulk physical (frame) and acoustical properties that differ from the surrounding materials. Bacterial abundance and activity are seasonal (DeFlaun and Mayer, 1983). This may also result in seasonal variations in heterogeneity in the physical properties that describe the frame in partially consolidated sediment. Some organisms produce a variety of long-chain polymers. These complex molecules may diffuse into interstitial pore waters and create local zones with different pore water viscosities, thereby locally changing the acoustic propagation. Richardson *et al.* (2001) include additional discussion of some of these biochemical and biological processes, as does Richardson *et al.* (1983). Resuspension processes can also change the properties within the sediment volume through wave action, currents, or biological activity (Wheatcroft, 1994). In many *in situ* experiments, it appears that most of the spatial and temporal variation of acoustic backscatter can only be explained by intense biological activity rather than by hydrodynamic events (e.g. Dworski and Jackson, 1994; Jackson *et al.*, 1996a; Jumars *et al.*, 1996). One should not assume that the conditions at or in the seabed are static. Similarly, sound-scattering from the seabed is to be expected to vary, temporally as well as spatially. Volume scattering from inhomogeneities within a sediment and the sound scattered from the volume below the sediment–water column interface have been addressed by Ivakin and Lysanov (1981a, 1981b), Hines (1990), and Tang (1991). In a classic paper on the subject, Jackson and Briggs (1992) addressed the relative importance of surficial roughness and volume scattering. Papers by Crowther (1983) and Jackson *et al.* (1986b) are also worthy of study.

Scattering from discrete objects on and in the seabed has not yet been addressed fully. However, Stanton's work (Stanton *et al.*, 2000; Stanton, 2000) is a notable start in the process of fully describing scattering from both inclusions in, and proud or partially buried shells on, the ocean floor. Mud inclusions have also been found in shallow coastal environments subject to terrestrial run-off and advection of silt and mud by currents (Tang and Orsi, 2000). Experimental data have been collected in a shallow fjord where the seabed consists of a fine silt sediment, revealing that low-angle acoustic backscatter can be used to observe at least some populations of benthic animals over a large area, e.g. ca. 8000 m^2 (Self *et al.*, 2001).

Bioturbation can either generate local changes in the acoustical properties of the sediment, or it can rapidly destroy such structure. Richardson *et al.* (2001) reported major changes over periods of minutes to hours as the result of diel emergence and re-entry of bentho-pelagic zooplankton and the formation of "pockmarks" by foraging nekton. For additional discussion of the effects of bioturbation on geo-acoustical properties, see Richardson and Young (1980), Richardson and Briggs (1996), Briggs and Richardson (1997), and Richardson *et al.* (2002).

Embedded gas bubbles

Gas bubbles are excellent sound scatterers, providing large impedance contrasts relative to the material around them. They also resonate at frequencies related to their size, the local pressure, and their shapes. They are almost ubiquitous in the sea, both in the water column and in the sediments. In the seabed, their abundance varies greatly from place to place and, for some bubbles, with time. Sources include macrofauna such as swimbladder-bearing fish that hide on or just under the surficial sediments, gas hydrates, natural gas seeps, and interstitial bubbles associated with biological decay processes (biogenic methane) and with photosynthesis (oxygen; Albert *et al.*, 1998; Anderson *et al.*, 1998; Berninger and Huettel, 1997; Holliday *et al.*, 2003, 2004). Carbon dioxide, hydrogen sulphide, and ethane have also been found in marine sediments. Both biological and abiological processes are involved with the formation of gas bubbles in sediments. Abiotic sources include thermogenic production by heating sedimentary rocks at depth, while bacterial action on organic material at shallow depths is the source of much of the methane found in the top few metres of marine sediments (Floodgate and Judd, 1992). Gas hydrates are common in many marine environments and have long been recognized as contributors to volume heterogeneity in marine sediments (Anderson and Hampton, 1980a, 1980b; Hampton, 1967).

Chu *et al.* (2001) used tomographic imaging in shallow-water sediments to map sound speed and attenuation in two dimensions, *in situ*, at fine scales. Their results suggest that microbubbles may add to volume heterogeneity. Such bubbles have been detected in computed tomgraphy analysis of cores from muddy seabeds. Their presence may result from natural decay processes that generate methane. They are often vertically elongated, suggesting a slow upwards migration of the gas. Evidence of the widespread presence of free gas in sediments is not only suggested by Anderson's work in the Gulf of Mexico, but also is found in over 100 documented cases found in the scientific and engineering literature (Fleischer *et al.*, 2003).

The presence of gas bubbles in sediment can directly modify physical properties that affect sound-scattering and propagation, e.g. the elastic moduli (Wheeler and Gardner, 1989). Wilkens and Richardson (1998) discuss several of these effects in attempts to understand the frequency sensitivity of acoustical scattering and propagation involving the presence of bubbles in the sediments.

Relevant models for predicting the scattering of sound from gassy sediments have been developed by Anderson and Hampton (1980a) and Boyle and Chotiros (1995a, 1995b). Voids in soft sediments are often elongate. Tang (1996), therefore, has adapted Anderson's free bubble model (Anderson, 1950) to approximate the scattering one might expect from oblate spheroids.

Scattering from benthic and epibenthic macroflora and macrofauna

Numerous papers have been presented at conferences and workshops, reporting on acoustic methods for examining and delineating the boundaries of living undersea communities and structures such as coral reefs, kelp, or seagrass beds, and even benthic algal mats (e.g. ICES Annual Science Conference 2004, Session T; Acoustic Seabed Classification Workshop, Sidney, BC, Canada 2004; Acunto *et al.*, 1999; Hermand, 2003, 2004a, 2004b). Contributions of this kind leave little doubt that benthic and epibenthic fauna and flora can be detected and mapped efficiently with acoustical sensors, often by using data from existing instruments. Although a few relevant papers can be found in the peer-reviewed literature (e.g. Sabol, *et al.*, 2002; Tegowski et al., 2003), publications discussing mathematical models that quantitatively describe the physics of sound-scattering from benthic animals and plants on, in, and above the seabed, are few and far between (Stanton *et al.*, 2000; Stanton 2000; Stanton and Chu, 2004). Most published quantitative work on sound-scattering from life on, in, and just above the seabed involves statistical analyses of spatial patterns of scattering, often without attention to absolute values of the scattered intensities. A variety of statistical approaches for describing the spatial patterns of acoustical backscattering from reefs, seagrass beds, and kelp have been documented in the grey literature. Although much of this work is based on relative rather than absolute measurements, ample ground-truth exists, largely from the simultaneous deployment of imaging optical sensors, to reveal fairly robust relationships between acoustical scattering data and known distributions of biota, based on local ground-truth.

The development of quantitative theories and mathematical models to describe the scattering of sound from such biological entities as corals, kelp fronds or holdfasts, or blades of seagrass will be determined largely by funding for future research programmes. At present, quantitative models that describe the mechanisms controlling the characteristics of sound-scattering from these entities are either incomplete or do not exist at all. This creates an unfortunate gap in our ability to predict the characteristics of acoustical scattering from coral reefs, aggregations of sponges, colonies of bryozoans, seagrass beds, kelp beds, fish covered with a blanket of sediment, oyster beds, and other live structures found in the sea. However, this situation also creates almost unlimited opportunities to propose and conduct new, ecologically important research projects.

Grain-shearing (GS) theory

In many instances, simplicity is key to a good scientific theory. Buckingham, in an attempt to simplify the rapidly increasing complexity revolving around Biot's approach, as modified by Stoll and many others, has proposed a somewhat non-traditional view of the seabed. His theory recognizes that unconsolidated, saturated sediment often consists of a fairly loose assemblage of mineral grains with seawater in the interstitial spaces. Noting that dry, consolidated, porous granular materials exhibit a linear dependence on the acoustic frequency over at least six decades, he suggests that acoustic attenuation in such a medium may be modelled as a single, dissipative loss mechanism arising at grain-to-grain contacts.

Although this assumption is arguable in a water-saturated medium, this having given rise to Biot's approach as well as that of many others, Buckingham argues that the need for a model that assigns losses to a quasi-rigid frame is not mandatory, at least in some realistic environments and sediments. By assigning all of the dissipative losses to intergranular friction in a fluid-saturated, granular, unconsolidated, two-phase medium, and invoking hysteresis (memory) as a characteristic feature of the processes of frictional dissipation at the contact points between rough particles, one can argue for the eliminating effects of pore-fluid viscosity and all of the complications that arise from attempts to describe, estimate, or measure the parameters that characterize the Biot–Stoll frame model. Because Buckingham's postulated two-phase medium has no skeletal frame, a mechanism must be developed to allow shear waves to propagate. In Buckingham (1997), arguments are made for an "effective dissipative rigidity with hysteresis" at the intergranular contacts and the needed characteristics of transverse (shear) wave propagation in the medium results.

The GS model is clearly a radical deviation from the historical approaches to sound-scattering in marine sediments, yet it is simpler while explaining most, if not all, of the characteristics that have been experimentally observed *in situ* for a wide range of marine sediments. No Biot slow wave is predicted by this theory; however, as mentioned earlier, experimental evidence for such a wave has yet to be convincingly demonstrated outside a laboratory.

Although the scientific community continues to test and evaluate Buckingham's GS model, its simplicity and ability to address a wide range of sediments and environments with far fewer parameters than are needed for other approaches make it worthwhile to consider as the debate continues. The series of key papers that describe the GS model are Buckingham (1997, 1999a, 1999b, 2000a, 2000b, 2004a, 2004b).

In addition to the GS model, there are other novel approaches to characterizing the seabed, such as the use of multiple echoes or ambient noise to classify seabeds.

We have tried to provide an extensive, if not completely comprehensive, bibliography for this section on scattering theory. It includes both papers that are observational and of historical importance, and citations for recently published literature. Increased interest in, and funding for, seabed classification and mapping have also recently resulted in a major resurgence of research efforts to levels not seen since the 1960s. Literally dozens of good scientific publications on theory and measurement methods appear in the scientific literature almost monthly. There are also numerous opportunities to educate oneself about new developments in the field during special sessions at major meetings of several professional societies.

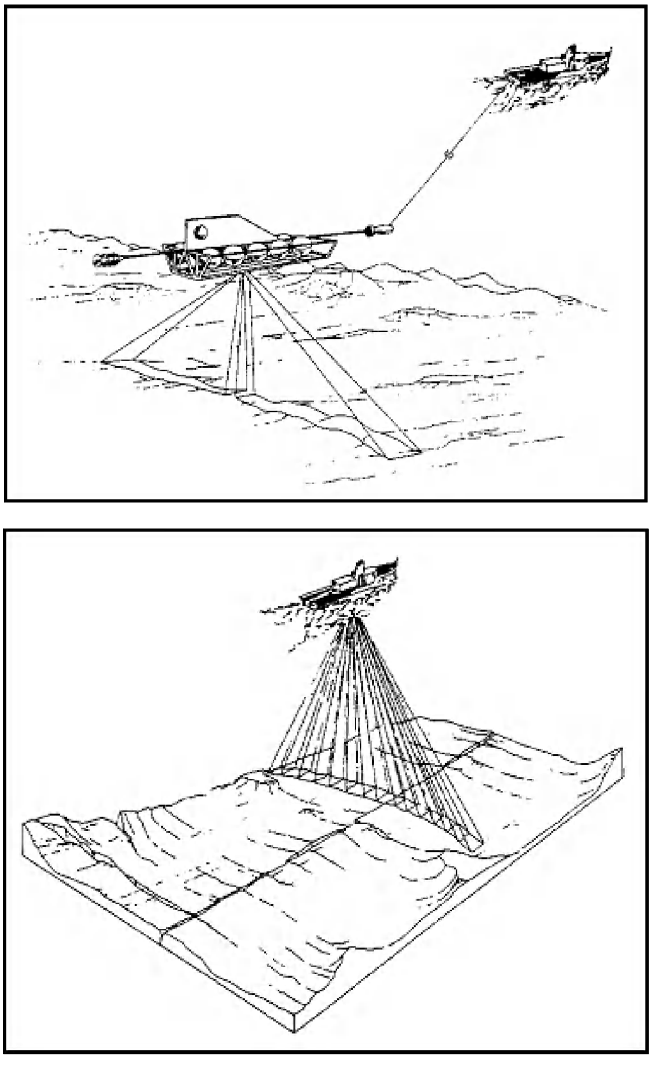
Although the average user of acoustical instrumentation for conducting surveys may not need to understand all of the issues to the depth that is possible, some will want to browse selectively through the literature cited to better understand how their efforts can – and it is to be hoped – will be used. Others, we hope, will find the field sufficiently interesting to add their own imprint on this developing field in acoustical oceanography. For those, we hope that this section on scattering theory, its references, and the papers listed in Annex 2 will serve as an entry into the field.

3 Acquiring and preparing acoustic data

Robert Kieser, Jon Preston, Andrzej Orlowski, Ross Chapman

3.1 Introduction

Seabed classification is an acoustic remote-sensing tool that allows us to "see" the seabed in "pseudo-colours" that provide information on the material and topography of the seabed. Seabed classification maps are built from acoustic data that are acquired from single-beam echosounders, sidescan sonars, or multibeam sonar systems (Figure 3.1). The echosounder can be a precision calibrated instrument (scientific echosounder) or a simpler version; both types generate analogue or digitized time-series of individual echoes. The current variety of single-beam classification methods exploits the characteristics of the available acoustic backscatter data, which can be in absolute or relative units. Sidescan and multibeam sonar systems present the seabed backscatter amplitude or intensity from a series of pings as a raster image. These data have various characteristics and may be supported by associated data such as detailed bathymetry. Specialized sonar systems and software suites are available for image-based seabed classification.



(a)

(b)

Figure 3.1. Artist's rendering of (a) sidescan sonar (SSS) and (b) multibeam sonar (MBES) operation.

This section discusses single-beam echosounders and imaging sonar systems. It describes how the acoustic data are generated, collected, and manipulated. Practical advice on installation and survey procedures is given. The requirement for sonar with stable and linear signal-processing characteristics and with adequate dynamic range is highlighted. In addition, we distinguish between uncalibrated and calibrated sonars, the former presenting backscatter values in arbitrary units, while the latter provide data in scientific or engineering units.

It is more common to classify the seabed with acoustic data acquired primarily for other purposes than to perform surveys exclusively for classification. Seabed classification can be a value-added result from fish-census or hydrographic surveys, for example. However, sonars and surveys designed for other purposes may not be optimal for acoustic classification, typically having too high a frequency or beams that are too narrow, but classification is often still possible. If classification is intended, its requirements should be considered early to anticipate the necessary compromises. Data from a fishing operation, for example, will not be as useful as data from a designed survey grid. All backscatter values are affected by sediment type, and also by range, grazing angle, and an array of other variables. For accurate classification, dependence on everything but sediment type must be removed or compensated. Methods for compensation and quality control are discussed. Finally, most classification methods do not use the backscatter values themselves but features calculated from them. Some feature algorithms are presented, while classification methods themselves are discussed in Section 5.

3.2 Power and data flows

A systems approach that includes survey design, data collection, feature extraction, statistical analysis, and verification and interpretation of results is central to the success of a seabed classification project. The block diagram in Figure 3.2 highlights major steps in the generation, acquisition, and preparation of acoustic data. The same steps are involved for any acoustic system, be it an echosounder, a sidescan sonar, or a multibeam hydrographic system. An acoustic pulse is transmitted towards the seabed as a vertical beam or a thin fan (Step 1). The pulse travels through the water column (Step 2), is scattered from the seabed (Step 3), travels on the reverse route (Step 4, we consider only backscatter), and is received by the transducer and sonar system (Step 5). Data processing (Step 6) includes amplification, filtering, compensation for effects that are not related to the seabed (e.g. time-variable gain, TVG), and feature extraction (numeric description of the corrected seabed echo). This section focuses on technical aspects while underlying physical and measurement principles are described in other sections and the literature. Important references include Urick (1975), Clay and Medwin (1977), MacLennan and Simmonds (1991), Medwin and Clay (1998), and Lurton (2002).

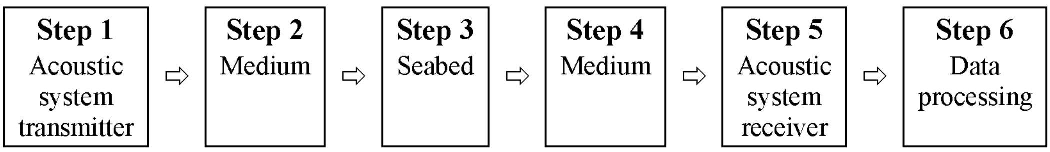


Figure 3.2. The major steps in data collection for acoustic seabed classification.

Step 1: Acoustic system transmitter

The sonar transmitter and transducer generate a pressure wave that propagates radially through the water. Its directional intensity is described by a beam pattern (Figure 3.3). A single downwards-looking transducer is used with a single-beam echosounder (SBES). A pair of sidewards-looking transducers produces beams that are narrow fore–aft and broad across-track in a sidescan sonar (SSS, Figure 3.1a), and a downwards-looking transducer array is used in the multibeam sonar (MBES, Figure 3.1b). The transmit-and-receive operation generally uses the same transducer, except in MBES, which typically use a Mill's Cross arrangement with the beamforming on receive. All these systems measure backscatter from normal and/or oblique beam incidence on the sea floor.

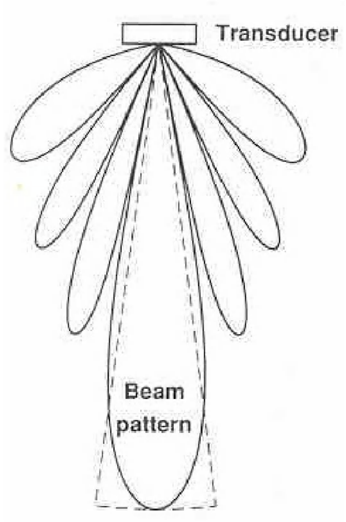


Figure 3.3. The beam pattern gives the directional intensity of the radial pressure wave that is generated by the transducer. Most of the energy is directed into the central lobe. From MacLennan and Simmonds (1991; p. 15).

Transducers or arrays may be installed on the hull of a vessel or may be in a towfish or an autonomous underwater vehicle (AUV). Use of a single frequency between 20 kHz and 400 kHz or more is common, but data at several frequencies are often acquired. Some chirp systems provide data that are suitable for acoustic seabed classification. True broadband sonar systems have been developed but are not used today for acoustic classification. A review of current and emerging acoustic seabed classification systems is given in Section 7.

Step 2: Medium

The medium for sound propagation may be fresh or salt water, and it may be homogeneous or inhomogeneous. A homogeneous medium is characterized by constant sound speed and absorption, and sound propagation is described by straight ray paths. Sound speed and absorption depend on temperature, salinity, and pressure. In the ocean, these parameters can depend strongly on depth but less on location, resulting in a horizontal layering of sound speed and hence an inhomogeneous medium. In coastal waters, it is often true that water temperatures decrease with depth. If so, applying Snell's Law shows that sound rays directed generally downwards are refracted towards the vertical. In practice, refraction effects are negligible for echosounding when the beam direction is near vertical, but may be significant for imaging sonars where at least a portion of the beams is launched at substantial angles from the vertical. Thus, temperature and salinity profiles and sound propagation characteristics can be important, especially for MBES and SSS observations.

Media properties are also important for sound generation and reception, which may be adversely impacted by transducer motion (pitch, roll, yaw, and heave), transducer aeration, and high transmit power. The first two depend on sea state, wind velocity, and vessel speed and course, with respect to wind and wave directions. It is difficult to judge, let alone measure, the degree of data degradation that occurs, but it is useful to establish reference values for sea state and operating conditions in which good echoes can be recorded. Measurements of platform motion (pitch, roll, yaw, and heave) are useful and provide opportunities to correct for these effects. Measurements of this type are frequently made for hydrographic MBES surveys, but seldom during SSS and SBES observations. In all cases, it is important to carefully observe the echogram and watch for image degradations that include sinusoidal changes in bottom depth or missing echo returns. However, data quality may be seriously compromised well before adverse effects are visible. These issues are dealt with in more detail in Section 4.

Good coupling of the transducer face to the medium is essential to the formation of a strong and stable pressure wave and for reception. The near-surface bubble layer that increases with wind and wave action may reach the transducer face and may lead to signal reduction or complete blanking of the transmitted pulse and echoes. Turbulence created by the hull or transducer mounting has a similar effect. Good hull design and transducer mounting are essential to minimize these effects. Adverse effects from unwanted transducer motion and aeration have been recognized in fishery acoustics, where accurate measurements of the echo energy (echo integration) are required to estimate fish density and hence biomass (MacLennan and Simmonds, 1991). Effects of transducer motion on echo integration have been described and modelled by Stanton (1982) and others. Putting the sonar on a towfish can greatly reduce these problems, particularly with systems like a two-part tow, but it can introduce other practical problems, such as establishing the attitude and position of the sonar. Alternatively, transducers can be mounted on a centre board that is lowered below the keel of the vessel to minimize aeration. Measurements of the backscatter intensity from a layer near the transducer face have shown the effectiveness of this approach (Ona and Traynor, 1990). Similar approaches are useful for the acquisition of seabed classification data.

High transmit power may lead to cavitation (Clay and Medwin, 1977). Cavitation occurs when large amplitude vibration at the transducer face and in the near field leads to the expansion of microbubbles and medium ruptures, and hence to attenuation and possible blanking of the beam. The pressure thresholds for cavitation increase with transducer depth and frequency, and decrease with pulse repetition rate and pulse length, and with the presence of microbubbles and silt load in the water. The same is true for power threshold (power to the transducer), except that the power threshold for the onset of cavitation decreases with frequency when beam width is constant. For low-power commercial seabed classification systems, cavitation and its deleterious effects are generally negligible. However, cavitation has been observed in riverine acoustic work with a 200 kHz, 30° transducer at 100 W transmit power and a source level of 206 dB re 1 µPa@1 m (Yunbo Xie, pers. comm.), indicating that care is required, especially at higher frequencies and wide beam angles. In addition, distortions of the beam pattern have been observed at 200 kHz and higher frequencies, even at moderate power, in seawater (Tichy *et al.*, 2003).

Step 3: Seabed

This step deals with the scattering of the incident wave from the seabed. Most of the scattered energy will be from the area covered by the main lobe of the beam. Given a level substrate and normal incidence of the acoustic beam, backscatter amplitude and character change with substrate type. However, backscatter also changes substantially with surface roughness, slope (beam incident angle), and beam footprint. In addition, acoustic system parameters, such as frequency, beam width, and pulse duration, affect backscatter.

Acoustic seabed classification involves comparisons among echoes from regions of the survey area. It is, therefore, essential that acoustic systems parameters remain fixed, particularly transmit power and pulse duration. Minimal transducer roll, pitch, and aeration are important. Under these conditions the acoustic data reflect the combined effects of seabed properties, such as material type, grain size, surface roughness, and slope as well as depth. However, this may be compounded with backscatter from the surface and benthic vegetation and organisms, and subsurface inhomogeneities such as buried pebbles or gas bubbles.

Backscatter theory is discussed in Section 2. Even for simple, flat, homogeneous seabeds, a large number of model parameters are needed to describe the acoustic properties of the substrate and echo formation. The complexity increases with oblique rather than perpendicular (nadir) incident angles and with grain size inhomogeneity, layers, mixtures, and relief gradients. In contrast, only a small number of independent parameters can be measured from the backscatter signal. Except in specialized cases, seabed classification is an underdetermined inverse problem, with fewer measured parameters than unknowns. It is for this reason that the emphasis is on segmentation into regions that are acoustically similar, rather than direct estimation of geo-acoustic variables.

Step 4: Medium

All sonar systems considered here are monostatic, that is, they measure only backscatter. The same transducer is used for transmit and receive or, if separate, they are next to each other. The return path of the echo duplicates the path of the transmit pulse through the water column. Media effects are discussed above.

Step 5: Acoustic system receiver

The receiving transducer converts the returning pressure wave into an electrical signal that is amplified and filtered by the receiver to generate convenient signal levels and to eliminate out-of-band noise. The most important properties of the transducer–receiver combination are stability, gain, linearity, and dynamic range. These terms are used here in the same sense as with an ordinary amplifier. Gain is the ratio of output-to-input voltage; linearity requires that the output is proportional to the input; and dynamic range is defined by the minimum and maximum input levels between which amplification is linear. The dynamic range must include the entire variation in possible echo amplitudes from all seabed types at a given depth as well as TVG that compensates for beam spreading and absorption. An exceptional dynamic range, such as 160 dB (Simrad, 1993), is required if echoes from a large depth interval (e.g. 5–500 m) are to be recorded with the same receiver gain settings. Insufficient dynamic range leads to saturation, also called clipping, a severe distortion that flattens echo peaks that exceed a certain level.

The purpose of TVG is to maintain a constant sensitivity for the observation of a given target at any range. For a circular piston transducer with beam width θ, and a relatively flat, smooth, and horizontal seabed, the transmit pulse will insonify a circular area or pulse footprint. Relatively uniform insonification of the seabed occurs when the pulse footprint is smaller than the beam footprint. This is the case when:

$$\frac{c\tau}{2} > r\left(1-\cos\frac{\theta}{2}\right).$$

Where c, τ and R give sound speed, pulse duration and range, respectively. The size of the pulse footprint is given by the area covered within a pulse length near the beam axis. As the range increases, the beam footprint will exceed the pulse footprint, insonification of the seabed will start from the acoustic axis, then travel outward as an annulus towards the beam boundary. Assuming uniform scattering from the seabed, the TVG will change from 20 to 30 $\log R + 2\alpha R$ as the pulse footprint changes from greater to smaller than the beam footprint. Here α is the absorption coefficient for seawater. Thus, if range is the only variable, the TVG will change from 20 to 30 $\log R$ as range increases.

This simple model can only provide a guide as backscatter cross section changes with incident angle and as seabeds are seldom flat, horizontal surface scatters. In addition, the seabed echo is dominated by volume backscatter at sonar frequencies below about 10 kHz and by surface backscatter above about 100 kHz. A similar trend exists when changing from soft to hard seabeds. In most practical cases, equation 20 $\log R + 2\alpha R$ provides a good approximation. In exceptional cases of short pulse length, long range, and smooth bottom, 30 $\log R + 2\alpha R$ is used; 40 $\log R + 2\alpha R$ is never appropriate for seabed backscatter. A detailed and insightful discussion of the subject is given by Lurton (2002).

Finally, it is important to realize that, in seabed classification, TVG is only part of a series of corrections that are required to preserve the echo characteristics (features) that are used for classification. TVG requirements differ from those accepted in fishery acoustics and are partially determined from practical experience. However, independent of any particular choice, it is most important that parameters are recorded and that TVG is applied accurately to avoid receiver saturation and allow for correction in post-processing.

Platform noise (Mitson, 1995) is a major concern in fishery acoustics, where it may affect fish behaviour and mask fish detection. It is less important for seabed classification, because the seabed does not swim away and echo levels tend to be higher. A common oversight is to operate another sonar system of a similar frequency, such as the ship's navigation echosounder, while acquiring data for classification. Echoes from the extraneous system can "walk over" some of the recorded echoes, or appear as a regular pattern on sonar images. Either source of noise can be very deleterious to getting good seabed classes.

Scattering from fish or plankton, silt, bubbles, or other structures in the water column all contribute to reverberation. Dense fish or plankton aggregations may lead to high reverberation levels that, in extreme cases, can reduce or block the seabed echo and lead to secondary echoes that may interfere with the primary echo. Fortunately, these situations are easily recognized on the echogram and are infrequent in most areas.

Step 6: Data processing

The first five blocks have produced an analogue or digital representation of the echo as seen on the display of the sonar receiver. They describe all types of active sonars that record backscatter, including single-beam echosounders and imaging sonars. Three more steps are required to prepare the data for acoustic classification. Echoes of low quality must be set aside because they are often very different from true bottom echoes. Compensation for effects that are not related to sediments is essential; otherwise, the classes would be influenced by depth, slope, or changes in transmit power, for example. Finally, classification usually uses features that provide a numerical description of the echo shape, frequency content, and other characteristics, rather than with the actual echo data. Between single-beam echosounders and imaging sonars these three steps do differ, so they are presented in more detail in separate below.

3.3 Single-beam echosounder (SBES)

The block diagram for a single-beam echosounder is shown in Figure 3.4. The transmitter and transducer generate the transmit pulse (Figure 3.4a); the same transducer then receives the echo, which includes signal (backscatter information) and noise (Figure 3.4b). A transmit/receive switch provides appropriate connections during the transmit/receive cycle (ping). The received echo is filtered. Its upper frequency sets the sample rate required by the A/D converter, which transforms the analogue signal to a digital signal or data stream (Figure 3.4c). A detector and low-pass digital filter follow to remove the carrier and higher frequency components, including the out-of-band portion of the remaining noise; a smooth echo envelope results (Figure 3.4d). Finally, decimation may be used to reduce the data rate, often in a process that includes digital filtering. The resulting digital signal may be stored on disk and displayed as an echogram, serving as the raw material for sediment classification (Preston *et al.*, 2000).

Transmitter and receiver characteristics must be stable over time, and environmental conditions, such as temperature, moisture, and vibration to record backscatter information with the precision and accuracy that is required for successful seabed classification. Time here spans milliseconds to years; examples are accurate range measurement (1 ms corresponds to approximately 75 cm) and possible ageing of transducers and other components, which may require years.

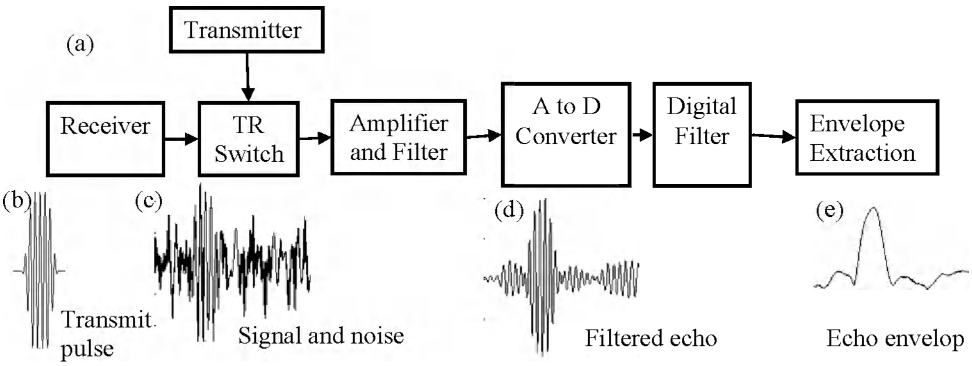


Figure 3.4. Diagram of single-beam echosounder with A/D conversion and envelope extraction in the digital domain. The lower row shows (a) transmit pulse, (b) echo received by the transducer including backscatter from a point target and broadband noise, (c) filtered echo with carrier, and (d) echo envelope obtained by removing the carrier and low-pass filtering. Pulse amplitudes are not to scale. TR Switch = transmit/receive switch; A/D Converter = analogue to digital converter.

Many present-day systems record echo data digitally. Voltages from the transducer have to be filtered before sampling and A/D conversion. Filtering has two aims: to limit bandwidth to prevent aliasing in sampling and to suppress noise that is outside the echo bandwidth. Aliasing occurs if the sample rate is less than twice the highest frequency in the analogue signal. This minimum sample rate is called the Nyquist rate (Lyons, 1997). The frequencies in an echo are centred on the sonar frequency, which in radio terms is the carrier and has a bandwidth that is roughly equal to the reciprocal of the duration of the transmit pulse. Two representations of echoes can be recorded digitally: full-waveform and echoenvelope data (Figure 3.4c and d). These waveforms include and exclude the carrier, respectively. Full-waveform data are received at the transducer and must be low-pass filtered before A/D conversion. Frequencies above carrier plus the reciprocal of the pulse duration are suppressed and sample rate is twice this frequency, at least. The envelope representation is available from full-waveform data using the Hilbert transform (Haykin, 1994). More common is making analogue envelopes by analogue demodulation, although an echo is not just a modulated carrier. After demodulation, the low-pass filter should suppress frequencies above the inverse of the pulse duration, and the theoretical sample rate need only be twice this value, much lower than that required for the full waveform.

The echosounder applies filters (Figure 3.4) to reduce noise and avoid aliasing. The waveforms in Figures 3.4b and 3.4c demonstrate a substantial noise reduction. Noise is reduced by removing the portion of the frequency spectrum that is outside the frequencies that are required to capture the details of the echo envelope. As explained above, the sample rate must be at least twice the highest frequency that remains in the echo. In practice, sampling rates much higher than two are in wide use.

Suppressing noise sources often requires a lot of attention. Vessel and ambient noise may be dominant at low frequencies, while internally generated or receiver noise appears at higher frequencies and at longer ranges, where TVG is large. Transducer cabling and electrical interference from other instruments are a more frequent concern that may appear in a new or changed installation or when a portable mobile system is moved to a different vessel. Noise from various sources may be apparent on the echogram, especially when display sensitivity is increased and when in areas of the water column that are free of scatterers are selected. Tests with a disabled transmitter are also useful.

3.3.1 Typical echoes and digital sample rate requirements

Figure 3.5 shows a typical echo envelope from a point target (a target that is small compared with the transmit pulse length). Transmit pulse length is 1 ms or approximately 75 cm. The sample rate is 7.5 kHz or 7.5 points per transmit pulse length, satisfying the Nyquist criterion with a comfortable margin. A sufficient number of data points are used to describe the smooth pulse shape. Little would be gained by using a higher sample rate because the natural bandwidth of the envelope is being sampled fully. Minimum sample rates of four samples per transmit pulse length (twice Nyquist) are now used in scientific echosounders. Echoes recorded with this, or a higher sample rate, are suitable for seabed classification. It is important to note that sample rates used for signal processing in the echosounder may be higher than those used for data output and storage.

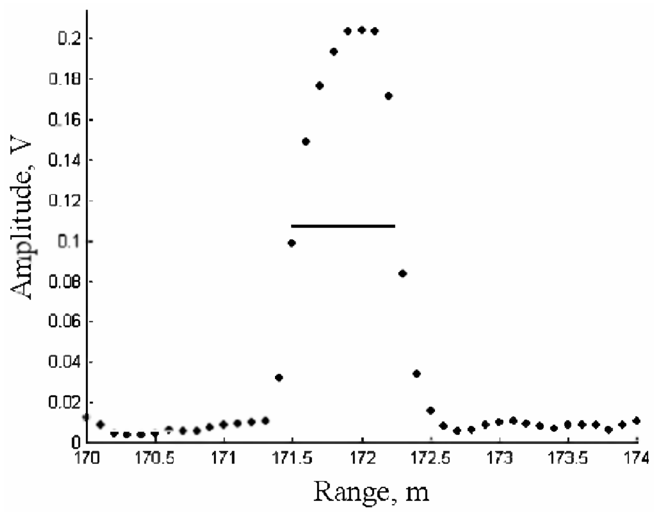


Figure 3.5. Echo from a small midwater target recorded with a digital echosounder. The horizontal line shows the echo duration at half amplitude, which is about 1.0 ms or 0.75 m.

A typical seabed echo (Figure 3.6) is much longer than a single target echo (Figure 3.5). The steep initial rise begins when the leading edge of the transmit pulse has reached the seabed and has returned to the transducer. Factors that contribute to the extent of the echo are discussed below.

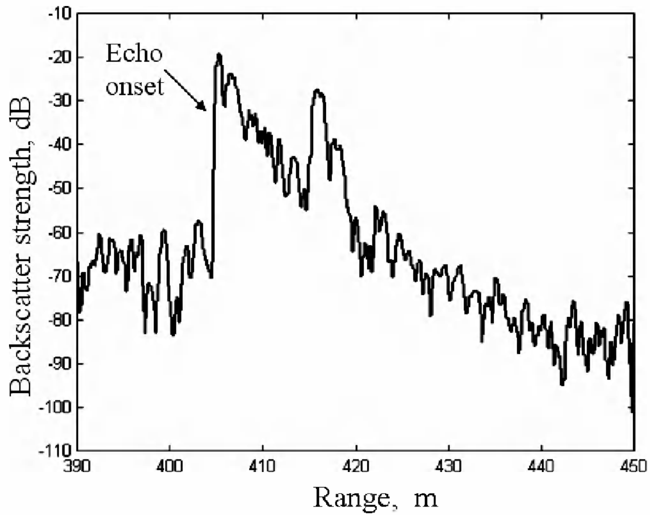


Figure 3.6. Representative seabed echo from a calibrated echosounder. The water depth is the range to echo onset; after that, echo duration depends on beam width, seabed slope and roughness, and penetration into the sediment.

3.4 Sonar verification and calibration

3.4.1 Verification

Initial verification of a sophisticated sonar system is an important and often extended process that will consider its design, construction, and use. It requires the attention of specialists and users to assure proper functioning of the hardware and software under a wide range of conditions. Collaboration is essential to standardize measurement procedures, assure appropriate use, and take corrective action as needed. Initial verification is a communal effort that ideally results in an instrument that can be deployed with confidence by technical and non-technical users. Instruments that have experienced a reasonable level of detailed communal verification are much more desirable than those that have not, because many critical properties cannot be verified on an individual basis.

Routine verification is a different matter. It is generally performed within a limited time and with limited effort. For an echosounder, it may include the following:

- Check physical condition, e.g. physical damage, transducer fouling
- Check cables and connections
- Check hardware and software settings
- Use test procedures, e.g. internal oscillator
- Check for noise by operating sonar in passive mode (transmitter off)
- Collect echogram in an area with a known seabed
- Review a small dataset

This list may serve as a guide, with its length and detail depending on factors such as operating conditions, time interval between operation, and severity of consequences of failure.

Total failure of a component such as the transmitter is easily detected if appropriate precautions are in place; however, intermittent problems or subtle changes and drift in gain may escape even careful verification and observation during operations. Problems of this sort can degrade the final map of acoustic classes. They can be difficult to diagnose if they are sporadic; examples are drift in transmit power or receiver gain or occasional noise that saturates an amplifier.

3.4.2 Calibration

A calibrated sonar provides an absolute measurement of the backscatter cross section of a target. This is expressed in scientific or engineering units, and may be given in decibel (dB) relative to an agreed standard. Most seabed classification procedures only use relative rather than absolute backscatter information and thus may use data from uncalibrated sonars. However, absolute backscatter provides a direct measure of the mismatch in acoustic impedance at a reflecting boundary, which is the basis of all seismic surveys and an important method of sediment classification. To calculate sediment impedance, the angle of incidence and the footprint size must be known. A practical reason for the use of calibrated sonar is to monitor the short- and long-term stability of the sonar and its associated measurement process. Changes in transmit level, transducer characteristics, and receiver gain are difficult to detect without calibration. Only when detected, remedial action can be taken. A calibrated sonar assures that sonar parameters remain stable, surveys can be repeated, data from different surveys (and possibly different instruments) can be combined, and echograms and other visual displays look familiar.

Echosounders for quantitative fisheries work are routinely calibrated by suspending a calibration sphere with the known backscatter cross section below the transducer. The split-beam function of these echosounders is used to position the sphere in the centre of the beam before calibration measurements are made. The calibration process and the choice of optimal calibration spheres are described in detail by Foote *et al.* (1987). Calibrations are accurate to better than 0.2 dB. In addition, *in situ* beam pattern maps may be prepared to monitor their stability (Simrad, 1993).

Hydrographic and general-purpose echosounders that are used to collect seabed classification data normally do not have a split-beam function. On-axis calibration is still possible, but more time will be required to locate the target on the beam axis by finding the alignment for maximum backscatter. Other methods are available, but require the use of hydrophones and an underwater calibration facility. Typically, a TVG of $40 \log R + 2\alpha R$ is used for calibration measures. However other TVG functions (20 or 30 $\log R$) can be used and, given an appropriate model, existing calibration results can be converted after the fact.

3.5 Quality control and compensation of SBES echoes

3.5.1 Quality control

Usually some echoes in each dataset are flawed. Possible causes include extreme vessel roll and pitch, sound absorption by bubbles or fish, saturation of the receiver amplifier, and incorrect choice of depth for the seabed echo. The best remedy is to review the echoes on screen carefully and to filter, that is set aside, the degraded echoes. To decide which echoes or groups of echoes to filter, one can examine both the echoes themselves and their bottom picks. The echo amplitude expressed in dB can be displayed in pseudo-colour on a depth vs. ping number plot (echogram) or as a collection of amplitude vs. time or depth plots. Echo quality issues can be seen in displays like these. Interference from other echosounders, for example, may appear in the echogram as bright regions at regular but unsynchronized depths. Clipping can be diagnosed if the maximum possible digital value is often achieved or appears in a series of consecutive samples, or if some lesser digital value is frequent but never surpassed, which suggests clipping before the final amplifier. Rapidly changing bottom pick values can indicate excessive slope, while inconsistency in the bottom picks in a neighbourhood suggests canyon walls or extremely steep and varying bottom. Poor echo quality leads to information loss and hence poor signal-to-noise ratio. Certainly the best way to avoid this loss and labour is with vigilance and good quality control during the survey.

3.5.2 Compensation

The amplitude and shape of an echo depend not only on the sediment in various ways, but also on water depth, characteristics of the water column, and bottom slope. For quality sediment classification, non-sediment effects have to be removed or compensated whenever possible.

Compensating for depth effects is challenging. Echo shape depends on depth because the time it takes for the leading edge of the pulse to spread from first contact with the bottom out to the edge of the beam is proportional to depth. For this reason, shape characteristics, such as rise time and decay time, increase with depth. To compensate, one resamples the digital echo time-series so that the echo has the length it would have had if it had come from some selected reference depth (Pouliquen, 2004). In shallow water, less than 20 m or so, major contributions to echo duration are not dominated by the spreading time of the beam front on the seabed, so calculating the resampling rate is more complicated (Preston, 2003). Without compensation by resampling, acoustic classes are heavily influenced by depth (Lubniewski and Pouliquen, 2004), so compensation is mandatory. However, confidence that depth artefacts have been adequately suppressed is elusive because sediments often do change with depth.

The relationship between amplitude and depth is removed to first order by TVG in the echosounder. Identifying the TVG function that should be used can be challenging, as discussed above. High-end echosounders often provide well-defined and stable TVG; this may not be the case in more general echosounders. TVG profiles are often imprecise and, for example, may ignore absorption, although it can be very significant at higher frequencies. TVG corrections require knowledge of both the desired and accurate TVG function and the TVG function that was used during data recording.

Significant bottom slope has marked effects on echo amplitude and shape. Echoes from normal incidence can be rich in sediment information because the backscatter amplitude depends on near-nadir angles differently for different sediments. Away from nadir this is not true: amplitudes differ among sediments, but all dependencies on angle are similar. There are two situations: either there is a normal incidence reflection within the beam width or the slope is so steep that there is not. The largest backscatter amplitudes, by far, are at normal incidence. Thus, within the range of slopes small enough that there is a normal incidence reflection, the amplitudes do not vary much, and the echo shape remains rich in sediment information. With steeper slopes, amplitudes are much reduced, and echo shape loses its information content. Sediments in areas with slopes more than about a half beam width cannot be classified acoustically in the same manner as flatter regions (von Szalay and McConnaughey, 2002). It is often possible to separate them into a “slope” class, which may be adequate if it is known that only particular sediments, bedrock perhaps, are stable with these slopes. These observations apply also to ship roll and, less commonly, pitch.

Another characteristic of echoes is ping-to-ping variability; some averaging is often carried out before classification. Echo averaging is called stacking by some, from the days when one just added amplitudes and did not waste computer time dividing by the number stacked. With high-frequency backscatter, ping-to-ping variability can be very high, and it has been found that stacking can give more representative and useful echo time-series. One cannot guarantee that all the pings in a stack are from the same depth, so it is important to align the depth picks in the stacking process.

3.6 Features from SBES data

Now that we have good-quality, artefact-free SBES echoes, how do we classify seabed sediments? As discussed above, if we have calibrated backscatter cross sections, we can calculate acoustic impedance changes at each boundary from the nadir reflection amplitudes. It is not possible, in general, to calculate individual sediment geo-acoustic variables, such as grain size, from the echoes themselves (acoustic impedance is the product of sound velocity and density). If only homogeneous sediments have been surveyed, inversion is possible by using a backscatter model to generate a library of echo envelopes, followed by finding the best match between observed echoes and an entry in the library (Sternlicht and de Moustier, 2003b). In general, though, and as discussed elsewhere in this report, a phenomenological and statistical approach is the only practical route, and can be used with both calibrated and uncalibrated, but consistent, data. High-quality phenomenological classes are derived from features, not from the echo amplitudes themselves.

Amplitude features are readily available. Peak amplitude is easily found. Averages of a few values near the peak can show less ping-to-ping variability than the peak value by itself, thus averages may be better indicators of sediment type. Integrated amplitudes or power have been found to be useful for classification. Integrated power of direct and multipath echoes was the methodology of one of the first papers in acoustic seabed classification (Orlowski, 1984). This approach is still available today as RoxAnn and EchoPlus (Dyer *et al.*, 1997). The sample numbers at which the integral starts and ends can be defined by some fraction of the peak amplitude; another approach is to start at the peak itself. The integral of the second echo, after a surface reflection and second bottom reflection, is also useful, but acquiring it demands more from the data acquisition system and may require a slower sonar ping rate to allow enough time for the second bottom echo, which appears at about twice the depth. Whether integrating one or two echoes per ping, there can be irregularities if the amplitude occasionally dips briefly below the threshold value at which integration stops.

Normally the bottom echo will rise from a background or baseline that is much lower than the echo peak. However, noise from reverberation or other sources may lead to a high baseline that should be subtracted before picking maxima or integrating. Usually, the baseline before the echo starts is subtracted, because reverberation can continue long after the echo peak.

The number of shape features is limited only by one's imagination. One starts with the echo time-series as a sequence of digital samples, and the sample number that corresponds to the bottom pick. The aim is to capture descriptions of the echo shape and spectral character as numerical values. Simple characteristics, such as rise time, can be the number of samples between the start and the peak or the bottom pick and the peak, with similar expressions for decay time and echo duration. Ping-to-ping variability and noise, even after stacking, can cause problems with deciding when the echo starts and stops. Practical features measure the time-period (as a number of samples) between some small fraction of the peak, 5% say, and the peak itself, or the length at 50% of peak. Features that depend on arbitrary numbers, such as 5%, are less desirable, but do have practical value.

Perhaps a better approach to finding shape features in the presence of variability and noise is with cumulative sums, quantiles, and histograms. These statistics can be obtained from a window of a predefined number of samples. The sample numbers, at which the cumulative sum reaches various fractions of its maximum, capture the rise time in a manner less susceptible to noise and variability. With the amplitude values binned to make a histogram, the relative numbers of samples in each bin express echo duration and decay rate with respect to the length of the sample window. Many other variations are possible. In general, echo amplitudes do not affect shape features like these, which are derived from the number of samples.

A second group of features captures the spectral character of the echoes. For a single-frequency sonar the spectrum considered here is related to the receiver bandwidth which generally is similar to the bandwidth required by the transmit pulse. Variability in the echo tail depends largely on sediment roughness, so features that capture spectral content in this variability can be useful for discrimination. Many transforms provide numerical estimates of spectra. The fast Fourier transform (FFT) is familiar. The FFT of the echo amplitudes is a spectrum of amplitudes, while the power spectrum, the FFT of the autocorrelation of the amplitudes, expresses echo power in frequency bands. Wavelet transforms can give complementary spectra if the elementary wavelet is chosen carefully (Tegowski and Lubniewski, 2002). These methods usually operate on normalized echo time-series (with the maximum scaled to one) so that these features are independent of echo amplitude. Some commercially available classification processes use many amplitude and shape features (Hamilton *et al.*, 1999).

3.7 Imaging sonar systems (SSS and MBES)

The remainder of this section deals with imaging sonars, not echosounders. The acoustic principles and block diagrams are the same, but there are differences in implementation, particularly in beamforming. Conceptually, sidescan sonars (SSS) are little more than two echosounders in the same housing, facing in different directions, and with different beam patterns. Their transducers are long fore–aft and short vertically, so their beam patterns are tight fore–aft and broad vertically, and they are positioned to transmit to port and starboard (two transducers) rather than vertically. Because of the large vertical beam width, SSS echoes last longer than echosounder echoes and are presented as a raster image rather than as echograms or waveforms. SSS TVGs are often more complicated than echosounder TVGs, with more user controls, because both range and angle of incidence affects backscatter amplitudes.

As a rule, MBES transmit similarly to the SSS. The SSS use the same transducer for transmit and receive, but MBES receive on transducer arrays. Beamforming is the process of adding signals received at array elements after shifting their phases to obtain a fan of individual beams. Individual beams may be as narrow as 1° in the port–starboard plane, while their fore–aft beam pattern is determined by the transmitter and may be almost the same size. Each beam records backscatter as the transmit pulse sweeps across the seabed. The transducer-to-bottom range is obtained from the echo in each beam through phase comparison and other algorithms that pick the middle of the echo or the moment when the echo is centred in the beam footprint. Knowing range and depression angle (that is, beam angle), the depth from each beam is available from trigonometry. Acquiring these depths is often the primary purpose of an MBES survey. Depths are also valuable to compensate the image that is used for classification. In principle, two types of images are available from MBES. The mean intensity from the within-beam bottom echoes can be stitched together, carefully keeping track of initial and final ranges in each beam. This is called a beamformed image. The alternative is to add together the echoes as received on the port and starboard sides of the receive array, without the beamforming phase shifts, which makes the arrays mimic sidescan receiving transducers. These non-beamformed images have many characteristics of sidescan images with coarser resolution. Two advantages of beamformed images are the rejection of multipath interference and a parent–child relationship between image pixels and beams, which is useful for quality control.

3.8 Verification and calibration of imaging sonar systems

Verification procedures for single-beam and sidescan sonars are similar. Good cables, no physical damage, on-deck performance checks, etc. are basic to any sonar. When collecting data for acoustic classification, consistency is important. In many cases, there are few user choices in echosounders, sometimes just range-setting, so consistent operation is not hard to achieve. SSS tends to have many more adjustments, trim TVG for example. If these user-controlled settings affect the recorded image data and are not themselves recorded, artefacts may be introduced into the acoustic classes. To take a specific example, image amplitudes in Klein datafiles are not affected by user settings, which are stored in the file and applied during on-screen playback, while data from other SSS, as recorded in XTF format, are usually affected by user-applied gains that regrettably are not recorded automatically.

Hydrographers often speak of calibrating MBES, meaning establishing that the depths it measures meet standards for accuracy and precision. Acoustic seabed classification focuses on backscatter amplitudes, not on very precise depths, so here we reserve the word calibration for processing amplitude data. The process that is called calibration by hydrographers is here called MBES verification; this is a specialized and well-established procedure. One can be reasonably confident that an MBES that has been verified in this manner will give consistent images that meet common-sense checks. However, independent of sonar type, an active user who frequently changes transmit power, receiver gain, and other settings will probably make images that are useless for classification.

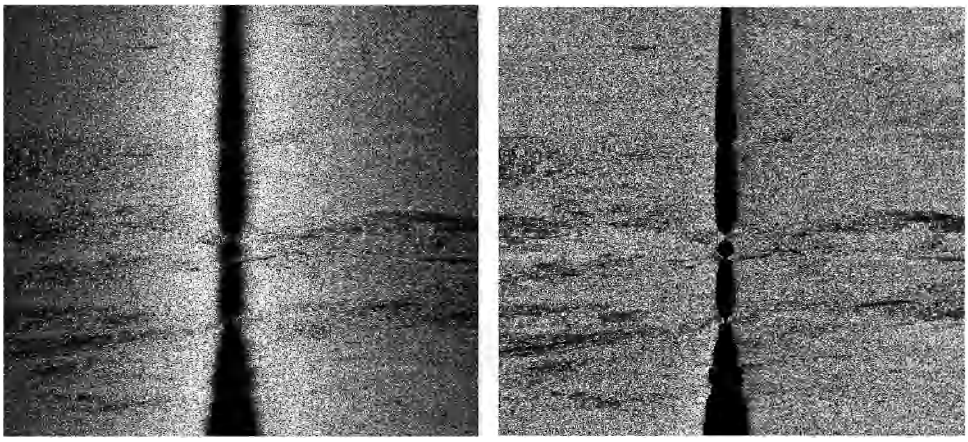
In the context of this report, calibration is the process by which the backscatter amplitudes are made available in engineering units. At present, calibration of a MBES is difficult, but methods are being developed and may become practical in the future (Cochrane *et al.*, 2003; Foote *et al.*, 2005). With SSS as well, the calibration challenge is much larger than with echosounders because of transducer mounting and geometry, non-reproducible gain and TVG, and other issues. In addition, calibration may be less useful because backscatter cross sections and footprint areas vary markedly with angle of incidence on the seabed.

3.9 Image compensation

Seabed images generated by a sidescan or multibeam sonar depict seabed objects and the sediment, but are affected by source level and receiver gains, pulse length, transmit and receive beam patterns, attenuation, seabed grazing angles, and ship (or towfish) motion. Because classification is a search for differences, changes in these non-sediment variables can put artefacts into the classification maps. Compensation is the process of returning the image to what it would have been if the variable in question had remained constant. Compensating for source level and receiver gains, for example, is a simple multiplication of the echo amplitudes and is easily accomplished if the gain changes are known. However, none of the other variables have linear effects. MBES and SSS calibration would remove these effects, but are not accepted procedures at this time. An empirical compensation method for the combined effects of beam patterns, attenuation, and grazing angle is described in Preston *et al.* (2004b) and summarized below. It is effective at suppressing most artefacts but does not compensate for all the consequences of these variables. Compensation for changes to pulse length and for excessive wave-driven transducer motion is challenging and is not discussed here.

Among sonar manufacturers, Simrad, for example, uses a two-part TVG to compensate for beam depression angle and range (Pouliquen, 2004). Depression angle is only an approximation of the grazing angle, however, and absorption is not fully considered. In short, there are a variety of effects that, if not controlled by further compensation, can cause artefacts in sediment classes. These usually appear as class borders parallel with the ship track. Controlling them is perhaps the biggest challenge in developing a sonar-image classification system. An effective compensation technique, often called the IFREMER approach, considers the physics of backscatter in the various angular domains (Hellequin *et al.*, 2003). Quester Tangent uses an empirical approach that compiles tables of amplitudes with range and grazing angle as the independent variables and uses them to compensate for range and angle effects (Preston and Christney, 2003). Some companies use adaptive compensation algorithms, which can suppress many range artefacts in sonar images, but modifying echo amplitudes based only on nearby amplitudes are not consistent throughout the survey and therefore not appropriate for segmentation.

When working with data from a multibeam system, the grazing or incident angle at each beam footprint can be calculated by fitting a plane to the depths in that neighbourhood, using the bathymetric data acquired during the same survey. For a particular beam, the beam incident angle is given by the dot product between a unit vector in the direction of the beam and the tangent normal to the depth surface at the location of the beam footprint. With sidescan, flat bottom has to be assumed and depression angles are used as proxies for grazing angles. Compensation, as exemplified in Figure 3.7, is not as effective as it is with multibeam data unless the bottom is nearly flat.



(a) (b)

Figure 3.7. (a) Uncompensated (raw) and (b) compensated sidescan images of a homogeneous sandy seabed. Classification of the raw image without compensation would lead to artefact classes with borders parallel with the ship track.

Rather than compensating images for the variation in backscatter with angle, some authors have used characteristic amplitude vs. grazing angle curves for sediment classification (Hughes Clarke *et al.*, 1997). Challenges in this approach involve removing all the influence of the sonar system on these curves and the assumption that the sediment is uniform across the swathe.

3.10 Image features

To classify with images, the borders of rectangular patches are distributed over the good-quality regions of backscatter images. The matrix of amplitudes in each patch is presented to the image feature algorithms. Good image features capture amplitude and texture, using some of the published methods for discrimination in sonar or other images. Basic features are the mean, standard deviation, and higher moments of the amplitudes in the rectangular patch. Additional amplitude features include quantiles, histograms, and other measures of the amplitude distribution. Texture features respond to the "feel" of the image, discriminating between uniform and irregular regions and among types of patterns (Blondell *et al.*, 1999, for example). The major category of texture features is derived from a grey-level co-occurrence matrix (GLCM) that captures the changes in grey level between neighbouring pixels. Haralick *et al.* (1973) first described a family of GLCM features with evocative names like prominence, shade, and entropy. Pace and Gao (1988) have described empirical ratios of power spectra that discriminate well in sidescan images; fractal dimension, with amplitude treated as if it were altitude, is another useful feature that captures image texture (Carmichael *et al.*, 1996; Tegowski and Lubniewski, 2000).

The resolution of classification maps is set by the size of these rectangular patches. Small patches give high resolution, but can restrict the selection of features. In the limit of single-pixel rectangles, the only possible feature is amplitude and the classification map is the sonar mosaic organized into units by a set of amplitude thresholds.

3.11 Conclusions

Seabed classification is based on acoustic measurements that must be performed to reasonable standards to provide reliable and repeatable information. Developing standards for a particular application may be a substantial task, but the information presented here should provide a useful starting point. Model, measurement, and analysis challenges will increase with the anticipated introduction of multifrequency, broadband, and other measurement systems, but better results are expected and will compensate for the effort.

4 Seabed backscatter, data collection, and quality overview

Rudy Kloser

4.1 Introduction

This section overviews the collection, quality, and display of the acoustic seabed backscatter data in relation to seabed scattering theory from three types of commercially available acoustic systems: single-beam sonars (SBES), sidescan sonars (SSS), and multibeam sonars (MBES). These acoustic devices, discussed in Section 7, are used to collect bathymetric and backscatter data that are used to produce classifications of the seabed. The collection and quality of the data will determine the utility of the data for both the local area (relative measurements) at the time of the survey and for the comparison of data between surveys of the same area and between areas (absolute measurements). The objectives of appropriate acoustic seabed data collection, quality, and display are to achieve:

- Repeatability of maps
- Relative measurements
- Portability of classifications
- Absolute measurements

The ability of the acoustic instruments to provide relative or absolute measurements is outlined by introducing the sonar equation. Using the sonar equation, it is possible to show the major error sources that can affect the use of the data collected for relative or absolute uses.

4.1.1 Sonar equation

To investigate the influence of external factors on acoustic instruments, it is useful to introduce the sonar equation as it relates to surface seabed scattering. Consider a simplified acoustic system where a narrowband monostatic sonar at incident angle θ_i to the seabed, with transmitting sensitivity $b(\varphi,\phi)$ and receiving sensitivity $b'(\varphi,\phi)$ (where φ and ϕ are the angles relative to the beam axis), emits a short sinusoidal pulse of duration τ and average source intensity $I_s(\theta_i)$, measured at a unit distance from the source. The pulse propagates through an unbounded medium spherically, spreading and being absorbed and refracted. At a range R, the pulse interacts with the seabed and insonifies an area A of random homogeneous distribution of scatterers producing surface reverberation $s_s(\theta_i)$ at any one instant of time. Neglecting volume scatter within the seabed, a part of the signal is backscattered towards the source as the sum of random scatterers emanating from a large number of elemental areas dA within the area A. This surface reverberation $s_s(\theta_i)$ from throughout the insonified area is further spherically spread, absorbed, and refracted back to the source.

At the receiver, the signal intensity $I_r(\theta_i)$ can be derived from the sum of the elemental areas by:

$$I_r(\theta_i) = \frac{I_s}{R^4 10^{\frac{2\alpha_w R}{10}}} \int_A s_s(\theta_i) b(\varphi,\phi) b'(\varphi,\phi) dA \cdot \quad (4.1)$$

Often this equation is expressed in logarithmic form as the sonar equation to conveniently describe and evaluate the performance of acoustic systems (e.g. Urick (1983); p. 246) as:

$$EL(\theta_i) = SL(\theta_i) - 2TL(\theta_i) + TS_b(\theta_i) \cdot \quad (4.2)$$

The sonar equation is usually expressed in decibels with reference distances (1 m) and reference sound pressures (1 µPa). The source level ($SL(\theta_i) = 10\log I_s(\theta_i)$) at 1 m from the transducer face and echo level ($EL(\theta_i) = 10\log I_r(\theta_i)$) at the transducer is at a referenced intensity I_{ref} of a plane wave of root mean square pressure 1 μPa. The two-way transmission loss $2TL = 10\log(R^4 10^{\frac{2\alpha_w R}{10}})$ at range R with spherical spreading and sound absorption in seawater α_w dB m^{-1} for plane waves is given by:

$$2TL = 2\alpha_w R + 40\log R\,. \tag{4.3}$$

The backscattered target strength, TS_b, of the object in its broadest definition used here is defined as the logarithmic ratio of the echo intensity at 1 m from the target divided by the incident intensity $TS_b = 10\log(\frac{I_{echo\_1m\_t\arg et}}{I_{at\_t\arg et}})$ and in this case.

$$TS_b = 10\log\int_A s_s(\theta_i) b(\varphi,\phi) b'(\varphi,\phi) dA \tag{4.4}$$

Assuming that the backscattering coefficient of the seabed, $s_s(\theta_i)$, is constant over the incidence angles within the insonified area, this expression can be simplified to the sonar equation where:

$$\overline{S_s(\theta_i)} = EL(\theta_i) - SL(\theta_i) + 2TL(\theta_i) - 10\log\overline{A(\theta_i)} \tag{4.5}$$

Note that Equation (4.5) is an average of the true backscatter cross section $\overline{S_s(\theta_i)}$ within the pulse resolution area. In the near nadir region, where the true backscatter strength changes rapidly within the pulse resolution area, this integration yields a bias (e.g. Matsumoto *et al.*, 1993). Hellequin et al. (2003) showed that for the Simrad EM1000 multibeam system, the magnitude of this bias varies with seabed type and backscatter-processing method implemented within the MBES software.

Assuming the simplification in Equation (4.5) is consistent within a common seabed type (no relative error), the equivalent surface area insonified $\overline{A(\theta_i)}$ is determined by:

$$\overline{A(\theta_i)} = \int_A b(\varphi,\phi) b'(\varphi,\phi) dA \tag{4.6}$$

For MBES, the pulse resolution equivalent insonified area $\overline{A(\theta_i)}$ on a flat horizontal seabed can be separated into two components, one being circular or elliptical at near normal incidence (nadir) with maximum at t_2 and a thin rectangle at high incident angles with centre of beam intensity at t_4 (Figure 4.1; Kloser *et al.*, in press; de Moustier and Alexandrou, 1991).

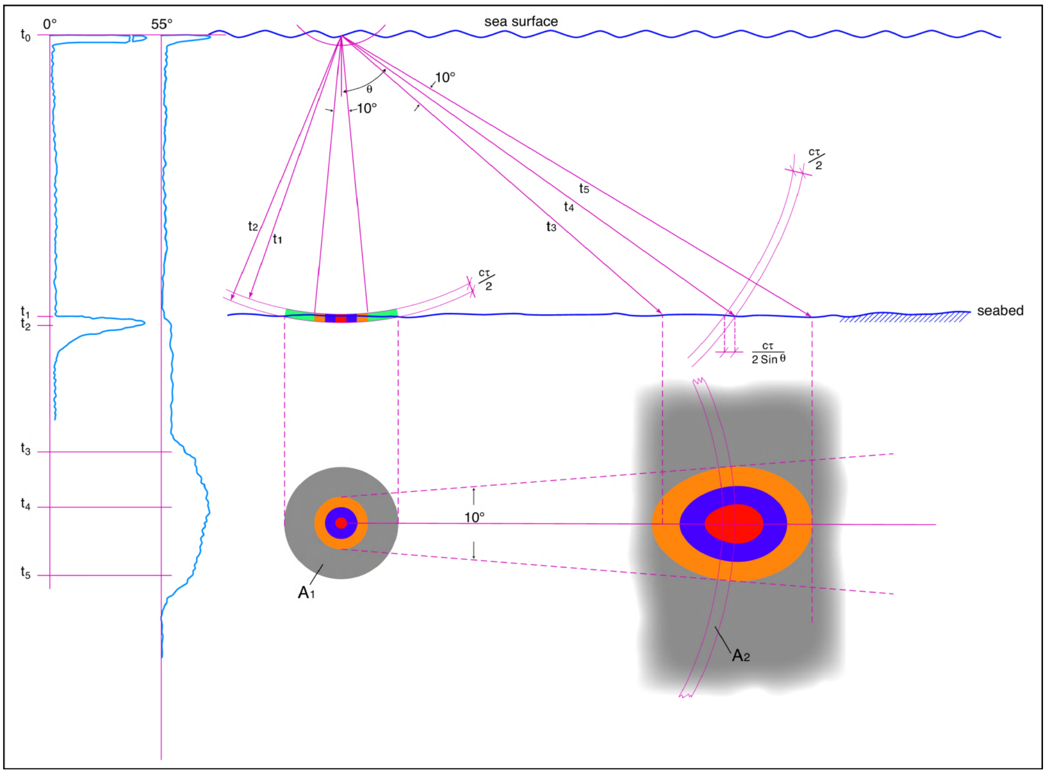


Figure 4.1. Stylised example of the area insonified by an MBES on a horizontal seabed at normal incidence (A_1) and at 55° angle of incidence (A_2). The beam geometries shown to the − 3 dB power levels are 10° along-track and 10° across-track at 0° and 55° incidence (10° chosen for clarity in the diagram) (Kloser *et al.*, in press). Colours represent decreasing intensity levels from red to grey.

The time-dependent insonified area of SBES at near normal incidence on a flat horizontal seabed can be described by an expanding disk at normal incidence between bottom contact time t_1 until the time t_2 approximately $c\tau/2$ later (Figure 4.2a). After this time, the insonified seabed area can be described as an expanding annulus of time width approximately $c\tau/2$ (Figure 4.2b; e.g. Lurton 2002, p. 252; Sternlicht and de Moustier 2003a). As the vessel pitches and rolls or the seabed is sloping, the seabed incident angle θ_i, and area insonified $A(\theta_i)$ changes (Equation (4.6); Figure 4.2c and d). Without monitoring the effect of changes in seabed slope and vessel motion characteristics, and compensating for them, the time-dependent seabed backscatter from an SBES system will appear different for the same seabed type (Figure 4.2). This represents both an absolute and a relative measurement error.

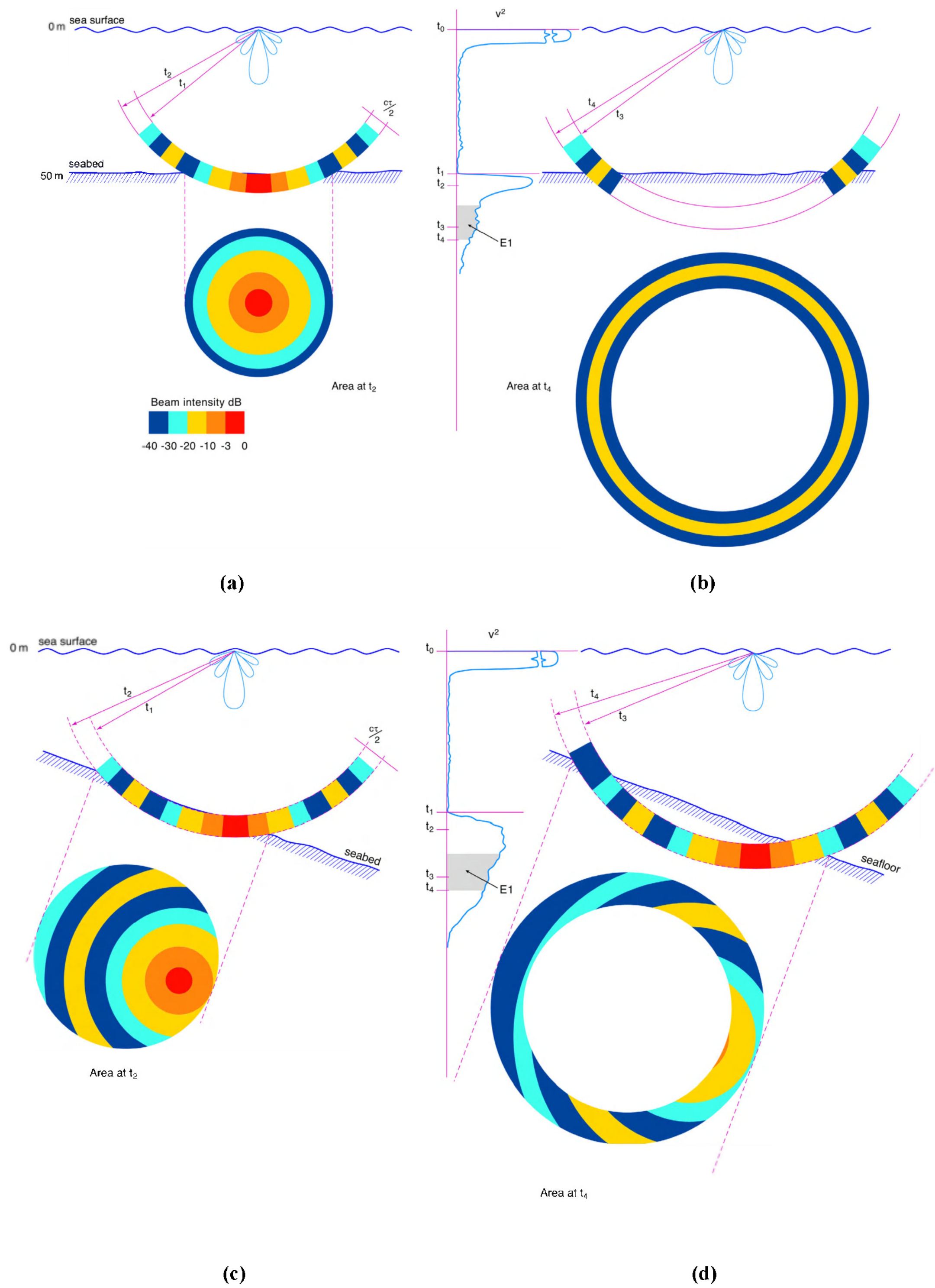


Figure 4.2. Stylized example of a single-beam sonar (SBES) showing the insonification area as a function of time expanding from (a) a circle to (b) an annulus, with varying intensity based on the transducer beam pattern on a flat horizontal seabed; and from (c) an ellipse to (d) an annulus, on a flat sloping seabed. Tail of first echo integration (E1) showing effect of slope (Kloser *et al.*, in press).

A similar process can be undertaken in defining the volume backscatter from the sediment, and the total backscatter can be represented as the superposition of seabed roughness and volume backscatter (e.g. Sternlicht and de Moustier, 2003a). To minimize data quality problems in the collection of both absolute and relative acoustic data, each of the variables in Equation (4.5) needs to be monitored for error. An important point to note is the dependence of the seabed backscatter return on the incidence angle.

4.1.2 A simple model of seabed backscatter (10–300 kHz)

To illustrate the effects of data collection, quality, and display, it is also useful to understand the reflection of the seabed to a monostatic echosounder based on a model of the seabed scatter at common frequencies of 10–300 kHz (Section 2). High-frequency scattering from the seabed is related to the roughness of the seabed–water interface, roughness of the interfaces between the seabed layers, discrete scatterers within the seabed, and fluctuations in the seabed volume density and sound speed (see Section 2). The diversity of seabed types encountered in the ocean and the wide range of acoustic frequencies used has led to a range of model realizations (Jones and Jackson, 2001; see Section 2). Modelling and validated measurements at high frequencies have been limited by the difficulty of accurately characterizing seabed properties at centimetre scales. Advances in two-dimensional digital photogrammetry and three-dimensional X-ray computed tomography are changing this situation (e.g. Pouliquen and Lyons, 2002). Physical measurement techniques are now able to take into account the effects of bioturbated sediments.

The motivation to develop acoustic seabed models is that such models lead to solving the inverse problem, where the acoustic backscatter from a region is used to predict the seabed characteristics (see Section 2). In practice, the inversion of seabed backscatter measurements at limited incident angles and frequencies is not unique. This is illustrated by the monostatic reflectance as a function of angle for various typical seabed types that exhibit various degrees of coherent and incoherent scatter (Figure 4.3). At some incidence angles, a high-impedance, smooth surface (Figure 4.3a) could reflect back towards the source the same intensity as a low-impedance, rough surface (Figure 4.3d).

It has proven difficult to produce a single acoustic model of seabed scattering in terms of its roughness and geo-acoustic properties, including the effects of flora, epifauna, infauna, and gas bubbles (see Section 2). Although, in the frequency range of interest, 10–300 kHz, a useful fluid sediment model has been developed over a variety of soft to hard seabed types and this has been validated with acoustic measurements (Jackson *et al.*, 1986a; Jackson and Briggs, 1992; APL94, 1994). The APL94 model combines the most dominant seabed-scattering mechanisms of homogeneous sediment volume, $s_v(\theta)$, and surface roughness, $s_s(\theta)$, coefficients as a superposition of incoherent scatter to estimate the seabed backscattering strength $S_b(\theta)$, where:

$$S_b(\theta) = 10\log_{10}\left[s_s(\theta) + s_v(\theta)\right] \quad \text{dB}. \tag{4.7}$$

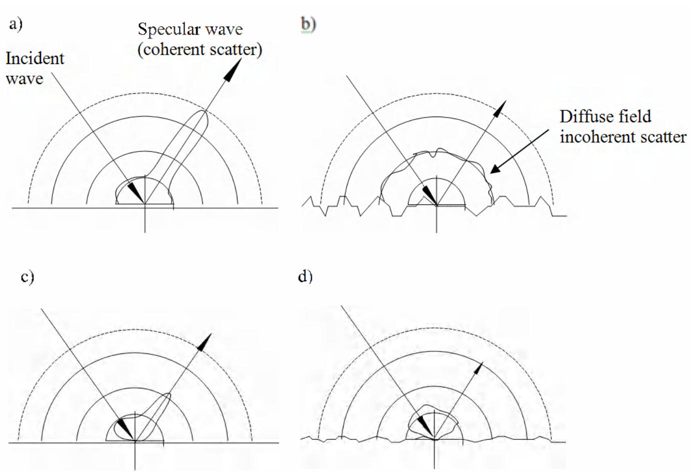


Figure 4.3. Representation of bi-static acoustic scatter from high impedance for (a) a smooth and (b) a rough surface and low-impedance contrast for (c) a smooth and (d) a rough surface (modified from Urick, 1983 p. 140; Kloser, in press). Solid arrows show the direction of the specular echo, and the dashed arrows show the monostatic backscatter signal towards the source.

This simple fluid sediment model will have poor geo-acoustic parameter prediction for the following seabed conditions:

- Inhomogeneous sediment layers (Jackson and Ivakin, 1998);
- Rock seabeds for shear waves (Ivakin and Jackson, 1998);
- Poroelastic (Biot) effects of sands (Williams *et al.*, 2002);
- Other volume-scattering mechanisms, compressional–compressional, shear to shear, compressional to shear (Jackson and Ivakin, 1998);
- Non-isotropic surfaces (Pouliquen and Lyons, 2002);
- Very rough surfaces that violate the Kirchhoff scattering criteria;
- Frequencies above 100 kHz;
- Inclusion of discrete inclusions within the sediment volume, such as shell fragments and other biological material;
- Representation of texture and echo statistics.

Despite the potential for a number of limitations in the APL94 model, measurements on a variety of seabed types have supported the dominant physical scattering mechanisms (e.g. Jackson and Briggs, 1992; Williams *et al.*, 2002).

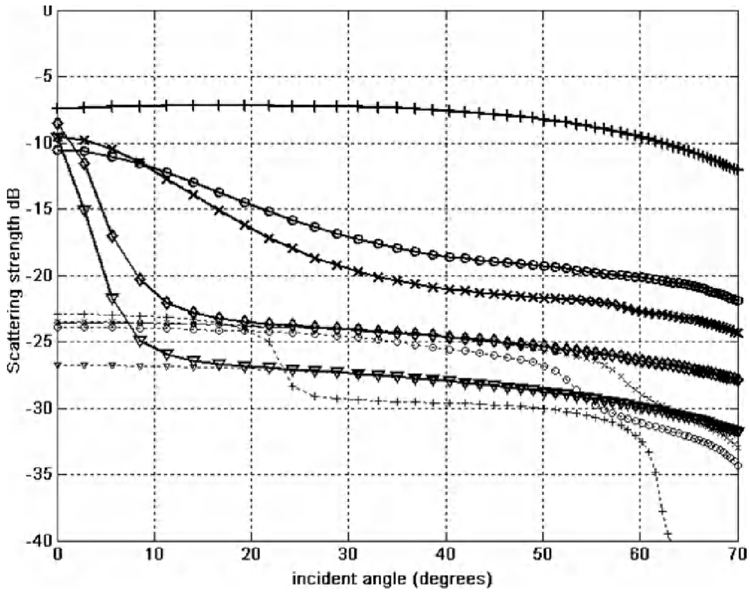


Figure 4.4. Model seabed scattering strength of seabed types at 95 kHz using the geophysical parameters quantified in the APL94 model (APL94, 1994). Total seabed scattering strength (solid) and volume scattering strength (dotted) for seabed types of rock (plus), coarse sand (circle), medium sand (cross), coarse silt (diamond), and sandy mud (triangle; modified from Kloser *et al.*, (2002)).

The APL94 model illustrates the discrimination in amplitude that is possible between modelled seabed types at varying incidence angles (Figure 4.4). At normal incidence (0° incidence), there is very poor discrimination between seabed types, and the discrimination improves at higher incidence angles. Typically, the commonly used commercial acoustic systems provide the following seabed scattering strength information over a range of incidence angles:

- SBES incidence angles from 0° to 40°
- SSS incidence angles 40° to 85°
- MBES incidence angles 0° to 70°

Therefore, based on this simple model, an SBES normal-incidence, wide-beam transducer would provide better discrimination (depending on seabed patch size) than a narrow-beam system at the same frequency and same signal-to-noise ratio. Also, a normal-incidence, narrow-beam system with high side lobes would provide better seabed discrimination than a similar system with very low side lobes at the same range, signal-to-noise ratio, and instrument settings. Another important metric based on the model seabed scattering strength would be the rate of decrease of seabed backscatter as a function of seabed incident angle.

4.2 Overview of generic acoustic data collection issues

The following collection procedures need to be considered to ensure that relative or absolute backscatter data are obtained from measured seabed incidence angles.

- Geo-referencing of signal returns and signal timing issues;
- Angle of incidence to the seabed (e.g. transect direction, across or along slope);
- Acoustic noise, e.g. vessel (engine, propeller, and other instruments), background (biological, environmental);
- Electrical noise – instruments/machinery;

- Propagation medium characteristics – sound speed and absorption coefficient for the region; sound speed at the transducer face for beamforming systems such as MBES;
- Environmental gradients;
- Aeration close to transducer – monitor when caused by rough weather, at high speed or poorly located transducer.
- Calibration – precision/accuracy:
  - Beam pattern characteristics (transmitters/receivers);
  - Instrument stability (transmitter, receiver, transducer);
  - Equivalent area insonified and absorption time variable gain (TVG) corrections;
  - Instrument integration/timing issues;
  - Timing issues for bathymetry MBES;
  - Between-beam backscatter gains for MBES.
- Instrument information:
  - Frequency band;
  - Pulse length/shape/amplitude stability;
  - Transducer transmit and receiver characteristics and beamforming method;
  - Transducer depth;
  - Pitch, roll, heave, and yaw;
  - Calibration settings;
  - Software and hardware version recording;
  - Preprocessing algorithms and pre-applied TVG gain.
- Environmental conditions (wind, swell direction, tide level, etc.).

Many of these parameters can be monitored if the digitized echo from pulse transmission to end of seabed echo (second echo in some cases) is recorded along with instrument configuration and peripherals with good time recording. When using multibeam sounders, integration of the motion reference units with the geo-referencing and echosounder signals is important for accurate geo-location of measurements and for calculation of incidence angles.

In addition to these generic issues for range-independent measurements, special attention is required to account for correct compensation of the equivalent insonified area and for exclusion of unwanted targets such as pelagic and demersal fish.

4.3 Data quality

High-quality acoustic data are obtained from the chosen instrument by first minimizing noise- and motion-induced artefacts, along with recording of the appropriate instrument and environmental characteristics as outlined above. To illustrate data quality, collection, and display issues, each acoustic system (SBES, MBES, SSS) is treated separately with examples of possible interference. The overall philosophy of detecting and minimizing artefacts is the ability to view and detect errors in the acoustic data at the most detailed level possible at the time of collection (Kloser *et al.*, 2001b). An alternative method is to flag and remove inconsistent data based on viewing the raw data or the processed data using area or point-based methods (e.g. Foster-Smith and Sotheran, 1999; Kloser *et al.*, 2001).

4.3.1 Single-beam sonar (SBES)

For good data quality, the instrument's frequency and transducer beam pattern shape need to be carefully chosen to suit the depth and resolution of the study (see Section 3). For example, a narrow beam-width, low side lobe SBES operated around normal incidence is not as useful in seabed mapping as an instrument with higher side lobes. This is a result of the greater separation of seabed types at higher incident angles off normal incidence (Figure 4.4). Once an instrument configuration is chosen, it is important to understand the noise characteristics of the whole survey system. This could include monitoring the noise on the system caused by vessel speed and working out the optimal speed for low-noise recordings while also ensuring timely completion of a survey.

First echo interference problems:

- Platform motion and aeration
- Bottom detection stability and consistency
- Fish schools and their multiple scatter that extend to the seabed
- Seabed slope
- Noise interference masking echoes originating off the acoustic axis (e.g. notably from side lobes)

Second echo interference issues:

- More susceptible to acoustic and electrical noise
- Vessel hull size, shape, and depth
- Water surface roughness
- Vessel speed

Figure 4.5 highlights some specific noise/interference problems that need to be removed or quantified before undertaking processing of the seabed signal. The effect of aeration under the transducer, caused by bubble sweep down from the vessel hull or by surface bubbles, significantly degrades backscatter intensity. Note the reduced and occasionally non-existent first seabed echo. The TVG compensation is $TVG = 2\alpha_w R + 20\log R$. This TVG will not be suitable for all components of the seabed echo return for varying ranges and incidence angles (Equations (4.5) and (4.6); Lurton, 2002). Vessel noise changes with speed and, depending on the magnitude, can dramatically affect the intensity and shape of both the first and second seabed echo. As shown in Figure 4.2c, the seabed echo can change shape as a result of slope and not necessarily because of a change in the seabed properties. Fish schools in the water column may also cause interference; they may cause excessive attenuation of the seabed echo, the echosounder's bottom detection may use the top of the fish school as the start of the seabed signal, or the multiple scattering within the school may influence the seabed echo. Figure 4.5 also shows the effect of interference from other echosounders. The second seabed echo is used in many commercial and visual seabed classification systems, and this echo is also susceptible to changes in sea surface roughness and vessel hull shape; because of the lower signal strength, it is more sensitive to background noise (Figure 4.5).

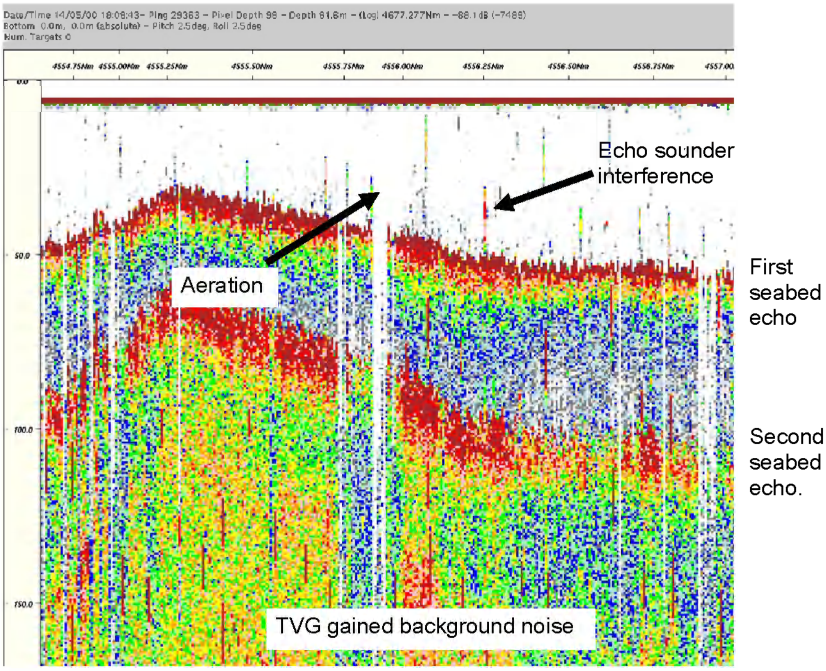


Figure 4.5. Typical data quality problems associated with SBES data showing aeration under transducer caused by bubble sweep down and effect of interference from other unsynchronized echosounders. Echogram collected at 120 kHz at 20 log*R* TVG and minimum display threshold of −80 dB to emphasize the background noise that increases with range as a results of the TVG.

The magnitude of potential or actual errors caused by poor data quality in acoustic seabed surveys is not often reported, but examples and references are often made for specific equipment.

Previous researchers using commercial equipment – the RoxAnn system based on the classification scheme of Chivers *et al.* (1990) – to classify seabed type have restricted their operation over narrow depth ranges (Magorrian *et al.*, 1995) or reported a depth bias (Greenstreet *et al.*, 1997). Furthermore, data quality problems (e.g. Greenstreet *et al.*, 1997) and biases from varying ship speed (e.g. Magorrian *et al.*, 1995; Hamilton *et al.*, 1999) and weather (e.g. Kloser *et al.*, 2001b) have been reported. Von Szalay and McConnaughey (2002) investigated the effect of seabed slope and vessel speed on the QTC View single-beam classification system. For the system and vessel used, there was no measurable effect from vessel noise between 3 knots and 12 knots, but bottom slopes of more than 5° to 8° significantly changed the seabed classification being derived. Changes in seabed slope are similar to changes in transducer orientation, and their effect would be beam-pattern-specific as well as platform-motion-specific, highlighting that these commercial systems do not resolve seabed incidence angles.

A major consideration when carrying out seabed classification derived from metrics of the first and second echo is that different interference artefacts can be induced. Therefore, as the number of metrics increases, so will the need for extra data quality control checking. To date, SBES systems have provided coarse segmentation of seabeds into varying grades of diversity, usually defined in terms of acoustically soft to hard and from smooth to rough. These classifications have generally been restricted to local sites, where interference effects and depth range are minimized. Classification of the seabed in these cases relies on physical and or visual sampling of the seabed to determine the actual seabed characteristics. The challenge lies ahead to determine the robustness of the classifications to varying noise and or interference effects and the portability of the classifications to other regions.

4.3.2 Multibeam sonar (MBES)

Several major improvements occur when moving from single to multibeam systems (see Section 6):

- Spatial resolution of sampling improves for both bathymetry and backscatter;
- Motion compensation and geo-referencing of data;
- Across track width sampled improves;
- High-resolution measurement of seabed slope across and along vessel track for incidence angle calculations and corrections;
- Measurement of backscatter at varying angles of incidence to the seabed.

Commercial multibeam echosounders, as distinct from phase differencing sidescan sonar (Denbigh, 1989, Section 6), are a relatively new instrument, designed initially to measure the topography of the seabed (e.g. Kleinrock *et al.*, 1992). Initially only low frequency (12 kHz) instruments were used in deep water, with a minimal number of beams (de Moustier, 1986; Mitchell and Clarke, 1994). Over the past decade there have been significant advances in the frequency range of instruments (10–500 kHz) reductions in beam widths (20–0.5°), an increase in the number of beams (20 to >400), and reduction in cost (MBESTC21, 2000). These developments have coincided with improved and less costly (since ~1986) differential global-positioning system (DGPS) accuracy and platform motion measurement devices. Commercial MBES were primarily designed to infer depth by measuring time of echo returns, with acquisition of acoustic backscatter for seabed characterization being a secondary objective. Depth, and hence bathymetry, is an important metric for seabed habitat classification (e.g. Roff and Taylor, 2000). Typical preprocessed data obtained from multibeam sonar include depth and centre of beam backscatter (Figure 4.6a and b). With minimal processing, derived metrics of seabed slope (Figure 4.6c) and bathymetry-contrast (Figure 4.6 d, oblique lighted surface) can be obtained, permitting a visual classification of the seabed (e.g. Kloser *et al.*, in press).

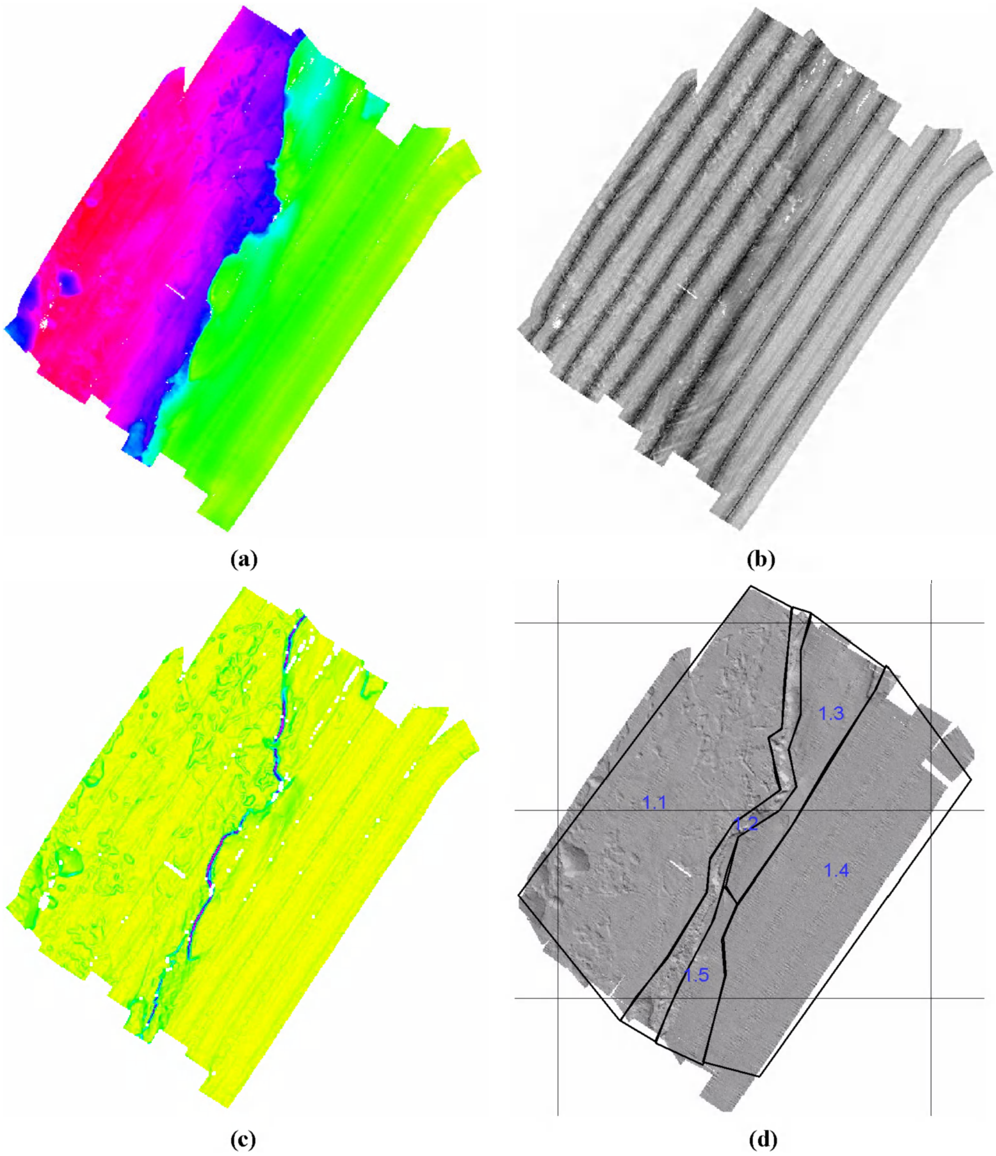


Figure 4.6. Example of the (a) bathymetry (red 115 m to yellow 130 m), (b) raw beam centre backscatter strength −5 to −60 dB (black to white), (c) seabed slope (yellow 0.5° to blue 10°), and (d) bathymetric contrast (oblique lighted-bathymetry) with visual megahabitat analysis of the region characterized by a low-relief limestone reef (1.1 hard–rough), reef edge (1.2 hard–rough), and sediment flat of changing substratum (1.3–1.5 soft–smooth; Kloser *et al.*, 2002).

Methods have been evolving to process and interpret the depth and seabed backscatter data from MBES instruments. The processing of depth data, removing unwanted errors caused by ray bending, platform motion, fish schools, bottom detection method, and noise, have been investigated (e.g. Mitchell 1996; Canepa *et al.*, 2003; Calder and Mayer, 2003). Advances are also being made in the processing and understanding of seabed backscatter from multibeam instruments (de Moustier, 1986; Hughes-Clarke *et al.*, 1993; Matsumoto *et al.*, 1993; Talukdar *et al.*, 1995; Hellequin *et al.*, 2003). Several commercial software products provide a phenomenological seabed backscatter processing system (e.g. Simrad, 1999; Preston, 2003). Scientific applications of multibeam sonars in depths <500 m have concentrated on describing the geology of the seabed using both the detailed bathymetry and the seabed backscatter (e.g. Todd *et al.*, 1999; Gardner *et al.*, 2003). Recently, there has been an effort to use multibeam sonars for habitat mapping (e.g. Kostylev *et al.*, 2001; Kloser *et al.*, 2002; Edwards *et al.*, 2003).

The seabed backscatter will have both relative and absolute measurement errors. Absolute errors will be caused by sonar system calibration and oceanic environmental conditions, as well as the correction for the equivalent area insonified based on the sonar beam pattern, seabed slope, and transmission/reception angles. To calculate the absolute level of backscatter requires good estimation of the range compensation of absorption owing to seawater (Francois and Garrison, 1982) and the absorption owing to surface bubbles (e.g. Dalen and Lovik, 1981). Relative non-range-dependent changes in backscatter can be caused by changes in instrument performance or absorption owing to seawater and surface bubbles. Range-dependent changes can be influenced by changes in transmitter output (e.g. pulse length and power) and seawater absorption.

A checklist of data quality for multibeam sonars could include some or all of the following considerations.

Bathymetry

A standard procedure for the relative calibration of bathymetry from multibeam instruments is to carry out a patch test (e.g. Simrad, 1999). This ensures that the integration of the positioning system (e.g. DGPS), motion reference unit, and MBES produce reliable and repeatable results across all the angles of incidence insonified. This procedure removes most geo-referencing errors, but dynamic motion errors may remain (Figure 4.7a). Processing the data it is often necessary to correct for the appropriate sound velocity profile and, depending on the transducer shape, the sound velocity at the transducer's face is required. The accuracy of depth detections often depends on the incidence angle, with depths collected near normal incidence and at high-incidence angles being less accurate as a result of amplitude bottom detection errors and background noise, respectively. To correct the data in post-processing, it is often necessary to have detailed platform motion information.

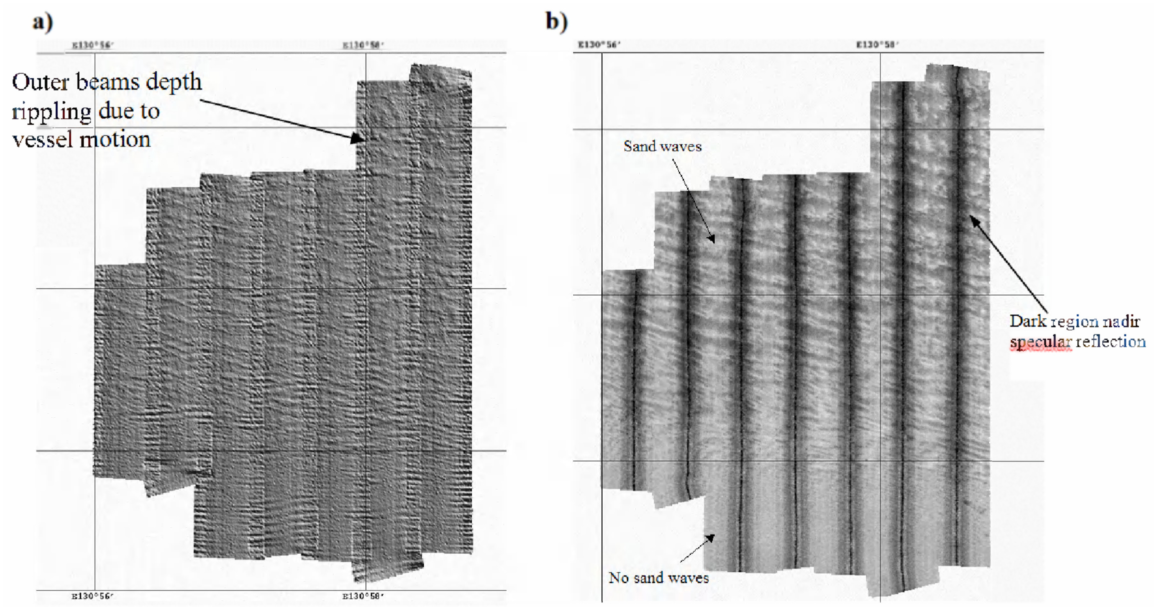
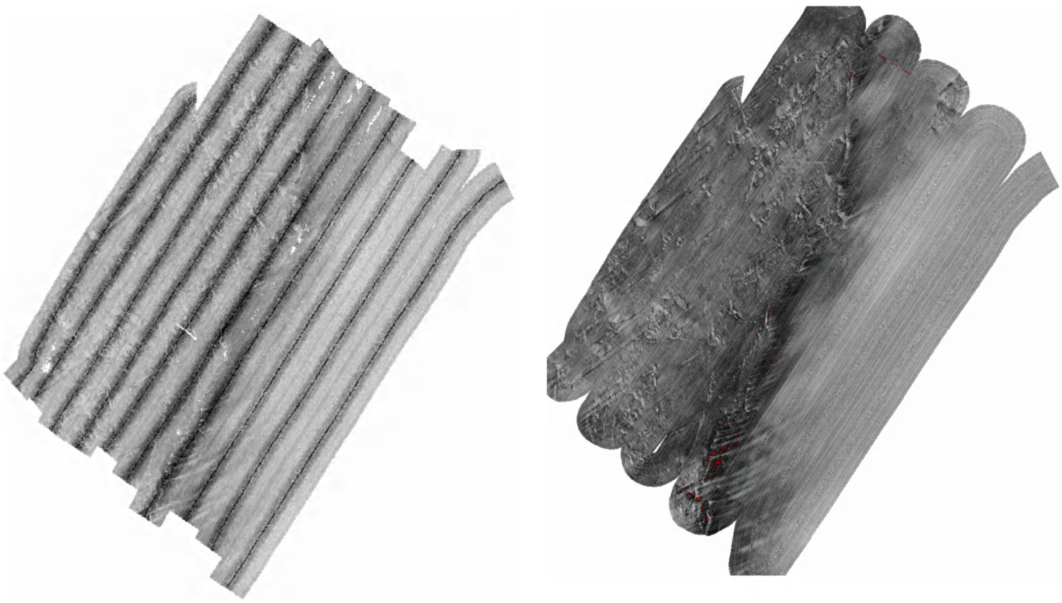


Figure 4.7. Example of (a) preprocessed Simrad EM1002 MBES bathymetry texture (shaded bathymetry vertical exaggeration eight times) in the flatly sloping <1° Great Australian Bight region, depth 135–145 m, showing the depth rippling at a high incidence angle (60–70°) on the outer beams because of vessel motion and/or incorrect surface sound speed, and (b) preprocessed MBES centre of each beam backscatter in areas with and without large sand waves (high backscatter is black; Kloser *et al.*, in press).

Backscatter

There is no standard *in situ* procedure to obtain a relative or absolute backscatter calibration from MBES. Calibration of MBES instruments *in situ* is developing, and standards are being proposed (Cochran *et al.*, 2003; Foote *et al.*, 2005). Manufacturers generally calibrate their instruments to varying degrees and can provide some of the necessary transmitter and receiver information. An inspection of the backscatter during patch tests at well-described reference sites of relatively homogeneous seabed types at various incidence angles can ensure that the backscatter has some internal consistency and relative accuracy (e.g. Kloser *et al.*, 2002). Data collected at the centre of each beam have high backscatter at normal incidence; this is reduced as the incidence angle increases, but then increases slightly again, presumably at the critical incidence angle (Figure 4.8a). Common artefacts in the backscatter incidence angle profile can be observed because of incorrect beam gains, with artefacts aligned along the platform track (Figures 4.7b and 4.8b). Figure 4.8b shows a common preprocessing technique that reduces the seabed incidence-angle-dependent backscatter, in this case referenced to 40° (Kloser *et al.*, in press). Notably, in Figure 4.8b, there is along-track striping, caused by between-beam gain differences which can be removed in post-processing. Before feature extraction, the collected backscatter data need to be checked for regions affected by surface bubbles caused by waves and vessel motion, surface bubbles, and electrical and acoustic noise. A correction to apply the calculated absorption profile for the region, based on the collected salinity, temperature, and depth measurements, may be required. Usually the backscatter reported from multibeam instruments is given as incidence angles assuming a horizontal flat seabed. The seabed slope and transducer motion make it necessary to correct for the equivalent area insonified and incidence angle, as referenced to the seabed.



(a) (b)

Figure 4.8. Simrad EM1002 centre of beam backscatter (Figure 4.6b) with (a) recorded backscatter with emitted incidence angle (scale range −5 to −60 dB) and (b) removal of incidence angle backscatter dependence referenced to 40° incidence angle (scale −20 to −40 dB) (Kloser *et al.*, in press). Note the remaining along-track between beam gain error striping.

4.3.3 Sidescan sonar

Sidescan sonars can be hull-mounted, or they can be towed at depth to provide insonification of the seabed at a higher angle of incidence. These high incidence angles at higher frequencies (100–800 kHz) produce data that create acoustic shadows and lead to a phenomenological seabed classification based on relative backscatter and echostatistics (e.g. Pace and Gao, 1988). As the data are generally obtained from towed systems, transducer orientation and motion are required to quality check the data. Also, the geo-location of data on a flat horizontal seabed requires an accurate estimate of the towed transducer's position with reference to the survey vessel, as well as its motion and orientation in the water column. If the seabed has high roughness and slope, then accurate geo-location is difficult because simple SSSs provide no angular resolution. On rough and high-slope seabeds, bathymetry is not directly obtained, and a correction of the backscatter to an angle of incidence to the seabed is not easily derived. More detail on the use of SSS appears in Section 7.

4.4 Displays for data-quality identification and control

There have been many advances in displays for data quality identification at various stages of seabed classification. The overall philosophy is to maximize the quality of the data collected while minimizing the interference from noise and artefacts. It is useful to have adequate displays of the data at all stages of the data-quality process, starting with the raw data and finishing with the mapping and correlation with other metrics (Figure 4.9; see Section 3). The volume of data collected has required improved data display and data cleaning, using point- or area-based methods (Calder and Mayer, 2003).

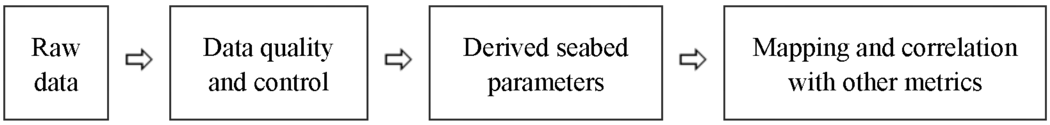


Figure 4.9. The steps to view acoustic data at various levels of data quality, starting with the raw data through to preprocessing, parameter derivation, and mapping and correlation with other variables.

The need for data-quality and control tasks are often significantly reduced if noise and artefacts are detected and mitigated at the data collection stage. Display of the acoustic data in its rawest useful form greatly aids artefact detection and improves data quality. For narrowband SBES data, the echo enveloped data including transmission, water column, and seabed scattering with some nominal range compensated gain applied (e.g. $TVG = 2\alpha_w R + 20\log R$) can greatly assist in artefact detection and mitigation (Kloser *et al.*, 2001b).

Several research-based and commercial software products have been designed to examine SBES, SSS, and MBES bathymetric and backscatter data. These products enable the user to:

- Display the raw data at the data collection phase to identify interference or artefacts;
- Map individual metrics over raw data or other data (e.g. depth, vessel speed, ground-truth data) to remove outliers/corrupted data;
- Check metrics for internal consistency – outlier removal;
- Use a combination of all three.

Increasingly, seabed habitat survey displays combine acoustic and geo-referenced video sensing data with the physical samples collected to interpret the seabed acoustic data at small and large spatial scales towards production of the final interpreted product (Figure 4.10).

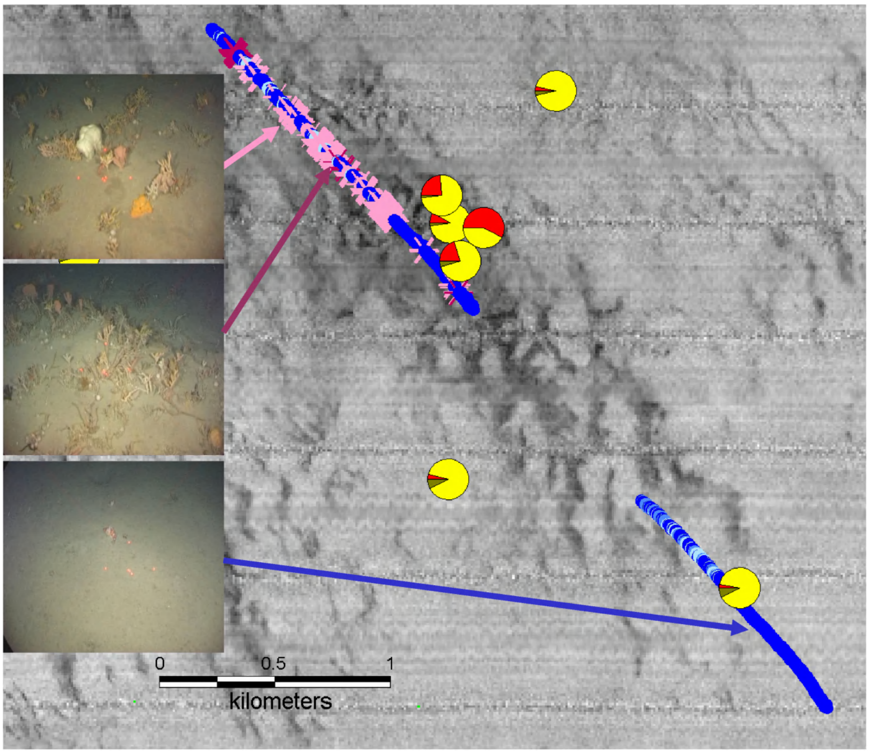


Figure 4.10. Example of MBES backscatter referenced to 40° incidence angle (high backscatter dark) of small features (~4 × 4 km) showing the overlay of two geo-referenced and scored video transects (soft terrain classes, blue circles; hard terrain classes, pink asterisks) of varying geological and biological characteristics. Note the prominent horizontal line along-track normal incidence with other along-track lines between beam gain artefacts. Geo-located sediment grab composition (pie charts) in percentage gravel (red), sand (yellow), and mud (brown) (Kloser *et al.*, in press).

4.5 Conclusions

The objectives of the seabed study and subsequent usage of the data will determine the extent of the data collection and quality requirements. A well-calibrated acoustic system with an appropriate data collection, including peripheral instruments such as motion reference systems, will greatly assist in post-processing of the data. Single-beam, normal-incidence systems have proven to be effective in segmenting the seabed for the geological and biological sampling required. It is best to collect the whole echogram data, including the transmitted pulse and water column and seabed echoes, to assist in identification and elimination of noise and artefact errors (Kloser *et al.*, 2001a). Many errors can be removed from the data before the selected algorithms are applied. Removing noise and artefacts becomes more important at the raw data phase, when multifrequency instruments are considered. A complementary and alternative approach is to map the derived acoustic metrics in time and space with other information, including bathymetry, motion, temperature, and visual physical samples, as an example to aid in the identification of outliers and anomalies. Area-based editing complements or replaces traditional point-based editing approaches within the MBES field (Calder and Mayer, 2003). The area-based editing approach is being aided by improved visualization of the acoustic data and associated metrics.

5 Classification methods and criteria

Yvan Simard and Andrzej Stepnowski

5.1 Introduction

Acoustic seabed classification (ASC) is an emerging methodology designed to detect various characteristics of the seabed remotely, from the information content of seabed echoes of acoustic pulses transmitted from various types of echosounders and sonars. Besides the particular hardware characteristics of each ASC system, the heart of the method is a classification module that extracts a series of features from the echo signal and processes them to sort the echoes into *relatively homogeneous groups* according to *classification objectives*. This section reviews common approaches used in this field to realize this classification step.

Objective classification of objects is a widespread task in engineering, physics, chemistry, biology, social sciences, and other disciplines. Many numerical methods have been developed to perform this task (e.g. Legendre and Legendre, 1998). Starting with a representative sample (Cochran, 1977; Thompson, 2002; see Section 9) taken from a population of objects to sort according to a given objective, a classification generally involves a series of steps, each one conditioned by the preceding ones (Figure 5.1).

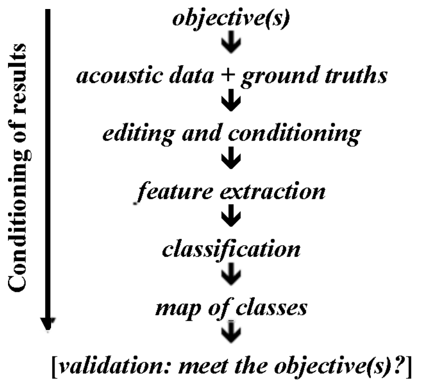


Figure 5.1. Sequence of steps in an ASC classification process.

Defining the objective(s) of the classification is, of course, the first and most important step of the whole classification process. It not only conditions the material and methods used to collect and analyse the data, but also affects how the classification success will be evaluated. The prerequisite consideration of the scales of observations that are relevant to the objectives (see Section 6) is part of this step. This involves both the total spatial and temporal domains of the studied area and the sample support (i.e. size of sample unit, cf. Glossary). The data acquisition can be made using various instruments (Section 7); ideally, the most appropriate ones for the objective of the study should be used. In practice, however, this is seldom the case, and the sampling is carried out using the instrumentations that are available, which often imposes limits on the information content of the data and so on the classification possibilities. For example, to survey non-flat areas, constant-altitude acoustic samplers, e.g. a transducer mounted on a towed body or on an autonomous underwater vehicle (AUV), may be required to obtain constant sample support (size) and spatial resolution throughout the survey area, to extract the same classification information from each acoustic footprint, independent of its range from the transducer. Similarly, ground-truth sample support (e.g. grabs and dredges, stereo cameras, laser profilers) must be comparable with the acoustic data support for proper *a priori* or *a posteriori* ground-truthing of the acoustic classes without resolution mismatch. More details on this important point, which conditions the whole classification, are presented in Section 8.

Before extracting the potentially discriminant features from seabed echoes, the acoustic backscatter data must previously have undergone an editing and conditioning step (see Section 3). Data screening and editing are required to eliminate the inevitable unwanted signals or artefacts, such as interference from other acoustic instruments, bad pings resulting from transducer aeration, excessive pitch and roll of the platform, erroneous bottom detections, demersal fish schools, and low signal-to-noise (SNR) data (see Section 4). This also often includes the selection of data, for example within given ranges of bottom depths or platform pitch and roll angles, or acoustic incident angles. The data then go through conditioning to prepare them for feature extraction and multivariate analysis. This step is sometimes combined with feature extraction. Common procedures are:

- Selection of the metric(s) to use for expression of the signal (e.g. area backscattering strength in dB re 1 m^2 m^{-2});
- Averaging of adjacent pings to damp unresolved small-scale variability;
- Incident angle (time) alignments;
- Considerations of platform roll or bottom slope effects (e.g. Von Szalay and McConnaughey, 2002);
- Limitations to high SNRs.

More details on such data preprocessing are presented in Section 3.

Extraction of the signal's characteristic features is a crucial step in any classification process. Constant, weakly varying, random noise or unstructured signal properties will not contribute to the classification or sorting of any set of seabed echoes; rather, they will hinder the classification process. Often, only a few characteristics, or a combination of them, will be responsible for classifying the objects in separate groups. Several classification methods require statistical properties of the data or features, such as normal or multi-normal distribution of the features and linearity of their relations, while some are robust to departures from these assumptions (cf. Legendre and Legendre, 1998). These conditions, therefore, must be checked, and a transformation must be applied when necessary. Large-scale spatial trends may be either heuristic or unwanted and filtered out in some cases. Several numerical methods can be used to classify seabed echoes into relatively homogeneous groups from their uni- or multivariate features, which can sometimes be as few as two features (see Section 3). Some classification methods, such as spatial clustering (cf. Legendre and Legendre, 1998) may include spatial constraints to associate a seabed echo with a given group. More details on these two central classification steps are given below. The final step of this whole process is to validate the resulting classification. This is the object of Section 8, and only general comments are given here.

5.2 Classification methods

5.2.1 Overview

The aim here is to extract some properties from the measured seabed echo that will allow the bottom to be classified into relatively homogeneous categories to meet the objective of the study. As described in Section 2, the seabed echo is influenced by a panoply of bottom properties (grain size, density, water content, roughness, benthic flora and fauna, etc.); these combine to form an acoustic signature from which we hope to extract some of these properties by signal-processing methods. Ideally, one looks for the minimum number of most discriminant properties for the seabed characteristics under study. Simple tasks, such as extracting the bottom reflection coefficient (Orlowski, 1984) or separating hard and soft bottoms, may be achieved with very few features from the seabed echo, such as RoxAnn E1/E2 processing (Chivers *et al.*, 1990). However, in general, the tasks are much more complex, for example classifying the seabed according to the benthic communities or biotope types (see Glossary). Additional information is then required, and the common assumption that it is present in the recorded signal may prove to be wrong. Although we look for objective universal features that are independent of the equipment type (see Section 2), the features that can be extracted strongly depend on the type of acoustic gear used, its parameters (acoustic frequency(ies) and beam(s) characteristics), and the quality and quantity of the data output of these systems.

These features can be separated into two groups: (i) those measuring the acoustic backscatter energy integrated over the whole transducer beam or incident angle intervals, or corresponding to particular grazing angles; and (ii) those measuring indices of shape or amplitude variability of the seabed echo trace (Table 5.1). Features can also refer to reconstructed features of the seabed itself, such as high-resolution relief from multibeam sonar or bottom roughness. The features can be measured on single echo signals or on a series of adjacent or successive echoes, in one or two dimensions, depending on the data acquisition system. As in other disciplines, additional ancillary information can be added and used in the classification process. Bottom depth is an obvious one, but others, such as temperature, mean current speed and direction, dominant wind and waves, the distance from the coast, shoals, sea mounts, reefs or rivers, etc., can contribute to the classification and orient the interpretation of the results towards the study objectives. Some of this ancillary information (Table 5.1) is sometimes available everywhere (e.g. bathymetry, aerial photographs or satellite imagery, modelled mean current, geological map) and may be useful to interpolate results to unsampled areas, by taking advantage of cross-correlations and multivariate mapping, like trend surface modelling, and geostatistical methods such as co-kriging and kriging with external drifts (Chilès and Delfiner, 1999).

The ground-truth samples (Table 5.1, shaded rows) share the same information as the other samples, but their class relative to the seabed classification objective is already determined *a priori* by the user from other independent methods. In several classification methods, these samples (or a subset of them) constitute the "training dataset" that will be used to optimize or "train" the algorithm to classify the other samples. This is referred to as the seabed class catalogue in some papers. Because this training dataset becomes the reference for the whole domain to classify, it is important that it is representative of the diversity of the seabed acoustic signatures that are likely to be encountered in the whole survey area. The algorithm cannot classify a seabed type that is not part of its catalogue, nor can it classify a seabed type that does not have a distinct expression in the features. For example, the training dataset should include samples from the whole range of depths, slopes, survey direction, sea state conditions, and SNRs, among others. The final subset of samples of a complete seabed classification dataset is the series of independent validation samples (Table 5.1, bottom rows) that should be collected at the same time as the rest of the dataset to minimize possible seabed changes with time. These samples share the same information as the ground-truth samples, but do not contribute to the classification process. They serve to verify the accuracy of the classification results *a posteriori*. They could also help to specify the location of the boundaries between the seabed classes, when their positions are chosen for this purpose after a classification has been established.

Table 5.1. Feature matrix and ancillary variables, with ground-truth (shading) and validation (asterisk) samples. A dash indicates not available. The matrix contains one row for each acoustic sample, which may include signal features such as energy and frequency and image features such as texture. Ancillary variables include bathymetry, geological maps, etc.

Acoustic samples	Features matrix: Energy, frequency, shape, texture, etc.																Ancillary variables						Ground-truth
1	F_{11}	.	.	.	.	.	.	.	.	.	.	.	.	.	.	F_{1R}	A_{11}	.	.	.	.	A_{IK}	–
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N	F_{N1}	.	.	.	.	.	.	.	.	.	.	.	.	.	.	F_{NR}	A_{N1}	.	.	.	.	A_{NK}	N_G
Validation	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Validation	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

5.2.2 Data conditioning

Common data-conditioning steps preceding feature extraction are listed in Table 5.2. Besides the obvious removal of echo spikes from electrical or acoustic interferences and other corrupted data, several data-conditioning steps have been used for different types of acoustic instrumentation. A calibrated echosounder (e.g. Foote *et al.*, 1987; Cochrane *et al.*, 2003) is desirable for consistency and to decouple acoustic features as much as possible from the acoustic gear and its setting (see Section 3). It is mandatory to obtain features that are expressed in absolute physical units, such as the root mean square pressure in Pa or volume and aerial backscattering strength in dB re $1\ m^{-1}$ and re $1\ m^2\ m^{-2}$, respectively. Such calibration concerns source level, pulse length, beam pattern, receiver sensitivity, and time varied gain (TVG) to compensate for spreading and absorption loss with range (r). Even when absolute physical units are not sought for the classification process, an accurate compensation for propagation loss is necessary when the data were not collected at constant ranges. The two-way TVG compensation depends on the water mass structure for the absorption coefficient and the sound speed used to estimate the range. In survey areas with stratified water columns, the TVG should consider the vertical profiles. For oblique transmission, such stratification implies refraction in the water column, according to Snell's Law, which changes the incident angles of the acoustic path with the seabed. This effect is particularly noticeable at high incident angles in multibeam echosounding and sidescan sonars (MBES and SSS) systems and it is often a first step in data-conditioning considerations. The pitch, roll, yaw, and heave of the measurement platform affect the incident angles of the sound wave and the range of the seabed echo. When these fluctuations are not automatically considered in real time, via a connection to a platform attitude system, they must be considered before feature extraction and corrections must be applied where possible. Alignment of bottom echoes in a series of pings according to some characteristics of the bottom echo and exclusion of high angular oscillations are among the usual corrections. The seabed local slope is another type of angular effect that can be considered in the estimation of the incident angles. Rejection of low SNR data and outliers and the averaging over a number of pings are essential to robust estimation of the average seabed backscattering strength. Such averaging, of course, is detrimental to spatial resolution, but is often well-justified by the usual high degree of overlap from ping to ping and the relatively large sample support (acoustic footprint size) given by the echosounder beam width and bottom range (see Section 6). Data conditioning for MBES data may include the removal of corrections that have been made during the acquisition process to enhance the bottom for range estimation, and subtraction of the along-track local trend.

Table 5.2. List of data-conditioning steps often used before extraction of seabed echo features. SBES = single-beam echosounders; MBES = multibeam echosounders.

DESCRIPTION	NOTE
Echosounder calibration	Foote *et al.*, 1987 Cochrane *et al.*, 2003
TVG adjusted to actual sound speed and absorption profiles	Hutin *et al.*, 2005
Normalization of maximum echo amplitude to 1 to remove the effect of propagation loss with range caused by spreading and absorption	Preston *et al.*, 2004b
Correction for refraction of beam paths in stratified water columns	Mitchell, 1996
Alignment of the bottom echo envelope through the ping series relative to a given threshold in the bottom echo rise	Sternlicht and de Moustier, 2003a, 2003b
Consideration of the pitch, roll, and heave fluctuations of the transducer platform (see Section 3)	Mitchell, 1996
Removal of range-dependent effects in computing E1 features by mean of a linear regression	Siwabessy *et al.*, 1999
Incident angle alignment by compensation for the range-dependent duration of the bottom echo leading edge by resampling (see Section 3)	Preston, 2003; Pouliquen, 2004
Rejection of side lobe bottom echoes in tilted SBES using time of flight and split-beam phase angle; rejection of data where ray bending due to sound speed profile was not negligible	Jackson *et al.*, 1986a; Jackson and Briggs, 1992
Taking into account the seabed local slope in estimating the incident angle	Stewart *et al.*, 1994
Alignment of bottom echoes, normalization of the amplitude to a maximum of 1, and summation by stacks of five pings	Preston *et al.*, 2004b
Average of backscattering strength over groups of 20 and 100 successive pings or time periods, rejection of low SNRs and significant angular oscillations of the platform	**SBES** Jackson and Briggs, 1992; Sternlicht and de Moustier 2003a, 2003b; Pouliquen and Lurton, 1994; Lurton and Pouliquen, 1994 **MBES** Hughes-Clarke *et al.*, 1997
Average of backscattering strength over 0.05 nautical miles or 20 pings at 10 knots in estimating E1 and E2 features	**SBES** Siwabessy *et al.*, 1999; Kloser *et al.*, 2002
Backscattering strength moving average on five successive pings along survey track, removal of depth trends in the backscattering strength features using a regression against bottom depth	**SBES** Hutin *et al.*, 2005
Multibeam backscattering strength correction, subtraction of the local trend estimated from a moving average along the survey track	**MBES** Kostylev *et al.*, 2001, 2003
Removal of automatic modifiers applied by MBES equipment manufacturer to bottom backscattering data, such as beam-pointing tramlines, Lambert's law, and centre beam smoothing	**MBES** Kloser *et al.*, 2002
Standardization of the features to the same numerical range and/or normalization	

5.2.3 Features

A short list of the features that have been extracted from seabed echoes is given in Table 5.3. They include reconstructed features of the seabed itself and signal or acoustic data features. The bottom depth, which is included here as an ancillary variable, is also considered as a feature when this information is available at high resolution from data acquisition systems such as MBES and SSS. In these cases, high-resolution relief or bottom roughness often becomes the main feature of the seabed classification; it is then presented in three-dimensional maps, where oblique illumination and surface reflections are tuned to enhance the seabed type of interest or are colour coded to allow three-dimensional viewing with appropriate stereo-viewing glasses. The widespread use of such maps for geological, sedimentological, and benthic habitat interpretation provides ample evidence of their importance for seabed classification in many disciplines. In addition, this basic information can be used to estimate additional seabed properties such as local slope and surface roughness on the scale of the measurements.

The extraction of additional properties of the seabed requires, however, much more information from the seabed echoes than their range given by time of flight and sound speed. The first series of additional features are estimates of the energy of the seabed echoes. For SBES, this energy is measured in different time windows, after the leading edge of the echosounder pulse has hit the bottom. The bottom echo amplitude first peaks (often to saturation in many echosounders) in response to coherent reflection near normal incidence, then decays down to a level at a rate that depends on beam pattern and seabed properties, while the pulse is gradually covering an increasing annulus size at oblique angles from the beam axis (see Section 4). The energy content and the duration of the tail of the seabed echo that follows the initial peak at normal incidence are often used to represent the seabed roughness from surface scattering and volume backscattering (see Sections 2 and 3). This is summarized by the E1 feature in the RoxAnn ASC approach. The energy content of the initial peak is thought to reveal the seabed hardness. For echosounders that are not saturating the bottom echo, or that are set to do so, this energy can be measured on the first bottom echo. Most often, it is estimated from the second bottom echo, after a first reflection at the sea surface and a second two-way travel to the bottom again. This estimate is known as the E2 feature of the RoxAnn ASC approach. Other energy features are the representation of the bottom backscattering strength profile by a series of discrete values characterizing the seabed echo and their descriptive statistics, such as the mean, standard deviation, histogram and quartiles values, probability density functions, or normalized cumulative function of the echo envelope, etc. Such features combine echo energy and shape information. A particular seabed echo shape feature for detecting and measuring seagrass and benthic algae in coastal areas can be obtained using a robust bottom tracking algorithm and a component of water column backscattering strength. Further information about echo shape and energy include the power spectrum and wavelet packet transform of the bottom echo signal, fractal dimension, and other statistics used with one-dimensional signal series or two-dimensional images (texture analysis) that are thought to be useful in discriminating the echoes for the objective of the study. Additional features obtained by other means of bottom sensing, such as small-scale bottom roughness spectra from laser ranging, grain-size statistics, seabed density, and sound velocity, are used for building models of bottom backscattering that can be used in seabed classification (see Section 2). Ancillary variables used in seabed classification or its interpretation include, of course, water depth and slope, speed and direction of currents, and temperature. Aerial photographs, especially from multispectral cameras, can be useful in shallow water along coastlines. Such continuous ancillary variables significantly correlated with the seabed classes of interest that are available everywhere in the study area can be formally integrated into the mapping process through spatial statistical methods and geostatistics (see Chilès and Delfiner, 1999) or used *a posteriori* for interpretation or Boolean combinations in geographic information systems (GIS).

Table 5.3. Non-comprehensive list of classification features and ancillary variables. SBES = single beam echosounding; MBES = multibeam echosounding; SSS = sidescan sonar; PDSSS = phase-difference sidescan sonar.

TYPE	DESCRIPTION	NOTE
Reconstructed seabed features	High-resolution bottom range and slope from time of flight	**MBES** all multibeam bathymetry maps
Signal or acoustic data features: (a) energy, (b) shape and incident angle response, (c) interrelation between successive echoes.	Bottom energy threshold and its continuity in a sliding window, range of energy threshold preceding the bottom pick, and its corresponding altitude	**SBES** Sabol *et al.*, 2002
	Square root of the ratio of the total significant energy of the second bottom echo to that of the first bottom echo, averaged over a number of pings	**SBES** Orlowski, 1984
	Sum of the energy from the tail of the first bottom echo (E1), used as an index representing the seabed roughness	**SBES** Chivers *et al.*, 1990; Heald and Pace, 1996; Siwabessy *et al.*, 2000
	Sum of the total energy of the second bottom echo (E2), used as an index representing the seabed hardness	*ibid.*
	Normalized cumulative function of the echo envelope	**SBES** Lurton and Pouliquen, 1994
	Probability density function of seabed backscattering amplitude	**PDSSS** Stewart *et al.*, 1994
	Cumulative normalized echo amplitude and ratios of samples of cumulative normalized amplitude, amplitude quantiles, amplitude histogram, power spectrum, and wavelet packet transform of the echo shape	**SBES** Preston *et al.*, 2004; Moszynski and Dung, 2000
	Profile of volume backscattering strength of the first bottom echo	**SBES** Sternlicht and de Moustier, 2003a, 2003b Hutin *et al.*, 2005
	Mean, standard deviation, and higher order moments, amplitude quantiles and histogram, power spectral ratio features, grey-level co-occurrence features, fractal dimension	**MBES, SSS** Preston *et al.*, 2004
	Residuals of the volume scattering strength (S_V) of the first bottom echo profile after regression on bottom depth	**SBES** Hutin *et al.*, 2005
	Bottom roughness power spectrum; slope of the averaged spectra in a given orientation	Briggs, 1989; Jackson and Briggs, 1992
	Bottom roughness expressed by the power spectrum of de-trended bathymetry, modelled by a power law, integrated over a band of roughness	**PDSSS** Stewart *et al.*, 1994
	As in the row above, but with bathymetry instead of de-trended bathymetry	**SBES** Sternlicht and de Moustier, 2003a, 2003b
	Similarity in proportion of the local variability of echoes described from principal components transform	**SBES** Kim *et al.*, 2002
	Seabed backscatter strength shape as function of the incident angle, described by a set of parameters	**MBES, SSS** Hughes-Clarke *et al.*, 1997
Ancillary	Water depth, slope, current strength, variance of temperature field over seasons	Kostylev *et al.*, 2001
	Aerial and multispectral camera images, satellite images	

5.2.4 Classification methods

The segmentation or partitioning of the whole dataset into homogeneous subsets of objects is here called classification. Strictly speaking, classification should be used when the classes are known or defined *a priori*, and the objects to classify must be sorted out into these classes. In the ASC literature, this is often referred to as *supervised* classification. The classification algorithm is then trained on a subset of ground-truthed samples of the seabed, where the classes are set *a priori* by the human "supervisor" according to his knowledge and objectives (e.g. classification of substrate types, particular biotopes, or habitats). When the classes are unknown *a priori* but must be differentiated by the algorithm partitioning the dataset into homogeneous subgroups, the ASC literature refers to this approach as *unsupervised* classification. These two approaches are conditioning the classification results. The classification from the supervised approach is highly dependent on the training dataset (its size, representativeness, and information content) defining the existing classes, while the classification from the unsupervised approach depends on the dataset variability, and therefore the seabed diversity, which is to some extent related to the size of the surveyed area in XYZ. A summary of classification methods is given in Table 5.4.

Classification methods are numerous, and the simplest one is the binary classification of objects according to a given value of a single attribute, such as seabed reflection coefficient, bottom hardness, slope or roughness thresholds, presence of sea grass, sand dunes, ripples, etc. Binary maps of this type can be generated easily by GIS software with two-dimensional quasi-continuous data, such as those from SSS or MBES systems, and contribute significantly to seabed classification. Multiple layers of such information can be combined with GIS tools or multivariate spatial analysis to extract particular seabed properties for specific classification objectives. However, in the general case, the information is not available everywhere and at the same scale for all features; the sorting thresholds or functions are not known *a priori* and statistical tests must be used to allocate an object to a population with a given probability at sampled locations. Classification of unsampled areas could take advantage of the spatial autocorrelation functions that characterize most variables and multivariates sampled in earth sciences.

In the simple case where only two attributes are available, the objects to classify are plotted in the two-dimensional space, and the data cloud is divided into subsets around points defining the different classes. An expert can do such segmentation from *a priori* knowledge of the boundaries between the classes. The classification of the sediment from the E1 and E2 features of the bottom echoes is an example of this approach. The segmentation of such bivariate data can be done with objective methods to allocate the objects to the nearest class centroid, initially computed from representative ground-truth data subsets in the supervised case, or using multivariate cluster analysis methods, as defined below, to sort the observations objectively into homogeneous subgroups in the unsupervised approach (see Legendre and Legendre, 1998).

When several features are involved in the classification, the problem is often simplified by principal component analysis (PCA; Legendre and Legendre, 1998) to summarize the information into a few orthogonal components, each explaining a decreasing proportion of the dataset total variance. The number of principal components (PC) to keep for the classification is open to debate (see Legendre *et al.*, 2002), but altogether they must represent the major part of the variance. It is useless to keep components that explain a proportion of the variance that is smaller than what is expected with an equal contribution of each component. Highly correlated attributes are redundant, and only one of them should be used in the PCA. Each resulting PC score can be mapped to see the spatial structure of this component of the seabed echo properties. A classification product may reveal interpretable patterns related to the objective sought or inherent properties of the dataset and analysis. By colour-coding the PC scores with primary colours for example, the maps can be combined into a single map to rapidly provide an unsupervised classification showing the spatial structure of the seabed variance. Other PC decomposition approaches are performed on sliding windows along surveyed transects to extract a single variable (cf. Kim *et al.*, 2002). Often, the first PC extracts the general trend, such as the relations with the bathymetry, the distance from the coast or topographic features, and the latitude and longitude. This may result from a real trend in seabed properties or from an artefact of the method (for example, as a result of increasing the footprint size with range). In the latter case, the masking trend should be removed (e.g. Hutin *et al.,* 2005) or the PC ignored in the classification process.

As for the bivariate case, the observations can be presented in the reduced features space represented by the PCs and sorted into classes according to their distance relative to the different constellations they form. Various clustering methods can be used here to find homogeneous subgroups in the whole dataset (Legendre and Legendre, 1998). A common one is the *K*-means partitioning, which separates the whole dataset into *K* non-overlapping subsets by minimizing the sum of within-group variance, using one of various algorithms (cf. Legendre *et al.*, 2002; Legendre, 2003; Preston 2003, and Preston *et al.,* 2004b). The determination of the optimal number of subdivisions, *k*, is performed by the experienced user guided with some statistics tracking the evolution of the segmentation process, or according to some objective statistical criteria including the fit with an assumed Gaussian multimodal model and Monte Carlo simulations (cf. *ibid.*).

Discriminant analysis (DA) is another common multivariate classification method that can be used in supervised ASC (e.g. Hutin *et al.*, 2005). Its aim is to find the best linear combination of the training dataset features that will maximize the difference among the predetermined seabed classes while minimizing the variations within the classes. The classification success of the solution can be estimated for each class, and the discriminant functions are used to assess the contribution of each feature to the classification. The unclassed observations are then allocated to the predetermined classes using the computed classification functions or from the minimum of their Mahalanobis distance from each class centroid (Legendre and Legendre, 1998).

Principal coordinate analysis (PCoA) and non-metric multidimensional scaling (MDS; cf. Legendre and Legendre, 1998) allow the use of features that are not quantitative (e.g. geological group) in the multivariate classification process. These Q methods (*ibid.*), however, require the computation of the distance matrix between all the objects to classify, and are therefore limited to small datasets.

One can think of other canonical analyses, such as redundancy analysis (RDA) or canonical correspondence analysis (CCA; cf. Legendre and Legendre, 1998), as additional multivariate analyses that can be exploited to classify the seabed for a given substrate or biotope with a supervised approach. These methods can produce a classification function for the ground-truthed training dataset, described by a series of separate variables extracted from direct samples (e.g. grain-size spectrum, list of species density) by maximizing a linear combination of the explanatory features from the acoustic data. The particular case of a single ground-truth variable is a multiple regression, and the computed least-square solution can be used as the classification function to apply to the rest of the acoustic dataset. In CCA, input features are nominal or rank-ordered classes organized in contingency tables. Therefore, CCA can accommodate several types of variables (continuous or not), notably when a continuous metric is not justified (e.g. low SNR, calibration, and propagation medium uncertainty levels), and shape of relation with the explanation variable (e.g. species preferences for some sediment grain size). Its implementation, however, is more laborious than RDA.

Common classification methods in engineering, including artificial intelligence or learning approaches such as neural nets, fuzzy logic, genetic algorithms, decision tree, vector quantization (VQ), Gaussian mixture models (GMM) classification, and dynamic time warping (DTW) are other methods of working with the feature matrix or its reduced version that can be explored for developing automatic ASC solutions (e.g. Dung and Stepnowski, 2000; Moszynski and Dung, 2000; Stepnowski *et al.*, 2003).

Seabed backscattering strength templates from acoustic models corresponding to different substrate or biotope classes can also be used as references for the classification with the supervised approach, using one of the above methods to allocate the observations to the most similar class (e.g. Lurton and Pouliquen, 1994). Various textural analyses of two-dimensional SSS and MBES acoustic images can also be incorporated in a seabed classification scheme.

All supervised methods depend strongly on their training dataset. Large, representative training datasets are therefore required. To improve the robustness of the solutions, jackknife or bootstrap methods can be applied in the development of the solutions from the training dataset. A part of the training dataset can also be reserved to serve as validation samples (Table 5.1) for assessing the performance of the classification, i.e. how it meets the objectives established initially. Such validation with independent samples, collected before or after the classification according to a sampling plan, is an essential final step of the processing, giving the significance of the performed ASC and the limits of its interpretation and usage.

5.3 Conclusions

Classification methods are numerous, and only a few of them have been exploited so far in ASC. The wide range of possible data-analysis paths is summarized in Figure 5.2. The diversity of methods offers the versatility required for addressing the large variety of specific problems and objectives that we can find in ASC applications in several disciplines. Their use will require special attention through all the various steps of the classification process, from the definition of the objective and data collection to the final classification. An emphasis should be put on the proper acquisition, extraction, and identification of the discriminant features – the prerequisite condition to successful classification with any algorithm. The robustness of the solutions, as well as the possibility for generalization – a goal requiring substantial further research – will depend on the efforts and care expended at each of these steps. Local and specific solutions to particular problems, however, are already available, even when limited to high-resolution multibeam bathymetry and relief, and are improving rapidly with the development of new acoustic systems, the increasing information richness to feed the discrimination algorithms, and the growing multidisciplinary expertise and basic knowledge of ASC.

Table 5.4. Non-comprehensive list of classification methods. SBES = single-beam echosounding; MBES = multibeam echosounding; SSS = sidescan sonar.

TYPE	DESCRIPTION	NOTE
Subjective methods		
Expert intervention	Geological interpretation of high-resolution multibeam bathymetry and backscattering strength with ground-truth samples published in a geological journal (Todd *et al.*, 1999), and the affinity of community assemblages to the sediment types to produce an interpreted habitat map	**MBES** Kostylev *et al.*, 2001
	Sediment type classification by the expert according to the histogram of bottom reflection coefficients compared with ground-truth samples	**SBES** Orlowski, 1984
	Biplot of E1 vs. E2	**SBES** Chivers *et al.*, 1990; Bax *et al.*, 1999
	Expert reinterpretation of the catalogue of acoustic classes produced according to the QTC supervised approach, for a post-classification using additional information on the study area based on submersible observations	**SBES** Anderson *et al.*, 2002
Objective methods		
R-analyses	Biplot of the first PCs of separate PCAs of E1 and E2 measured at 12 kHz, 38 kHz, and 120 kHz, followed by *k*–means partitioning	**SBES** Siwabessy *et al.*, 2000
	Classification index based on PC transform (Karhunen–Loeve) of the echo shape	**SBES** Kim *et al.*, 2002
	PCA ordination of the seabed echo score on the first PC as the first step in the ASC	**SBES** Preston *et al.*, 2004; Hutin *et al.*, 2005
	Discriminant analysis (DA)	**SBES** Hutin *et al.*, 2005
	Canonical correspondence analysis (CCA), redundancy analysis (RDA)	cf. Legendre and Legendre, 1998
	Images of parameters of the seabed backscattering strength angular response and extraction of seabed type typical responses	**MBES** Hughes-Clarke *et al.*, 1997
	Vector quantization (VQ), Gaussian mixture models (GMM), dynamic time warping (DTW), neural network, fuzzy logic, decision tree	e.g. Dung and Stepnowski, 2000; Moszynski and Dung, 2000; Stepnowski *et al.*, 2003
Q-analyses	Various cluster analysis methods	cf. Legendre and Legendre, 1998
	Other Q analyses, such as principal coordinate analysis (PcoA), non-metric multidimensional scaling (MDS), may be useful for small datasets and non-quantitative features	
R-Q analyses	PCA ordination of the seabed echo shape or features on the three first principal components followed by a *k*-means cluster analysis on these three-dimensional PC scores	**SBES** QTC-analysis
	K-means clustering of scores on PC with eigenvalues >1 of depth de-trended volume backscattering strength (S_v) profile of the first bottom echo	**SBES** Hutin *et al.*, 2005
Models	Extraction of geoacoustic parameters from the bottom echo envelope using a physical model of bottom backscattering	Jackson and Briggs, 1992; Sternlicht and de Moustier, 2003a, 2003b
	Classification of measured seabed echo shape given by the normalized cumulative backscattering strength according to seven seabed types from a theoretical model, taking into account the sounder characteristics and bottom range	**SBES** Pouliquen and Lurton, 1994; Lurton and Pouliquen, 1994
Textural analysis	Various textural analyses of seabed acoustic images	**SSS, MBES** e.g. Blondell *et al.*, 1998

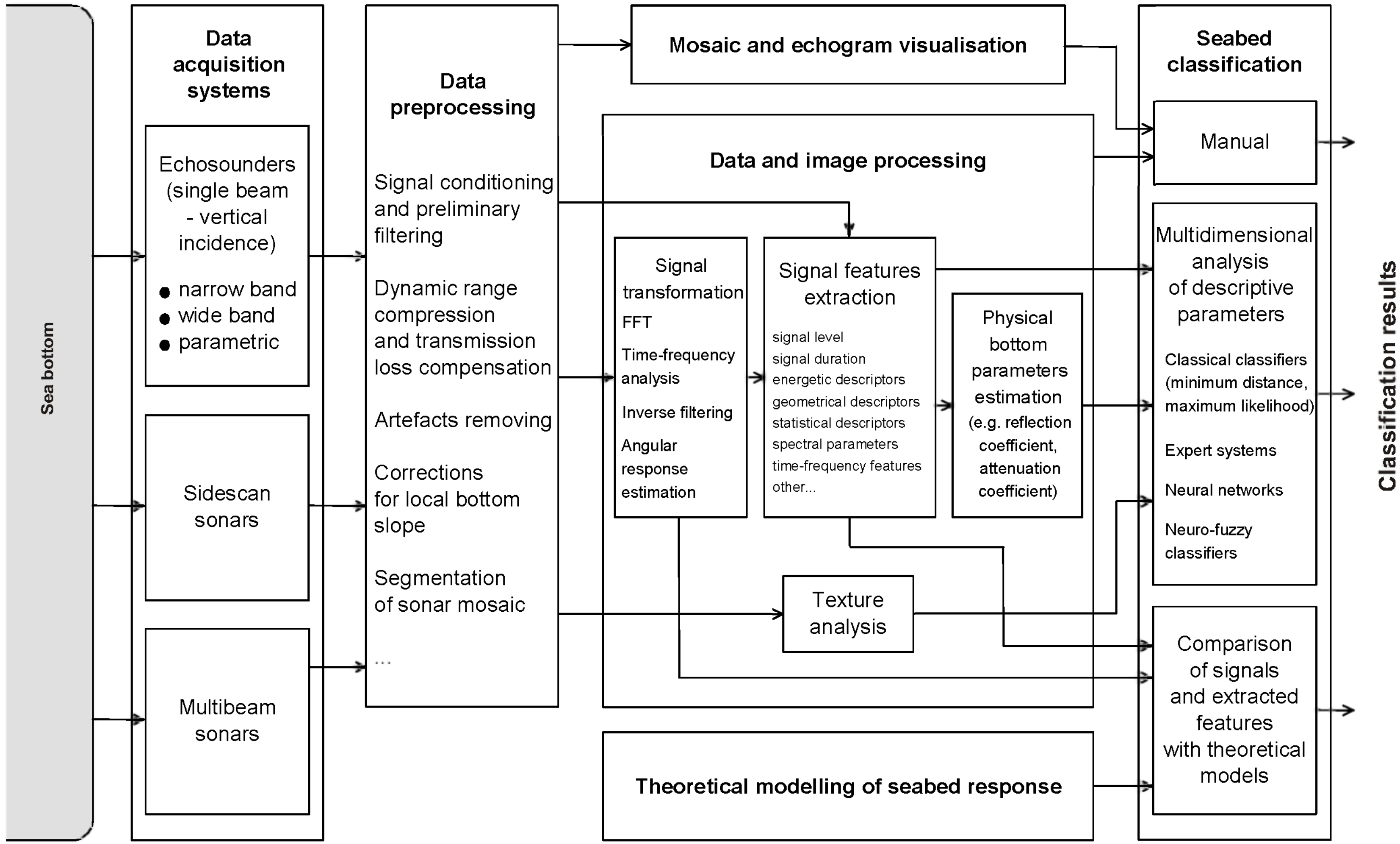


Figure 5.2. Schematic diagram of acoustic data-processing paths and methods of seabed classification.

6 Accounting for spatial and temporal scales and interpolation in acoustic seabed classification surveys

David Reid

6.1 Introduction

One of the primary applications of acoustic seabed classification (ASC) systems is the development of maps that provide information about the seabed. The type of information of interest should determine the type of map and the spatial resolution of the surveying required. Terrestrial mapping provides useful examples of how this would work. It is possible to develop maps of large areas of a continent (analogous to ocean basins) that show broad-scale features: lakes, mountains, forests, cities, etc. We know that such features will conceal considerable variation within them, but we understand this when viewing such maps. We can then have maps of smaller areas at higher resolution, showing, say, green areas within cities, villages in the open country, etc. We can also have specific types of maps: physical, political, geological, biological, topographical, etc. Very high-resolution maps will usually be of very restricted areas. Boyd *et al.* (2005), discussing marine mapping, described this well: “There is generally an inverse relationship between resolution and spatial scale”. For instance, we could map the biota in a single small field on one farm. All this is well understood in terrestrial mapping. In the marine context, the system being observed is no less complex, but we often overlook the question of why we are mapping something and simply ask, for example, for a habitat map of the UK shelf area. However, as with terrestrial systems, the seabed has a nested series of significant spatial scales from the basin level down to cracks in rocks or interstitial pores in sand. The acoustic systems we have available to survey the seabed make the problem more intense. Acoustic surveys are expensive and time-consuming. ASC systems, in particular, but also visual systems, require ground-truthing data (see Section 8.3 and 8.4) to allow their interpretation; however, these are expensive and often difficult to co-locate with our remote acoustic data. Acoustic seabed classification systems can be used across a variety of different scales, from basins to areas as small as a few tens of metres, but the survey design, data acquisition and analysis, and interpretation will vary across these scales. Temporal variability makes the situation even more complex. In the terrestrial domain, a field can be seen as a field whether or not it contains cows or sheep. In the marine domain, an area of sand may look quite different from our ASC systems depending on the biota in or on it, for example, if there are burrowing organisms, such as heart urchins, which can be on the surface at one time and down in the substrate at another (Jumars *et al.*, 1996). Marine environments can change on a tidal, daily, multi-day, seasonal, and interannual timescale, because of anthropogenic, biological, or environmental factors. Many of these variations will give rise to changes in what is seen on both normal and oblique incidence systems.

The key element in dealing with the impact of spatial and temporal variability in ASC surveys is to understand the purpose and application of our mapping. There will be no single satisfactory approach to mapping marine seabed habitats. Each survey should be designed for purpose, and the issues of spatial and temporal variability should be taken into account in that design (see Section 9).

This section will deal with the issues of spatial and temporal scales separately for convenience, but it should be remembered that these tend to interact in any ASC survey and mapping exercise.

6.2 The five spatial scales for ASC surveys

We have identified five levels of spatial scale as important for consideration in ASC surveys. These are based on the tools available and the methods for their deployment, rather than any intrinsic characteristics of marine habitat. They are not, for instance, directly related to the proposed scales for marine habitat mapping (Greene *et al.*, 1999). Table 6.1 relates the five levels described here to the six used by Greene *et al.* Although not all these scales are completely relevant to ASC surveys, they are presented to illustrate the scales across which ASC surveys are useful and their limitations. The five scales are:

Fine-scale structure	<1 metre
The Footprint Scale	~5–50 m
The Transect Scale	~50 – 500 m
Scales Between Transects	~100 m–2000 m
Scales between Strata and Survey Areas	>2000 m

Each will be dealt with separately.

Table 6.1. The five spatial scales can be related to the six used by Greene *et al.* (1999) for habitat description.

Type	Scales	Habitats (Greene *et al.*, 1999)	Survey scale (*depth-dependent)
Basin	>100 km	Megahabitats	Between surveys
Large	10–100 km	Megahabitats	Between strata and surveys/transects
Medium	1–10 km	Megahabitats	Between transects, between strata
Small	100 m to 1 km	Mesohabitats	Transects, between footprints*
Very small	10–100 m	Mesohabitats	Footprints*
Ultrasmall	1–10 m	Macrohabitats	Inside footprint* (fine-scale)

6.2.1 Fine-scale structure

It is difficult to assume any lower limit to the spatial scales at which one could monitor any given seabed. In most cases, it is likely that this will continue down to submillimetre level. For example, sand-grain size and/or form (rounded or sharp) may vary on very small scales. In turn, this will have an effect on the type and abundance of the interstitial or burrowing organisms that will occupy the area. Surface textures, as seen with oblique incidence systems, will also vary down to the centimetre or millimetre level, for example, the presence of small invertebrates on the surface at different times of day (Richardson, *et al.*, 2001; Kringel, *et al.*, 2003). One system that is able to work at these scales is the Dynamically Responding Underwater Matrix Sonar (DRUMS). This is a broad-frequency spectrum and narrow-beam acoustic system that has been used to look at macrofaunal structures such as tubes, burrows, and mollusc shells (Guigné *et al.*, 1993). It has also been used to look at the impact of trawls on the high-resolution structure of soft seabeds (Schwinghamer *et al.*, 1996). Alternative systems, using synthetic aperture sonar, have been developed in the defence industry (see review by Hayes and Gough, 2004). This technology is generally used for mine hunting (Hetét *et al.*, 2004), but may also have applications in more general imaging of the seabed. Kenny *et al.* (2003), in their review of seabed mapping technologies, suggested that, at these scales, appropriate methods included: grab or core sampling, sediment profiling cameras, or X-ray photography. For surface observations at this scale, good-quality TV systems would be appropriate (see Section 8).

6.2.2 The footprint scale

For ASC systems, the next scale of variability is at the scale of the acoustic footprint – that piece of seabed insonified by the beam for normal incidence systems or beams in the case of midbeam echosounder (MBES) or sidescan sonar (SSS). The size of the footprint depends on the beam angle, the range from the instrument to the seabed, and the system used.

Beam angle

The echosounder acoustic beam can be seen functionally as a cone, with its base on the seabed. The solid angle at the base of this cone is defined as the equivalent beam angle of the transducer. The beam angle will determine how wide the cone or beam will be. Most modern transducers are supplied with a beam angle specified by the manufacturers. In practice, the beam angle and the beam pattern are not precisely what would be expected from theory, but are reasonably close (Simmonds and MacLennan, 2005). The acoustic energy in the beam is highest on the axis of the transducer, i.e. the centre of the beam, and will fall off as the angle away from the acoustic axis increases. The definitions provided by Simmonds and MacLennan may not be completely applicable to calculating a footprint for single-beam echosounder (SBES). For example, RoxAnn integrates the tail of the first bottom echo to provide E1 (Burns *et al.*, 1985; Chivers *et al.*, 1990), and this is considered as coming from the edges of the beam, hence the longer time to receipt. It is not clear how far out the "edges" of the beam might be. Close to the axis of the sounder, the beam generally completely insonifies a circular area of seabed. However, farther off axis the insonified area is actually best represented as a ring (see Sections 3, 4, and 7). This is because the tail edge of the pulse on-axis takes less time to reach the seabed than the *leading* edge of the pulse at large angles off-axis. For more information on footprint, see Section 4. Foster-Smith and Southeran (2003) recommend a beam angle of between 15° and 25°, although many modern fishery echosounders will have narrower beams.

For multibeam systems, the footprint is more complex to calculate, being an ellipse at near normal incidence and changing to a thin rectangle at higher incident angles (see Section 7 and de Moustier and Alexandrou, 1991). However, it should be remembered that resolution within that overall footprint is defined by the footprint of the individual beams making up the full swathe. For instance, Hughes-Clarke *et al.* (1998) calculated that a multibeam with 1.2° beams was poor at resolving objects smaller than 2 m in 40 m of water.

Range

Clearly, if the beam can be considered as a cone, the base of that cone will increase with the range, and will be circular in cross section. At close range, the footprint will be small and will be larger with increasing range. This is illustrated for an echosounder with an 11° beam in Table 6.2. This is, however, only the theoretical footprint, and only within the 3-dB points. As discussed above, the effective footprint could be much larger (see Figure 4.1).

Table 6.2. Examples of 3-dB footprints at various ranges for a 11° echosounder beam.

RANGE (m)	FOOTPRINT DIAMETER (m)	FOOTPRINT AREA (m^2)
10	1.9	11.7
30	5.8	104.9
50	9.6	291.3
100	19.3	1165.1
150	28.9	2621.5
200	38.5	4660.4

An additional complication is that real surveys will probably be carried out from a vessel, which will not generally be a stable platform. Each ping will also have a position stamp, generally provided by a GPS navigator, adding more uncertainty. To illustrate, for a 15° beam, given 5° of movement, a GPS uncertainty of 8 m, and a range of 100 m, our theoretical footprint of 26-m radius, or 530 m^2, is actually taken from somewhere within a possible circle of 40-m radius or 1250 m^2.

The ASC data from this footprint will be an integration of the whole area. As discussed above, there is likely to be variability within such a footprint. So the signature obtained could be for a particular combination of substrates with patchiness at a smaller scale than our observation footprint, e.g. sand trenches in bedrock or sea grass patches. The operator must then decide if this is acceptable for the type of map he aims to produce and the degree of ground-truthing available.

In broad terms, multibeam systems are likely to provide better resolution than normal-incidence, single-beam systems, although they too have their limitations in terms of the size of detail they can resolve (Miller *et al.*, 1997; Kenny *et al.*, 2003). To illustrate, for the sounder system described above, the theoretical footprint at 40-m range would be a circle of diameter 7 m. This is based on the 3-dB beam angle, and would be greater for systems that use the tail of the first echo. At similar range, the multibeam system described by Miller *et al.* (1997) was unreliable below 2-m resolution.

Potential sampling areas (per hour) and resolutions for a range of acoustic systems scale over several orders of magnitude (Table 6.3). Actual resolution will depend on range; greater range would provide lower resolution.

Table 6.3. Potential area mapped per hour and horizontal spatial resolutions for six types of acoustic seabed classification systems (after Kenny *et al.*, 2003).

Acoustic system	Approximate area mapped ($km^2 h^{-1}$)	Minimum resolution (m)	Optimum resolution (m)	Maximum resolution (m)
Chirp type side scans	10	100	1	1
Multibeam echosounders	5	100	1	0.1
Standard side scans	3.5	100	0.1	0.01
Synthetic aperture sonars	3.0	0.1	0.01	0.001
Single-beam AGDS	1.5	100	1	0.1
Acoustic sub bottom profilers e.g. DRUMS	0.8	1000	1	0.1

6.2.3 The transect scale

The next level up is the scale along the survey transect. For vessel-mounted systems and for a given depth, ping rate and survey speed will define the maximum resolution at which we can discriminate. This includes the effect of overlap of the footprints, or lack of overlap, and of the degree of correlation between the return on adjacent pings. For SSS, the general mode of deployment would be to have overlap between the footprints of adjacent pings. For MBES, the situation would be analogous to that of SBES, where the overlap would be a function of ping rate and vessel speed, although in a seabed survey situation, we would also want overlap between pings.

In general, we should be able to obtain relatively highly resolved data along the transect for any of the systems. A normal ping rate for a standard fishery echosounder in shelf waters would be in the order of once per second. At a sound speed of 1500 m s^{-1} this would allow the sound to travel to the seabed and back twice, as required to obtain the E1 and E2 values used by the RoxAnn or Echoplus systems, or the single path for the QTC system. Given a 100-m range, 15° receipt beam, 10 knots of speed and a 5°roll, we would have a footprint overlap of 600%. The same would be true of a sidescan system. Given a 1° beam angle, the beam would be about 1 m wide at 50-m range. With a repetition rate of 20 pulses per second and a vessel speed of 5 knots, this would give an overlap of 800%. This means that successive samples will not be independent observations. So, it would be reasonable to use some sort of averaging to combine a number of adjacent pings. This would be expected to reduce variance and increase the statistical independence of sequential samples (see Section 5).

One possible method for this would be to use a geostatistical approach to handle this type of potential pseudo-replication (Millar and Anderson, 2004). The nugget value, representing the unresolved local variability, could be considered as the measurement variability. We could then combine two or more adjacent samples to reduce the unresolved small-scale variability. The range of the variogram would also provide information on the spatial scale of variability along part or all of the transect, and would provide valuable information for determining the choice of transect spacing (Foster-Smith *et al.*, 2004), and for interpolation between transects.

Consider how this might work for SBES data measuring seabed roughness for the tail of the first return echo (E1, Figure 6.1). The left panel shows E1 values in raw form, then at three different levels of moving average (5, 15, and 30 pings). The reduction in the nugget effect can be seen in the right panel. The use of an averaging interval of 15 or above has reduced the nugget to close to zero, while retaining the range and the overall structure of the variogram. It is also possible to see two elements of the variogram at ranges of approximately 200 m and 600 m. Transect spacing of 200 m would then encompass both these features.

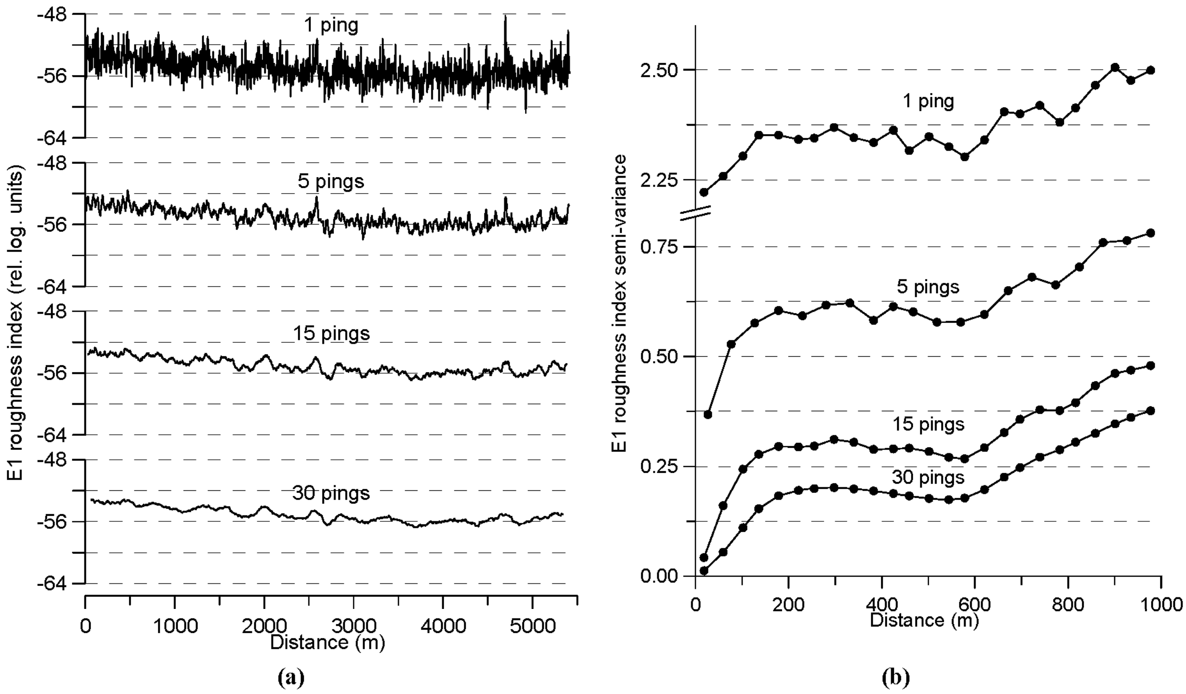


Figure 6.1. Example of seabed roughness (E1) variability damping with the size of ping integration bins along a 5.5-km transect surveyed at 9–10 knots on a 75–85 m deep scallop bed lying on a sandy bottom, from a 7° transducer at 38 kHz. The inter-ping distance is about 5 m. (a) Dataseries for different moving averages, (b) corresponding variograms (note the broken *y*-axis).

An example of geostatistics in seabed mapping is provided by Murray *et al.* (2002). For general texts on the use of geostatistics see Goovaerts (1997) or Chilès and Delfiner (1999); for a text written for fishery scientists, see Rivoirard *et al.* (2000).

It may also be possible to use the ping-to-ping variability, at different levels of combination, to provide information on seabed homogeneity along the transect. An example of a similar approach would be that used by Legendre *et al.* (2003). These authors used a *k*-means approach to cluster the variables used in QTC systems, then incorporated a matrix of geographic contiguity (Legendre and Legendre, 1998). These were then linked into geographically consistent subsets.

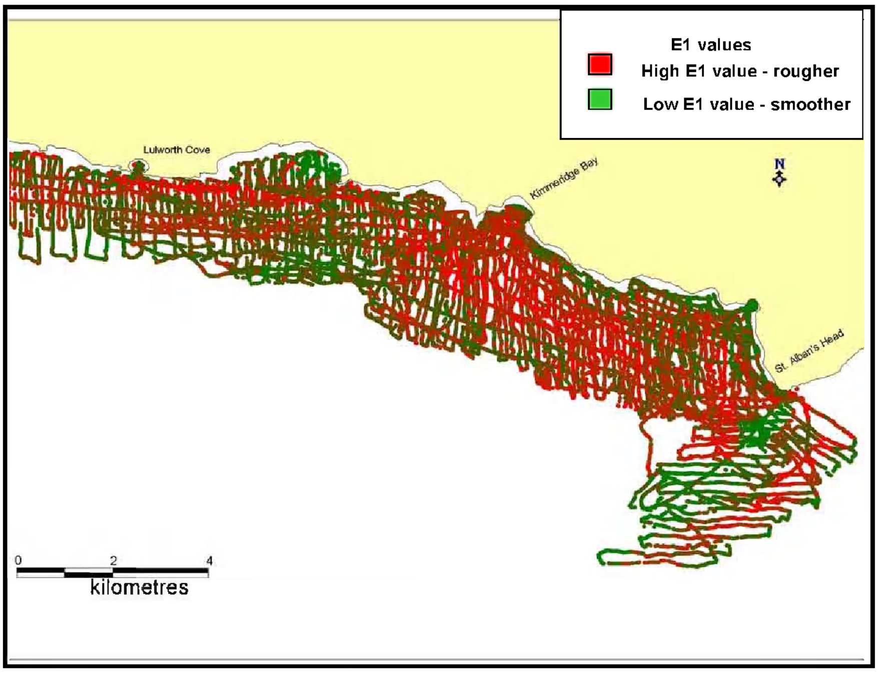
There is also potential for different correlation structures at different points along the transect or in the survey area. This could then be used as an effort stratification criterion, with areas of high variability being mapped more intensively, i.e. with closer transects. However, it would be necessary to check first for anisotropy in the data. If the variability along the transect was different from that in other directions, say normal to the transect, then this would have to be used with caution.

6.2.4 Scales between transects

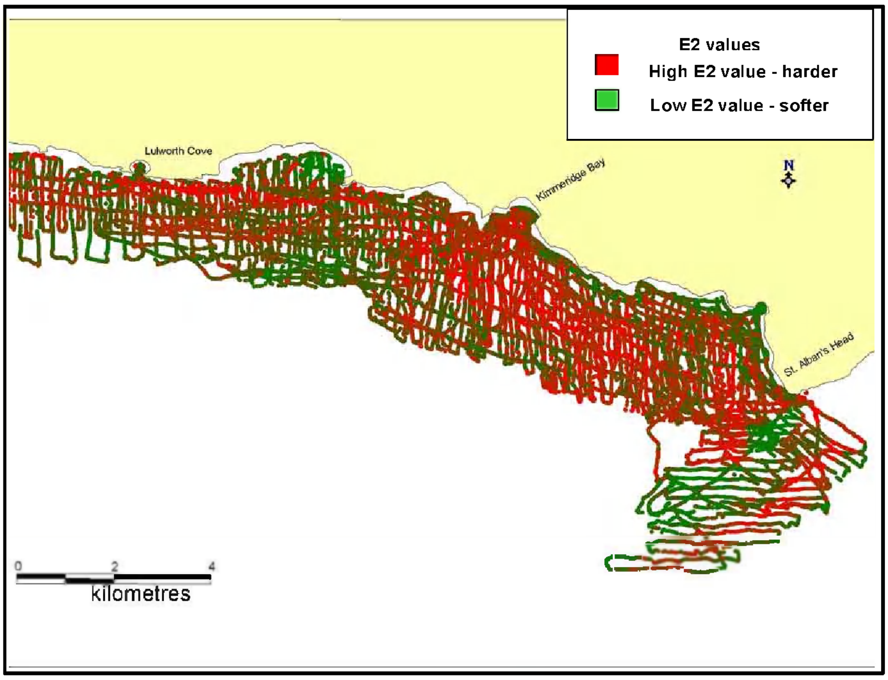
The next scale is between survey transects. In general at this level, the situation is probably different for SBES approaches, compared with SSS and MBES methods, because of the swathe width covered. SSS and MBES systems have a much larger coverage to the side of the vessel and are often operated with a transect spacing that allows overlap of the recordings from adjacent transects. In most cases with SBES systems, we would expect to have to interpolate between transects to produce a map of the survey area. The same would be true of SSS or MBES if the spacing were greater than the range of the instrument. The key question is: how far apart transects can be and still allow valid interpolation? To some extent this can be determined by the degree of along-track correlation, i.e. the spatial scale of the features of the seabed, and also the purposes of the survey.

With MBES, as with more conventional acoustic survey methods, we tend to have highly detailed data available along the transect and much less across the transects. One possibility would be to include tie-lines or transects placed normal to the main transects. In the absence of these, therefore, the choice of transect spacing becomes critical. The key factor in determining the transect spacing should be the type and detail of the map we wish to produce. However, it should also be possible to use the information on variability *along* the transect to help determine an appropriate distance *between* the transects. As described above, transect spacing could be determined using a geostatistical approach, using the range of the variogram as a guide to the distance between transects. If there is a large nugget effect (unresolved small-scale variability), that may also suggest closer transects. Other factors that should be taken into account include the depth and footprint interaction described above, the depth in the survey area, and the presence of islands, cliffs, etc. Generally, the smaller the footprint, the closer together the transects should be. Topography and substrate in shallow areas will generally also have more variability than in deeper areas, as will areas of high relief, e.g. the west coast of Scotland, which is characterized by many areas with sharp peaks and rocky outcrops, compared with the Wadden See, which generally has a flat, muddy, or sandy seabed. In shallow or complex areas, therefore, transects should be closer together.

Foster-Smith *et al.* (2001), considering coastal-zone surveys in particular, recommended a transect spacing of no more than 500 m. Davies *et al.* (1998) recommended 250 m for broad-scale mapping and 100 m for detailed resource mapping. The maps illustrated in Figures 6.2 and 6.3 are from a survey by Foster-Smith *et al.* (2001) and illustrate the effects of different transect spacing. The maps are coloured according to the E1 and E2 values used in RoxAnn, and are categorized as “roughness” and “hardness”. In the complex inshore areas, closer tracks were used than in the more uniform offshore areas. The increased substrate complexity can then be seen in the classification map (Figure 6.3a) and in the final substrate map derived from these data (Figure 6.3b). The chosen differences in track spacing represent the type of effort stratification discussed in more detail in Section 9.

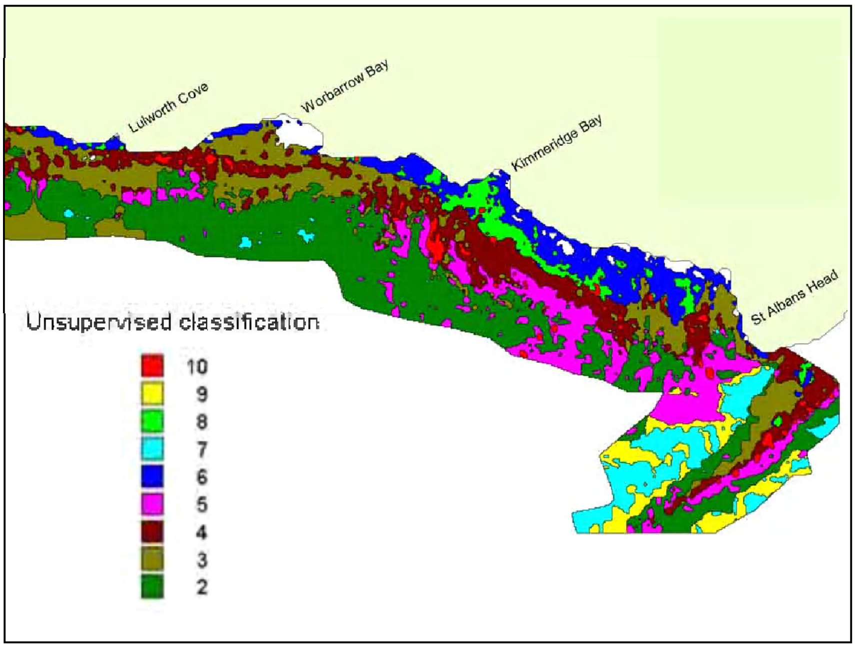


(a)

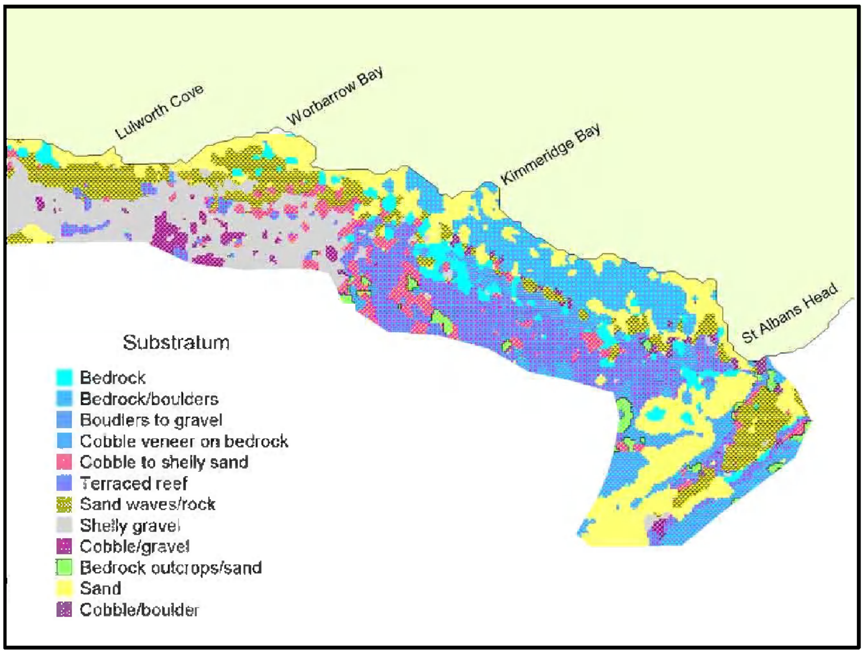


(b)

Figure 6.2. Surveyed area showing the track layout and (a) RoxAnn E1 and (b) E2 values (after Foster Smith *et al.*, 2001).



(a)



(b)

Figure 6.3. Based on the data collected by Foster Smith *et al.* (2001; Figure 6.2). (a) the resulting classification maps from the RoxAnn data and (b) the final substrate map from these data.

6.2.5 Interpolation between transects

There are many different approaches to interpolating between tracks. Here we deal with four of the most common tools applicable to these data. These are presented with their likely advantages and disadvantages. Detailed methods are not covered, but references are provided. Many interpolation approaches lead to maps of the data. However, it should be emphasized that this section focuses on how and what to interpolate rather than on mapping *per se*. For overviews of the different methods and other aspects of spatial statistics, see Schabenberger and Gotway (2004) or Ripley (2006). Venables and Ripley (2002) provide a valuable reference source for using many of these routines in S+. There are many routines for the interpolation of spatial data in commonly used languages. The best sources are:

www.CRAN.R-project.org or www.r-project.org for R routines

www.mathworks.com/matlabcentral for MatLab users.

One of the commonest software tools used for interpolation and surface construction is SURFER, http://www.goldensoftware.com/products/surfer/surfer.shtml. SURFER provides twelve different interpolation tools:

- Inverse distance to a power
- Modified Shepherd
- Minimum Curvature
- Natural Neighbour
- Nearest Neighbour
- Polynomial regression
- Radial Basis functions
- Triangulation with linear interpolation
- Moving average
- Data Metrics
- Local polynomials
- Kriging

The methods highlighted here are:

- Nearest Neighbour
- Inverse distance to a power
- Kriging

We have also considered generalized additive or linear models. It is not our intention to provide a comprehensive guide, but to indicate some of the possibilities available for interpolation of acoustic seabed data.

Nearest Neighbour

This method simply takes the point nearest the interpolated point and uses that value. One advantage is that it is relatively simple. It produces no artificial or meaned data points, so it uses a real data value that can be associated with ground-truth, if required. It would be expected to work well in gaps along transects and with evenly spaced data, but the latter case is probably rare in the type of data considered here. The disadvantage is that it produces a weak and potentially spurious interpolation between transects. The resultant map tends to be very “blocky”. The nearest neighbour method is increasingly weak at long range, and uses no information other than the single point from which the interpolation is derived. Because this approach uses a single point for interpolation, it is also vulnerable to interpolations of errors in the data. This is less of a problem for those approaches using multiple neighbouring points. Nearest neighbour algorithms are provided in both R and MatLab. An even simpler and related approach is to carry out the interpolation manually (e.g. Boyd *et al*., 2005). In such cases, the analyst is basically interpolating using the nearest observed data and is also extrapolating contours between adjacent tracks by eye. In this example, the relationship between the tracks and the interpolated maps becomes immediately obvious, and in such situations the nearest neighbour method is arguably as effective as any more complex approach.

Inverse distance to a power

With this method, numbers of points can be used with their weighting being smaller with increasing range. This depends on the power function used and the choice of range. With powers greater than two, it provides good adherence to the nearest data and works better between transects than nearest neighbour. It is most valuable when the continuity of the data is in doubt. Its major disadvantage is that it tends to create hot spots. With powers between 1 and 2, it also provides reasonable adherence to nearest data and tends to smooth out hot spots. It is likely to be good for general trends with wide transect spacing. The major disadvantage is that it tends to smooth out any local variability. For an excellent example, inverse distance squared was used for the interpolation of RoxAnn data by Brown *et al.* (2005). The authors used a pixel size (i.e. the grid used) of 10 m^2, corresponding to the system footprint at the survey depth, and used a search radius of 150 m, corresponding to the smallest sill on the experimental variograms. This approach, using information from the dataset to parameterize the interpolation, is much better than using arbitrary values, possibly chosen to make a "good" map. The data interpolated were E1, E2, depth, and the acoustic variability. The modified Shepherd method uses inverse distance least-squares and is broadly similar to inverse distance, but the local least square approach can reduce or eliminate hot spots.

Kriging

Kriging has achieved wide use in the analysis of fisheries data (Rivoirard *et al.*, 2000). This approach is more mathematically complex, using the local correlation structures (the variogram) to calculate the interpolation. It can use ancillary data, e.g. depth, to assist in the interpolation. It is mathematically robust and works well with regular and close transects. Issues of statistical stationarity and isotropy need to be considered.

The simplest version of kriging is ordinary kriging, in which the variogram is calculated and modelled in space from the original variable, e.g. E1. The kriged map honours the original points, although the interpolated points will be some average of the local sample field. It is also possible to use another related variable to improve both the quality of the relationship and the subsequent map. An obvious example would be to use depth as an auxiliary or covariable. A number of methods are available, such as co-kriging, in which all covariable values in the neighbourhood are used, or co-located co-kriging, which uses the covariable information at the sample points. Alternatively, if there is a trend in the primary data that can be explained (at least in part) by a covariable, then kriging with external drift can be used. An alternative approach to smoothing with these methods is to use the analysis to create a simulated map.

For further information on these methods see Goovaerts (1997) or Chilès and Delfiner (1999), Most of these methods are also implemented in R or MatLab routines.

Generalized additive or linear models

Generalized additive or linear models (GAM/GLM) have been used extensively in fishery science to map fish and plankton abundance, e.g. Beare and Reid (2002), Maravelias *et al.* (2000), Augustin *et al.* (1998). These models assume that the mean of the dependent variable depends on an additive predictor through a non-linear link function. So, they can be used to model and interpolate acoustic ground discrimination system (AGDS) data that are based on location and a range of external variables, e.g. depth. A major advantage of the method is that it allows the use of a number of auxiliary variables. A drawback is that GAM will fit smoothed regressions through the observed data and so does not honour the original data. However, the extent of this smoothing is often difficult to determine, though it can be checked by post-validation. Using GAM interpolations of, for example, E1 and E2, may then result in artefacts. Examples of the use of GAM/GLM in mapping marine habitats can be found in

Garza-Perez *et al.* (2004) and Stoner *et al.* (2001). The classic text on GAM is Hastie and Tibshirani (1990). GAM/GLM routines are available for both R and MatLab.

Other methods used in SURFER

Natural Neighbour – This approach uses polygons between data points, then adds a new (to be interpolated) point and recalculates the polygons. The area "borrowed" from the original polygons is used as a weighting factor to average neighbouring data points. One advantage of this approach is that it does not extend contours outside the data range.

Minimum Curvature – This approach generates the smoothest possible plane and tries to honour the original points, but not completely. It tends to produce highly smoothed outputs.

Polynomial regression – Rather than straight interpolation, this approach looks for large-scale trends or patterns in the data rather than predicting on a grid. The output will tend to be highly smoothed and may not honour the data points.

Radial basis functions – These are approaches that can be seen as analogous to artificial neural nets and are designed for datastreams rather than datasets. They are generally exact interpolators and will honour the original data.

Triangulation with linear interpolation – This approach creates a triangular tessellation, with points on the interpolation grid within each triangle being calculated from the tilt and elevation of the triangle. The method honours the original points and is best on regular data. It can tend to produce large triangular elements in data-sparse areas.

Moving average – This approach creates an average within an ellipse, centred on each grid node. The ellipse needs to be large enough to avoid blanking if not enough points are available.

Local polynomials – This method uses a weighted least-squares fit from within a search ellipse.

Data Metrics – Although available in SURFER, this is not technically an interpolation tool, but provides information for each point and its relationship with its neighbours.

The author drew heavily for the other SURFER interpolators on a review of this software written by Yang *et al.* (2004), available at:

http://www.isprs.org/istanbul2004/comm2/papers/231.pdf

In general, it should be noted that in some of the approaches described above, the interpolation method will honour the original points, e.g. nearest neighbour methods or the variety of kriging approaches. Other approaches, particularly the regression approaches such as GAM or polynomial regressions, may not honour these original points and tend to smooth the points. Neither of these approaches is wrong; the approach used will depend on the purpose of the mapping and on the use to which it will be put.

What to interpolate?

An additional matter to consider is what we wish to interpolate. Do we use measured variables or derived substrate classes? In the case of RoxAnn or QTC we have a set of continuous variables or vectors (E1 and E2, Q1–3), so these are well-suited for interpolation. However, if we interpolate each one individually, we might generate "artificial" combinations that were not seen in any of the real data points. Where these correspond to one of the observed substrate classes, the interpretation is reasonably simple. It becomes more difficult, and arguably wrong, when it does not. An extreme case might be when we had two adjacent transects, one all hard rock, the other all soft mud. If we interpolate each vector individually, we may end up with intermediate values that were never actually seen and that could be interpreted as a third ground type. Linear or nearest neighbour interpolation can retain the original values most easily, but there may be problems in many interpolators. The key point is that what we wish to interpolate is the mode of our data and not the mean. Creating new, arguably artificial, combinations of our extracted parameters is not desirable.

Substrate classes themselves are categorical rather than continuous, and so are less simple to interpolate. Nearest neighbour is probably the simplest to realize, and interpolation will be of "real" observed seabed classes. It is probably most appropriate with a small number of categories and a consistent pattern on multiple tracks. Geostatistics can also provide solutions, such as indicator kriging (Caeiro *et al.*, 2003) or covariable kriging, which can interpolate with categorical or binary data. A further possibility is to use disjunctive kriging (Chilès and Delfiner, 1999); however, this is designed more for data that are divided into classes than the categories we have in seabed classification. One alternative proposed for categorical data is kriging with categorical external drift (Monestiez *et al.*, 1999). It is also possible to use categorical variables in GAMs, although this has not so far been used in the context of seabed mapping. One approach would be to set up a multinomial model in which the probability of each substrate would be modelled occurring as smooth functions of say E1 and E2. If sediment type can be considered to have a "natural order", i.e. from rock to boulders down to fine mud, this would probably work well as a type of semi-categorical interpolation. One final possible tool in this context is the use of neural networks (Haralabous and Georgakarakos, 1996; Bishop, 1996; Lek *et al.*, 1996; Basheer and Hajmeer, 2000). Neural nets are often good at handling this type of non-linear problem and have been used in other mapping situations.

This discussion of interpolation has been aimed principally at SBES where, in most cases, it will be impossible to carry out an exhaustive full coverage with AGDS because of the relatively small footprint, and hence the larger distances between transects. SSS and MBES are generally operated to provide complete overlap of adjacent transects (e.g. Brown *et al.*, 2004b). This is more feasible with these systems because of the relatively larger width of the transect swathe. In some cases, however, this will not be possible (e.g. Boyd *et al.*, 2005) and interpolation will be required. One dubious advantage of SBES is that each sample, or group of samples, can only be interpreted in terms of a single category or classification because of the relatively small footprint. This makes interpolation relatively easy and allows the use of the simpler interpolation tools described above. With SSS and MBES, it is possible to get multiple categories of seabed in a single transmission, or series of transmissions, so the interpolation problem becomes more complex. In this case, interpolation could be carried out using a modelling approach, such as indicator kriging (Gossage, 1998).

Related to the interpolation of data *per se* is the issue of boundaries between mapped regions, e.g. biotopes, facies, or substrate types. In many cases, particularly in soft sediments, we would expect gradual changes in habitat rather than sharp borders. Eastwood *et al.* (2004) examined the potential for mapping habitats as continuous distributions. Their conclusions were that, although this was possible, the probabilistic maps were difficult to interpret. Greenstreet *et al.* (1997) adopted a similar approach to producing a map, based on the probability of encountering a particular substrate type or habitat. Again, the choice to be made between a deterministic or probabilistic approach depends on the purposes of the survey. If we are aiming for an overall map encompassing all the substrates encountered in the ground-truthing, a deterministic approach is probably best. If, however, we are interested in the distribution of only one or two categories, for instance cold-water corals, or maërl beds, then a probabilistic map may be better. This would indicate that a given area had a high probability of having these features, while another had a much lower probability.

The impact of transect spacing on survey interpretation

Two studies serve as examples of the impact of transect spacing and the types of interpolated maps that the interpolations produce. Both studies use many of the approaches described in this section and represent useful examples of acoustic surveys to map habitats. The first is from a study by Pinn and Roberston (2003), mapping habitats in the Minches on the west coast of Scotland. The second is from a study by Boyd *et al.* (2005), mapping gravel extraction areas in the English Channel.

The Pinn and Robertson (2003) survey used a RoxAnn system and a 38-kHz sounder. Transect spacing was 1 km. Analysis was performed at 1-, 2- and 4-km spacing. E1, E2, and depth data were interpolated using kriging, and classification was by unsupervised cluster analysis using a peak histogram technique (Richards, 1986). These clusters were then compared with substrate type, based on the ground-truthing samples. Variograms were calculated to examine appropriate interpolation distances (Pinn *et al.*, 1998).The study also looked at the pixel size in the gridding exercise and used three levels: 1000-m, 500-m, and 250-m pixels. The geostatistical analysis indicated that interpolation was probably valid out to 6 m. The results of the analysis at the three transect spacing and with 1000-m and 500-m pixels are presented in Figures 6.4. and 6.5.

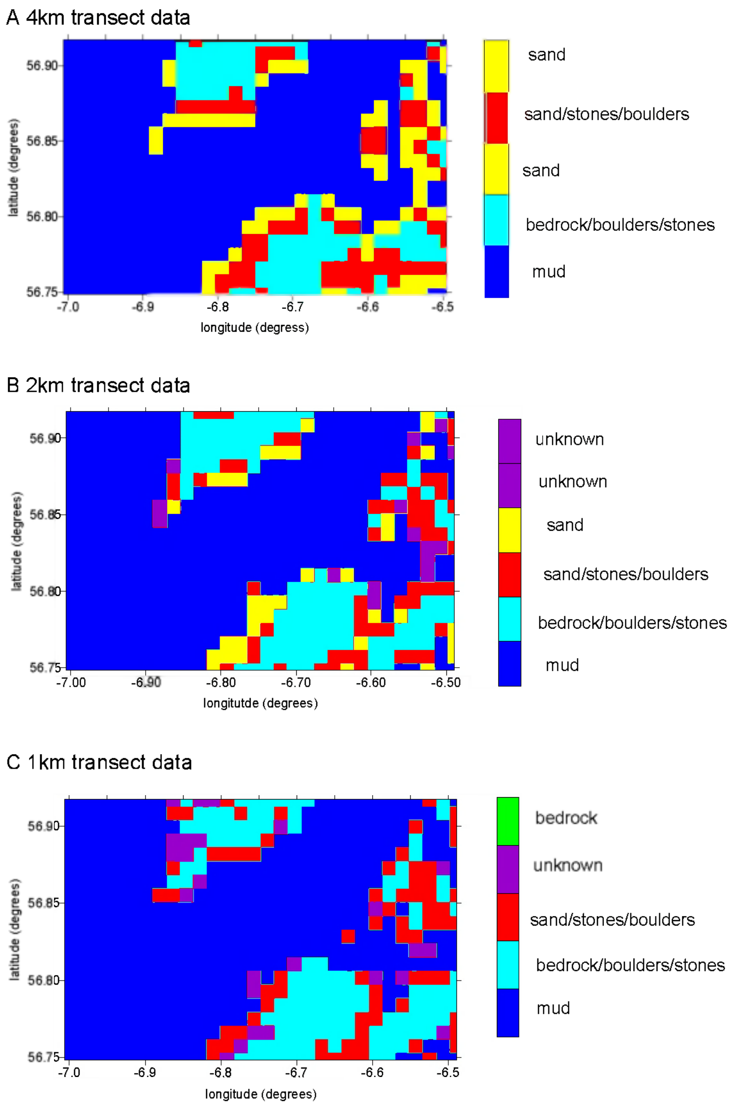


Figure 6.4. Mapped results from the analysis of RoxAnn data using three different track spacings of (a) 4 km, (b) 2 km, and (c) 1 km at 1-km pixels (from Pinn and Roberston, 2003).

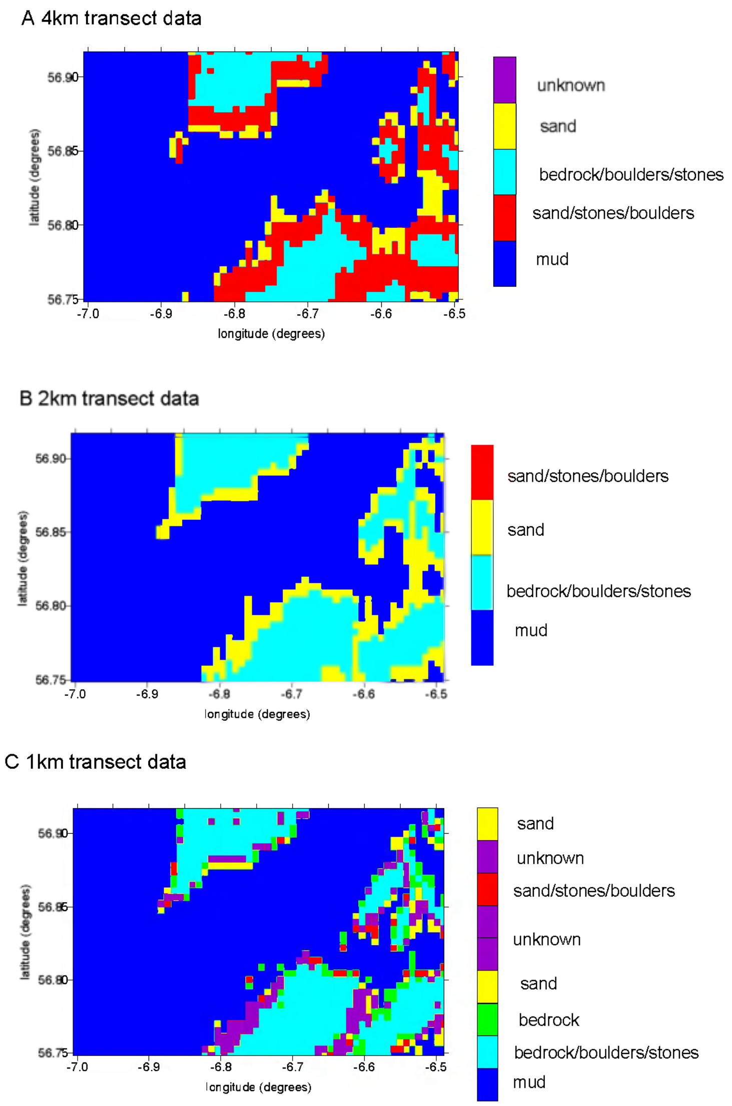


Figure 6.5. Mapped results from the analysis of RoxAnn data using three different track spacings of (a) 4 km, (b) 2 km, and (c) 1 km at 500-m pixels (from Pinn and Roberston, 2003).

The general substrate distribution was the same at all three track spacings, although there were differences in fine detail, particularly in the transition zones and with intermediate types, e.g. sand and sand/stones/boulders. The area covered by the sand/stone/boulder category was greatest at the 4-km spacing, while the area covered by the sand category was greatest at the 2-km spacing. The accuracy of the map (derived from the unsupervised cluster analysis) compared with the ground-truth stations was 73%, 93%, and 83% for the 4-, 2-, and 1-km spacings respectively. The study clearly showed that both track spacing and the dimensions of the grid over which the data were interpolated had an impact on the map produced. The authors identified a pixel size of 25% of the track spacing as being the best choice in *this* study, but this may well reflect the acoustic system used and the spatial scale of the variability in this area. The varying maps with different track spacings undoubtedly reflect the additional data available to the analysis with more track data.

The second study, by Boyd *et al.* (2005), used a sidescan system to provide the survey data. The analysis was based on data collected and reported in Brown *et al.* (2001) and Foster-Smith *et al.* (2004). These data comprised tracks approximately 2 km apart and with swathe coverage of 400 m. Boyd *et al.* collected further tracks to infill this sampling at 1- km spacing or less. They then used the full dataset and subsets, with spacings of 4 km, 2 km, and 1 km to map the seabed facies. Fourteen different seabed facies were identified from this and the previous studies and were used for the mapping scenarios explored. Interpolation was carried out by eye. Maps showing the track data and interpolated seabed facies at the four levels of spacing are presented in Figure 6.6.

Examination of the maps shows a clear increase in resolution and detail with the closer tracks. At the higher densities, the maps show more of the known facies types and more detail in their shapes and boundaries. Several facies types are missing from the coarsest map, e.g. the dredged areas. More detail appears with closer transects. For instance, the area identified as being “sandy gravel with boulders”, which was absent at 4-km spacing, appeared with the 2-km spacing and with the 1-km spacing, the area was shown to include smaller areas of “sandy gravel with sand patches”. To some extent then, the increased detail comes simply from the increase in the amount of data available rather than just from the closer transects. Boyd *et al.* observed that when the full dataset was used, the improvement was minor, and that 1-km spacing would suffice.

Both these surveys used similar transect spacing for their analyses. However, it is important to remember that the Pinn and Robertson survey was an AGDS (RoxAnn) survey, and the survey by Boyd *et al.* was a sidescan survey. As discussed above, the footprint for an AGDS system is not easy to calculate, but given the average depth of 100 m in this survey, the footprint could be estimated to be between 20 and 50 m in diameter. The sidescan system in the Boyd *et al.* survey was using a swathe of 400 m. So at the 1-km spacing the RoxAnn system provided approximately 5% coverage of the ground at best, and the sidescan gave coverage of 40%.

The broad conclusion from the two studies is that choice of transect spacing is vitally important in the construction of an appropriate map. This conclusion returns us to the issue of designing an ASC survey for its particular purpose (see Section 9). It may be that the 4-km spacing used in both examples was adequate for the particular aims of that survey. None of the maps was fundamentally “better” than the others; each was different and provided different information. It is easy to assume that the “best” map of the English Channel site was the one at 1-km spacing, but it is important to remember that the survey could have covered four times more ground at the 4-km spacing in approximately the same amount of time. The question we should ask is: do we want more detail or a wider area? We cannot have both without multiplying the cost.

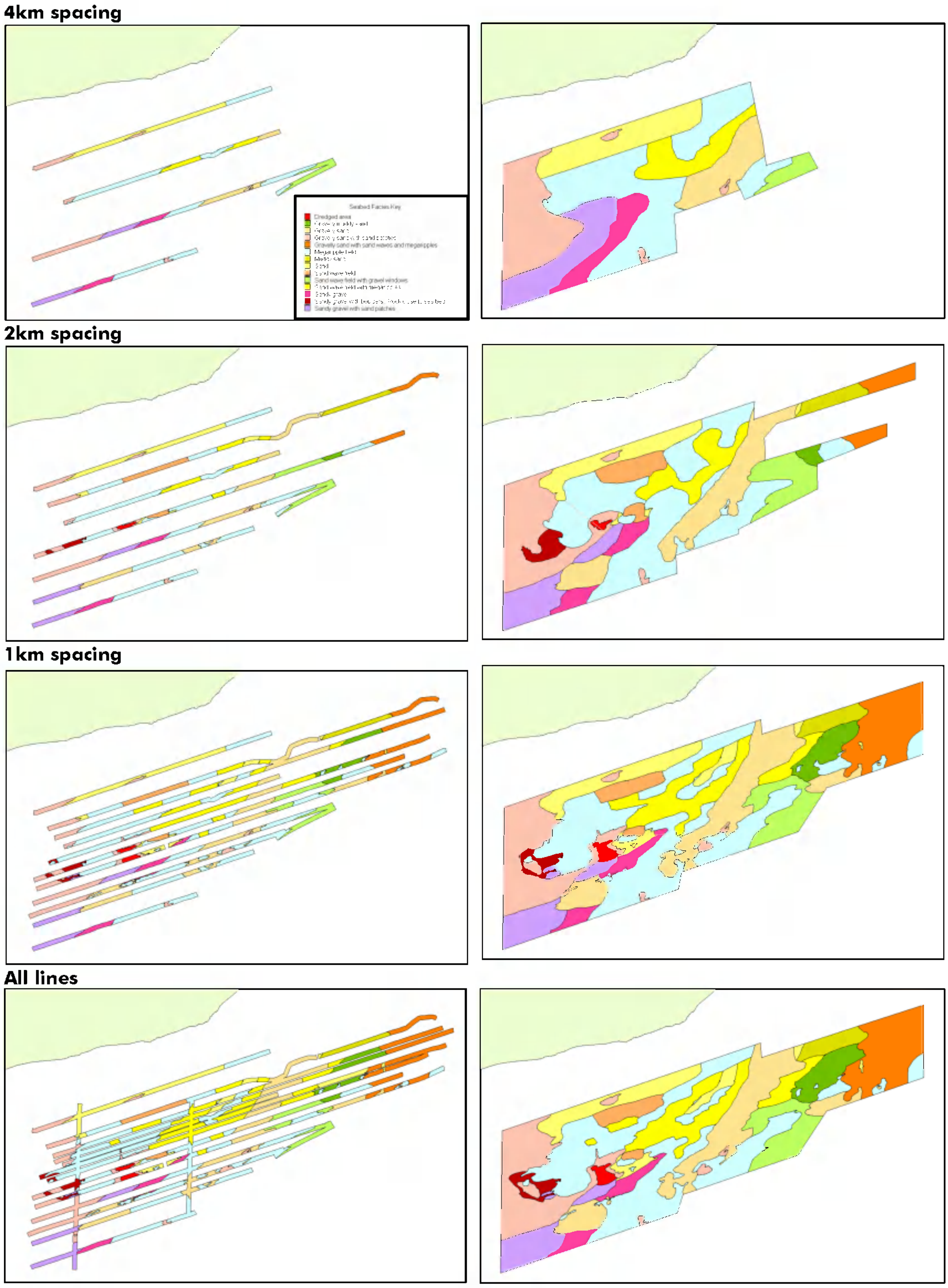


Figure 6.6. Sequence of seabed facies maps (right column) derived by interpolation of interpreted sidescan lines (left column), showing the effect of progressively closer line spacing (top to bottom; from Boyd *et al.*, 2005).

6.2.6 Scales between strata and survey areas

The final scale would be that between surveys or between strata within surveys. For all acoustic systems, the problem is to be sure that the seabed classifications provided by the system and by subsequent analysis and ground-truthing will be coherent. For example, a particular range of E1 and E2 may represent different substrates, or perhaps different biota on or within that substrate, on different surveys. This is principally a question of using an appropriate level of ground-truthing and of using standardized methods on different surveys. The problem of reducing variability within surveys may not be easy however (e.g. Hamilton *et al*., 1999; Wilding *et al*., 2003). There are many reasons, beyond system set-up, why two surveys may vary; see the section on temporal scales below. Although this discussion has concentrated on single-beam AGDS, the same problems would also be expected to occur with SSS and MBES.

Most of the ASC surveys to date have been either at the medium scale 1–10 km (e.g. Anderson *et al*., 2002; Freitas *et al*., 2003) or large scale 10–100 km (Pinn *et al*., 1998; Kloser *et al*., 2004). There have been few basin-scale studies of 100 + km, although an exception is work reported by Preston *et al.* (2004) in the Bering Sea. The large-scale shelf margin mapping projects, such as GLORIA (e.g. Chavez *et al*., 1987), are not considered here. Often the ASC surveys of different areas or strata will have been conducted at separate times and under different conditions. There are likely to be major problems in the combination, ground-truthing, and interpolation of such data. There are also likely to be problems with non-unique acoustic signatures, a wide variety of substrates/biotopes, and the spatial scales, particularly between transects.

One further issue of spatial scale should be considered. Kenny *et al.* (2003) suggest that SSS can provide a more detailed, and even “photo-realistic”, view of the seabed than SBES. SSS sonograms can also be analysed, using texture mapping, to provide information about the substrate. However, there are drawbacks to the use of SSS. The textures seen and interpreted to substrate will depend, in some cases, on the angle of observation; a sand ripple field will look very different when seen along the ridges than across them. This is less the case with the normal-incidence beam of an AGDS (SBES). Second, SSS are generally based on towed vehicles and provide data only about the seabed itself. Essentially, they provide high-detail, topographic data that can then be interpreted in terms of substrate/habitat. Fish, plankton, and other water column features must be observed by another system, i.e. an echosounder. One other advantage of an AGDS system lies in its relative simplicity of use. However, its main advantage may be that it is usually used coupled with a calibrated fishery echosounder. This can provide valuable data on many other features in the water column, including fish and plankton and, critically, these are collected simultaneously with substrate data. This coupling can also help to reduce, or compensate for, the diel changes in seabed backscatter caused by faunal migrations in and out of the seabed, e.g. sandeels (Freeman *et al*., 2004; van der Kooij *et al*., 2004). As discussed above, SSS and MBES systems are able to provide a wider area of coverage, and this can be interpreted into a number of seabed types within a single transmission or group of transmissions. However, if adjacent transects are farther apart than the width of the swathe, the interpolation into the unsampled areas will become more difficult.

6.3 Temporal scales

Mapping of the marine environment is often viewed as broadly similar to mapping in a terrestrial context (Kenny *et al*., 2003). Once a map is constructed, it is assumed to remain stable in the medium term. Obviously, this is not absolutely true, because changes will occur over time, particularly as a result of human activities. In the marine context, this is even less likely to be true, and particularly when we are using acoustic remote sensing. As with spatial scales, the key question should be: what is the purpose of the mapping. Marine habitats can be subject to substantial changes over time, particularly in areas of softer, mobile sediments and high current activity, but also in other situations; an extensive table detailing Seabed Environmental Conditions Against Physical Seabed Process is provided in Kenny *et al.* (2000).

6.3.1 Short timescales

Bubbles

This section details some of the potential sources of variability, what can change and on what timescale. Short timescales refer to processes occurring from seconds to days, while medium to long timescales describe days to seasons to millennia.

The formation of gas bubbles in soft sediment is likely to be a critical source of variability in acoustic return from shallow soft seabeds (Briggs *et al.*, 2002). Holliday *et al.* (2004) studied variability in the occurrence of oxygen bubbles from photosynthesis and the impact on the acoustic return. They were able to show a significant change in the acoustic properties of sand over the diel cycle, related to sunlight and photosynthesis. Although this was a laboratory experiment, the clear implication is that we might classify a given substrate differently according to the time of day at which it was surveyed. Repeat surveys, but at different times of day, or indeed season, might give conflicting results. The presence of methane gas bubbles in sediment *in situ* was shown in another study in a fjord (Anderson *et al.* 1998). Release of these bubbles from the sediment was related to the tidal cycle; lower pressure at low tide allowed the bubbles to escape, leading to a tidal pattern in acoustic return. Methane hydrate deposits can also produce gas bubbles in surficial sediments (Riestenberg *et al.*, 2003; Haeckel *et al.*, 2004). Finally, gas bubbles would be expected also to change volume, and hence acoustic cross section, subject to changes in temperature (MacDonald *et al.*, 2005).

Although these findings are obviously important for normal incident acoustic methods, they will also have an impact at any angle above critical (V. Holliday, pers. comm.). We cannot ignore the possibility of bubbles on the surface either, possibly trapped in, or growing on, algae. These might also alter the return signal for SSS, giving different textures at different points in the day. The possible presence of surficial bubble layers and its impact on acoustic returns is discussed by Anderson *et al.* (1998). There are also anecdotal reports of bubbles developing on seagrass during the day, which may affect acoustic return for both acoustic approaches.

Fauna and flora

Animal migrations represent another possible source of short-term changes in acoustic returns. Freeman *et al.* (2004) and van der Kooij *et al.* (2004) demonstrated that high densities of sandeels (*Ammodytes marinus*) can affect the acoustic return and that there was a diel pattern in their emergence from the sediment. Lambert *et al.* (2001) reported up to 30% variability in acoustic response from sediments that reduced with depth, and associated this with bioturbation. Jumars *et al.* (1996) reported similar changes in acoustic response and attributed the circadian pattern in this to the vertical migrations of the burrowing urchin *Brisaster latifrons*. This species also emerged onto the surface at night, which may also alter the surface texture as seen by oblique incidence acoustic systems. Bioturbation was also implicated in changes in acoustic responses in another study in the Florida Keys (Briggs and Richardson, 1997).

A variety of benthic zooplankton is known to leave the bottom during the night hours, often in a swarm within a few minutes (e.g. bentho-pelagic copepods, mysids, and amphipods). The emergence at dusk, and the re-entry, almost certainly change the surficial microtopography, and physical and acoustical properties of the host sediment (Richardson, *et al.*, 2001; Kringel *et al.*, 2003). Nekton, foraging at the seabed during times of emergence and re-entry, also often leave shallow "pockmarks" in the sediments. The persistence of these shallow pockmarks usually depends on both the local bioturbation and the local physical mechanisms that produce resuspension and sedimentation. Evidence of these structures and their destruction can be found where artificial roughness (a raked area) disappeared in a few hours at a shallow sandy location characterized by a relatively benign physical environment (Thorsos *et al.*, 2001).

Another mobile species that could introduce substantial changes in acoustic return would be shellfish species, such as scallops. Stokesbury (1999) described how scallops (*Placopecten magellanicus*) would aggregate for mating and move around in groups. The sudden aggregation of a group of scallops on the surface could result in a dramatic change in acoustic return. There are anecdotal reports of other scallop aggregations, e.g. *Pecten maximus*, and of very dense brittle star aggregations. In coastal areas, the migration of shore crabs (*Carcinus maenas*) in and out of the intertidal zone may also have an effect. Many animals will also modify the area where they live, often on a short-term basis. For instance, the edible crab (*Cancer pagurus*) will dig foraging pits in sandy seabeds (Hall *et al.*, 1991), and these will take up to a month to recover.

Although there are no specific reports of flora causing changes in acoustic properties, there are likely to be changes in photosynthetic activity over the diel cycle (Silva and Santos, 2003) that might be expected to cause changes in acoustic return.

Weather

Sudden, catastrophic weather events may also cause dramatic and rapid changes in the make-up of the seabed, and hence its acoustic returns. Briggs and Richardson (1997) implicated storm events as one of the sources of variability in sediment acoustic properties. Hurricane events have been shown to have significant impact (Holliman, 1981; Yang *et al.*, 2001; Banks, 2003) and can alter the physical and biological make-up of an environment over a few days. Heavy winter storms in 1993 led to substantial changes in seagrass communities in the Tijuana estuary (Ward *et al.*, 2003), and seagrass has been mapped successfully with AGDS in the past. A related effect would be ice scouring (Peck *et al.*, 1999), which again can cause dramatic and immediate changes to an area, although it can also be a chronic feature in Arctic ecosystems.

Anthropogenic activities

The most obvious immediate or short-term impact on an environment and on the acoustic returns used in AGDS would be from human activity. AGDS methods have been related to fishing impacts (Briggs and Richardson 1997; Humborstad *et al.*, 2004), so it would be reasonable to take account of these in AGDS surveys aimed at habitat or substrate mapping. Examples of human activities that could affect AGDS returns include the effects of extractions from the seabed, e.g. gravel or sand extraction (Groot, 1996; Takahashi and Murakami, 2002; Boyd *et al.*, 2005), or subsidence after oil or gas extraction (Fluit and Hulscher, 2002). A second impact would be from the dumping of materials, such as sewage sludge (Clarke *et al.*, 1990; Ahnert and Borowski, 2002), which could immediately and dramatically affect the physical and biological characteristics of the seabed. Perhaps the most obvious is the impact of fishing activity, particularly trawling for which there is an extensive literature; for an overviews see Collie *et al.* (2000), Kaiser and Groot (2000), and Thrush and Dayton (2002). Although fishing impact is generally seen as a chronic effect, many fishing fleets change equipment and areas rapidly in response to changes in management and markets. The most obvious would be fishing around closed areas, where effort on a given piece of seabed could increase dramatically in a short time (Murawski *et al.*, 2005).

6.3.2 Medium to long timescales

Several of the categories described above can be considered as having longer term impacts, causing changes in the biological and physical characteristics of an area, and hence in the acoustic return used in AGDS.

Anthropogenic activities

The most obvious would be anthropogenic activities: fishing impact, extraction industries, and dumping. It is important to identify whether the changes can be considered as one-off step changes or whether the seabed is continuing to change as a result of ongoing activity. For example, a recent meta-analysis of a wide range of trawling impact studies (Kaiser *et al.*, 2002) suggested that the changes in the community of the benthos was greatest from the early tows and much less from repeated tows. Equally, once an area has been used for some time as a sludge-dumping site, does it change with further dumping?

When looking at medium-term changes in substrates and habitats in response to human activities, we also have to look at the recovery of an area after the end of such activity. The literature contains many references to recovery of areas after fishing activity (e.g. Dernie *et al.*, 2003; Gaspar *et al.*, 2003), but also to sludge dumping (Clarke *et al.*, 1990) and gravel extraction (Boyd *et al.*, 2004). In each case it can be assumed that the area will "recover" over a greater or lesser period. If the initial damage changed the acoustic character to either normal or oblique incidence systems, then recovery would be expected to do so also.

Animals

Changes in animal populations on a seasonal or interannual basis may also cause medium-term changes in the acoustic return from the seabed. To return to the example of sandeels (Freeman *et al.*, 2004), this population can fluctuate dramatically. Currently in many areas of the North Sea, it is seriously reduced in abundance (ICES, 2005), and this will consequently change the likely patterns in acoustic returns. Seasonal migrations of epibenthic animals, such as scallops, would also be expected to have an impact on the acoustic returns from the seabed. Bioturbation effects caused by, for example, burrowing urchins (Jumars *et al.*, 1996), may also be expected to show seasonal and interannual variability. The Norway lobster (*Nephrops norvegicus*) creates large, complex burrows that can impact on both surface and subsurface acoustic returns. However, the spatial pattern of these burrows can change on a seasonal basis, being aggregated in summer and more randomly distributed in winter (Tuck *et al.*, 1994). Pinn and Robertson (1998) showed that *Nephrops* burrows were the key factor in changing the RoxAnn E1 value in an area of largely uniform soft sediments. Acoustic surveys of benthic sediments in Humboldt Bay, California, between 1995 and 1998 (Fenstermachar *et al.*, 2001) showed significant differences between surveys because of the change in distribution of the sand dollar (*Dendraster excentricus*).

Dynamic sandbanks

Sand and gravel banks are known to move in response to tidal and wind-driven currents. This can be over a wide range of temporal scales, from a few days (Schmitt *et al.*, 2004; Bastos *et al.*, 2004), through seasonal changes (Keulen and Borowitzka, 2003), to multi-annual changes (Cuadrado and Perillo, 1997; Williams *et al.*, 2000). Thus, an area mapped at one time to show sand or gravel areas or banks may be completely different on a subsequent survey, even within a short time.

Mobile substrates raise another problem. It has been shown that we can monitor and possibly quantify transport of gravel and shingle by means of the noise generated by such movements, using passive acoustics (Rouse, 1997; Voulgaris *et al.*, 1999). By extension, if we are carrying out a simultaneous ASC survey, we may also pick up this signal. Given the complex signal processing used in some AGDS, different characterization depending on current state are possible.

Earthquakes

Earthquakes and other tectonic activity are a major source of change in seabed characteristics. Shilts and Clague (1992) showed disturbance in lake sediments following an earthquake and documented this with acoustic profiling. Earthquakes can also cause gas release into surficial sediments, resulting in a change in acoustic properties (Field and Jennings, 1987).

6.3.3 Conclusions in relation to temporal scales

The important point to be taken from this section is that marine seabeds and the associated habitats and biotopes may not always remain consistent over time. This may seem obvious, but it is often ignored in actual surveying and mapping. Many of the temporal changes can and do affect the acoustic returns from both normal- and oblique-incidence acoustic systems. Short-term phenomena – biological cycles and migrations, weather, or human activities – could change responses within the scale of a single survey, or possibly even a single transect. Longer term phenomena, such as sand bank migration, changes in biota on and in the sediment, and human activities, could change responses between surveys within or between years. Seasonal changes may occur, e.g. in animal migration or in the plant content and activity in a given substrate. An example of significant temporal variability was reported in an AGDS survey, provided by Wilding *et al.* (2003). The authors identified changes in the E1 and E2 RoxAnn values between surveys a few days apart and also a few months apart. This led them to suggest that there were problems with the system itself (see Section 3). While not excluding that possibility, we have attempted to show that there are many reasons why we might expect change over short or medium timescales. The *reductio ad absurdum* here would be an AGDS survey carried out for several weeks over a uniform area of soft substrate with all its associated biota and subject to the usual human and weather influences. It is conceivable for the operators to get a range of different responses from the seabed depending on time of day, tidal cycle, weather, etc. If they surveyed six months later, seasonal affects may come into play. If they surveyed a year later, they may get a different picture again, although this would need to be tested in a real-world situation.

In developing this overview, it was striking that there were many examples where AGDS had been used to study particular aspects of change in seabed habitats, e.g. those caused by trawl damage or animal occupation patterns. In most cases, these were aimed at answering a single-issue question and were not portrayed as general potential sources of variability. Notable exceptions were the studies on bubble formation (Holliday *et al.*, 2004) and those by Briggs and Richardson (1997) on short-term changes. The aim of this section is to highlight a range of factors that may confound ASC surveys, particularly where the aim is to produce a definitive map of a seabed area for, say, management purposes. This also raises the issue (also discussed under spatial scales) of the need to define the purposes of a survey and mapping operation in advance. If the aim is to develop a single, one-off representation of an area, then it should be remembered that this would be essentially a snapshot of a potentially quite variable system. Much of this can be addressed with careful and well-designed ground-truthing, but should be provided with a health warning.

7 Review of acoustic seabed classification systems

William L. Michaels

7.1 Introduction

Loss of essential fish habitat is a primary, long-term concern of fishery managers, resulting in recent research efforts that focus on the identification, monitoring, and conservation of those marine habitats that are important for fish production and biodiversity. Acoustic seabed classification (ASC) is a fundamental tool for measuring the predominant biotic and abiotic features of the seabed necessary for classifying marine habitats. Considerable effort and investment are currently under way to map and classify the ocean seabed in support of marine fishery and habitat management. Therefore, we must implement the best available technologies that afford accurate data in a cost-effective and timely manner. ASC, in conjunction with high-resolution bathymetry using a variety of acoustic instrumentation, provides the foundation for marine habitat classification. The most accurate interpretations for marine habitat classification result when ASC technologies are applied in conjunction with other remote-sensing technologies (aerial and underwater optics) and conventional sampling. The goal of this section is to provide an overview of ASC systems that are routinely deployed for fisheries habitat research, emphasizing the operational design that dictates their applications and limitations. Although most acoustic seabed mapping systems have been designed to measure the acoustic response of the geophysical characteristics of the substrate, this section will also discuss the need to measure synoptic geophysical and biological backscatter from the marine habitats associated with the seabed in support of fishery management. This section begins by describing the operational design and deployment of the different types of acoustic instrumentation, to provide the necessary background for reviewing the available ASC systems commonly used by scientists.

7.2 Operational design of acoustic instrumentation

The architecture of ASC systems depends on the operational design and deployment of the underwater acoustic instrumentation. Various types of underwater acoustic instrumentation have been designed to accomplish specific tasks, ranging from water column detection to seabed mapping (Medwin and Clay, 1998; Lurton, 2002). For this report, underwater acoustic instruments that are commonly utilized for ASC are grouped into four distinct categories to describe differences in their operational design:

- Single-beam echosounder
- Simple sidescan sonar
- Multi-row sidescan sonar
- Multibeam sonar

To select the acoustic instrumentation most suitable for ASC, the researcher must consider the research objectives, operational strategy, costs, and capabilities of a system to measure the various acoustic responses from the seabed. In addition to the distinctly different acoustic responses obtained by each category of instrumentation, the spatial and temporal requirements of the ASC research as a function of the acoustic footprint on the seabed will be introduced. A more detailed description of the spatial scale of acoustic surveys for ASC is discussed in Section 6. This section gives an overview of the underlying acoustic principles for each category of instrumentation, with regard to the operational design, deployment, beam pattern, and the resulting echo return from the seabed. The theoretical principles of seabed scattering are discussed in Section 2; so, only a brief discussion of the acoustic seabed responses obtained from each type of instrumentation is necessary to understand how ASC systems differ. Optimal measurements of seabed features will vary with the sampling objectives, with regard to survey depths, resolution, and target detection requirements.

The system design, operational deployment, and its beam pattern determine the acoustic properties of transmitting and receiving sound waves. There is always a trade-off between resolution and operational range when selecting an acoustic system for ASC, especially its frequency. Transducers with smaller apertures tend to produce wider beam patterns at higher frequencies. Smaller apertures have improved shorter pulse length and wider bandwidth capability, resulting in better range resolution, which is particularly important for target detection and angular resolution. For example, a 12-kHz system (with pulse lengths of 0.4–0.8 ms and bandwidths of 1–2 kHz) may have range resolutions of 30–60 cm, while a 300-kHz system (with pulse lengths of 0.02–0.03 ms and bandwidths of 40–60 kHz) would have improved resolution of 1–3 cm. Longer apertures produce a narrower beam pattern and its longer pulse duration transmits more power through the water column, increasing the operational range. Hence, the maximum operational range of a 12-kHz system (12 000 m) would be much greater than that of the 300-kHz system (200 m).

Another prerequisite for this section is to understand that ASC derives categories of similarity from the acoustic response from the seabed, but does not provide seabed composition. For this reason, ground-truth sampling (grabs, nets, and video) must be conducted in conjunction with ASC operations (see Section 8). The ability to measure the acoustic response from the seabed will vary as a function of the instrumentation parameters (frequency, beam pattern, bandwidth, and pulse length), operational deployment (grazing angle), and the characteristics of seabed (roughness, hardness, texture, and composition).

The quality of the seabed echo will vary as a function of the outgoing pulse length, which can influence the ASC statistics. Longer acoustic pulses are typically used for deeper depths. Changes in the echo return from the seabed at various grazing and incidence angles (Figure 7.1) are important distinguishing features between oblique incidence swathe sonar (sidescan and multibeam) and a downwards-looking echosounder with a narrow single beam at nadir.

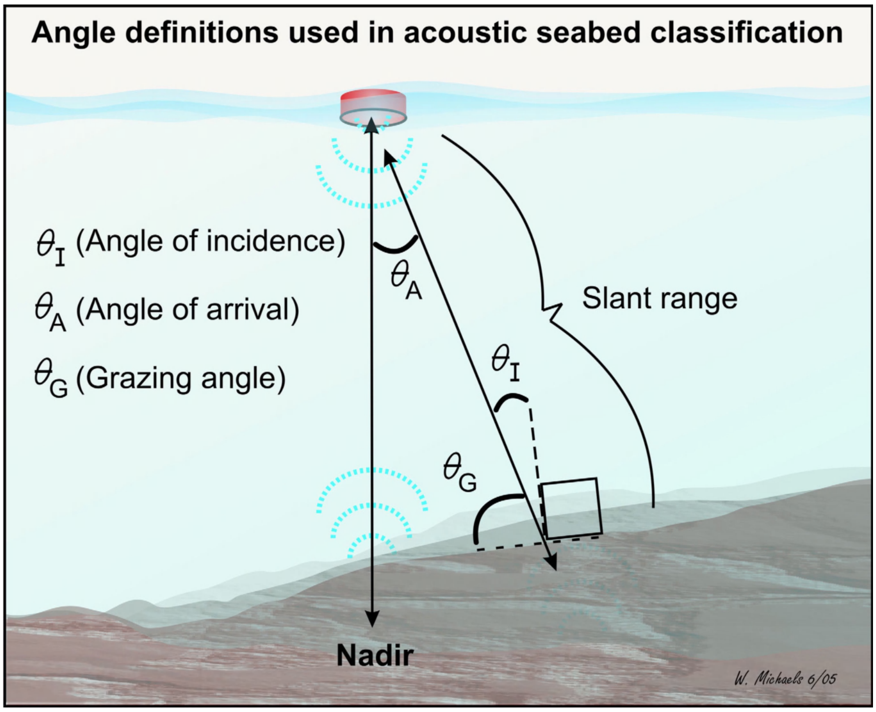


Figure 7.1. Generalized illustration showing angle terminology used for describing sound propagation by normal-incidence and oblique-incidence sonar systems.

7.2.1 Single-beam echosounder (SBES)

Single-beam echosounders operate one or more transducers, which are designed with narrow-beams at specific frequencies. These echosounders were initially designed for commercial use as depth sounders and fish finders, and their electronics were improved with advances in low self noise, time variable gain (TVG), digital signal processing, and high dynamic range (e.g. 150 dB) for fishery acoustic surveys. The quantitative backscatter measurements from the water column were also improved when dual-beam and split-beam transducers were developed to replace the single-beam transducer. During fishery acoustic and seabed classification surveys, the transducers are usually hull-mounted or towed mid-ship to provide a downwards-looking beam with a narrow symmetrical pattern (Figure 7.2). Multiple single-beam transducers at different frequencies are often operated simultaneously by a scientific echosounder to enhance its target detection and classification capabilities. SBES are the least expensive and least complex underwater acoustic system and, therefore, have been widely utilized for ASC (Orlowski, 1984; Pouliquen and Lurton, 1992; Collins *et al.*, 1996; Hamilton *et al.*, 1999; Anderson *et al.*, 2002; Brown *et al.*, 2002; Kloser *et al.*, 2002; Wilding *et al.*, 2003). A major disadvantage of the echosounder for ASC is the limited coverage of its narrow-beam footprint (see Section 6). Fishery acoustic surveys are typically conducted along a systematic grid design with widely spaced transects; therefore, bottom coverage is often less than 5%. ASC and seabed mapping surveys relying solely on echosounder operations generally conduct systematic grid surveys, and sometimes incorporate an adaptive star-like cruise track in selected shoal regions. Therefore, ASC results from SBES surveys must rely on contour interpolation to produce seabed classification maps because of the limited seabed coverage. Regardless of its limited coverage, SBES are reportedly the most common instrumentation employed because of the low cost, availability, simple operation, and less complex data processing.

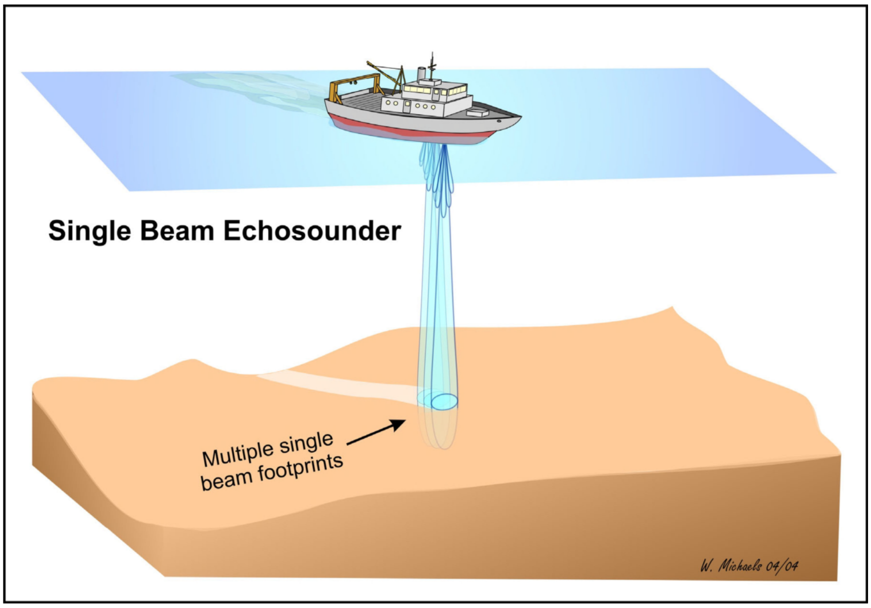


Figure 7.2. Single-beam echosounder operations include one or more transducers at selected frequencies, which provide narrow downwards-looking beam patterns.

Another advantage of SBES is the ability to conduct routine system calibrations to ensure that the instrumentation and transducers are working properly (see Section 3). Standardized sphere calibration procedures to obtain fixed beam pattern and gain parameters for the transducers are well established (Foote *et al.*, 1987). System calibration is accepted as imperative when using SBES to derive fish population estimates for fishery management. Unfortunately, system calibrations are rarely performed for echosounder operations during ASC surveys. Given the recent mandates to include marine habitat in fishery management plans, system calibrations will become increasingly important for ASC operations to obtain the repeatable results needed to defend regulatory decisions. Refer to Section 3 for further details on calibration.

The sweep echosounder system is designed for seabed mapping by arranging a series of single-beam transducers along a boom to each side of the vessel to increase seabed coverage (Figure 7.3). For example, the Kongsberg EA400/600 Simrad provides a sweep array of single-beam transducers, and its echosounder system includes software for real-time ASC. Deployment of this system, particularly with regard to the booms, is more difficult than most systems. Sweep echosounders with a series of beams at normal incidence provide more accurate bathymetric data than a multibeam system, which is one reason why a sweep echosounder system is often preferred for obtaining bathymetric data in shallow waters and harbours.

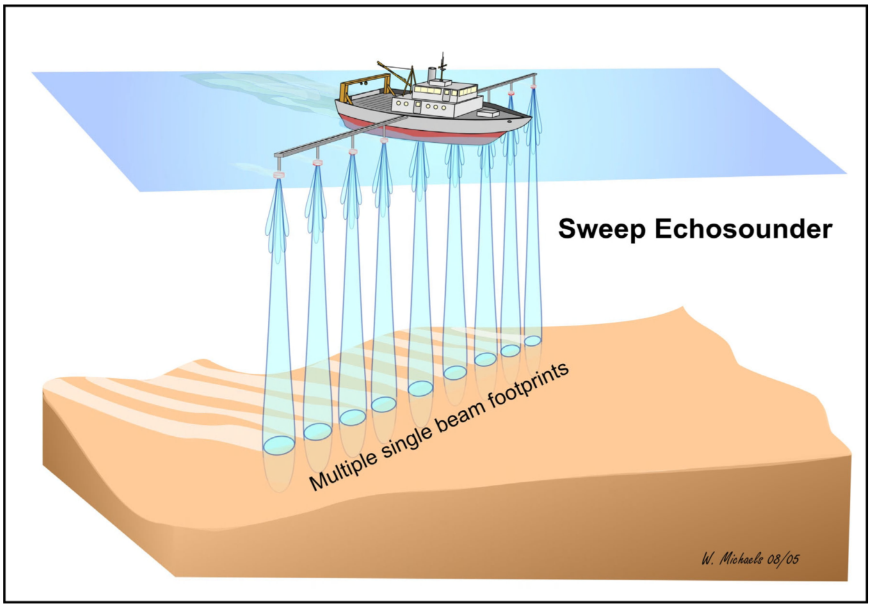


Figure 7.3. Sweep echosounder operations include a series of single-beam transducers positioned on booms on each side of the vessel to obtain accurate bathymetric measurements, typically in shallow waters, such as restricted harbours.

A downwards-looking echosounder insonifies the seabed with a narrow vertical beam, resulting in most of the acoustic reflection from the seabed surface occurring at normal incidence (perpendicular from the seabed is often referred to as nadir). At normal incidence, this first-order echo gives the strongest return because of the reflectivity from the seabed surface, and the trailing portion of this first echo (E1) is backscatter from the near-surface substrate (Figure 7.4). Within the ASC literature, E1 is often referred to as a roughness feature of the seabed. E1) is correlated with the topography, grain size, and attenuation of the near-surface portion of the seabed. For example, rough bottom or large grain size results from more complex scattering at the seabed–water interface, as indicated by a wide E1 echo envelope of lower amplitude, compared with flat bottoms, which reflect a narrow E1 envelope of higher amplitude. The second-order echo return (E2) results primarily from complex scattering caused by refraction from the sea surface and the substrate (Figure 7.4). E2 is commonly referred to as a hardness signature of the seabed. E2 varies when the sound wave penetrates the seabed surface and is reflected by a substrate layer of different density. The attenuation of sound increases as it encounters higher density medium, such as when sound propagates from water to the seabed. The resulting backscatter intensity from a seabed made up of rock is significantly greater than that from a sandy substrate. The angular response from the seabed can vary within the acoustical footprint, and higher reflectivity is expected at nadir. Hence, the width of the footprint and angle of incidence are particularly important for ASC, and the angular response from the seabed enhances the ability to discriminate the categories of seabed grain size (sand, gravel, and cobble). SBES data generally collect less angular responses from the seabed compared with swathe sonar. The optimal angular responses for classifying seabed made up of sand, gravel, and cobble occur at grazing angles ranging about 7–20° depending on the source level, frequency, pulse length, and operational range of the system. Refer to Section 2 for further details on the theory of sound-scattering from the seabed.

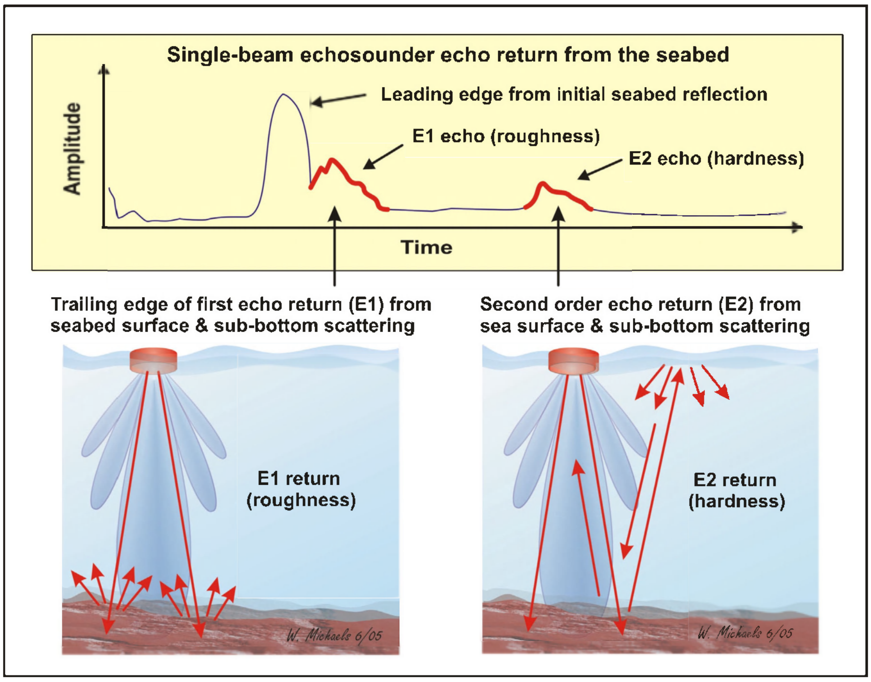


Figure 7.4. The single-beam echosounder receives the trailing edge of the first-order bottom echo return (E1) and the second-order bottom return (E2), which are utilized for ASC.

7.2.2 Simple sidescan sonar (SSS)

Simple sidescan sonar is equipped with a single-beam transducer on each side of a towfish; these transducers are tilted towards the seabed, and their elongated beam patterns are horizontally narrow in azimuth (e.g. about 0.1–2.5°) and vertically wide (e.g. about 40–60°) to insonify a swathe-like portion of the seabed (Figure 7.5). Sidescan sonar is designed with wide apertures that transmit a longer, narrower footprint, which is advantageous for increasing its maximum operational range. A wide aperture also increases the angular resolution from its narrow-beam in the horizontal azimuth direction. Some sidescan systems are designed with smaller apertures to increase the range resolution with short pulse lengths and to reduce the size of the towfish. The footprints are elongated perpendicularly along each side of the cruise track, and a narrow blind zone occurs at nadir (directly below the towfish). Compared with SBES, the swathe footprint provides more seabed coverage in less time and is relatively easy to operate (e.g. Brown *et al.*, 2002).

Sidescan sonar is typically deployed from a towfish, which is towed at slow speeds near the seabed (distance above bottom is optimally about 10% of its maximum operational range) to obtain echo ranging amplitudes from the seabed surface at low grazing angles and high sampling rates. Seabed mapping operations in harbours may use pole-mounted sidescan because of the difficulties of deploying a towfish in shallow water. A sidescan towed near the bottom can operate at higher frequencies, generating increased range resolution, particularly with regard to vertical resolution of the seabed surface. The sidescan is designed operationally to obtain high-resolution imagery and object detection along the seabed surface; however, its deployment close to the bottom reduces its swathe coverage in contrast to hull-mounted multibeam sonar on surface vessels. Sidescan towfish systems are also less subject to vessel motion and are more difficult to geo-reference compared with hull-mounted systems. Another advantage of a sidescan towfish near the bottom is that the effects of changes in sound-velocity profiles within the water column are reduced. However, it is also noteworthy that the wobbling of the towfish can be a problem during rough seas. Towing the SSS at a constant range above the seabed, to maintain the same grazing angles, is important during seabed mapping surveys. This can be difficult when the altitude of the towfish above the seabed might drop as the result of changes in the course heading and vessel speed at transect waypoints. Furthermore, sidescan surveys are typically conducted at slow speeds (4–6 knots) to obtain continuous footprint coverage of the seabed along the cruise track, while surveys using hull-mounted systems (i.e. SBES and multibeam) can be performed at twice that speed.

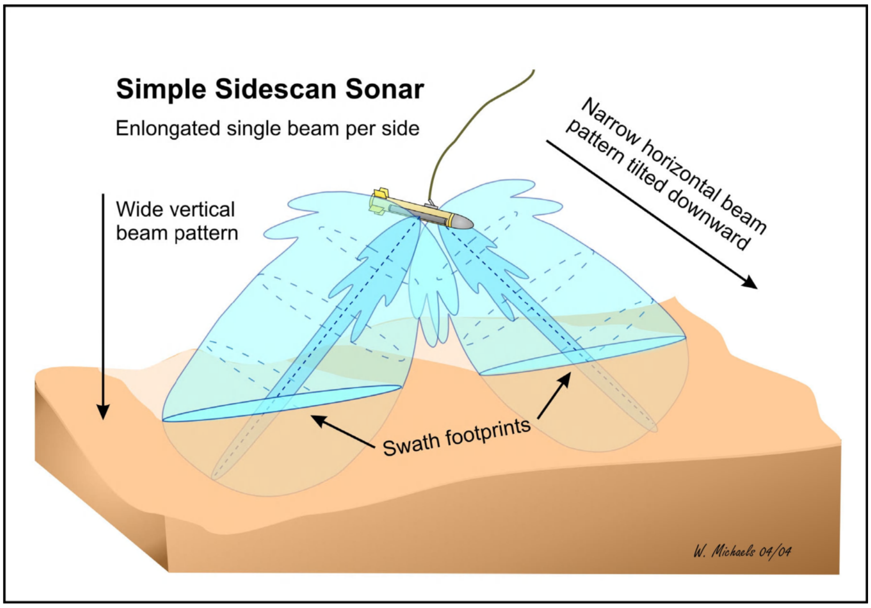


Figure 7.5. Simple sidescan consists of a single-beam transducer per side, which produces an elongated footprint and is towed near the bottom to give low grazing angles for mapping the seabed surface and for detection of objects on the seabed.

The predominant features of towing SSS close to the seabed are the shadowed regions resulting from the low grazing angles (Figure 7.6). An important principle of simple sidescan is that its echo-ranging capabilities simply provide accurate slant-range measurements. Accurate time-range measurements at high frequencies and low grazing angles produce high vertical resolution relative to other types of acoustic instrumentation. Slant ranges to an object and to the end of its shadow are utilized, using simple right angle geometry, to accurately derive an object's height from the seabed surface (Figure 7.6). This requires an assumption of a flat, horizontal bottom, which is one reason why sidescan must be towed at a constant distance from the bottom. Given this assumption, sidescan is well designed to detect objects along the seabed surface using simple geometry.

When surveying complex bottom topography, range data compression problems may occur with sidescan because of the small time difference of returning slant ranges from bottom reflections and the inability to determine the direction of the angle of incidence. For example, horizontal range discrepancies can occur when the slant range from a tall object is less than the slant range of bottom closer to nadir (Figure 7.7). For this reason, simple sidescan is more suitable for mapping smooth, flat, bottoms than rough bottoms with significant slopes. Sidescan collects accurate echo-ranging amplitude measurements of unknown absolute levels from the seabed surface, but does not collect calibrated backscatter strength. It is also important to note that sidescan survey operations typically use an autogain setting rather than a calibrated gain setting, as does the scientific echosounder survey. System calibration procedures, similar to those applied to SBES, do not exist for sidescan, and system checks for sidescan often involve only a hand "rub test" on deck to simply verify signal detection.

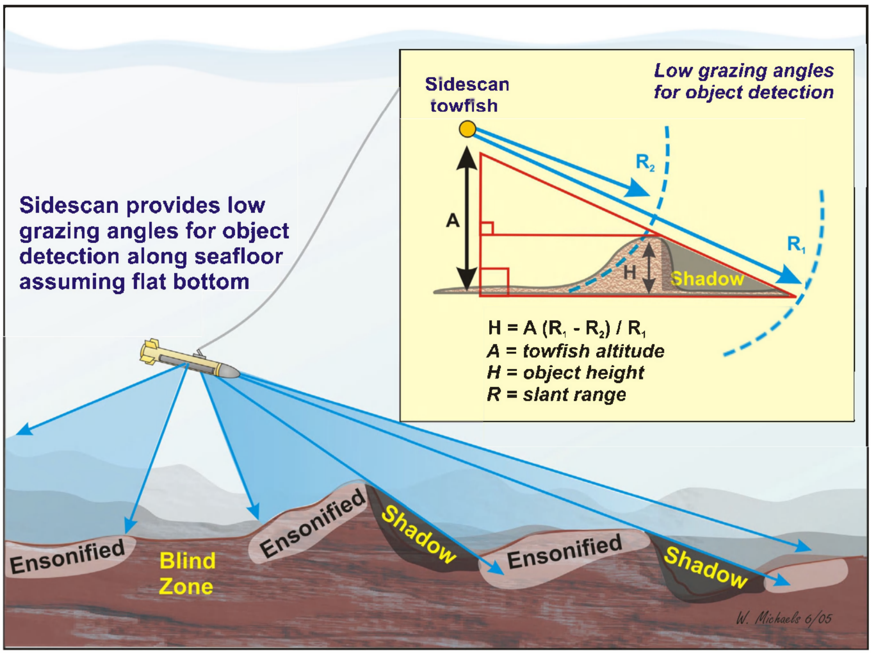


Figure 7.6. Sidescan systems are designed for high-resolution imagery of the seabed surface at low grazing angles, resulting in shadows used for object detection.

The predominant echo received by sidescan is the reflectivity from the seabed surface. Given that sidescan is typically towed close to the seabed, the high frequencies and low grazing angles produce photograph-like imagery of the seabed surface. Sidescan produces raster-based mosaics of the seabed surface and does not provide point-based (vector) backscatter data. Grey-scale seabed images from sidescan provide a photograph-like negative image, with light regions reflected by areas of less backscatter (flat bottom, smooth, and soft substrate, or seabed topography that slopes away from the towfish). Grey shading represents regions of higher backscatter (hard substrate or seabed topography sloping towards the towfish). Sidescan images can be false coloured to emphasize seabed features (shadowed regions, topographic texture). The echo amplitude from the pixel data can produce textural features, which are utilized for ASC. The textural features for ASC depend on the angular response of the echo return from the seabed. The sidescan echo return from a flat homogeneous bottom will be less complex compared with the echo from a rough heterogeneous bottom (Figures 7.7 and 7.8). The lack of angular response near nadir and the reduced signal-to-noise ratio from the outer regions of the sidescan footprint also cause interpretation bias. Although the angular response from the seabed can be useful for classifying substrate types, the shadowed regions cannot be classified. This is an important consideration because a shadowed region can occur when sidescan is towed in one direction, and this same region could be insonified with high amplitude when towing is in a different direction. Therefore, sidescan may produce less consistent ASC results from rough rather than flat seabed surfaces. Unlike SBES data collected at normal incidence, sidescan gives textural information from oblique-incidence echo returns at low grazing angles. Although the benefits of the sidescan shadowing effects provide distinctly beneficial information on the seabed textural features, these effects could be a concern when repeatability in ASC is required for marine habitat and fishery management (see Section 6).

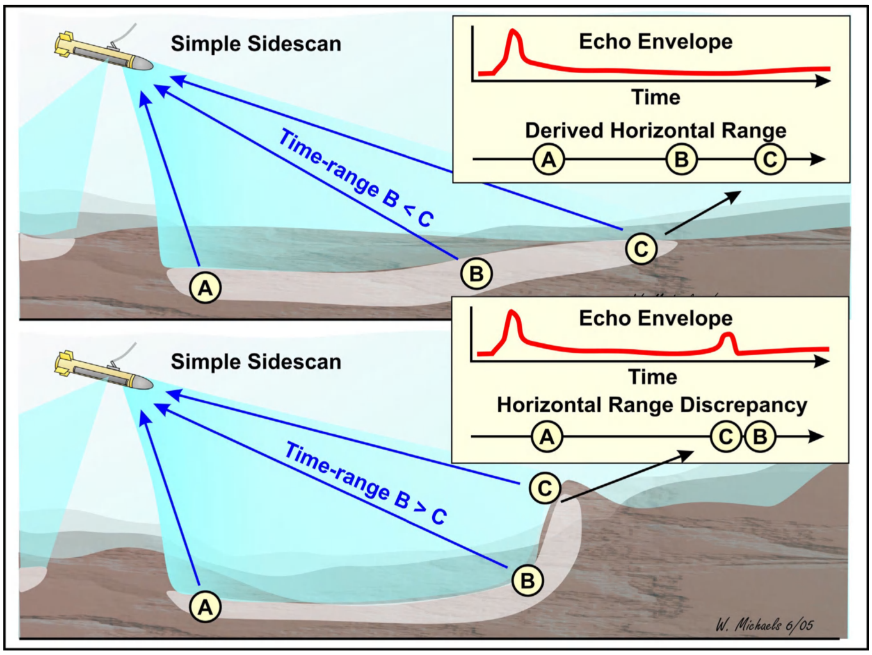


Figure 7.7. Simple sidescan can have horizontal range discrepancies because of difficulties in measuring the time range with different incidence angles from rough bottom.

Typically, simple sidescan operates within a single frequency, while dual-frequency sidescan systems have been designed to switch between a low frequency for long-range mapping and high frequency for short range with higher resolution. Split aperture sidescan systems were developed to transmit dual frequency to take advantage of the features of low and high frequencies. A higher frequency provides increased range resolution, while the lower frequency improves its operational range.

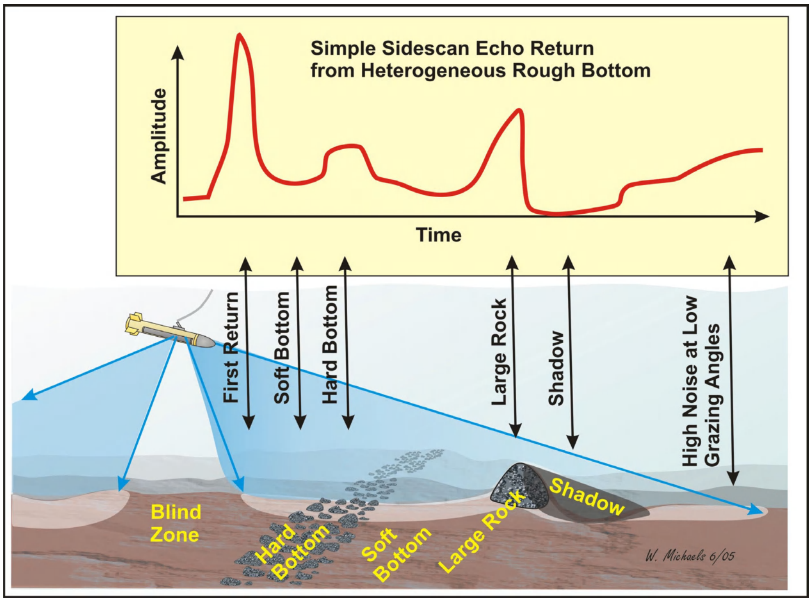


Figure 7.8. The echo of simple sidescan will vary as a function of the incidence angle, topography, shadows, surface texture, and substrate composition.

7.2.3 Multi-row SSS

More advanced SSS systems are designed with multiple elements (staves) arranged in a row to improve the accuracy of estimating incidence angles, horizontal range, and to obtain bathymetric data. Multi-rowed sidescan developments incorporate interferometry and beamforming techniques providing more geometric information of the returning echoes (Lurton, 2002; Gens and Van Genderen, 1996). Multi-row sidescans are designed for improved seabed imagery; on the other hand, their sophistication requires an additional investment in cost, expertise, data processing, and interpretation. In this section, we will discuss the operational design and principles of multi-row (interferometric and bathymetric) sidescan instrumentation.

Interferometry is the applied science of combining two sources of wave data to form an enhanced image by accounting for the constructive and destructive wave interference. This principle is based on two waves that coincide with the same phase, these will amplify each other (constructive inference), although two waves out of phase will cancel each other (destructive interference). Interferometry was originally applied to radar and astronomic research; however, this technology was not practical for SSS until techniques were developed to measure accurate motion compensation from towfish platforms. Interferometric sidescan transmits a single frequency from a transducer on each side of the towfish with a footprint and amplitude similar to that of the simple sidescan. The design improvement with interferometric sidescan is the vertical row arrangement of two or more transceivers per side to measure the differential phase and arrival time at the same frequency (Figure 7.9). Time-range differences combined (or cancelled) with changes in phase amplitudes provide more accurate estimates of incidence angles, given accurate motion compensation. The assumption of a flat, horizontal seabed surface is also needed to apply the simple geometry for determining the phases of parallel waves. Given this assumption, interferometric sidescan generates improved estimates of incidence angles and resolution compared with simple sidescan.

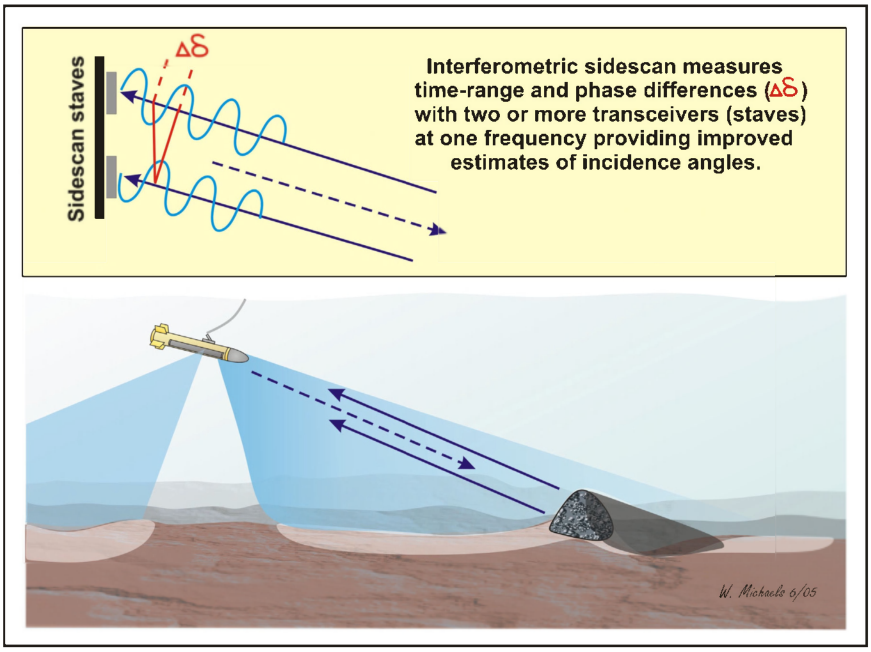


Figure 7.9. Interferometric sidescan is designed with a row of two or more transceivers per side to measure the time-range and phase differences of an echo return to derive improved resolution and estimates of incidence angles.

Although horizontal range discrepancies may still occur with complex bottom topography, interferometric sidescan provides improved mapping and three-dimensional imaging of objects on the seabed, assuming that the motion of the sensing platform is accurately compensated for in the calculations. A disadvantage of interferometry is the difficulty of interpreting seabed reverberation because of the effects of phase interference resulting from the banding of amplitudes. A single incidence angle from a reflected wave can be estimated from interferometric measurements, but this can be more easily corrupted by multiple scattering (multipath), not only from rough seabed features, but also from water column targets. One example of sidescan development that resolved the multipath problem was construction of the interferometric sidescan sonar with split-beam apertures (Schneider *et al.*, 2000). The split aperture allowed the application of the quadrature sampling procedure used with split-beam technology to more accurately calculate phase difference for target location.

Bathymetric sidescan systems are enhanced from interferometric sidescan design by incorporating multiple transducers arranged in a row on each side of a towfish. This design improvement combines interferometric and beamforming techniques, for improved phase detection, to obtain more accurate angle of incidence measurements and bathymetric data. Bathymetric sidescan is similar in concept to multibeam sonar except for its lower number of beams and typical towfish deployment for low grazing angles (Denbigh, 1989; Bates and Byham, 2001). The beam steering and focusing techniques applied to multibeam sidescan result in several adjacent parallel beams generated per side, with the ability to obtain bathymetric data. Although horizontal resolution remains dependent on the ability to measure multiple slant ranges, computed from concurrent angles of arrival, bathymetric sidescan provides sidescan imaging and bathymetric mapping capabilities through the increased geometry from its multiple beams. The increased geometric information from bathymetric sidescan also requires accurate motion compensation.

A recent signal-processing development, called computed angle-of-arrival transient imaging (CAATI), was implemented to reduce inaccuracies from the multipath problems. This concept is based on increasing the number of concurrent angles of arrival, which provide more complex geometries, from the phase differences that can be imaged (Kraeutner and Bird, 1995; Bird *et al.*, 2004). CAATI has been applied to small aperture range vs. angle (SARA) sidescan sonar. SARA sidescan was designed with a stacked row of vertically aligned transducers spaced one-half wavelength with sufficient bandwidth for array signal processing. The CAATI technique of bathymetric sidescan utilizes an angle-of-arrival estimation similar to interferometry instead of beamforming in the vertical plane. Unlike beamforming in the vertical plane, CAATI uses an angle-of-arrival spectrum to derive the vertical dimension. Compared with interferometric sidescan, SARA sidescan with CAATI has more accurate vertical resolution compared with multibeam beamforming, reduces the horizontal range discrepancies of simple sidescan, and provides more accurate bathymetric data. Unlike interferometric sidescan, the bathymetric sidescan CAATI approach can resolve the concurrent arrivals from multiple angles of incidence, assuming a time-varying impulsive spectral model.

When selecting which type of sidescan system best achieves the ASC objectives, it must be remembered that the operational objectives will probably dictate the design that is most suitable, based on costs, complexity, deployment, maximum range, resolution, and other constraints. Simple sidescan is a widely used design because it is relatively inexpensive, easy to operate, and less difficult to interpret compared with the more sophisticated multi-row sidescan systems. However, using simple sidescan in areas with complex topography is not recommended, because its geometrics assume a flat horizontal bottom. Multi-row sidescan is designed for improved seabed-mapping capabilities, but the more sophisticated designs are more expensive and difficult to interpret. Problems with horizontal range discrepancies inherent in simple sidescan are reduced with the application of interferometry to distinguish between echo amplitudes of different incidence angles with the same range-time from phase differences in the vertical plane (Figure 7.10). However, this advantage is accompanied by the increased difficulty of interpretation because of the isophase amplitudes from interferometry. The incorporation of multiple beams in bathymetric sidescan provides beamforming capabilities to resolve multipath concerns and obtain bathymetric data, which makes it a suitable selection for surveying seabeds with complex topography (Figure 7.10). However, the additional costs and difficulties with interpretation should be considered when implementing this sophisticated design. Accurate motion compensation and geo-referencing are critical requirements for acceptable results from beam stabilization. This is difficult to achieve with towed sidescan, which is why most beamforming is done preferably with data from a hull-mounted multibeam instrument.

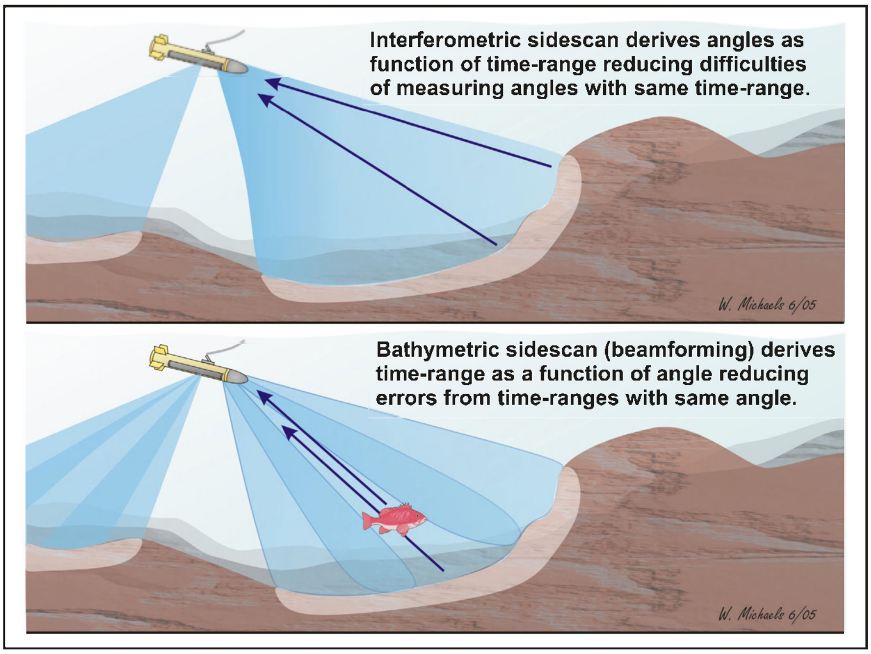


Figure 7.10. Interferometric sidescan was designed to reduce horizontal discrepancies using interferometry to estimate incidence angles. Bathymetric sidescan was designed to reduce time-range discrepancies and generate bathymetric data from its multiple beams.

7.2.4 Multibeam sonar (MBES)

Multibeam is designed for the collection of bathymetric data and backscatter intensity for hydrographic seabed mapping and classification purposes. The multibeam sonar head is arranged in a Mills Cross with an array of transmitters and an array of beam-steered hydrophones, resulting in an insonified swathe of narrow-beams arranged orthogonally to the cruise track for seabed mapping (Figure 7.11). TVG compensates for depth dependency in its measurements. The multibeam transducer head is usually hull-mounted (including pole-mounted) on the vessel, which provides a number of advantages over the towed sidescan. Hull-mounted multibeam has the advantage of having more accurate motion compensation and is geo-referenced, compared with the sidescan towfish operations, providing the advantage of stabilized beams. Hull-mounted operations need to minimize the bias of changes in bottom depth within a survey area, while the sidescan can be towed at a constant altitude above the bottom. For this reason, multibeam and sidescan seabed mapping operations typically follow bathymetric contours to minimize changes in depth and swathe footprint. Hull-mounted multibeam systems do not have the same degree of shadow effects as the low grazing angles of sidescan; hence, more consistent ASC results are expected, as previously discussed. Although MBES systems are more complex and expensive than SBES or SSS systems, they are actually more cost-effective when their increased swathe coverage and ability to conduct surveys at faster speeds (10–12 knots) are taken into account.

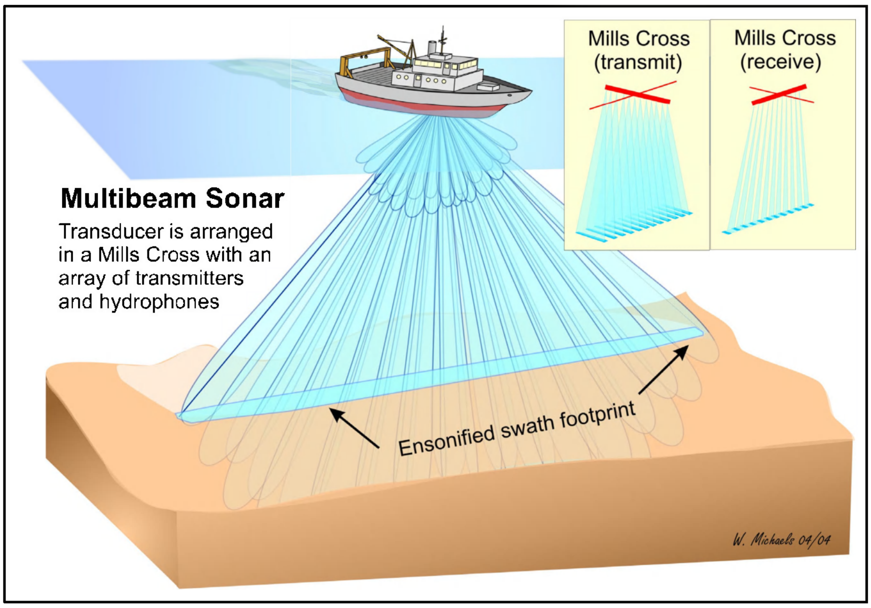


Figure 7.11. The multibeam sonar head is arranged in a Mills Cross with an array of transmitters and an array of beam-steered hydrophones resulting in an insonified swathe of narrow-beams arranged orthogonal to the cruise track for seabed mapping.

The main advantages with the multiple narrow-beams of MBES are the ability to detect the angle of incidence for various echoes that arrive simultaneously and the accuracy of the bathymetric measurements throughout its swathe footprint (Figure 7.12). The multiple beams also allow detection of multiple scattering, and resolution is determined by the system's ability to separate the scattering from two targets. Accurate motion compensation and navigational data are required for beam stabilization, and various beamforming techniques (e.g. Fourier transform, spectral-based, and parametric methods) can be applied to resolve scattering sources that are closely spaced. Determining the direction of wave propagation is relatively easy, while determining the angular resolution and number of multiple wave sources with beamforming methods is computationally complex.

The high density of multibeam data provides high-resolution mapping with the ability to obtain 100% coverage, depending on the spacing of survey transects. This provides more accurate seabed mapping, in contrast to the contour maps of interpolated echosounder data. Given the high density of multibeam pixel data, illumination filters can be applied to produce bathymetric images with a realistic, sun-shaded appearance. The echo amplitude is typically segmented into rectangular patches, in which acoustic response features for ASC are extracted from the seabed backscatter.

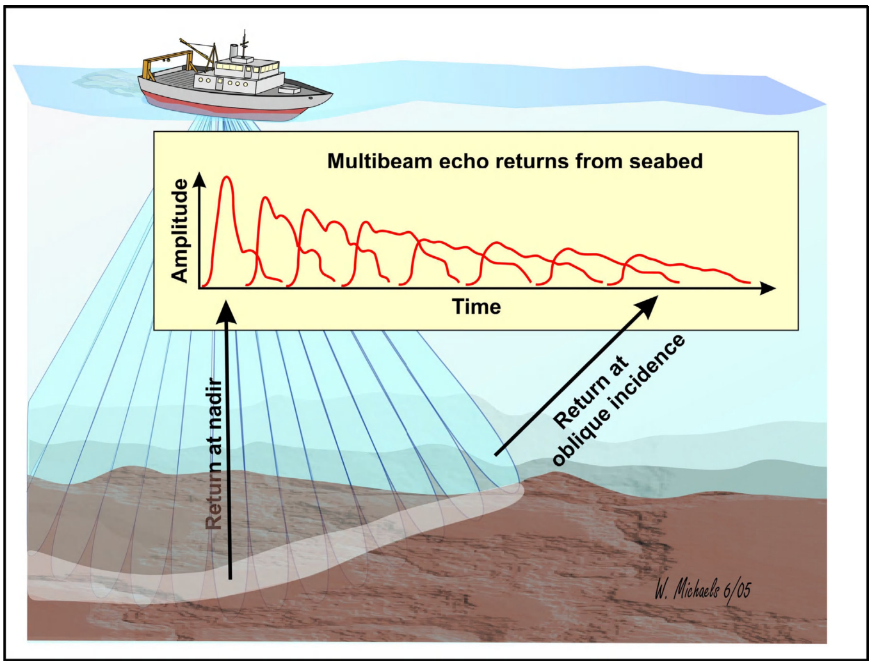


Figure 7.12. Generalized diagram showing changes in multibeam echo returns from the seabed in relation to the angles of incidence within the swathe.

The "patch test" is a routine calibration procedure for multibeam operations, which includes a series of field tests required to ensure accurate motion compensation and geo-referencing for beam stabilization. Research has only recently been initiated to establish system calibration procedures for selected multibeam systems, particularly recent models with increased instantaneous dynamic ranges to obtain both water column and seabed backscatter data (see Section 3). IHO S44 standards for conducting hydrographic surveys (IHO, 1998) can be applied to MBES (as well as echosounder and LIDAR surveys) to produce accurate bathymetric maps. IHO standards also provide for quantifying spatial uncertainties within the data. An important consideration when selecting a multibeam system is the ability to log and process data to absolute calibrated levels and accurate geographical scaling. The seabed backscatter data from MBES provides bathymetric maps, and acoustic backscatter of geophysical and biological characteristics of the seabed surface and subsurface layers. Water column backscatter can also be obtained, particularly from recent developments in multibeam systems that provide improved instantaneous dynamic range (about 150 dB), to prevent saturation of the backscatter from the bottom signal. This is advantageous for marine habitat research that requires synoptic geophysical and biological backscatter measurements from the seabed and water column.

7.3 Acoustic seabed classification systems

ASC systems include hardware and software for signal processing and discrimination of the seabed echo return using different types of underwater acoustic instrumentation. ASC systems are often designed with universal interfaces for operation with various models of acoustic instrumentation, while other ASC systems operate with only a specific model of instrumentation. It is recognized that many private and academic institutions are making important developments to ASC systems; however, these are currently unavailable to the scientific community. For this reason, this section is not intended to be a comprehensive review of ASC systems, but it does attempt to describe the ASC systems that are readily available and implemented by scientists. Furthermore, this section is not an endorsement of any ASC system, given that each system provides unique attributes for consideration and evaluation. Pertinent literature is provided here to direct the reader, with additional information on the performance of these commonly used ASC systems. This should give fishery biologists the necessary background to decide which ASC system and instrumentation will best meet the objectives of their marine habitat research initiatives.

The procedures of ASC systems vary, particularly in instrumentation that collects vertical vs. oblique incidence echo returns. The result is the discrimination of the acoustic response from the seabed into categorized regions of similarity. ASC procedures can be generalized in some basic steps for data collection, processing, and analysis (Figure 7.13; see Section 5). Raw waveform data are collected using the appropriate procedures, which vary with the type of instrument deployed, as discussed in the previous sections. Data processing for ASC involves noise removal, bottom detection editing, data segmentation, and geometric compensation, which vary between normal and oblique incidence data. For example, correcting for geometry is more critical to oblique incidence data from swathe sonar operations than normal incidence data from SBES. The raw waveform data are examined for acceptance. Normal incidence data from downwards-looking SBES utilize the E1 and E2 returns for acoustic feature extraction from the seabed. Normal incidence returns are smoothed by stacking a number of pings into averages. Oblique incidence data from sidescan and multibeam operations are segmented into geo-referenced patches. Statistical algorithms, some of which are proprietary, are then used to extract several acoustic response features from the seabed echo. The primary acoustic features accounting for at least 90% of the variability are identified and clustered into discrete geo-referenced classes, based on similarity using either a statistical or artificial neural network (ANN) approach (see Section 5). The ASC can be done using an untrained (unsupervised) approach, which is entirely data driven, or ASC catalogues based on known seabed types from previous studies can be used to conduct trained (supervised) ASC. Conventional sampling (grabs, nets, video) is critical for good interpretation of the ASC to describe the predominant geophysical and biological attributes of the seabed composition (see Section 8). Overall, the basic steps and requirements for conducting ASC operations are similar to those employed with the discrimination of other types of remote-sensing data. The acoustic response, however, varies as a function of its angular dependence, according to the operational design of the instrumentation, as previously discussed.

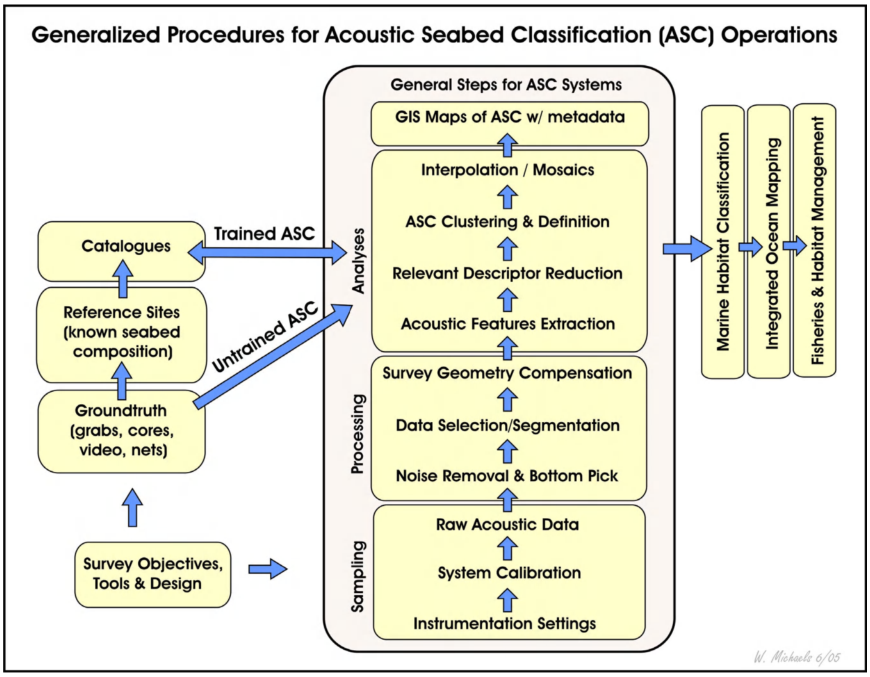


Figure 7.13. Generally, ASC operations can be described in similar stages of data collection, processing, and analysis, although some difference exists between normal and oblique incidence data.

ASC systems for analysing vertical incidence returns from SBES have been used widely and have been evaluated by scientists. The angular response can vary within the footprint, with higher reflectivity occurring closer to nadir. The width of the footprint, hence the incidence angle, is especially important when the seabed is made up of different grain sizes (sand, gravel, and cobble). SBES data generally have more limited angular responses from the seabed than swathe sonar. However, the ASC results derived from vertical incidence echosounders appear to be robust. The seabed backscatter at nadir contains the first-order echo return, with high amplitude primarily from surface reflectivity. The trailing portion of the E1) results mainly from the near-surface backscatter from which ASC features are extracted. The E2 returns from the seabed are also received from SBES and vary when the sound wave penetrates the seabed surface with varying degrees of attenuation as a function of substrate composition. Lower E2 amplitude is expected from softer substrates, such as mud, because of the increased sound penetration in contrast to hard substrates. The E1 and E2 theory was developed by Chivers *et al.* (1990). The E1 and E2 responses from the seabed were further shown to be indices of roughness and hardness, respectively (Heald and Pace, 1996). Some investigators suggest that there is too much variability in the E2, while others find this additional variability useful for the ASC. ECHOplus, RoxAnn, Simrad SEABEC, and Biosonics ASC systems all use the E1 and E2 returns, while the QTC Impact ASC relies on the E1 echo envelope for ASC (Table 7.1). These systems will be discussed further in this section.

ASC systems for swathe (sidescan and multibeam) sonar have become available in recent years, and have not been as widely used as ASC systems designed for normal incidence echo returns. QTC Sideview, QTC Multiview, RoxAnn Swath, Genius, Triton SeaClass, and SWATHplus are examples of ASC systems designed for swathe sonar, to be discussed later in this section (Table 7.1). The oblique incidence returns from swathe sonar provide more angular response information from the seabed, which is particularly useful for discrimination of the seabed composition and texture. Angular dependence of seabed backscatter is widely reported (Hughes-Clarke, 1993; Chotiros, 1995; Jackson *et al.*, 1996; Novarini and Caruthers, 1998). Angular response is the variability of seabed reflectivity and backscatter intensity relative to the angle of incidence of an impinging sound wave striking the seabed. Oblique incidence data collected from swathe sonar require additional data processing, with angular and geometric compensation, than vertical incidence data from the SBES. The pixel data obtained from oblique incidence SSS and MBES provide geo-referenced spatial distributions of grey level shading of amplitude reflectivity. These data can be analysed statistically for textural features, which provide indices of coarseness, contrast, directionality, and other textural features of the seabed image mosaics (Haralick *et al.*, 1973; Haralick, 1979; Pace and Gao, 1988; Du Buf *et al.*, 1990; Jackson and Briggs, 1992).

Energy or angular second moment (ASM) is a common textural feature, in which the measure of homogeneity within an image is derived from grey-scale co-occurrence matrices. Another common textural feature is contrast, which is the difference or local variations in measuring the spread of the grey-scale matrix values. Entropy is another common textural feature, representing the randomness of the image texture, where high entropy indicates greater randomness in the image's spatial co-occurrence matrix. These pixel-based textural features are segmented by the ASC, and the feature extraction and statistical clustering are performed to derive the ASC results. Textural seabed discrimination is more vulnerable to misinterpretation, because of variations associated with grey-level shading and geometric distortions, than the ASC of vertical incidence data collected by SBES.

Table 7.1. Examples of commonly used acoustic seabed classification (ASC) systems are listed with contact information for obtaining further details on hardware and software specifications. This table is not an endorsement these ASC systems.

ASC SYSTEM NAME	ACOUSTIC INSTRUMENTATION	CONTACT INFORMATION
QTC View/Impact QTC Sideview QTC Multiview	Single-beam echosounder Sidescan Multibeam	Quester Tangent Corporation Sidney, British Columbia, Canada www.questertangent.com
ECHOplus SWATHplus	Single-beam echosounders Bathymetric sidescan	SEA (Advanced Products) Ltd, UK www.sea.co.uk
RoxAnn GroundMaster RoxAnn Swath	Single-beam echosounder Multibeam	SonaVision Ltd, Aberdeen, UK www.sonavision.co.uk
BioSonics EcoSAV BioSonics VBT	Single-beam echosounder (BioSonics DT/DE series)	BioSonics Inc., Seattle, WA, USA www.biosonicsinc.com
DHI Genius ImageClassifier using NeuroSolutions SOM_MLP Seabed	Sidescan	Danish Hydraulic Institute www.dhi.dk www.Neurosolutions.com
Triton SeaClass SS-MosaicRT	Sidescan	Triton Imaging Inc. www.tritonelics.com
Kongsberg SIS/Triton Neptune C Software	Multibeam (EM series)	Kongsberg Maritime Simrad www.Kongsberg.com
L-3 ELAC Nautik Sediment Classification	Echosounder (Hydrostar), Multibeam (SeaBeam)	L-3 Communication ELAC, Germany www.l-3com.com
Kongsberg SEABEC Seabed Classifier	Single-beam echosounder sweep echosounder	Kongsberg Maritime, Horten, Norway www.km.kongsberg.com
Kongsberg SEABEC SEABEd Classification	Echosounder (EA400/600)	Kongsberg Maritime Simrad www.Kongsberg.com
SeaScan System	Single-beam echosounder	Seatronics Ltd, Aberdeen, UK www.seascan.net; www.seatronics-group.com
Echoview Fish Habitat	Single-beam echosounder	SonarData, Hobart, Australia, www.sonardata.com

QTC View/Impact ASC

Quester Tangent Corporation (QTC) provides commercially available hardware and software to collect and process the first bottom echo envelope. QTC View logs time-stamped geo-referenced raw envelope data from the seabed using a variety of SBES (Simrad EK500, EK60, EY500, Biosonics DT, ISAH-S). QTC Impact is ASC software for processing raw waveform data (Prager *et al.*, 1995; Collins *et al.*, 1996; Collins and McConnaughey, 1998; Anderson *et al.*, 2002). The recent QTC View Series V logs the raw waveform data, which is an improvement over the older Series IV, which only logs preprocessed echo descriptors (Freitas *et al.*, 2003). QTC Impact is used to extract 166 seabed echo response features, called full feature vectors (FFV), from the raw digital waveform data using proprietary algorithms. Principle component analyses (PCA) are used to identify the dominant FFVs, explaining at least 90% of the variability of the acoustic diversity in three multidimensional "Q-spaces" (Q1/Q2/Q3). Considerable time was spent with manual PCA iterations to derive the seabed discriminant clustering; so the QTC Impact version 3.40 was made available recently to conduct automatic PCA analyses. QTC Impact can conduct seabed discrimination using an untrained (unsupervised) approach; or a trained (supervised) approach can be made, using a catalogue of Q-space clusters relative to reference data of known seabed types. The Q-values eigenvectors can be exported for other analytical methods. The geo-referenced discrete ASC classes from QTC Impact can be exported to commonly used software for categorical interpolation (QTC CLAMS) and mapping (Surfer, GIS Arcview).

QTC Multiview

QTC Multiview is ASC software using data from several models of multibeam instrumentation (Atlas Fansweep 20, Reson 8101, Reson 8125, Simrad EM 1002, Simrad EM 120, Simrad 3000, Simrad EM 3000D). Data imports are either XTF, HSX, or raw waveform, depending on the instrumentation used. Each beam footprint is classified as a pixel. QTC Mulitview discriminates the acoustical angular response of multibeam data into discrete classes using trained or untrained ASC (Preston *et al.*, 2003). This software compensates for spherical spreading, absorption losses, and grazing angles. The echo amplitude from each beam is segmented into rectangular patches in which acoustic response features are extracted, based on the statistics of the backscatter. Each patch is compensated for artefacts from angular and time dependencies, absorption losses, and spherical spreading. Unsupervised classification uses 132 acoustic features in an automated PCA clustering, which in turn reduces these features to three Q-values per image patch. The final processing steps for QTC Multiview are similar to those in QTC Impact and QTC Sideview (see below). Bathymetric editing can be imported from the Caris depth-editing tool and the geo-referenced ASC data from QTC Multiview can be exported into Caris HIPS/SIPS geometric or geographic information system (GIS) software.

QTC Sideview

QTC Sideview is software for automated ASC processing from data collected by several models of sidescan (Benthos SIS-1500, EdgeTech 4100, Imagenex Yellowfin, Klein 595, Klein 2000, Klein 3000, Klein 5000, Knudsen, Marine Sonic, Odum). QTC makes regular upgrades to accommodate new instrumentation, and accepts most XTF-formatted sidescan data. QTC Sideview conducts either trained or untrained ASC from sidescan sonar (Preston *et al.*, 2004b). Data editing and processing can be accomplished individually from port and starboard to compensate for the effects of range and incidence angle. The acoustic features are extracted from segmented pixel-based data by QTC algorithms. Feature extraction is based on basic statistics, quantile, Fourier transform, ratios from power spectrum, grey-level co-occurrence, and fractal dimension algorithms. QTC Sideview's latest version 1.3 provides automated PCA to identify the predominant features as Q-spaces and provide clustering of the ASC. The ASC output can be exported as ASCII data for GIS mapping.

ECHOplus

The ECHOplus Seabed Discrimination System provides hardware for analogue to digital conversion and software for ASC. ECHOplus is an ASC that can process input from one or two frequency channels (20–230 kHz) using various models of SBES. ECHOplus conducts digital signal processing of the waveform data for ASC using the E1 and E2 seabed responses. The E1/E2 scatterplots distinguish regions with similarities in the ASC relative to the roughness/hardness indices. ECHOplus can also perform ASC from sidescan reflectivity by importing digitized sidescan mosaic data from their SWATHplus series software. The SWATHplus is signal-processing software designed for the SWATHplus series bathymetric SSS. SEA (Advanced Products) Ltd, UK (www.sea.co.uk) appears to be a division of Seatronics Ltd, Abeerdeen, (www.seatronics-group.com).

RoxAnn

RoxAnn uses analogue signal-processing hardware and software interfaced to a SBES for collecting acoustic reflectivity and backscatter properties from the seabed. RoxAnn software is used for data logging, real-time display, and data editing of the E1 and E2 bottom echo returns. The tail of the E1 is related to a roughness index, while the E2, primarily from acoustic impedance, is related to a hardness index. ASC is derived from plotting E1 and E2 responses and PCA analyses of the E1/E2 space clusters. Details about the classification methods are reported by Orlowski (1984) and Chivers *et al.* (1990). RoxPlot is used for dual frequency echosounder data logging. RoxAnn has been used widely and evaluated in various ASC studies (Pinn *et al*., 1998, 2003; Hamilton *et al*., 1999; White *et al*., 2003; Wilding *et al.*, 2003; Humborstad *et al*., 2004). RoxAnn GroundMaster Acoustic Ground Discrimination System is a portable ASC unit that operates as a single- or dual-frequency echosounder. RoxAnn Swath is a portable MBES (available at 50 or 200 kHz) with ASC system, which has become available recently for shallow-water operations.

BioSonics VBT-Bottom and EcoSAV Classifiers

The Biosonics VBT-Bottom and EcoSAV classifiers are designed to process the bottom reflectivity and backscatter for ASC using Biosonics SBES series DT-X and DE-X. The VBT-Bottom classifier collects the E1 and E2 bottom returns using a combination of methods for obtaining geo-referenced depth and seabed class results. The B1 (E1 plotted against E2) and B2 (E1/E2 ratio) methods are utilized for seabed discrimination. The method of cumulative energy (B3) from the E1 division developed by Pouliquen and Lurton (1992) is also utilized. Another ASC method (B4) employed is fractal dimension (FD), a measure of the irregularity in the seabed echo return for ASC that is obtained by plotting E1 against FD. BioSonics EcoSAV is a version specifically for extracting the digital signal of aquatic vegetation backscatter along the seabed using the DT-X/DE-X echosounders (Schneider *et al*., 2004). The EcoSav processing algorithms produce geo-referenced data on bottom depth, plant presence/absence, plant height, and areal coverage, which can be readily exported into GIS software. These BioSonics products have import and export format compatibilities with HypackMax (www.hypack.com) editing for GIS mapping.

DHI GENIUS Sea Bed Classification System

The Danish Hydraulic Institute (DHI) in Horsholm, Denmark developed the GENIUS Sea Bed Classification System using NeuroSolutions SOM_MLP software. This ASC software employs a combination of untrained and trained methods of artificial neural networks (ANN) for ASC of SSS images of the seabed surface, which is reportedly a useful approach (Babovic, 1999). ANN is one analytical approach for classification that includes data preparation, network design, training using a series of adaptive weigh vectors and functions, and performance assessment of the ANN. Selecting the ANN architecture depends on the objectives; therefore, selecting an overly complex design may train the ANN perfectly while generalizing poorly. The general-purpose Multilayer Perceptron (MLP) network is utilized as the supervised ANN for pattern discrimination and classification. The Self Organizing Feature Maps (SOM) network model is used as the unsupervised spatial exploratory tool, which in turn is used to train the MLP. SOM utilizes spatial features from two-dimensional textural grey-scale data corresponding to each pixel in the sidescan image. The ImageClassifier with GIS ArcView software categorizes the pixel data into groups, and segmentation is completed to divide the image into subimages that contain features of similarity. Statistically significant feature vectors are extracted and used in combination with the SOM network for clustering. The GENIUS system utilizes the image segmentation feature for median, third quartile, energy, entropy, and momentum. The hybrid SOM_MLP classifier produces the classified image segments for ASC mapping.

Triton Elics SeaClass

Triton Elics SeaClass software characterizes bottom types from reflectivity data collected by various sidescan systems. This software conducts trained ANN on several textural features for ASC. The user can train the ANN with selected areas from mosaic sidescan images to derive regions with seabed surfaces of similar textural attributes. Triton Elics should not be confused with the Triton Imaging Inc. (www.tritonimaginginc.com), which provides several seabed mapping software modules such as the Triton Isis Bathy, BathyPro, and TritonMap.

Kongsberg Triton and Neptune C

Kongsberg provides seabed classification software called Triton, which is a companion of their Seabed Information Software (SIS) supplied with their EM series MBES. This software is also a companion to Kongsberg's Neptune software for post-processing and Poseidon software for backscatter mosaics. The Triton manual does not describe the methodology with which the ASC results are produced, which may explain why results and evaluation of this software appear to be lacking in the scientific literature. Kongsberg also provides another sediment classification module to Neptune, referred to as Neptune C

L-3 ELAC Nautik

The L-3 ELAC Nautik is an ASC system utilized with SeaBeam multibeam and Hydrostar echosounder systems. The L-3 ELAC Nautik system was inherited from the early Honeywell ELAC system, which was originally developed for naval research and defence (Howard *et al.*, 1983). The echo strength measurements (amplitude and pulse character) from the seabed are used, with algorithms from multilayer acoustic theory to provide sub-bottom ASC. Differences in the seabed impedance are used to determine porosity and grain-size structure of the seabed. The L-3 ELAC Nautik does not appear to be widely used today.

Kongsberg-Simrad SEABEC

The SEABEC (SEABEd Classification) is ASC software used with the Kongsberg-Simrad EA400 and EA600 single-beam sweep echosounders, which provides real-time seabed discrimination ASC. SECBEC can also be used with other Kongsberg-Simrad SBES (e.g. Simrad ES60). Raw data from E1 are logged and processed using SEABEC. Resampling and filtering are applied to reduce the sampling variation for the ASC feature extraction, and the acoustic response spectrum is used with PCA providing ASC.

SeaScan System

The SeaScan System interfaces with several models of commercial-grade SBES (models from Furuno, Koden, JMC, Knudsen, Odum, Simrad, Elac, Skipper, Hydrotrac, and Atlas Deso). ASC is accomplished by plotting the E1 and E2 to identify the clusters of similarity. ASC maps are displayed in real time to assist commercial vessel operations with locating fishing grounds. This system does not appear to be commonly used by scientists. SeaScan is a division of Seatronics Ltd, Aberdeen.

Echoview Fish Habitat

SonarData recently offered Fish Habitat, software that works interactively with their Echoview software, providing a new tool for ASC research. The software allows researchers to analyse the first and second echoes obtained from various models of echosounders for deriving measures of seabed roughness and hardness. The companion Echoview Virtual Echogram module is particularly useful for developing new algorithms to improve ASC. SonarData software also provides QTC Impact export options.

7.3.1 Subsurface ASC Systems

Although subsurface ASC – lower than 1 m below the detected seabed – is not included in the terms of reference of this report, some of these systems will be mentioned briefly. For example, Automated Seafloor Classification System (ASCS) is a sub-bottom seabed classification system developed by the Naval Research Laboratory at the Stennis Space Center, Mississippi, USA (Lambert *et al.*, 1999). Acoustic Core is sub-bottom ASC software, available through Ocean Data Equipment Corporation in Providence, Rhode Island, USA (www.oceandata.com). Echo-Sounder Detection of Sediment-Layers and Properties (DSLP) is a sub-bottom ASC that uses an acoustic Doppler current profiler (ADCP) transducer (Eden *et al.*, 2001). ASC systems are also available through the Canadian Seabed Research Ltd. in

Nova Scotia (www.csr-marine.com). The Automated Seafloor Classification System (ASCS), developed by the Naval Research Laboratory, produces three-dimensional ASC sediment profile maps (Lambert *et al.*, 1999). Another example is the SEDCLAS, which is a ASC system for SBES developed by the Netherlands Organization for Applied Scientific Research (www.eu-seased.net/services/issue4/page9.html).

7.3.2 Other Software for ASC systems

An important development in ASC systems is the universal interface with various models of instrumentation, standardized formats (e.g. HAC, XTF, HSX), and the ability to import and export among supportive software for data processing and mapping. SonarData in Australia (www.sonardata.com) offers companion modules to their ECHOVIEW software for collecting raw data from the seabed using various SBES for export into QTC Impact (EchoIMPACT). Caris HIPS (for SBES and MBES) and Caris SIPS (for SSS) are comprehensive baseline bathymetry editing tools, offering geometric compensation from integrated motion sensors and a validation tool for digitized seabed charting (www.caris.com). QTC Multiview and QTC Sideview provide import and export capabilities with Caris Field Sheet Editor. HyPack Max software (www.hypack.com) is commonly used for processing, visualization, and mapping of acoustic seabed data; it has import/export options with various ASC systems (RoxAnn, QTC, ECHOplus, Biosonics). Idrisi32 software, available through Clarke Labs, Worchester, Massachusetts (www.clarklabs.com), is used to conduct colour-composite analyses for satellite reflectance bands, which in turn are used to produce GIS imagery from ASC features. QTC CLAMS Classification and Mapping Software does categorical interpolation on discrete ASC classes derived from QTC software, as well as other ASC systems (RoxAnn and ECHOplus). Many ASC systems export geo-referenced ASC that can be imported into common mapping software such as GIS ArcView, DelphMap mosaics, and Surfer. These are just a few examples of the important efforts to integrate ASC software with various software commonly used for data processing, visualization, and mapping.

7.4 Ongoing ASC development and recommendations

Undoubtedly, instrumentation, hardware, signal processing algorithms, and software for ASC will be improved in the near future, given the ongoing research and development efforts. There are ASC research efforts underway at private and academic institutions, with improved designs that are still in the testing phase; this is why this review should not be considered comprehensive. For example, the University of New Hampshire and National Oceanic Atmospheric Administration Joint Hydrographic Center (UNH/NOAA/JHC) is an example of considerable ongoing research and evaluation are being used to improve designs of instrumentation and ASC systems software (www.ccom-jhc.unh.edu). The University of New Brunswick is another example, where research is conducted to improve techniques for ASC (Mourad and Jackson, 1989; Hughes-Clarke *et al.*, 1997).

Another area of ongoing development is signal-processing and beamforming methods, which will provide more accurate acoustic measurements. New generation multibeam systems (e.g., Kongsberg EM3002 and EM710, Reson SeaBat 7125, 8111, 8125) include a recent beamforming technique, referred to as dynamic focused beamforming. Dynamic focusing increases vertical resolution while maintaining the narrow-beam required for horizontal resolution. This is achieved through a wider aperture array to produce a narrow-beam of high frequency with short pulse lengths and reduced side lobes. The Kongsberg ME70 is the most recent new-generation multibeam, recently developed for fishery research providing dual-purpose seafloor mapping and quantitative water column backscatter. The ME70 is unique in that its multibeam head is arranged with 20 by 40 elements in a rectangle rather than the typical Mills cross array. This provides the advantage of configuring 3 to 45 split-beams in a swathe operating in a wideband of frequencies (70–120 kHz). Synthetic aperture is another emerging beamforming technique that combines multiple physical beams to derive an artificial array of beams (Lurton, 2002). GeoAcoustics in England (www.geoacoustics.com) have developed their software GeoSAS for data processing and ASC from their synthetic aperture. Chirp sonar utilizes separate transmitters and receivers, and produces multifrequency pulses with increased bandwidths, to obtain improved theoretical range resolution, regardless of pulse length (Lurton, 2002). This technology has been successfully applied to sub-bottom profiling, and is being developed for SSS and MBES.

Improved instantaneous dynamic range (IDR) is necessary to measure simultaneously the quantitative backscatter from synoptic geophysical and biological parameters for marine habitat classification (see Section 3). Most systems are saturated by high seabed amplitude, preventing detection of the lower backscatter from the water column. The instantaneous dynamic range of these systems must be increased to include the high backscatter from biotic and abiotic components of both the seabed and water column, which is particularly important for classifying and managing our marine habitat. Scientific echosounders, such as the Simrad EK60 with IDR of 150 dB, have been commonly used for quantitative backscatter measurements from the water column and seabed backscatter for ASC. Only recently have new-generation MBES systems (such as the Simrad EM3002 and ME70) become available with sufficient IDR to measure water column and seabed backscatter. Ongoing developments in instrumentation and ASC systems will enhance our ability to survey the water column and seabed simultaneously.

ASC systems must be calibrated if the research objective is to support the mandated responsibilities, and to identify and monitor essential fish habitat and protected marine areas (see Section 3). ASC provides the foundation for classifying and monitoring marine habitats, and the results must be repeatable for fishery managers to defend their regulatory mandates. Investigators routinely conduct absolute calibrations of scientific echosounders for fishery acoustic surveys; however, echosounders are rarely calibrated for ASC studies, which may explain why results are often not repeatable. Therefore, it is recommended that SBES be calibrated regularly, using the standardized procedures described by Foote *et al.* (1987). Research for developing standardized calibration procedures for multibeam sonar is currently underway (Cochrane *et al.*, 2003; Chu *et al.*, 2003; Foote *et al.*, 2003). Repeatable results are unlikely for SSS in regions with rough bottoms, because of the variability in seabed echo reflectivity caused by low grazing angles and shadowed regions. The mandate for fishery management to identify and monitor essential fish habitat demands defensible scientific advice; therefore, absolute system calibrations are important for ASC, and the ease of calibrating a SBES is a distinct advantage over other types of instrumentation for ASC.

ASC simply categorizes the acoustic responses from the seabed; it does not provide the composition of the seabed. For this reason, proper interpretation of ASC relies on mechanical or visual sampling for verification to understand the underlying acoustic principles (see Section 8). The question of which advanced technologies should be integrated with ASC survey operations has created bottleneck for ASC operations. Some examples include laser-line scanning and automated optical recognition. Alternative platforms, such as AUVs and towfish, with integrated acoustical–optical sensors, can also resolve the problems of conducting ASC in deep-water regions, particularly with slope gradients.

Communication and collaboration between the users, developers, and providers are critical to ensure good progress in the development, evaluation, and acceptance of ASC systems. The accessibility of hardware and software codes and formats is also important to research. Scientists are more likely to use an ASC system that has been extensively implemented and evaluated by colleagues. Therefore, it is desirable for ASC systems to be upgraded regularly to include data codes from various types and models of acoustic instrumentation. Software, including complete descriptions of variables, calculations, and theory, are also more likely to be accepted by scientists and managers. The ability to import and export data and results between software allows scientists to integrate ASC systems effectively with their operational tools. For example, SonarData software provides a variety of post-processing and multifrequency tools that are unavailable in existing off-the-shelf seabed classification software; it has import and export capabilities for various seabed classification software, which provide an enhanced ability to process and analyse ASC data. Vendor participation in scientific workshops and conferences has resulted in timely upgrades with improvements recommended by the scientific community. Although proprietary concerns can hinder scientific progress, there is a trend to collaborate closely to improve ASC research and development, recognizing that this actually increases the marketability and creditability of ASC systems.

Overall, each type of acoustic instrumentation and ASC system provides different types of data useful for the classification and management of marine habitat and fisheries resources. The operational design, objectives, and costs will dictate which type of instrumentation and ASC to implement. Repeatable ASC results will be increasingly important when utilized for regulatory management of our marine resources. ASC operations must also collect the appropriate metadata and standardized formats for archival purposes, in support of integrated marine habitat GIS mapping. New-generation systems that allow researchers to integrate ASC with seafloor mapping and quantitative water column backscatter operations will improve marine fish and habitat assessments in a more accurate and cost-effective manner.

8 Verification methods of acoustic classes

Craig J. Brown and Roger Coggan

8.1 Introduction

Acoustic methods have been used to classify sediments on the seabed since the 1950s and 1960s (Taylor Smith and Li, 1966; King, 1967). The strength of an echo from an echosounder (and the way it decays with time) produces a complex signal, the shape of which depends, to a large degree, on the nature of the seabed; this is the basis upon which echosounders have been used for seabed classification (see Sections 2, 3, and 4). The main characteristics of the seabed environment that will affect the acoustic signal are seabed geology and benthic biota. It is, therefore, these two characteristics that require verification to establish the cause of different acoustic signatures over any particular survey site. No matter which type of acoustic system is used to obtain data from the seabed (see Section 7), it is the process of interpreting the acoustic data in terms of its physical and biological attributes that makes it useful to scientists and resource managers. The process of verifying (validating) acoustic data in terms of sediment composition, morphological structure, and biota is commonly referred to as ground-truthing. The goal is the production of seabed habitat maps at multiple spatial scales.

The ground-truthing data is normally grouped or classified by key seabed attributes (e.g. similar sediment properties, similar biological traits). Classifying the data in this way allows areas with similar seabed properties to be grouped together. Whichever ground-truthing method is adopted, the next stage is to link the *in situ* data with the acoustic data. Recording the exact location from which the ground-truth data is collected allows it to be linked to the acoustic data from the same geographical location. In this way, the two datasets can be linked, providing the required verification, and the *in situ* classes can be extrapolated to all the regions that fall within the same acoustic class. For purely biological data, the extrapolation must take account of the depth-dependent zonation of biological communities. However, it should be noted that the scale of observation from the *in situ* ground-truthing is often far finer than the resolution of the acoustic system(s), and not all seabed attributes that are recognizable from ground-truthing data methods will be acoustically distinguishable (see Section 6). This poses the problem of the maximum and minimum scales to which seabed attributes can be mapped using acoustic techniques.

This section summarizes the range of techniques that can be employed to ground-truth acoustic datasets and discusses issues of scale and resolution that are associated with linking verification data to acoustic data. The choice of ground-truthing technique will depend, to some extent, on the nature of the seabed at any particular survey site. A wide variety of sampling methods are available for collecting *in situ* seabed data (Boyd, 2002; Eleftheriou and McIntyre, 2005), with each technique suited to a particular type of seabed and a particular application. The methods described below are representative of those used for ground-truthing of acoustic data, and it should be recognized that there are many other sampling devices not described here that may also be used for this type of application. The reader is directed to Coggan *et al.* (2007) for a more comprehensive review of *in situ* sampling methodology.

8.2 Defining seabed attributes

The term habitat is commonly defined as "a place where a microorganism, plant, or animal lives" (Begon *et al.*, 1990). Habitats can be defined on the assumption that organisms distribute themselves along environmental gradients and that their clusters define distinct sets of environmental factors. Therefore, we are able to map habitats as spatially definable areas, where the physical, chemical, and biological conditions are distinctly different from surrounding areas (Kostylev *et al.*, 2001). A number of habitat classification schemes have been developed to standardize how we name and describe benthic habitats. Many of these schemes are hierarchical, reflecting the fact that the natural world is structured hierarchically and processes within natural regions operate across a number of spatial and temporal scales. In Europe, the EUNIS (EUropean Nature Information System) classification scheme is being developed and managed by the European Topic Centre of Nature Protection and Biodiversity (ETC/NPB in Paris) for the European Environment Agency (EEA) and the European Environmental Information Observation Network (EIONET; Davies and Moss, 1999), and is designed to incorporate national classification schemes (e.g. Connor *et al.*, 2004). Elsewhere in the world, other schemes have been proposed that take a top–down approach for a global application for the management of marine resources (e.g. Greene *et al.*, 1999; Madden and Grossman, 2004; Valentine *et al.*, 2005). Essentially, all of these classification systems rely on the combination of the seabed's physical and biological attributes measured using one or a combination of the acoustic-data verification methods described below. They tend to define habitats based on characterizing species (i.e. conspicuous epifauna) and key environmental variables (i.e. key substrate parameters). However, it is somewhat difficult to compare the schemes in detail, because various key attributes are placed at different hierarchical levels within the classification schemes. There is probably no right or wrong way to classify habitats and, at this moment in time, it is unclear which schemes can best be linked to acoustic datasets for the purpose of habitat discrimination.

Measurement of physical seabed attributes can be achieved using a range of verification methods. The collection of sediment samples will allow detailed analysis of the seabed substrata; measurements of sediment particle size distributions can be achieved through a number of established laboratory procedures (Boyd, 2002; Passchier, in Coggan *et al.*, 2007). Once particle size data are available, it is relatively straightforward to classify the substrates using established sediment classification schemes (Wentworth, 1922; Folk, 1974). However, this approach is limited to areas of unconsolidated sediments, where penetration by the sampling device and collection of a physical seabed sample are possible, but it is not suitable for sampling in areas of consolidated substrates or on hard, rocky substrata.

Visual methods of verifying acoustic data will allow broad seabed categories to be identified relating to the surficial substrate characteristics. Such methods can be applied to both hard and soft seabed types, thereby enabling this ground-truthing approach to be applied in all areas. The scale of observation using this method may also be more in line with the scale at which acoustic systems operate. Sediment features (e.g. sediment ripples, bedforms, sediment transport features), which can go undetected using physical sampling methods and which can significantly alter the acoustic properties of an area, may be easier to identify using visual techniques than physical sampling methods.

When characterizing the seabed biota of an area, the type of sampling gear used has a profound effect on how the community is described. Measuring and classifying biological attributes on the seabed can be done using a wide range of methods (see below). For example, the use of a grab to sample the biota of the seabed will result in detailed information regarding the infaunal community. However, the scale on which the grab operates, typically sampling around 0.1 m^2 of seabed, will fail to adequately sample larger, rare, or mobile epifaunal species. In contrast, the use of trawls or dredges to sample seabed biota is more appropriate for sampling mobile and epifaunal species rather than infaunal species, because these devices typically sample tens or hundreds of square metres of seabed, depending on gear specification and deployment methods. The use of either technique in isolation will result in the derivation of different biological classes based on the fraction of the benthos best characterized by the technique. The type of sampling gear, therefore, can be seen to have a considerable bearing, not only on the identification of the characterizing species from an area of seabed, but also on the power to discriminate between habitat types based on biological traits. For this reason the deployment of a combination of sampling techniques would provide a more realistic means of describing the benthic ecosystem, accepting that the capacity to discriminate between habitat types on biological grounds may often be method-dependent (Brown *et al.*, 2001, 2002, 2004a).

The process of classifying ground-truth data is a crucial stage in the production of seabed maps, but it should be recognized that not every hierarchical unit within a classification scheme can be linked to discrete acoustic classes. The scale at which seabed attributes can be defined is ultimately determined by the maximum resolution of the acoustic system and the limits of the ground-truthing accuracy with respect to positioning (Kenny *et al.*, 2003). There is also a mismatch in scale between what an acoustic system can resolve and the scale at which seabed attributes can be recognized from *in situ* techniques. *In situ* data are collected at a very high level of detail (e.g. conspicuous species, particle size distributions, infaunal information, etc.) at a scale of centimetres to decimetres. The resolution of acoustic data can be much coarser than of verification data, tending to be on the scale of metres to tens of metres (see Section 6). This point is illustrated in Figure 8.1, which shows a sidescan sonar image. The image is approximately 300 m across and indicates the level of detail distinguishable from a typical acoustic survey (i.e. unconsolidated sediments and large sediment transport features). The figure also shows a selection of verification photographs from the same area, each approximately 1 m across. It is possible from the verification data to distinguish three different seabed classes: gravel, sand, and mixed substrate. However, there is clearly a mismatch in the resolution between the two datasets and it should be recognized that not all the seabed classes distinguishable from ground-truth data can be accurately mapped from remote acoustic surveys. This highlights the fact that care should be taken when attempting to link verification data to acoustic classes. It is highly likely that a number of verification data "units" (whether habitats, sediment classes, or species information) recorded using visual or physical sampling survey techniques will fall within a single acoustic class and that it will not be possible to map every ground-truth unit using acoustic methods. It is paramount that there is a clear linkage between the classification units and the acoustic technique in use.

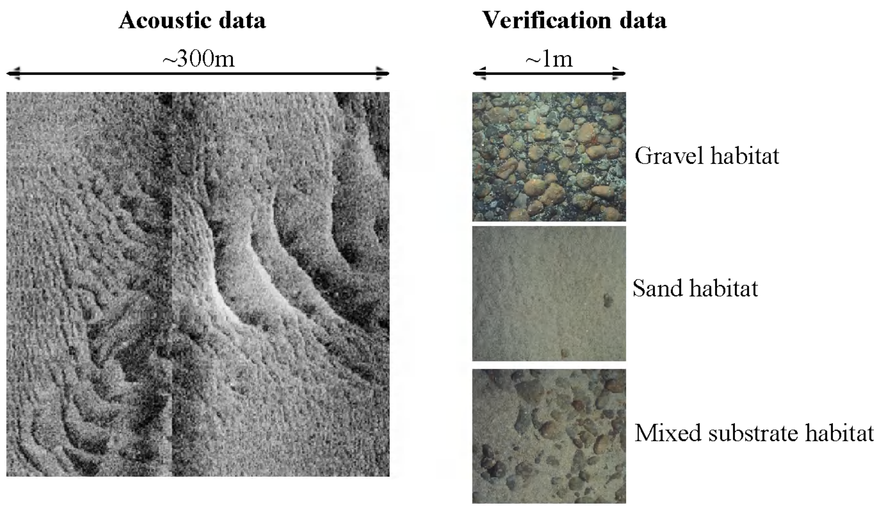


Figure 8.1. Comparison of the scale of resolution between an acoustic dataset and examples of verification of acoustic data photographs from that area.

8.3 Qualitative and semi-quantitative ASC verification methods

Many sampling methods provide only qualitative or semi-quantitative information, but are still effective in ground-truthing acoustic data, allowing subjective characterization of seabed features (e.g. sediment type, sediment transport features, and conspicuous or dominant benthic fauna), which can then be linked to the acoustic data. However, it should be noted that in most cases the conspicuous or dominant benthic fauna, which are commonly used to define habitats, are present in densities too low to create distinctive acoustic signatures themselves. In most cases, the biota can be considered "acoustically transparent" and the acoustic signature of an area is usually derived primarily from the physical attributes of the seabed. It is usually only the sessile massive or densely aggregated biota (e.g. biogenic reefs, bivalve beds, brittle star beds, dense kelp) that will create a distinct acoustic signature. Nonetheless, visual survey methods are appropriate in many cases to identify and classify the seabed environment, but the spatial resolution of the data and the level of discrimination of the various seabed characteristics depend on the sampling methodology.

8.3.1 Visual survey methods

Underwater video and still photography are valuable, non-destructive methods for the assessment of all types of seabed attributes. They can be particularly useful over hard or consolidated ground, where physical sampling methods are inappropriate. Their main limitation is in turbid waters, where the level of visibility can be low and image quality may be too poor to distinguish seabed characteristics. The collection of underwater video and still photography data can be achieved through the use of five broad survey methods.

(1) Passive, drop-down platforms

These systems usually consist of a robust, protective frame onto which a downwards-pointing still camera and a forwards- or downwards-pointing video camera and lights are typically mounted. The platforms, an example of which is shown in Figure 8.2, are deployed over the stern or side of a drifting survey vessel to record images of the seabed. The field of view from the cameras depends on the specifications of the camera system used, the water clarity, and the height above the seabed to which the platform is lowered. The camera systems may record data *in situ*, or they can be linked by way of an electrical umbilical cable to a recording unit on the survey vessel. These systems are relatively inexpensive and easy to use, but there are a number of drawbacks. The field of view will change throughout a deployment as the height of the platform above the seabed varies. This normally makes it difficult to extract any form of quantitative data from the video footage or photographs unless some sort of scaling device (e.g. laser scaling) is also fitted to the platform to estimate the area of seabed in view at any one time. One way of overcoming this is to use the device as a bed-hop camera, by allowing the legs of the supporting frame to come to rest on the seabed, in a series of leap-frogs. When the frame is static on the seabed, the camera will be a fixed distance from the substrate, and so have a known field of view. This bed-hop technique can be used with a still camera fitted with a triggering device (e.g. weighted rope) that causes the shutter to release at a fixed distance from the seabed (a common technique for drop-cameras used in deeper waters, i.e. >200 m, where a direct video link via an umbilical is impractical). As the systems are usually deployed from a drifting vessel, the capability to accurately target specific features/acoustic classes on the seabed is limited.

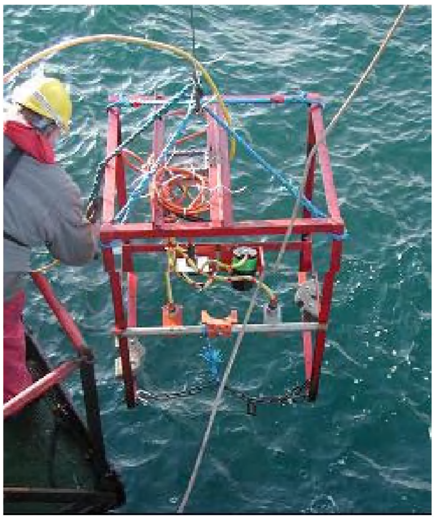


Figure 8.2. Typical drop-down camera frame fitted with an underwater video camera, lights, still camera, and strobe.

(2) Towed platforms

Towed platforms are also commonly used for the collection of underwater video and photographic data. They usually consist of a robust camera sledge, towed over the seabed from the stern of a survey vessel, and typically include a vertically mounted still camera and a forwards- or downwards-pointing video camera with lights. As with the drop-down platform, the camera systems may record data *in situ* or can be linked by way of an electrical umbilical cable to a recording unit on the survey vessel. A more sophisticated towed system is the remotely operated towed vehicle (ROTV), whose depth and altitude are controlled by rotors. However, the cost of the elaborate control systems required for these devices tends to limit their use. An example of a towed platform is shown in Figure 8.3. Towed systems that drag along the seabed have advantages over drop-down systems, because the area in view at any one time is constant and can be calculated and this, coupled with the knowledge of the distance covered in one haul, allows transect-type studies to be conducted. This enables semi-quantitative data to be extracted from the video/photographic images. However, as with the drop-down systems, there is also limited manoeuvrability on the seabed, making it difficult to achieve accurate targeting of seabed features. Particular consideration must be given to accurate geo-referencing of images acquired by towed systems – best done using Ultra-Short BaseLine systems, but frequently done (and less accurately) using layback calculation (also applies to remotely operated vehicles). Positioning issues associated with geo-referenced data are discussed in Section 8.5.

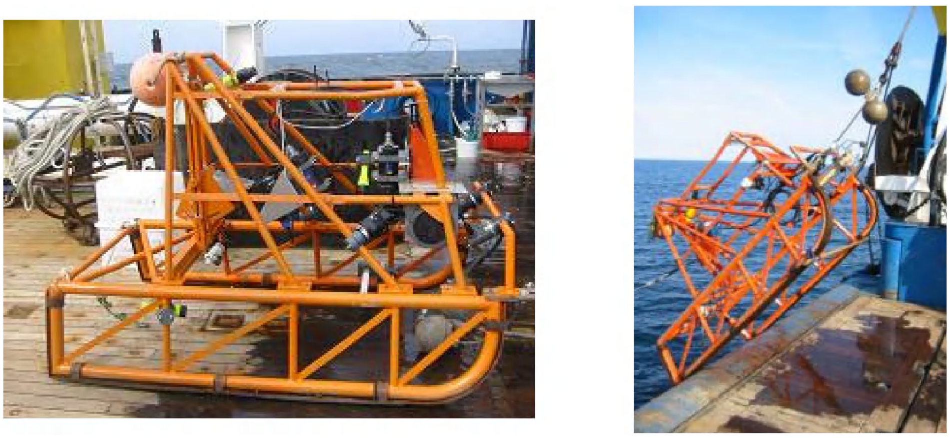


Figure 8.3. A towed platform, typically fitted with an underwater video camera, lights, still camera, and strobe.

(3) Remotely operated vehicles (ROV)

A more sophisticated and controlled method of collecting visual data from the seabed can be achieved through the use of an ROV. Such systems consist of a neutrally buoyant platform for mounting still and video cameras and lights (along with a range of other instruments as required) and a number of motors/thrusters that are used to drive the vehicle while underwater. The platform is controlled by an operator at the surface and an umbilical provides two-way electrical connection between the deck control unit and the vehicle. In this way, the operator controls the platform's position relative to the seabed and, therefore, the system allows much more precise positioning of ground-truthing data collection than the two passive platforms described above. ROVs are usually deployed from a stationary vessel (either anchored or through dynamic positioning). This facilitates precise targeting of seabed features of interest. However, there remain issues relating to changes in the field of view caused by the variable altitude of the platform and the ability on some ROVs to change the attitude of the camera(s). This can make it difficult to extract quantitative data from the video/still images unless some sort of scaling device (e.g. laser scaling) is also fitted to the platform. There are many types of ROVs in use that range widely in cost and complexity, examples of which are shown in Figure 8.4.

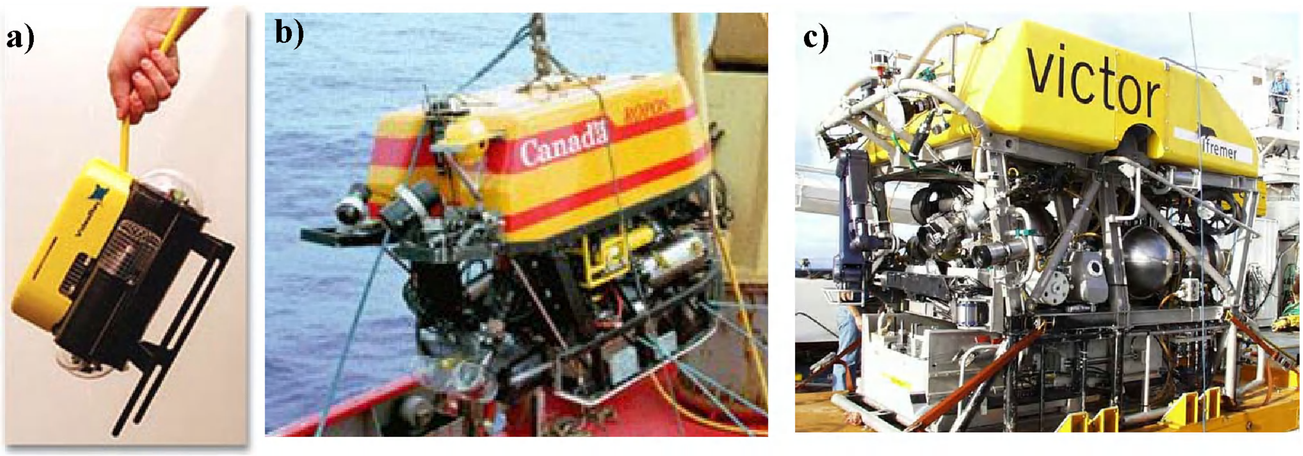


Figure 8.4. Examples of ROVs. (a) A small observation/inspection class ROV; (b) light work-class ROV; (c) heavy work-class/intervention ROV. Image sources: www.loxus.com/ fin/tuotteet2.htm, newport.pmel.noaa.gov/nemo_cruise98/technology.html, and www.ifremer.fr/fleet/systemes_sm/ engins/victor.htm

(4) Diver-deployed systems

The fourth method of collecting visual ground-truthing data is through the use of diver surveys. Divers (both scuba and snorkelling) can be employed in a wide variety of ways to gather data on the subtidal environment, which can then be used to verify acoustic datasets from the same region. Divers can record observations of seabed attributes from selected dive sites on underwater slates, quantify biota and sediment characteristic from transect or quadrat survey methods, collect physical samples (e.g. cores) from the seabed from selected sampling sites, or operate underwater video or still cameras to record data for later analysis. The use of divers allows precise targeting of seabed features and the collection of very detailed datasets. However, this approach is seriously limited because divers are restricted to shallow regions (usually less than 30 m) and are restricted by limited dive duration.

(5) Sediment profile imagery (SPI)

The SPI camera works like an inverted periscope, providing a photographic image of the sediment profile, to a depth of approximately 30 cm. The system comprises a camera mounted above a wedge-shaped prism with a Plexiglas faceplate and an internal light, provided by a strobe flash (Figure 8.5). On reaching the seabed, the camera's time-delayed shutter release is triggered, and the prism is smoothly driven into the substrate under gravity (weights acting against a hydraulic resistance), the photograph being taken after the prism comes to rest. In the US, the system is also known by the acronym REMOTS (Remote Ecological Monitoring of the Seafloor).

The SPI has applications in ground-truthing acoustic surveys over soft sediments, particularly those acoustic systems using low frequencies, which penetrate the substrate to some degree. The images reveal layering and voids in the sediment profile. Image analysis can be used to quantify over 20 physical, chemical, and biological parameters, including sediment type and grain size, prism penetration depth (indicating relative sediment compaction), and sediment boundary roughness (indicating the degree of physical disturbance or biotic activity at the sediment–water boundary).

The main limitation of SPI is its small footprint, so it is common practice to collect a series of images at each station by hopping the system across the seabed. Further, SPI only works on soft sediments (mud or muddy sand) without subsurface obstructions and is often used in combination with other sampling techniques (e.g. grabs or trawls) for ground-truthing remote-sensing techniques.

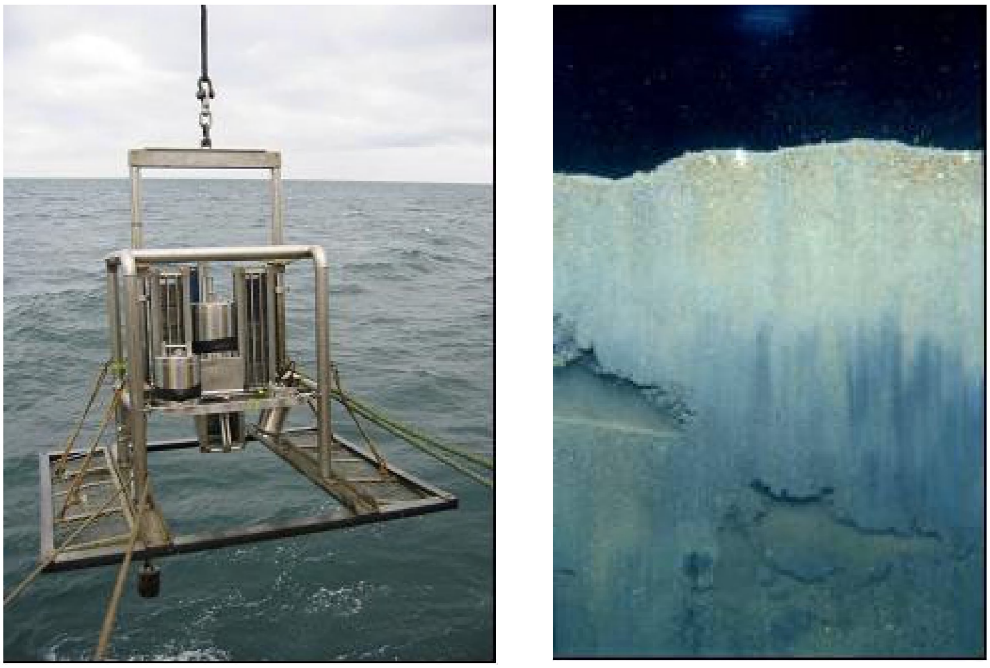


Figure 8.5. Sediment profile imagery (SPI) system (left) with example of an SPI image showing sediment layers and voids (right).

8.3.2 Analysis of visual datasets

Each of the above survey methods provides qualitative or semi-quantitative data relating to the seabed attributes. The choice of which of the above visual ground-truthing techniques are used will depend on a number of factors, including availability of equipment, seabed terrain, water depth and clarity, cost implications, and the preferences of the surveyor. However, the fundamental way in which the data are processed will be the same for all of the above approaches.

All video and photographic data must be geo-referenced before further analysis (see Section 8.5). Geo-referenced video and photographic data can then be subjected to a number of levels of analysis. A relatively rapid method of analysis is the scoring of visible species using a semi-quantitative abundance scale, such as the UK Marine Nature Conservation Review

SACFOR scale (Hiscock, 1996). If the area in view is known, photographic stills or video freeze-frames can be treated as quadrats and subjected to species counts or percentage cover estimates, which provide quantitative data. Video footage can be treated in a number of ways for processing, in either a qualitative or semi-quantitative manner. Video tows can be treated as transects when the field of view and the length of tow are known. Alternatively, where the field of view is constantly changing, such as for data collected using a drop-down system, species-time methods can be used to quantify the visual data (species counts, percentage covers, and substratum descriptions), and can result in measures of relative species abundance (Kimmel, 1985; Michalopoulos *et al.*, 1992; Service and Golding, 2001). All of these methods of analysis, when combined with substratum descriptions, can be used to classify the data using local and/or national habitat classification schemes (e.g. Connor *et al.*, 2004). Whichever method is used, the ultimate aim is to classify the data into seabed attribute classes, which can then be linked to the acoustic seabed classes.

8.3.3 Trawls and dredges

A wide range of trawls and dredges have been devised for remote epibenthic sampling, with various efficiencies of organism retention (see Eleftheriou and McIntyre, 2005). In addition, a number of devices, more commonly associated with epifaunal sampling, can collect large volumes of sediments when deployed on soft and/or unconsolidated sediments. In this mode of operation, such devices can be useful tools for qualitative or semi-quantitative sampling of the infaunal communities and sediments from a survey region.

Several types of trawls and dredges have been used successfully for the purpose of habitat identification and subsequent verification of acoustic datasets in a number of recent studies (Brown *et al.*, 2001, 2002, 2004a, 2004b; Foster-Smith *et al.*, 2004; Mackinson *et al.*, 2004). Trawls and dredges provide an excellent means of sampling the larger and mobile epibenthic species that can be missed using other methods, such as grab sampling. However, as stated earlier, the type of sampling gear chosen will have a considerable bearing on the fraction of the benthic community sampled, which in turn will influence how the verified acoustic data are classified. This will affect the power to discriminate between habitat types based on biological traits. Therefore, the use of trawls and dredges for verification of acoustic datasets is commonly carried out in conjunction with complementary techniques, such as grabs and video, in an attempt to sample all components of the seabed environment (Brown *et al.*, 2001, 2002, 2004a, 2004b).

Verification of acoustic data using trawls and dredges is not without its limitations. By their very nature, towed sampling techniques collect samples over a large sweep of seabed (from tens of metres up to several kilometres in dimension). Their use in areas of high acoustic variability/seabed heterogeneity, therefore, may be inappropriate because the sample collected will be integrated across several discrete seabed types and, consequently, cannot be linked to a particular acoustic class. In such situations, very short tows should be carried out or a different sampling technique should be adopted. There are also issues of sampling efficiency. It is difficult to ascertain whether the device has maintained good bottom contact during a tow or whether the gear has been sampling in the correct orientation. Thus, sample size and quality may vary significantly between tows. A degree of expert judgement regarding sampling efficiency will be a routine requirement during trawl surveys and samples will be rejected or accepted on this basis. It should be recognized, therefore, that the data generated from trawl and dredge samples are mostly qualitative or, at best, semi-quantitative in nature.

The destructive potential of trawls and dredges has led to criticism of their use as sampling devices. Their appropriate use must be carefully considered, particularly in areas sensitive to damage, such as biogenic reefs. Their safe use is also limited to areas of low local topographic complexity. Trawls used for scientific sampling are usually far smaller than those used for commercial purposes, although this tends not to be the case for dredges.

There is a wide variety of trawls and dredges that can be used in benthic surveys to ground-truth acoustic datasets. The following is a summary of the two more commonly used devices, but the reader is directed to Eleftheriou and McIntyre (2005) and Boyd (2002) for a more comprehensive account of this type of sampling gear.

(1) Beam trawls

Small sized trawls have been used successfully for ground-truthing of acoustic datasets (Brown *et al.*, 2001, 2002, 2004a; Mackinson *et al.*, 2004; Coggan *et al.*, 2007). Typically, 2- or 3-m beam trawls are the preferred sampling tools because they collect a manageable sample volume if the length of tow is kept short. Different trawl designs are often used depending on the nature of the seabed on which they are deployed. For level, soft sediment substrata, lighter weight, wooden beam trawls with a small number of tickler ground-chains are the preferred design (Figure 8.6a). On harder or coarser ground, heavier weight, steel beam trawls with heavy ground chains, such as the Jennings Beam trawl (Jennings *et al.*, 1999; Figure 8.6b), are more effective. The Agassiz trawl (Figure 8.6c) is also suitable for most substrates. It has an advantage over beam trawls in that the design is symmetrical about the horizontal axis, so it will fish effectively whichever way up it lands on the seabed. There are other types of trawls that could be used for verification of acoustic data; the reader is referred to Eleftheriou and McIntyre (2005) for details.

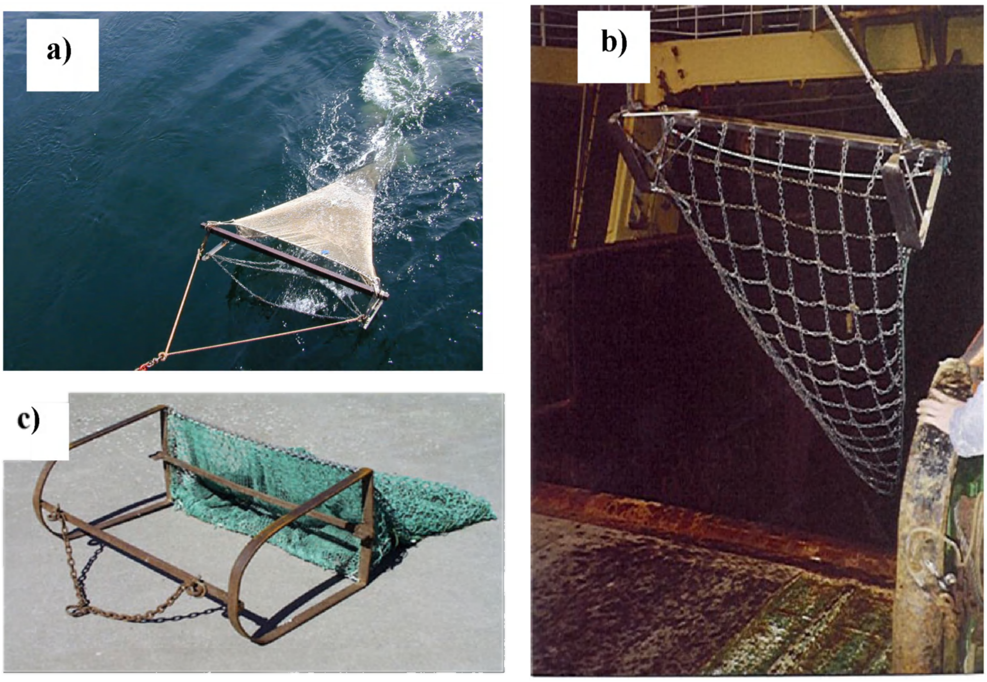


Figure 8.6. Two types of Beam trawl that have been used for verification of acoustic datasets. (a) a wooden 2-m Beam trawl; (b) a heavy-duty 2-m Beam trawl with heavy-duty ground chain mat for excluding large boulders (photograph: CEFAS); (c) Agassiz trawl (mouth width approximately 2 m).

(2) Dredges

Similarly, there are several dredge designs that could be used to validate acoustic datasets (Boyd, 2002; Eleftheriou and McIntyre, 2005). Commercial fishing gear, such as the Newhaven scallop dredge (Figure 8.7a), can be effective for sampling epifaunal and large infaunal species on very coarse terrain. Other types of dredges, such as the Anchor dredge

(Figure 8.7b) and the Rock dredge (Figure 8.7c), can collect qualitative data on the epifaunal and infaunal communities, especially in areas of coarse substrata where the use of quantitative sampling techniques (i.e. grabs) may be ineffective.

(a)

(b)

(c)

Figure 8.7. Examples of three different designs of dredge. (a) Newhaven scallop dredge; (b) Anchor dredge (photo: Jim Ellis, CEFAS); (c) Rock dredge. (photo: www.mbari.org/expeditions/EasterMicroplate/gear.htm

8.3.4 Data processing and classification from trawls and dredges

Trawl and dredge samples can be processed in several ways, ranging from a simple to a more thorough analysis. In the simplest method, the catch is sorted and the taxa are recorded as either present or absent. Next, the relative abundance of taxa can be recorded on a categorical scale, such as the UK Marine Nature Conservation Review SACFOR scale (Hiscock, 1996) to achieve a form of semi-quantitative analysis. This method can be difficult to apply in practice because of the subjectivity of the observer and the sometimes large variability in catch volumes. Lastly, the volume of the catch can be recorded, the taxa identified and enumerated, and their density estimated by swept-area calculation (Coggan *et al.*, 2007). This method will give estimates of species abundance for a given area of seabed, but it should be recognized that, at best, this type of data is semi-quantitative because it is usually impossible to determine the sampling efficiency of the gear (either between trawls or for the different taxon types). However, data generated using either of these methods will allow the characteristics of the benthic environment from each sampling station to be identified and classified into seabed (habitat) categories (usually in conjunction with other, complementary ground-truthing datasets).

Analysis of trawl and dredge samples is usually performed upon retrieval of the sample aboard the survey vessel. If the sample requires washing, this is normally carried out over a 5-mm sieve, or a sieve of at least the same minimum mesh size as that of the sampling gear. If washing is not required, the sample is processed on a sorting table. Taxa are identified as accurately as possible and individuals that cannot be identified are preserved for later examination in the laboratory. If the sample volume is large, or if certain taxa are very numerous, subsampling techniques are commonly used to speed up the sorting process. There are a number of subsampling strategies in use, and there is debate as to which approach gives the most accurate estimate of species abundances. The reader is directed to Coggan *et al.* (2007) for guidance on subsampling methodology.

When classifying *in situ* samples for the purpose of ground-truthing acoustic data (i.e. applying an *a priori* hierarchical classification system such as EUNIS), it is not always necessary to identify specimens to species level, because many habitat classes can be assigned based on higher taxonomic levels alone. Therefore, it is usually possible to assign a habitat class with a similar degree of confidence to that derived from semi-quantitative analysis of a trawl or a dredge sample, based on a far more rudimentary, qualitative assessment of the sample. This approach saves both time and effort and is often sufficient for broad classification of seabed habitats from an area. The use of dredges or trawls, therefore, may be appropriate for verification of acoustic datasets if their limitations are taken into consideration and if only a coarse level of habitat discrimination is required. This emphasizes the dependence of the classification procedure on the objectives.

8.4 Quantitative ASC verification methods (Physical Sampling)

Quantitative sampling of marine benthic fauna and sediments can be achieved using a number of different types of grab and coring devices. By design and operation, these devices should be capable of repeatedly taking a sample of a constant, standard area of seabed; for grabs this is commonly 0.1 m^2, though smaller (0.05 m^2) and larger (0.2 m^2) devices can be used. In addition, they should be able to adequately sample the benthic infauna and sediments below the area covered (i.e. have adequate penetration). In this way, it is possible to accurately quantify the fauna and sediments from each sample. This facilitates the objective classification of samples through the use of statistical routines, enabling samples of similar seabed attributes to be grouped together based on biological/sedimentological traits for the purpose of verification of acoustic datasets.

Ideally, a quantitative sampling device would be capable of collecting an undisturbed sediment sample from the seabed to a depth of 20 cm or more, including all the benthic infauna beneath the device. In practice, no such device exists because variations in seabed hardness and topography, sediment grain size, and a whole suite of environmental parameters (e.g. tides, sea state, vessel stability) lead to variations in the sampling efficiency of any device between sampling stations. Therefore, many different designs of grabs and corers have been developed over the years, each designed for a particular application or substrata type. The following are some of the more common devices, but the reader is referred to Boyd (2002), Eleftheriou and McIntyre (2005), and Coggan *et al.* (2007) for a more comprehensive account of the various types of sampling devices.

8.4.1 Grabs and corers

Despite the diversity in the design of different grabs and corers listed below, there are similarities in their function and operation. They are usually designed with a support frame that provides a stable platform when the gear reaches the seabed from which the mechanics of the sampling apparatus can operate. They all have a trigger mechanism, so that the device fires when it makes contact with the seabed; usually, they are all deployed vertically from a wire from the side or stern of a survey vessel; and usually they are weighted to facilitate penetration of the device into the seabed.

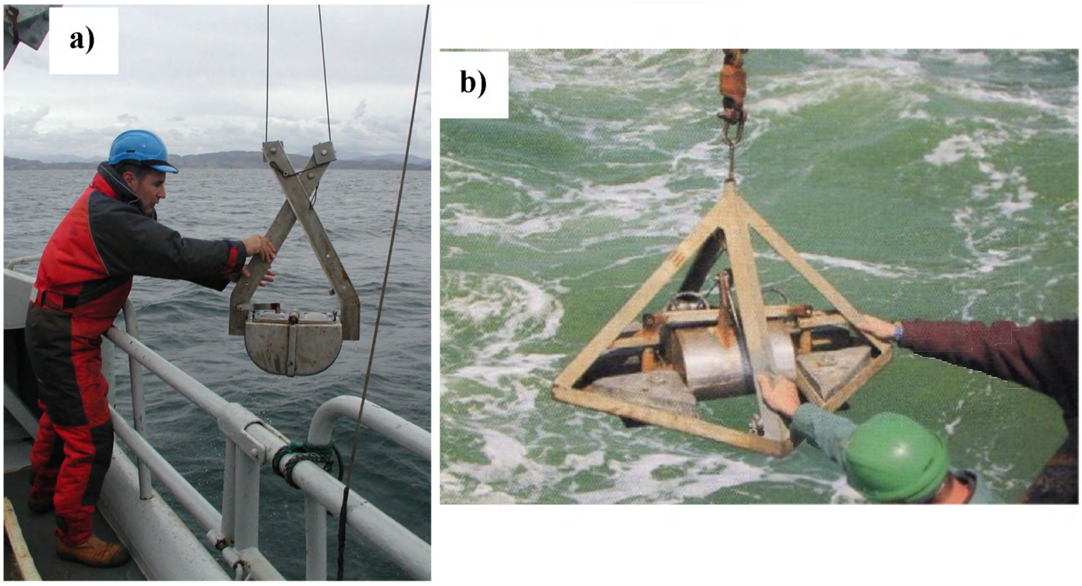


Figure 8.8. Two types of grab suitable for deployment on soft substrata. (a) van Veen grab; (b) Day grab (photo: CEFAS).

There is a range of grabs and corers specifically designed for collecting samples from soft, unconsolidated substrata, where it is mechanically easier to capture samples than on coarser or consolidated sediments. Grabs such as the van Veen or Day grab (Figure 8.8) sample by means of two steel jaws that penetrate the substrate and come together to form a bucket that retains the sample. Sampling efficiency is good in fine particulate substrates, but the devices do not function well if coarse sediments are present because there is a tendency for larger particles to become lodged between the jaws, preventing complete closure of the bucket and resulting in washout of the sample on retrieval of the grab to the surface. Corers are generally limited to use in soft substrates (fine sands or muds) to achieve sufficient penetration and allow a closing mechanism to drive through the sediment to seal the base of the core (e.g. boxcorers, Figure 8.9). Substantial weights can be added to the corer mechanism to aid penetration, which is usually limited either by the resistance of the substrate or by a mechanism controlling the maximum extent of penetration. Corers have not been widely used in acoustic mapping studies because they tend to be less reliable and flexible than the mechanically simpler grabbing devices, although they do have a specialist application in soft, mud substrates.

Effective quantitative sampling on coarse substrates, such as areas of gravel and mixed sediments, can be achieved using a Hamon grab (Figures 8.10 and 8.11), a robust device that is simple to operate. It consists of a rectangular frame forming a stable support for a sampling bucket that is attached to a pivoted arm. On reaching the seabed, tension in the wire is released, which activates the grab. Re-tensioning the wire during in-hauling moves the pivoted arm through a rotation of 90°, driving the sample bucket through the sediment. At the end of its movement, the bucket locates onto an inclined, rubber-covered, steel plate, sealing it completely. This results in the sediment rolling towards the bottom of the sample bucket, thereby reducing the risk of coarse material becoming trapped between the leading edge of the bucket and the sample-retaining plate, and thus preventing the sample being washed out. However, the drawback of this mechanism is that the sediment sample is mixed during the process of collection and retrieval, thereby precluding the examination or subsampling of an undisturbed sediment surface. The Hamon grab has been employed effectively as a quantitative benthic sampler for ground-truthing acoustic data in a number of studies (Brown *et al.*, 2001, 2002, 2004a, 2004b; Collier and Brown, 2005).

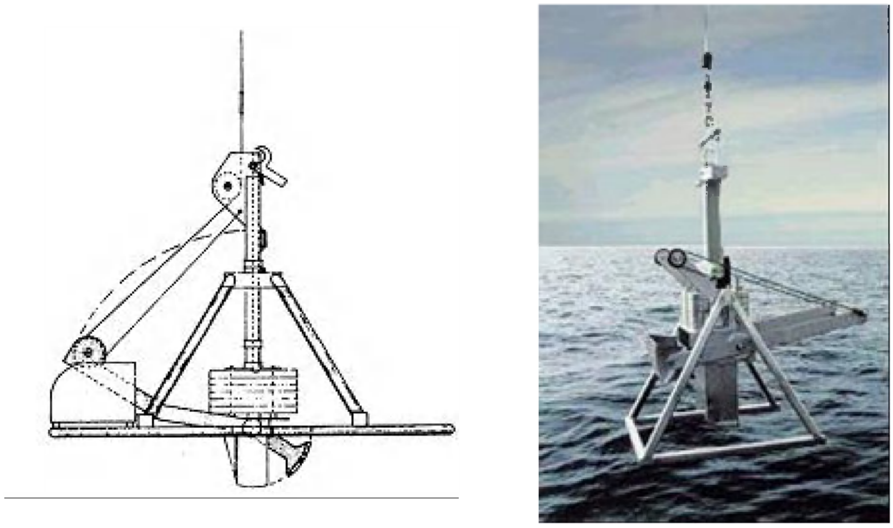


Figure 8.9. Typical boxcorer. The steel boxcore is driven into the seabed by the heavy weights. The sealing door then slices through the sediment to seal the bottom of the core before the device is hauled to the surface (photos: www.arpa.emr.it/daphne/progetto_mare/struttura_oceanografica_daphne.htm and www.tresanton.co.uk/graphics/kcboxcorer.jpg).

8.4.2 Data processing and classification from grabs and cores

For the purposes of ground-truthing acoustic datasets, it is the mega- and macrofauna (>1 mm body size) and detailed sediment data (e.g. particle size data and vertical seabed structure) that are of greatest use in characterizing habitats and acoustic/seabed facies. Although the meiofauna (<1 mm body size) can also be sampled using a number of the devices listed above, they are of little or no value in discriminating between different acoustic facies.

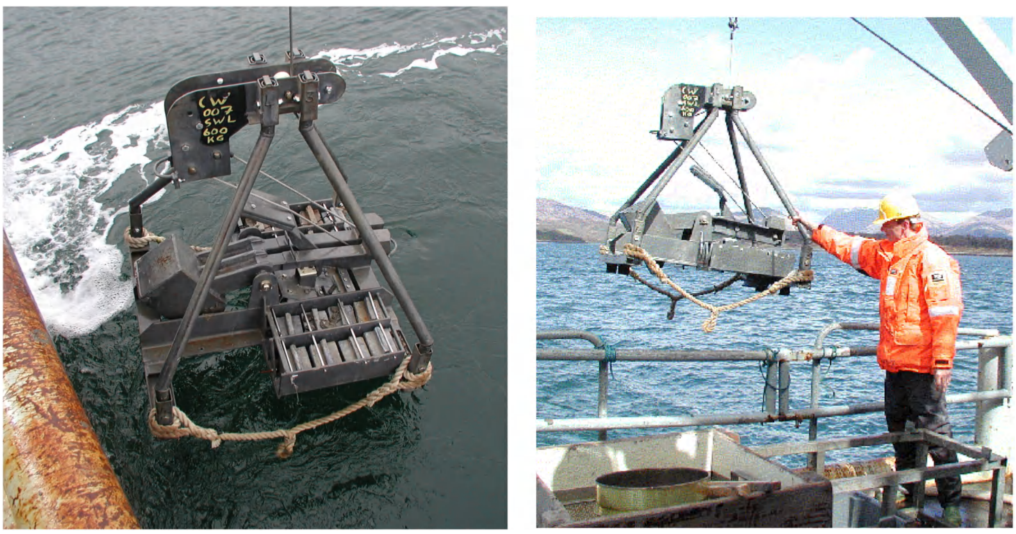


Figure 8.10. Hamon grab (0.1 m^2). A suitable quantitative device for ground-truthing acoustic data in regions of coarse, unconsolidated sediments.

Upon retrieval of a grab or core sample, it is first necessary to describe the physical appearance of the substrate before the sample is processed. The type of sampling gear used will determine which sediment properties can be measured. Grabs, such as the Day grab or van Veen, and all corers recover samples with the surface sediment layer of the seabed relatively undisturbed. In this way, the particle-size information from the actual seabed surface can be measured. This may be an important consideration if the sampling device is used to ground-truth high-frequency acoustic datasets, where there may be little acoustic penetration of the seabed and where most of the acoustic measurements are associated with the water–sediment interface. Other devices, such as the Hamon grab, mix the samples so that undisturbed surface properties cannot be measured. Particle-size measurements from samples collected using this technique can only represent the entire, integrated sample. This may not be a problem if the device is used to ground-truth lower frequency acoustic data, which may represent acoustic measurements of the top few decimetres/metres of the seabed (see Section 2).

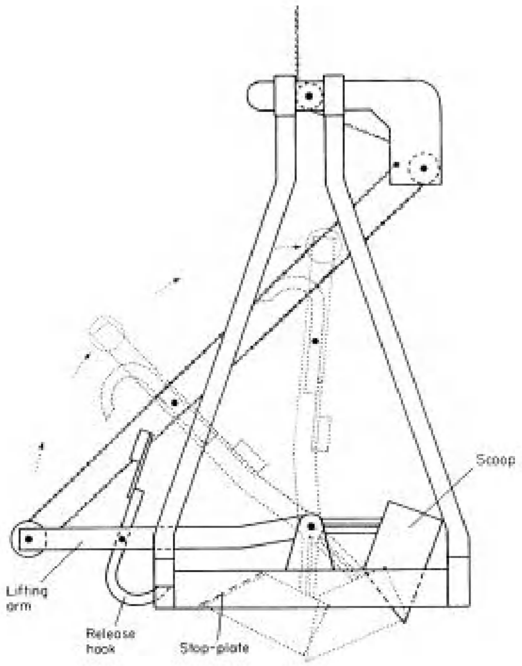


Figure 8.11. Hamon grab showing mode of action. The lifting arm rotates through 90° to drive the scoop through the sediment, closing against the top plate (reproduced from Eleftheriou and Holme 1984).

A subsample is normally removed for particle-size analysis, following standard granulometric procedures. This can provide objective classification of the sediments from each sampling station based on established and widely accepted classification systems (e.g. Wentworth, 1922; Folk, 1974), though the small size of many grabs limits their effectiveness in representatively sampling the larger particle sizes (i.e. cobbles, >64 mm). The remaining sample can then be washed over a sieve to extract the benthic macrofauna. For studies of shelf benthos, a minimum sieve pore size of 1-mm diameter is widely accepted (a pore size of 0.5 mm is occasionally used, depending on the objectives of the study). The process of sieving the sample washes out the sediment with a grain size smaller than the pore size of the sieve, so making it easier to extract the fauna. The fauna can then be preserved for later enumeration and identification back in the laboratory. The reader is directed to Coggan *et al.* (2007) and Boyd (2002) for a detailed description of sample processing.

Laboratory enumeration and species identification are time-consuming and highly skilled procedures, but the data generated allow statistical classification of samples based on the detailed biological information. The generation of a species list from each sampling station, coupled with the fact that a quantitative sampling device was used to collect the sample, allows the data to be processed using multivariate and univariate statistical routines to look for patterns in species distributions and sediment properties. There are several statistical packages available for this type of analysis and a variety of ways in which the data can be manipulated. The reader is directed to Boyd (2002) for a detailed account of methods for data analysis of benthic samples. However, the fundamental principle is to objectively group samples based on similar biological and sedimentological traits, based on the outcome of the statistical analyses. In this way, the relationship between the classes identified from the statistical analysis of the benthic data can be related to the acoustic classes identified from the remote acoustic surveys.

8.5 Positioning issues

The very nature of acoustic data verification involves the cross-referencing of two spatial datasets (acoustic data with point or transect *in situ* data). It is crucial that the positional information from both datasets is as accurate and precise as possible. Any errors incurred during the collection of the acoustic data and/or verification data will undermine confidence in the findings when linking the two types of data and may produce spurious results.

However, there will always be a degree of error associated with these types of data as a consequence of the individual errors from each system (the acoustics and the ground-truth observations) and the inherent approximations necessary when combining the results. Both types of data are subject to error from the positioning system used to record the location of each acoustic/ground-truthing data point. A global positioning system (GPS) usually has an accepted accuracy of ±10 m. This can be improved by using a differential GPS (DGPS) to achieve an accuracy of approximately 0.5–5 m. In addition, error may be introduced from the position of the direct measurement (acoustic transponder, grab, video, camera, trawl) relative to the vessel and DGPS antenna. Improving positional data from the acoustic system can be achieved in a number of ways, depending on the type of acoustic system in use. For example, the DGPS antenna could be located directly above the transponder on a single-beam acoustic ground discrimination system; a positioning beacon can be fitted to a towfish for systems that operate from a towed platform, such as most sidescan systems; or sophisticated motion-reference units can be utilized to position hull-mounted swathe systems (see Section 4). In this way, the positional error in any acoustic dataset can be minimized. Similarly, the uncertainty of the position of the ground-truth sampling device with respect to the vessel/DGPS antenna is related to the sampling depth and method of deployment. In general, the deeper the sampling station the greater the uncertainty, especially in conditions of strong drift arising from currents and wind forces (i.e. the greater the lateral distance will be between the sampling device on the seabed and the GPS antenna on the vessel). Introducing additional devices, such as positioning beacons, to position the gear accurately, relative to the DGPS antenna, can minimize these errors. However, it is accepted that there will always be a degree of measurement error, but that every step possible should be taken to minimize these errors.

The use of geographic information systems (GIS) for the manipulation and verification of acoustic datasets is now common practice. GIS is a powerful geospatial tool that can be used to overlay geo-referenced data and is ideally suited for laying verification data points over acoustic datasets. Acoustic data can be imported into a GIS as either vector or raster layers, depending on the data source. For example, interpolated acoustic ground discrimination system (AGDS) data can be imported as raster layers, or interpreted hardcopy sidescan polygons can be imported as vector layers. Acoustic data classes (in the form of a vector layer) can then be overlaid to establish the relationship between the verified (i.e. supervised) classes and the original, unsupervised acoustic classes (see Section 5). Seabed maps can then be produced by extrapolating the ground-truthing data for distinct acoustic facies to all areas with similar acoustic properties.

8.6 Conclusions

It is not possible to recommend any specific verification method(s) for general application for ground-truthing acoustic datasets. The choice of ground-truthing method depends on the purpose of the survey, the local conditions and seabed characteristics within the survey area, the availability of equipment, the size and capability of the platform from which the device is deployed, and the personal preferences of the surveyor. A degree of expert judgement is required for the selection of the most appropriate suite of ground-truthing methods by the surveyor on a survey-by-survey basis.

All of the verification methods described above are suitable, at some level, for ground-truthing acoustic datasets. However, to confidently identify key habitat characteristics and classify seabed habitats, a multi-technique approach is recommended. For example, in the context of characterizing the biological component of the seabed, the use of any single technique in isolation can lead to misclassification of the benthic environment, based on the fraction of the benthos best sampled by the chosen technique. The type of sampling gear, therefore, can be seen to have a considerable bearing, not only on the identification of characterizing species from an area of seabed, but also on the power to discriminate between habitat types based on biological traits. This problem can be overcome by using a suite of complementary techniques. Single techniques should not be used in isolation; a minimum of two complementary techniques is recommended.

Classification of the ground-truthing data is a crucial stage in the production of any type of seabed map from acoustic data. However, there are issues relating to the scale at which seabed characteristics can be distinguished using *in situ* verification techniques compared with remote acoustic methods. It should be recognized that not every seabed class, distinguishable from the verification methodology, will be acoustically distinct. Therefore, it is important not to attempt to map beyond the maximum resolution of the acoustic system, and to accept that it is likely that a number of classes distinguishable in the verification data will fall within each unsupervised acoustic class (see Section 6).

Verification of acoustic datasets requires the spatial linking of *in situ* data with remote acoustic data. Therefore, it is crucial to achieve good positional accuracy of the acoustic and verification datasets. During the collection of the acoustic data, every measure should be taken to ensure that the positional information linked to the acoustic data is as accurate as possible. This may involve positioning GPS antenna(e) as close to the data acquisition point (i.e. sounder) as possible, fitting appropriate motion reference devices, or fitting towed platforms with positioning beacons to take account of layback (see Section 4). Similarly, verification-sampling equipment should be fitted with positioning devices whenever possible, especially in deeper water survey sites when the sampling equipment can be some distance from the GPS source. A failure to do this will result in poor confidence when a mismatch occurs between acoustic and ground-truth data.

9 Survey design for acoustic seabed classification

John Simmonds

9.1 Introduction

The survey planning or design of acoustic seabed classification (ASC) covers the design and layout of the data collection. As this is predominantly acoustic data, collection the major source of data is from line transects. Though some consideration needs to be given to the correct allocation of time for the collection of other data, this section will concentrate mostly on track layouts. In this context, other data may consist of ground-truth data (see Section 8) or hydrographic data to obtain velocity profiles. Here we discuss sampling issues, sampling or exhaustive surveys, and statistical aspects of transect direction, with some consideration of sampling issues that relate differently to different instruments. The other survey design issues of instrumentation choice, such as transect direction, are dealt with in detail in Section 6. Here we consider only the issues that affect transect design once the decision on instruments has already been taken.

Hughes-Clarke (1999) proposes a protocol for data collection using multibeam echosounder systems for seabed classification. The document is part of a set of protocols put out by Land Information New Zealand (LINZ), and although it is described as provisional, it has not been updated since 1999. Other LINZ documents have been amended since, suggesting that this may be regarded as the current view for hydrographic surveys. The document deals with many of the issues described in this report, but is dominated by aspects that relate only to exhaustive survey coverage. The LINZ protocols are aimed predominantly at the exhaustive determination of depth, or at least seabed features characterized predominantly by changes in depth. Nevertheless, the list of issues discussed is comprehensive, dealing with depth accuracy, coverage, target detection, and touching on verification and classification of substrate. One important issue is how to define the sample spacing or sampling definition, which is dealt with in the report as required achievable accuracy rather than the resulting required sampling.

Fosså *et al.* (2005) provide a good description of methods used to map coral reefs, but provide little that addresses sampling design. Anderson *et al.* (2004) have collected data based on trawl stations using a random design. However, the design choices here have been dominated by the requirements of the trawl survey, not the seabed classification. The discussion in this section is limited to issues of sampling and sample location. Design issues concerning the quality and type of data from different instruments are discussed in detail in Sections 3, 4, 5, and 7. It is perhaps the initial choice between an exhaustive survey and a sampling plan that will have the greatest influence on subsequent choices.

While following the design issues discussed below, there are a number of ancillary issues that should be borne in mind.

Accuracy of depth measurement

Accuracy of the measurement of seabed depth, and to a much lesser extent classification, will depend on the properties of the propagation medium (see Section 2). Knowledge of the importance of the accuracy of depth measurements and their sensitivity to sound velocity should be used to determine the rate at which sound velocity profiles should be collected, and updated in the instrumentation of analytical calculations. Hughes-Clarke (1999) specifies depth accuracy by two types of error, a fixed height in metres and a proportional effect as a percentage, and for each, different error levels are specified, the most being 0.25 m and 0.75% and the least demanding being 1.0 m and 2.3%. In most cases, the highest levels of accuracy can be achieved only through frequent and accurate measurements of sound-velocity profiles at points along transects and including tidal height corrections; lower quality measurements can be obtained with only occasional measurements of sound velocity. Currently, moving vessel profiling systems (MVP) provide the best solution for rapid, almost continuous velocity profile measurement.

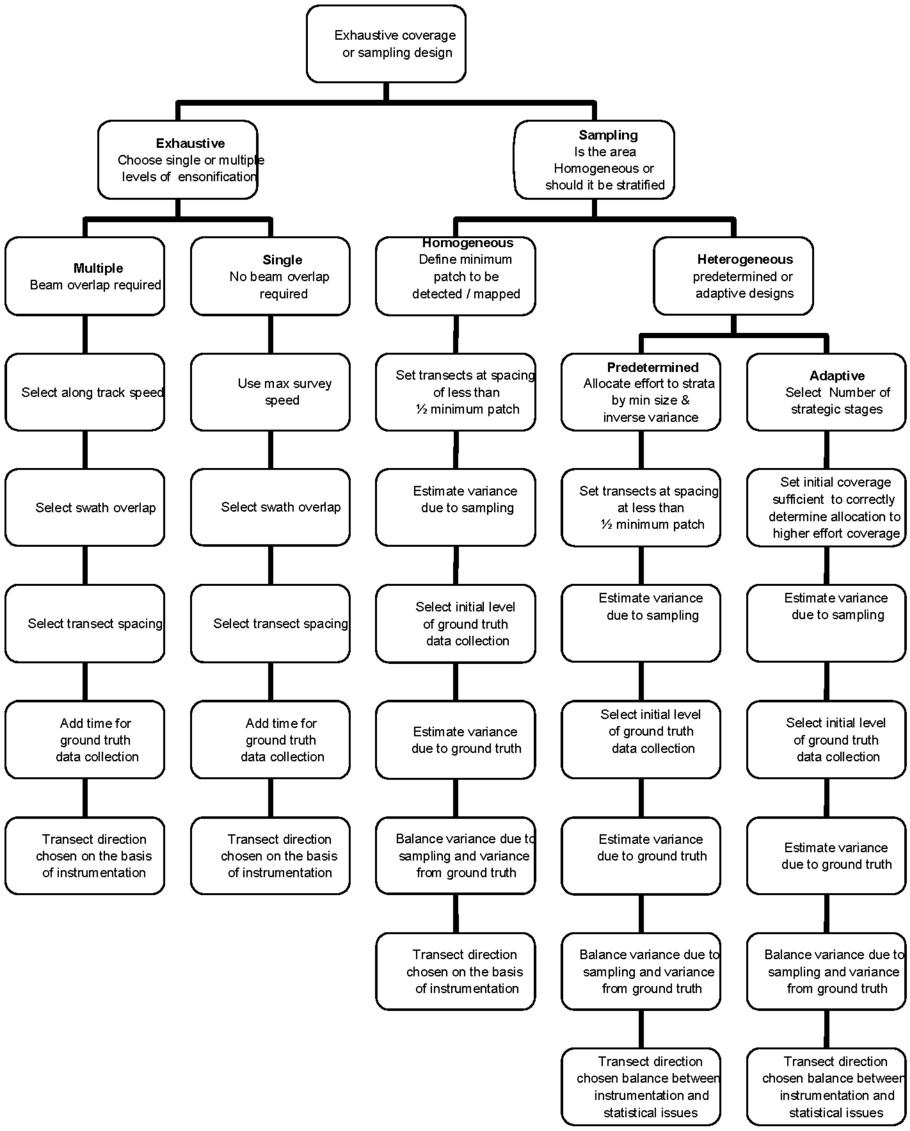


Figure 9.1. Decision tree for seabed classification survey designs.

Accuracy of positional information

There will be an upper limit to the precision of location data. While a ship can be positioned by differential global positioning system (DGPS) or GPS-WAAS (wide area augmentation system) rather precisely, acoustic systems will be less precise because of pitch, roll, and heave, which may need to be compensated. For towed systems, such as sidescan, the accuracy of layback positioning will dominate the location accuracy. It is important to consider the usefulness of the data if collecting acoustic data on a finer scale than can be achieved with the position instruments available. In some cases, this will be so because increased samples improves precision, but if the point variability is low, then increasing sampling in the absence of good position data may not be useful (see Section 4).

Ground-truth data

Ground-truth information from grabs or core samplers may be required and should be collected such that the variability of the classification process is balanced between spatial acoustic sampling for mapping classes and the variance associated with the classification algorithm. The correct balance will be obtained when the rate of change in variance with effort (measured as time) from these two sources is equal. If this balance is achieved, increasing sampling for one source of data at the expense of the other will decrease the precision (see Section 8).

Temporal changes in acoustically derived classes

Diel, tidal, lunar, and seasonal effects and episodic storm events may all influence the acoustic backscatter. This is dealt with in detail in Section 2.

Some of these effects may require specific attention to detail in survey design. Where acoustic systems are used directly to estimate the seabed class in situations where the organisms living in or on the seabed change behaviour with time of day or state of tide, this may need to be considered. In that case, the survey analysis must either use a method for correcting the classification or ensure that the design collects data only under controlled conditions that ensure uniformity of response.

The main sequence of design decisions is highlighted in Figure 9.1, which provides a tree structure for the sequence of decisions that are discussed in more detail later in this section.

9.2 Exhaustive surveys

Almost all ship-mounted instruments used for seabed classification can operate at ping rates that make the along-track information virtually exhaustive. Vertical echosounders, (e.g. single-beam echosounders (SBES)) and swathe systems (multibeam echosounders (MBES)) have ping rates and beam widths that give overlapping footprints on the seabed at ship speeds of approximately 10 knots (see Section 6). However, if precision is to be estimated through multiple measurements required at each location, then vessel speed may need to be reduced to increase the number of observations. The highest precision level for LINZ standards (Hughes-Clarke, 1999) for exhaustive surveys requires three insonifications for each location.

At 10 knots, towed units, such as sidescan systems with a narrow fore and aft beam towed close to the seabed at a height of say 10 m, will not provide exhaustive coverage at close range, but the sampling might conveniently be considered close enough to be exhaustive. For swathe systems, the athwart-ship sampling is either exhaustive or close to exhaustive. So once the instruments, taking care that the beam widths are selected to ensure that the footprint can resolve the sizes required, there are no further sampling considerations along the ship's track. For between-track sampling, there are a number of considerations. Hughes-Clarke (1999) suggests, because of poor resolution and high signal-to-noise ratio, some overlap between data collected at low incident angles and provides for increased coverage options by overlapping either sidescan or swathe data collection. The increase in variability off axis has two causes: increased uncertainty in angle at larger off-axis angles because of refraction and poorer estimation of bottom type from acoustic backscatter at incident angles less than 20°. Figure 9.2 shows the degrees of overlap, which change from fully 100% of high-quality coverage, where the extreme of good coverage is taken as the centre of the following transect. The chosen range equals the depth, equivalent to an incident angle of 45°. Quality is reduced slightly by allowing the overlapping section to include data from beams beyond 45°, which is regarded as sufficiently accurate coverage for most swathe systems. Single quality coverage is obtained with spacing equivalent to twice the depth, using data to 45° and overlapping only with poor data beyond 45°. The lowest level of exhaustive coverage is obtained when only the last one or two outside beams are used in the overlap area. In all these cases, there are no statistical issues regarding sampling, only the accuracy of the collection of data. For sidescan, the quality limit is normally set at a range of six times towing height or a minimum incident angle of 9° (Hughes-Clarke, 1999). In addition to these overlap criteria, it is necessary to include consideration of the minimum object size as a criterion. As the incident angle and range increase, the minimum object size that can be detected increases. So for any instrument, there will be a maximum transect spacing that can be linked to the desired minimum detectable object size.

For exhaustive surveys, however, there are still the issues of choice of transect direction and, in some cases, the need for multiple passes involving the interaction between terrain and instrumentation, which is discussed below.

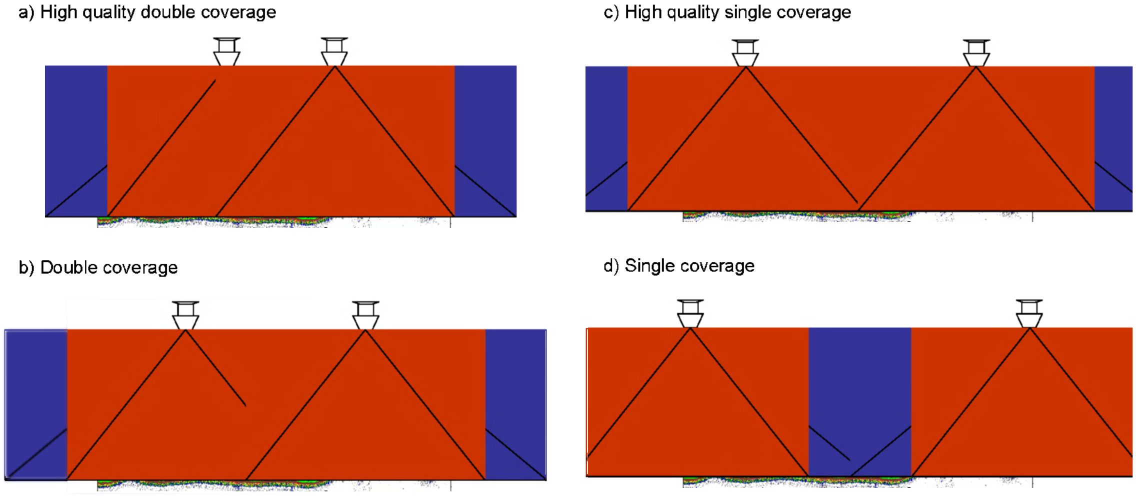


Figure 9.2 Extent of overlap, from double high-quality coverage to single coverage with no overlap. Pink shading indicates high-quality data at less than 45° incident angle; blue shading shows the lower quality outer beams. Illustration is for swathe systems, but the concepts are applicable for swathe or sidescan coverage. The limit for acceptable sidescan data would be incident angle ≥9° (Hughes-Clarke, 1999) for an appropriately deployed towed unit.

9.3 Sampling surveys

For situations where the survey is not sufficiently intensive to provide exhaustive coverage, a line transect sampling design is required. At this point, it is important to be clear about the objectives. If the aim is to obtain a complete map of the seabed, transect spacing must be sufficiently close to resolve the spatial detail required (see Section 6). That is not to say that the spacing must be sufficient to resolve the smallest feature of interest, rather that it must be sufficiently close to resolve the mapping scale required. It may be quite sufficient to define a region on a broad scale, characterized as having proportions of different classes of bottom type estimated from the along-transect data. Sampling theory from either a spatial statistical or frequentist standpoint (Nyquist) implies that two transects (two samples) are the minimum requirement for resolution of patches or regions. Or stated conversely, transects spaced at 1 km might be expected to provide information on patches on a scale of 2 km. Although this level of sampling could not be expected to provide accurate reconstruction of patches at this scale, it does guarantee their detection. For changes in seabed structure on a finer scale, the proportions of seabed type may be estimated from the along-transect data (assuming statistical stationarity). It is important to remember that the precision of these estimates does not depend directly on the proportion of the seabed covered, but much more on the variability of the seabed, the number of samples, and the total area to be surveyed.

Here we have dealt with preplanned survey methods. Adaptive methods show improved performance in simulations using adaptive cluster sampling, such as adaptive cluster sampling used for acoustic surveys of fish, e.g. Conners and Schwager (2002). In general, adaptive methods may be expected to perform well for seabed classification, but it is important to obtain unbiased estimates. Adaptive sampling is dealt with in detail in Thompson and Seber (1996), who present a number of methods that are unbiased. Unbiased adaptive surveys require several main features. Potentially, any error in the first stage that results in an incorrect allocation of additional sampling at a later stage can result in biases in the final survey. For example, failure to detect a small proportion of small patches on a first, low-intensity pass may result in no further effort being allocated to that stratum. If excess numbers of small patches are encountered, sufficient to trigger increased coverage, the subsequent effort will lower the number observed. Although the average detected on the first pass is unbiased, the erroneous second-level allocation can result in bias. Any bias of this kind decreases as the accuracy of the decision increases; perfect decisions are unbiased. Care must be taken to ensure that the multistage algorithms are sufficiently robust to these kinds of effort allocation errors.

9.3.1 Stratification

If the design is a sampling design (less than exhaustive coverage), the choice of transect placement should be first addressed in terms of strata. In the absence of information on variance, there is no basis for stratification. This implies a uniform coverage by area with no differential effort allocation. However, the seabed is highly structured in the sense that different seabed types will occur together for geographic reasons, such as geology and water flow, leading to similar types of sediment at close range. So, separation of areas into strata from previous knowledge is likely to yield considerable improvements in the estimation of the proportions of classes. Prior knowledge might include surficial geology, seabed depth, water velocity, or knowledge of biological distributions. Strata should be sufficiently large to ensure a reasonable number of samples and sufficiently small to reflect a level of homogeneity. Selecting strata may lead to different within-strata sampling effort levels because of the anticipated variability and the scale of features to be resolved in different locations. Among strata, collection effort (track length) would normally be allocated in direct proportion to the area of the stratum and inversely proportional to the within-stratum variance.

However, there may be other considerations that influence effort allocation over and above area size and variability of substrate; there may be specific requirements for additional knowledge of some areas over others. In this case, a third multiplicative modifier, reflection "importance" of an area, might also be employed to allocate effort.

9.3.2 Random/systematic surveys

Exhaustive surveys, by their nature, lead to systematic designs. For sampling surveys, the usual purpose of seabed classification surveys is to develop a map of the seabed. Once strata have been identified and effort has been allocated, the locations of transects should be selected. Transects would normally be placed in a random or systematic manner. In most cases, a systematic grid with a single random starting point would be preferred. Systematic grids maximize the information obtained by placing transects evenly over the area. Using this method, the distance from sample locations to the unsurveyed parts of the area are minimized (Simmonds and Fryer, 1996). In a spatial statistical framework, the uncertainty is minimized by regular grid spacing, using either parallel or triangular track construction to avoid overlap. The random starting point is required only to ensure that estimation is unbiased, by ensuring that each location has an equal probability of being sampled. A systematic design with a non-random starting point will give a very similar result, but has the formal problem that it may be biased. The random starting point, as a formal requirement, may seem unnecessary, but it is simple to implement and provides a well-founded basis for the survey. One aspect of sampling with regular grids is the small possibility of aliasing (the confounding of the spatial sampling frequency with spatial frequency of the seabed). This can increase the variance or give some slightly misleading results. However, spatial frequencies in the seabed would need to be very regular and contribute the majority of the variance before the influence would be important. Such regularity on the scale of typical sampling frequencies would be unusual.

Randomized parallel transects have helpful statistical properties for some estimation processes. If the transect mean (from a transect within a predefined stratum) is to be used in its entirety and no mapping is required, then such design methods give simple estimates of variance and unbiased means. The data from such designs can be used directly to infer the precision of the estimate for the strata as independent samples, one sample per transect. However, if it is intended to develop maps of the spatial distribution of seabed, assigning classes to segments of seabed along the transect, then systematic transects will provide a better result. In this case, or in any case where systematic sampling is employed, precision estimates will require more specialized analytical techniques. The issue of variance estimation is discussed briefly below.

9.4 Transect direction

As data are collected along transects, the designer must consider the issue of transect direction. The issues are both practical and statistical. For exhaustive surveys, the decision on transect direction will be dominated by instrumentation-based decisions (see Section 7). For sampling surveys, statistical sampling issues may be more important. Geostatistics (Matheron, 1971; Rivoirard, *et al.*, 2000) provides a formal framework for spatial sampling and concludes that line transects should be placed along a direction with maximum variability. In the case of an isotropic seabed, there is no preference in the choice of direction. For a sampling survey in the absence of any knowledge of the directional variability of seabed class, depth would be a good guide so that transects would be placed normal to the coastline or any other gradient feature.

The practical instrument-related considerations might override the statistical requirements. Examples of this are:

- Logistics of sidescan sonar deployment; this is simplest over level ground so transects normal to the greatest range of change in water depth may give significant operational difficulties,
- Sidescan measurement of ripples, or other linear seabed structures, are much more successful with the survey conducted along the line of the ripples (Bell *et al.* 1999).
- Swathe system beam masking occurs when rapid rises in seabed mask sections of the seabed farther from the vessel; designs need to include data collection to either side of sharply rising ground.
- Swathe system transect spacing depends on depth, (Figure 9.2) and parallel sampling is more efficient if depths are more homogeneous.

In addition to basic directions, some survey strategies call for verification, with additional transects running normal to the main data collection. These are used, for example, to compare the precision of data collected near the centre of a swathe and at the edges, checking the correct implementation of sound velocity. A limited amount of time, say 10%, used to collect data in a direction normal to the main sampling design can be used for validation of depth estimates and estimation of errors in both depth and seabed classification.

Some very irregular seabed features, such as sea mounts or canyons, may require additional data to map them fully. A common procedure for sea mounts or pinnacles is to follow a star design, with the centre of the mount at the centre of the star. This conforms to the collection of data in the direction of the greatest rates of change. It produces, for swathe or sidescan systems, an overlapping design at the centre or shallowest point, which is useful for navigation surveys. An alternative low-level overlap spiral design can give better area coverage and may simplify the deployment of towed units such as sidescan. Steep valleys or canyons may be best surveyed by swathe and sidescan by following the line of the valley, reducing the chances of losing data to shadowing.

9.5 Variance estimation

If exhaustive surveys are used, the source of variance is almost completely limited to the allocation of the ground-truth data to classes of observations obtained from the seabed surveys, though there will be some acoustic measurement error. Although some errors in depth may be estimated from any overlap, it is the accuracy of class allocation alone that is likely to be dominant. However, if sampling surveys are used, there is a spatial variance component to the precision of the estimates between transects, and this type of estimation leads, in almost all cases, to geostatistical methods of variance estimation (Cressie, 1993; Chilès and Delfiner, 1999; Rivoirard *et al.*, 2000). As the seabed classification is by definition a categorical process, the outcome at any location is a categorical variable; this leads naturally to two methods (see Section 5).

9.5.1 Indicator kriging

This method uses thresholds to create binary data (0 or 1 values), then uses simple or ordinary kriging to make spatial predictions based on the indicator data. Predictions using indicator kriging are interpreted as the probability of exceeding the specified threshold. The validity of indicator kriging relies heavily on the assumption of stationarity, and it should not be used with data that have a trend. Atkinson and Lloyd (2000) compared ordinary and indicator kriging in the mapping classes of chemical concentrations, which is analogous to seabed classes.

9.5.2 Disjunctive kriging

This method tries to do more than simple or ordinary kriging and indicator kriging by considering functions of the data, rather than just the original data values themselves. As usual, to obtain greater rewards, stronger assumptions are needed. Disjunctive kriging assumes that all data pairs come from a bivariate normal distribution, and the validity of this assumption should be checked. When this assumption is met and the functions of the data are indicator variables that transform the continuous data values to binary values based on a threshold, then disjunctive kriging is an alternative to indicator kriging. Examples of analyses involving disjunctive kriging for mapping environmental variables are Maynou (1988), Petitgas (1993), and Gaus *et al.* (2003).

9.5.3 Auxiliary variables

Other analytical methods that include explicit variance estimation use auxiliary variables to improve interpolation and reduce variance. Both methods work best when the auxiliary variable is known precisely at many more locations in the area than the variable to be mapped. Water depth would be such a variable. Co-kriging (Cressie, 1993; Chilès and Delfiner, 1999), which requires a model for covariance between mapped variable and covariable, is quite demanding in its assumptions, requiring multinomial normal relationships. Alternatively, kriging with external drift allows interpolation on to the auxiliary variable without the need for an explicit relationship between the variables, but with the assumption of a linear relationship.

10 Future directions for acoustic seabed classification science

John T. Anderson, D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard

10.1 Introduction

Science in support of ecosystem-based management of marine resources will require a new generation of assessment tools for ecosystem components ranging from single populations to integrated ecosystems. Monitoring natural and anthropogenic disturbances is a key component of ecosystem-based management. Many emerging issues are spatial in nature and require new mapping initiatives before monitoring. Fishery management now includes spatial components, such as establishing marine protected areas (MPA) and implementing fishery closed areas (FCA). These management strategies require the development of management objectives, decision rules, and monitoring plans with a clear understanding of uncertainty where accurate and precise data are required at spatial scales not previously available.

Priority areas of research include evaluating how the performance of decision rules protects ecosystem components such as benthic structures and biodiversity. To do this, it will be necessary to develop and integrate advanced technologies with habitat attributes and link them to population productivity and biodiversity. Advanced acoustic technologies are required for high-resolution bathymetry and seabed classification of habitats across multiple spatial scales. Acoustics is regarded as the most important remote-sensing tool for the mapping and monitoring of the subsurface oceans. Currently, acoustic data can be used to create digital elevation models (DEM) at the scale of metres over thousands of square kilometres, generating landscape perspectives never seen before. Acoustic backscatter from the seabed can be used to classify surficial sediments and, in some cases, biological communities. We believe the science of acoustic seabed classification is at its nascence. The rapid evolution of acoustic and data-processing technologies assures that significant new developments will be realized in the years to come. To that end, members of the study group discussed future issues in the field of acoustic seabed classification (ASC).

10.2 Future ASC issues

Study group members identified a number of issues that tended to recur in our discussions over the three years that the group met. These issues were specifically discussed and eventually prioritized into a top-ten list of "burning issues"; they tended to centre on two topics. The first involved the standardization of instruments and methods. Fishery acousticians (WGFAST) have a long history of developing internationally accepted methods that standardize how we measure and map fish and plankton in the water column and near the seabed. These methods include such things as standard calibration of echosounders, parameterizing target-strength measurements of fish, standard formats for data exchange, and standard definitions for acoustic variables and survey design.

The second topic related to measuring variability in seabed attributes in order to determine the natural variability of the seabed, independent of measurement error. This included measuring such things as along-track (i.e. small spatial scale) variability patterns in an attempt to establish survey line spacing, structured survey designs to assure unbiased observations and optimal coverage for uniform spatial uncertainty, measuring and taking into account natural seabed directionality in acoustic parameters, and the complex issue of verification (ground-truth) data and how seabeds are classified (towards establishing representative training acoustic datasets for supervised classification of seabeds). Combined, these topics aim to assure that our measurements are objective, repeatable, and comparable among areas and over time. Collectively, study group members felt that these issues require immediate and future attention by the international scientific community to meaningfully advance the field of acoustic seabed classification. Finally, other issues raised, but not ranked in our top ten, are listed for reference.

10.2.1 Statistical vs. interpretive classification

Statistical classification is based on objective criteria and data processing to partition the seabed variability (see Section 5). Interpretive classification is based on subjective analysis and classification, often based on backscatter mosaics of sidescan (SSS) or multibeam (MBES) data. This also applies to verification (ground-truth) data when various datasets (e.g. grabs, cores, trawls) are used to measure sediment composition, infauna, and epifauna to characterize a region into classes, biotopes, or hierarchical classification schemes, such as EUNIS (see Section 8). Members of the study group were highly in favour of statistical, objective classification procedures over interpretive, subjective classifications. The issue of repeatability and generalizability of results was ranked number one. This requires that special attention is maintained throughout all the steps of the classification process, including input data quality and control of interfering factors, the usefulness of extracted seabed acoustic attributes for the classification, the discriminating power of numerical classification methods, and the classification probability reflecting expected and ground-truthed variability at the observed scale. In many ways, repeatability of results will depend on acoustic instrument stability, settings, processing algorithms, depth, and environmental conditions, as well as the survey methods. Calibration of the instrument through reference sites is one way to check that instrument effects are not altering the repeatability of the classifications (see Section 10.2.5). Ideally, a more detailed calibration of the system will be required (see Section 10.2.6).

10.2.2 Spatial scales and sampling resolution

The issue of natural variability and hierarchical spatial scales, and our ability to resolve these using ASC, was ranked second in importance. Much of the discussion revolved around the acoustic footprint: what it was and what it meant. Discussion included both theoretical issues (see Section 2) and practical issues of feature resolution and the acoustic footprint as a function of range from the acoustic gear (see Sections 3, 4, and 6). It is generally believed that the seabed structure is less complex at greater depths and at greater distance from the coast. But is it, or does this simply reflect our lack of knowledge? ASC surveys using single-beam echosounders (SBES) and multibeam echosounders (MBES) are typically carried out from surface-mounted transducers, where the range varies with water depth. Greater depths result in larger footprints and a reduced ability to discriminate small-scale features, while introducing a disparity in observation sizes, which complicates the data processing and confuses interpretation (see Section 6). Sampling range for ASC can be standardized by using towed systems or autonomous underwater vehicles, where the height above the seabed is held constant. Resolving this issue before there is significant investment in mapping by coastal nations is a priority.

Considerable effort is being invested in the development of hierarchical classification systems for the ocean (e.g. Davies and Moss, 1999; Greene *et al.*, 1999; Valentine *et al.*, 2005). On the largest scales of shelves and basins, acoustic data concerning depth and bathymetric structure have been the primary determinant of these classes. As the spatial scales decrease, much more information is required to comply with the classification criteria. In some cases, concepts of hardness and roughness have been incorporated into the classification scheme (Valentine *et al.*, 2005), which probably increases the utility of acoustic seabed classification products to conform to the classification system. However, the future utility of acoustic seabed classification to match these existing classification systems remains to be demonstrated (see Section 6).

10.2.3 Verification of ASC

The primary issue here is one of the mismatch of spatial scales between acoustic data, representing seabed surface roughness and hardness, and the verification methods. In one instance, the resolution of acoustic data is coarser than the verification methods when comparing, for instance, SBES classification, where adjacent pings are normalized (stacked) into a single observation on a scale of, say, 100 m^2, compared with sediments from one or more grabs in the area, which are typically 0.5 m^2 (see Sections 6 and 8, respectively). Alternatively, high-frequency (>300 kHz) acoustic SSS and MBES can produce seabed backscatter with accurate geo-referenced locations at scales of 0.25 m^2 and 1–2 m^2, respectively, over vast areas of the seabed. Accurately positioning and interpreting the verification data on the acoustic backscatter maps with known precision remains a challenge for marine scientists. Other issues raised included the facts that verified data can include physical data, biological data, or both and that the classification of these data is often subjective (see Section 10.2.1). Often, species profiles from a number of grab samples are classified into communities based on a predetermined sampling effort for a given area. However, there is seldom any evaluation of how adequately these communities have been sampled using, for example, species area curves. Furthermore, temporal variability in benthic communities is seldom incorporated into biological classifications (see Section 10.2.4).

10.2.4 Temporal variability – the fourth dimension

Current mapping efforts typically produce three-dimensional spatial maps of the seabed topography, as well as physical and biological attributes. Despite considerable evidence demonstrating significant temporal variability in seabed properties and reflectivity (see Sections 2 and 6), there are few examples of this in acoustic seabed classification studies. In some instances, short-term temporal variability could be erroneously interpreted as spatial pattern when making three-dimensional maps. There are also reasonable questions about how long a map remains a valid representation of the seabed. Most important is the understanding of cyclical variation, especially between seasons, where a survey could provide quite different results depending on the time of year. Understanding how habitats vary as natural physical and biological processes occur, and determining the frequency of such changes, requires immediate attention before the accuracy and spatial stationarity of seabed habitat maps can be assessed.

10.2.5 ASC reference areas

Reference areas were often referred to as patch tests, where a known and previously sampled area of the seabed is resampled at frequent intervals with the same, or different, acoustic systems. In many ways, this is a poor man's corroboration where current technologies or research capabilities prevent formal system calibrations. It is acknowledged that reference areas can change over time. However, proper verification sampling should detect such changes and this, in turn, can contribute to our understanding of natural variability vs. instrument drift. Reference areas will remain an important aspect of verifying the whole of a system's operation in conjunction with more detailed instrument calibrations.

10.2.6 Acoustic system calibration

Some might argue that calibration of acoustic systems should have ranked higher; it did not because of the difficulties in calibrating an acoustic seabed classification system as a result of the angular response and relating backscatter to a classified seabed (see Section 5 and Sections 10.2.1 and 10.2.3). However, it was regarded as a critical step necessary to standardize measurements among types of acoustic gears and areas over time to make comparisons possible and to build the necessary knowledge for a better understanding of seabed backscattering processes (see Section 3). Calibration difficulty, which is a function of the complexity of the acoustic system used, may be low for narrowband SBES, but much more difficult for high-end systems such as multifrequency, wideband, interferometric SSS and MBES. In particular, the angular response of the acoustic system needs to be calibrated, and this is problematic for both SBES and MBES. Traditionally, SBES are calibrated for on-axis sensitivity, whereas the time-dependent seabed backscattering response requires calibration of the single beam's angular response. Similarly, MBES are difficult to calibrate, and the common method for ensuring system repeatability is to use references areas (see Section 10.2.5). More advances are needed in this area to provide routine calibration procedures of acoustic seabed classification instruments. There are many advantages to using systems whose measurements can be traced to international standards. Until calibrated systems are used to make the scattering measurements, it is unlikely that physics-based interpretations relating acoustical backscattering measurements to the seabed's physical surface and underlying volume can be reliably achieved.

10.2.7 Acoustic signal characterization

There was some concern among study group members about the lack of information on how the acoustic backscatter data are processed and interpreted using commercially available systems. This is a problem with SBES where, although commercial systems use known acoustic properties of the seabed, the processing algorithms are not always available and may not be replicable. With the development of MBES, where the beams encounter the seabed at a wide range of angles, the analyses used in commercial systems are likely to be more complex and even less easy for the user to understand or replicate. Although it is recognized that a vendor must protect their investment, it is clear that systems for which the details of operation are not available will not be useful for researchers whose aim is to understand scattering from a seabed habitat at an elementary level. Until such an understanding is achieved, it is likely that there will be considerable, justifiable concern that results obtained from "black-box" processors may contain results that, at best, cannot be uniquely associated with a single kind of bottom type and, at worst, may simply be unreliable indicators of the seabed character.

10.2.8 Single vs. multiple frequencies for ASC

Using multiple frequencies will increase our ability to classify seabeds′, because both surface and volume backscatter vary with frequency. A major difference is that lower frequencies penetrate the seabed to greater depths, and higher frequencies can resolve smaller spatial structures. We realize that the frequency palette considered by the study group penetrates seabeds only to the order of centimetres, possibly up to one metre, depending on the substrate. Combining frequencies is equivalent to optical satellite remote sensing, where multiple wavelengths measuring different physical characteristics are combined to classify and map land and ocean areas. Currently, two or more frequencies are combined for SBES to improve seabed classifications (e.g. Kloser *et al.*, 2001b; Fosså *et al.*, 2005). We expect that incorporating two or more frequencies through the range of 10–300 kHz will significantly improve ASC. Incorporating multiple-frequency SBES with single-frequency MBES during single surveys may be a cost-effective way of improving ASC (see Section 10.3).

10.2.9 Survey designs

Variability is present on all temporal and spatial scales, and this should be handled properly with a survey design strategy adapted to the required seabed classification. More consideration must be given to survey designs that are currently weighted towards systematic line transects with no randomization and little or no prior knowledge; or to multibeam surveys based on hydrographic requirements to sample along bathymetric lines to get a uniform strip width and to minimize outer beam variability (see Section 9). Most of the discussion on this topic centred on minimizing errors and bias associated with spatial interpolation of line transect data, and randomizing surveys, when necessary, to generate unbiased datasets over the region to map by SBES. Currently, we know very little about small-scale spatial variability in seabed attributes measured by acoustic systems across the range of depths being considered by national mapping strategies. Even within a given depth range we expect that there are spatial scales to the variability in seabed attributes that are currently unknown and are probably an intrinsic property of the habitat. Adaptive and nested survey designs should be considered in directed research programmes that address such issues.

10.2.10 ASC design in national habitat programmes

Many countries have now embarked on national programmes to classify and map their marine resources, with particular emphasis on the seabed. Discussions by the study group members often reflected our interest in, and sometimes concern over, the use of acoustic technologies for classification and mapping of marine resources. Genuine excitement is generated by these emerging technologies, which are producing a new family of data products that are allowing scientists to image, classify, and map the marine environment on a variety of spatial scales never before possible. We are concerned, however, that ASC is often considered a "black box", where the technology now has sufficiently matured and been adequately adapted to the diverse needs of the user community, such that it can now be unquestionably applied to habitat-mapping projects. The study group felt that we do not unquestionably understand ASC for two reasons. First was the general disconnect between existing theory and many current ASC applications. Second was our awareness of the rapid evolution in acoustic technologies, both in the capacity to generate vast volumes of data and the ability to process them with ever increasing sophistication. This evolution in technology is driving the science behind ASC, both in renewed interest in the theory of sound propagation from the seabed and in the generation of a new, spatial marine science on the landscape scale. To this end, we recommend that formal mechanisms be established to integrate ASC research and applications into national classification and mapping programmes.

10.2.11 Other issues

Defining fish habitats

Fish habitat is typically defined as some function of biotic and abiotic variables. Water depth is often important, but so are such things as structural complexity, where greater complexity is often associated with preferred fish habitats. However, associating marine fish with specific habitats has proven to be elusive (Rose, 2000; Beck *et al.*, 2001; Minns and Moore, 2003; Mitchell, 2005). Among the reasons for this is our poor understanding of life histories and habitats in the marine environment compared with terrestrial and lotic systems. The weak explanatory and predictive power of existing relationships is thought to arise largely from the application of easily measured or available habitat variables (e.g. depth) as opposed to relevant habitat variables that are independent of each other (Lipicius *et al.*, 1997; Stoner, 2003). Increasingly, landscape variables are recognized as being an important component of fish habitats, where issues such as spatial pattern (e.g. size, shape, fragmentation, connectivity) and relative location (e.g. to larval supply, other juvenile habitats, adult habitats) are recognized as important components defining fish habitats (Beck *et al.*, 2001). We believe acoustic mapping of seabeds on small scales (where fish can exhibit site fidelity) to landscape scales (where fish live through one or more life history stages) will be a critical component in defining and mapping fish habitats.

SBES vs. MBES

SBES are the standard instrument of fishery acousticians. MBES have been adopted by the hydrographic community as their standard instrument for detecting the seabed and an evolved, multifaceted version is now emerging as the new tool of fishery acousticians for simultaneous water column and seabed investigations. There are advantages and disadvantages to both systems. For SBES the advantages include: relatively low acquisition costs; ready availability and wide use; calibration (on axis) for scientific users; efficient data processing because of low data volumes and standard procedures; relative ease of understanding and operation; available and readily processed water column backscatter; use of multiple frequencies during a single survey. SBES disadvantages include: narrow footprint and sampled volume across-track, which necessitates inter-track interpolation. For MBES, the advantages include: a large swathe over a range of normal and oblique incident angles for a single ping that typically spans 120° to 160°, and three-dimensional imaging with minimum interpolation. MBES disadvantages include: high acquisition costs; steep learning curve; complex calibration; more complex backscatter processing; water column backscatter data not always available. Combining SBES and MBES data for seabed classification would provide significant value-added information, until new systems under development integrating both approaches become operational (see Section 10.2.9).

Directionality of the seabed

There is natural structure in seabed morphologies that generate different acoustic responses as a function of the direction in which the data are collected; these structures can change with time. Differences in acoustic backscatter as a function of sampling direction are particularly apparent in sidescan sonar (SSS) systems (see Section 7). However, directionality in acoustic backscatter can also occur for SBES and MBES data (see Section 2). Seabed directionality is seldom measured in current studies and ASC surveys. We recommend that ASC surveys be designed to specifically measure seabed directionality (see Section 9) and that temporal variability in seabed structure be incorporated into interpretive habitat maps (see Sections 6 and 10.2.9).

Acoustic diversity

Interpretation of seabed properties in terms of surficial geological structure and biological communities can often be subjective and can vary with the observational scale. What constitutes fish habitat is still poorly defined, and may vary between species and will often vary as a function of life stage within a species. Therefore, relating acoustic backscatter and topographic relief to an interpretation of what constitutes the seabed can be subjective and highly variable. Of potential use in its own right is the concept of acoustic variability, unsupervised classification, where distinct classes of acoustic properties occur contiguously over meaningful spatial scales. It may be difficult to relate the acoustic diversity to an interpretation of the seabed using standard verification techniques. However, patterns in acoustic diversity may ultimately provide useful information for characterizing and mapping seabed habitats. The requirement is, however, that such an acoustic diversity pattern is repeatable, ideally with diverse types of acoustic gears and independent of data-processing algorithms, and ultimately that it can be related to natural processes that are both understood and universal.

Classification of biota (infauna – epifauna)

Acoustic classification of infauna and epifauna is regarded as an important area of future research. Will it be possible to classify benthic communities identified by more traditional methods, such as species compositions derived from benthic grabs? Is it possible to detect acoustic differences that reflect functional communities, as opposed to taxonomically derived communities? Increased use of emerging acoustic technology by marine researchers to address these questions will be a high priority. When acoustic surrogates can be found for biological species and communities, then our ability to classify and map marine habitats will move forwards significantly. Currently, research focuses on the use of optical systems for remotely classifying biota and seabed relationships (see below).

Data management and information dissemination

The study group often referred to the dichotomy of data collection vs. processing and interpretation as the information conundrum; which is to say, we have developed the ability to collect vast amounts of data, but our ability to process, analyse, and interpret these data lags far behind. Data management of large, complex geo-referenced datasets was considered to be a significant issue facing the scientific community. The volume of data generated by acoustic systems can be immense, in the order of terabytes for a single survey. We anticipate an evolution towards the use of multiple frequencies and the increased use of multibeam systems; so datasets will only increase in size and complexity. It is necessary to incorporate verification data to generate supervised classifications. Verification datasets increasingly consist of more complex optical datasets that are large and complex in their own right. Future issues will include developing standard data formats for archiving, retrieving, and analysing ASC datasets. It was felt that too little effort is being put into data management, data analysis, and the dissemination of results.

Benthic/pelagic coupling

Integrating the benthic and pelagic environments is considered to be an important area of future research. Physically and biologically, there is a strong link between the benthic layer and the overlying water column. We defined the seabed as up to one or more metres above the detected water–sediment interface (see Section 1). This definition was intentionally open-ended because we regard the benthic layer as fuzzy (i.e. poorly defined). Ontogenetically, many marine species have both benthic and pelagic life history stages. In this context, there are ephemeral uses of benthic habitats dependent on life history stage. Biogenic structures attached to seabeds may range from centimetres to metres above the seabed, and such structures may vary over relatively short timescales. Dense aggregations of fish settling on, or into, the seabed may alter its acoustic properties. Diurnal variation in surface-dwelling phytoplankton activity can generate gas bubbles that will alter acoustic reflectivity. The ability of acoustic systems to simultaneously measure from the near-surface of the ocean to up to one metre below the water–sediment interface will allow marine researchers to study and understand many aspects of benthic/pelagic coupling that should contribute meaningfully to our understanding of how ecosystems function.

Integrating acoustical and optical data

Optical data include high-resolution photographs of the seabed, digital video mosaics, laser line scanners, and bathymetric lidar. These optical technologies are often used to verify acoustic backscatter from the seabed towards the development of supervised classifications and interpretive habitat maps. However, these optical data can be regarded as remotely sensed data in their own right. Fine-scale mapping using optical methods provides a remotely sensed interpretation of both physical and biological seabed attributes, which can be resolved to species for large organisms. These data, when appropriately geo-referenced, form an important record of the seabed environment and a measure for monitoring both natural and anthropogenic impacts on a fine scale. Extrapolation of these fine-scale data to larger scales usually relies on the use of acoustic data with interpreted physical seabed attributes, such as roughness and hardness.

A general issue with optical data lies in its interpretation. It is possible to measure grain size with physical samples (e.g. grabs), but not with cameras. Optical systems tend to have short ranges and hence small observation footprints. They are also difficult to operate in a line-transect mode, because moving a camera close to the seabed over long distances is much more difficult and complex than for a vessel-mounted acoustic system. This being the case, optical systems work best when providing detailed ground-truth data at a point; this is particularly useful for information on biota rather than just the physical aspects of the substrate. The information can then be used to ground-truth and test the habitat classification process. Members of the study group recommend further work integrating acoustical and optical data, as well as physical samples, in seabed classification and mapping research.

10.3 Conclusions

We conclude that acoustic seabed classification is an important new area of marine science and that ASC will advance scientific research and marine ecosystem management significantly in the future. We predict that there will be a rapid, ongoing evolution in technology and applications that will continue to provide new opportunities for marine researchers to address scientific issues. ASC and marine habitat mapping of the seabed necessarily crosses disciplines and jurisdictional boundaries. Scientifically, hydrographers, marine geologists, benthic ecologists, physicists, and fishery scientists must work together to generate habitat maps. ASC techniques will provide the underlying data that will allow this to happen, and organizational structures must be modified to allow this to happen. National ASC standards must be developed by the international community to allow standardization of ASC products. Standardization will allow for comparisons among areas and over time. This report attempts to capture the state of ASC science at the time of publication. However, we recommend that ICES revisits this subject in the near future to update and maintain the relevance of this report, as required.

11 Terms and acronyms

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Only common terms used in the report appear here. Specialized terms related to particular sections, such as porosity, tortuosity, viscosity, etc., are defined in standard sources, including *Oxford Dictionary of English* and *Webster's Third New International Dictionary*, among others.

Glossary

Acoustic diversity the diversity in seabed echo in a given area

Acoustic seabed classification the organization of bottom types into discrete units based on a characteristic acoustic response

Anisotropy the property of a measure to change with the angle of the direction of observation; the absence of directional changes is called isotropy

Attitude the inclination angles of the plane of a platform along the xyz axes, corresponding to the pitching and rolling inclination for a ship, for example

Azimuth horizontal angle of the heading or looking direction (generally of the platform, such as the ship or towed body)

Backscatter coherent and incoherent reflections of the acoustic waves in the same direction as the angle of incidence, used in general to mean back to the transducer

Beamforming formation of a transmitting or receiving beam of an acoustic signal by phase (time) shifting the signal from a series of transmitters or receivers; beamforming allows listening or transmitting preferentially along one direction

Beam pattern the transmitted power and sensitivity of the transducer as a function of the angle from the axis perpendicular to its face, also called directivity pattern

Beam width the angle in the centre of an acoustic beam delimited by the points on the **beam pattern** where the power drops to half of that on the central axis

Bedform three-dimensional shape of the seabed, generally at a scale much larger than the observation scale of the acoustic **footprint**

Biotope an area defined by its physical characteristics (e.g. soft substratum, hard substratum, regimen of currents, temperature, depth) and the organisms that typically inhabit it

Bioturbation the restructuring of sedimentary deposits on the seabed by moving organisms (e.g. worms and burrowing clams)

Bistatic when the transmitter and the receiver of an acoustic wave are located at two different locations, in contrast to the co-location in the same transducer as in most echosounders (SBES, MBES, SSS) – compare with **monostatic**

Calibration reference to a reference standard, traceable to internationally accepted units such as metres and seconds; should not be confounded with the operation of training a classification algorithm with a training dataset identifying different seabed classes

Classification sorting a series of different objects (here seabed acoustic backscatter) into homogeneous subsets based on their properties as defined by attributes (features) and a set of rules (algorithms)

Coherent backscatter coherent reflection of the sound waves on the bottom that preserves the time–amplitude structure of the incident wave, in the same direction as the incident angle – see Figure 1.1

Comparability the degree of similarity between different sets of results (e.g. seabed classification) originating in different sets of observations or data treatments

Critical angle incident angle (θ_c) above which the sound is totally reflected from the bottom and no longer refracted $\theta_c = \cos^{-1}$(water sound velocity/sediment sound velocity)

Demersal living or staying in the vicinity of the seabed

E1 sum of the energy from the trailing edge of the first bottom echo

E2 sum of the energy from the second bottom echo

Epibenthic fauna and flora living on the **substrate** of the ocean bottom between the low-water mark and the 200-m contour (also epibenthos)

Epifauna benthic fauna living on the **substrate** (as a hard seabed) or on other organisms – compare with **infauna**

Extent the size of the study area or the duration of time under consideration

Facies a body of rock with specified characteristics, such as **grain** size and mineralogy or fossil content

Fauna the animals characteristic of a region, period, or special environment – compare with **flora**

Feature property of an object (e.g. seabed echo) describing it according to one criterion (i.e. dimension), the feature vector gives the (multidimensional) description according to several criteria

Flora the plants characteristic of a region, period, or special environment – compare fauna

Footprint the effective area of the bottom insonified by the beam. This area is often presented as the section of the cone defined by the half-power beam width.

Geo-referenced to geo-reference in the context of mapping is to define an object in physical space using geographic coordinates for a specific geographic projection system, such as latitude and longitude in NAD83, or universal transverse Mercator (UTM) coordinates

GeoTIFF industry-standard graphics image file of **geo-reference** or geo-coded **raster** imagery using Aldus-Adobe's public domain Tagged-Image File Format (TIFF)

Grain the finest level of spatial **resolution** possible in a given dataset, defined by both vector and **raster** data

Grazing angle the angle of the sound path relative to the surface; horizontal path is 0° grazing angle and vertical path is 90° grazing angle. When dealing with a beam that is nearly parallel to the surface it is sometimes more useful to refer to the angle between the beam and the surface, rather than the beam and the surface normal – see **incident angle**

Ground-truth samples taken to cross-check measurements from a set of gear other than the acoustic systems

Habitat the habitat of a plant or animal is the place – locality or physical and biological surroundings – in which it lives. Thus, habitat is different, at some level of detail, for every different species, and many species use more than one habitat during their lifetimes. The term is used loosely in marine "habitat mapping" to refer to the combination of physical and biological attributes that describe a particular place on the seabed

HAC format standard format adopted by ICES for hydroacoustic data exchange – see *ICES Cooperative Research Report No. 278*

Hardness a seabed attribute proportional to the density of the material composing it, which is often also proportional to the acoustic **backscatter** intensity at normal incidence and typically relates to sediment **grain** size and porosity

Heave vertical movement of a platform

Hierarchy system of interconnections or organization wherein the higher levels constrain and control the lower levels to various degrees, depending on the time constraints of the behaviour

Incident angle the angle of the sound path with the vertical; horizontal incidence is 90° and vertical incidence (i.e. nadir) is 0° –see Figures 4.1 and 7.1

Incoherent backscatter random reflections of the sound waves on the bottom that do not preserve the time-amplitude structure of the incident wave, in the same direction as the **incident angle** – see **volume scattering** – see Figure 1.1

Infauna benthic **fauna** living in the **substrate** and especially in a soft seabed – compare with **epifauna**

Kriging a geostatistical unbiased interpolation method minimizing the estimation error based on a function (called the **variogram**) describing the autocorrelation of the studied variable (e.g. a seabed feature, class, etc.)

Macrofauna animals that are large enough to be seen with the naked eye; the **fauna** of a macrohabitat

Maerl Beds A Breton word (sometimes written maërl), referring to loose-lying, normally non-geniculate (i.e. unsegmented because they lack decalcified joints), coralline red algae

Megafauna the largest arbitrary size categorization of animals in a community

Meiofauna a classification of animals that are intermediate in size between those that can easily be seen with the naked eye (**macrofauna**) and those that are microscopic (**microfauna**)

Metric used here as expressing the numerical formulation of a signal or a feature, for example, the volume backscattering strength (Sv) is a metric used in fishery acoustics to express the echo strength per unit of volume on a logarithmic scale.

Microfauna animals that are too small to be seen with the naked eye (zoology); **fauna** limited to a microhabitat (ecology)

Monostatic when the source and the receiver are located at the same location, as in most echosounding systems – compare with **bistatic**

Nadir direction directly below the point of observation, for example directly below the transducer of an echosounding system, i.e. the vertical, angle of incidence from a vertical echosounder is 0°, and the **grazing angle** is 90° – see **incident angle** and **grazing angle**

Normal Incidence Systems typically, single-beam echosounders where the transducer is directed orthogonally towards the seabed and the return signal falls within the **specular zone** – synonymous with **vertical incidence acoustic systems**

Oblique Incidence Systems typically, sidescan sonar and multibeam systems where the transducers face off the vertical axis

Patchiness property of the spatial organization of a given variable (e.g. seabed roughness, animal abundance) to occur in discrete clumps in space. This property is reflected in the autocorrelation function or **variogram** of the variable, which then differs from that of a randomly distributed variable

Ping acoustic jargon referring to the acoustic signal corresponding to a single transmission/ reception cycle from an echosounder or a sonar, for example, one ping per second (1 pps)

Pitch inclination of the platform in the longitudinal plane

Pulse the short acoustic wave train transmitted by the echosounding systems (generally on the order of milliseconds)

Pulse duration the time (in seconds) of the acoustic pulse

Pulse length the length (in metres) of the acoustic pulse, often misused for **pulse duration**

Raster an image type format describing a pattern of evenly spaced rows and columns of data, here as geographical coordinates associated with a measurement variable, such as depth

Repeatability the degree of similarity in the observations or the results of an analysis resulting from the use of the same material and methods at different times (e.g. repeated surveys)

Resolution finest size of measurement or product (e.g. map) unit; **grain** size for spatial data

Roll inclination of the platform in the transverse plan

Roughness small-scale, three-dimensional topography of a seabed surface given by its small-scale features, such as ripples, holes, stones, **epibenthic** macrofauna, and macroflora, that contribute to the acoustic **backscatter** intensity at oblique observation angles

Rugosity surface area standardized by planar area; can be calculated in two (vector) and three (**raster**) dimensions and the value scales with the measurement distance (**grain**) of the observational data

Scale the size of a structure or observation window in space or time, characterized by both **grain** and **extent** (e.g. spatial scales of some benthic species assemblages); not to confound with the scale of a map as used in drawings or geography to give the ratio of the drawing or map relative to the real object

Side lobe a direction of a **beam pattern** of a transducer, away from the main axis (main lobe), where sensitivity is increased relative to the adjacent directions

Specular zone range of angles of incidence where direct and coherent reflection from the seabed is recorded from objects larger than the acoustic wavelength (< ~20°) – see **coherent backscatter**

Substrata one or more layers of sediment of different composition lying beneath the seabed surface

Substrate the physical nature of a seabed, such as sand, mud, rocks, that is the physical support of benthic life

Supervised classification a classification approach where classes are known *a priori*, often from a **ground-truth** training dataset, and used to classify the unclassified samples

Support (sample) geostatistical term referring to the size of the sample unit, such as the size of a quadrat or an acoustic footprint

Unsupervised classification a classification approach where classes are not known *a priori*, and the samples to classify are partitioned into classes according to their similarity in features

Variogram geostatistical (structure) function expressing the sample semi-variance vs. the distance (and the direction) between the samples; it is experimental when drawn from the observations and modelled when a function is fitted to the data

Zenith direction directly above the point of observation

Acronyms

AGDS Acoustic Ground Discrimination System, jargon acronym often used in connection with SBES acoustic seabed classification systems

ANN Artificial neural networks

ASC Acoustic seabed classification

ACSII American standard code for information interchange

ASM Angular second moment, also Haralick texture operator; a measure of homogeneity of an image

CEFAS Centre for Environment, Fisheries and Aquaculture Science

DGPS Differential global positioning system

EUNIS EUropean Nature Information System

FTC ICES Fisheries Technology Committee

GIS Geographic information system

GPS Global positioning system

HAC HydroACoustic standard data format

HSX Data format used for sidescan sonar systems

IBS International Biometric Society

ICES International Council for the Exploration of the Sea

IDR Instantaneous dynamic range of acoustic backscatter

IHO International Hydrographic Organization

LIDAR LIght Detection And Ranging

MBES Multibeam echosounder

MHC ICES Marine Habitat Committee

MLP Multilayer perceptron

PDSSS Phase-difference sidescan sonar system

SBES Single-beam echosounder

SGASC ICES Study Group on Acoustic Seabed Classification

SNR Signal-to-noise ratio

SOM Self-organizing feature maps

SONAR Sound navigation and ranging

SPI Sediment profile imagery

SSS Sidescan sonar system

TVG Time varied gain; the gain function echosounding systems use to compensate for spreading and absorption of the sound wave from its source point

USBL Ultra short baseline positioning systems

VES Vertical echosounder

WGEXT ICES Working Group on Marine EXTractions

WGFAST ICES Working Group on Fisheries Acoustics, Science, and Technology

WGMHM ICES Working Group on Marine Habitat Mapping

XTF eXtended Triton Format; a Triton Imaging, Inc. file format for recording various types of hydrographic survey data, including sidescan sonar, shallow seismic and multibeam bathymetry, as well as associated position and attitude information. XTF is the most commonly used format for this type of information in the hydrographic survey industry.

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Annex 1 Terms of reference for the Study Group on Acoustic Seabed Classification (SGASC)

The Study Group on Acoustic Seabed Classification (SGASC), Chair: John Anderson, Canada, will meet in Gdynia, Poland, on 16 and 17 April 2004 to:

a) Review and evaluate progress in:

- i) The theory of sound scattering from the seabed and the application of acoustic seabed classification systems;
- ii) The development of standardized survey designs and verification methods;
- iii) The development of standardized protocols for data collection, data quality and display, data effectiveness for classification, segmentation and classification methods and criteria;
- iv) The utilization of acoustic seabed classification products in habitat mapping and other marine activities.

b) Evaluate progress towards publishing an ICES Cooperative Research Report on "Acoustic Seabed Classification in Marine Environments".

SGASC will report to the Fisheries Technology, Marine Habitat and ACE Committees.

Annex 2 Further reading in acoustical sound-scattering from the seabed

This list of additional scientific references on hydro-acoustics not cited in the report is provided for readers particularly interested in theoretical and practical considerations of sound-scattering from the seabed.

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